Proceedings of the XVIII International Linear Accelerator Conference

26–30 August 1996
Geneva Switzerland

C. Hill, M. Vretenar Editors
Volume 1
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Proceedings of the XVIII International Linear Accelerator Conference

August 26–30, 1996
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Volume 1

EDITORS: C. Hill
M. Vretenar

European Organization for Nuclear Research
Abstract

These Proceedings cover the whole field of linear accelerators, from its original and continuing role in particle physics research to the wide range of applications found today in many other disciplines and technologies. The contributions were deliberately spread among the different conference sessions in order to maintain a broad interest.

The topics covered include: the design, construction and control of linear accelerators and the associated technology; dedicated test facilities, injection, wakefields, bunching, halo, dynamics, radio-frequency (RF), electron and ion accelerators, (laser) ion sources; active alignment, beam steering and spot size; simulation, monitoring and diagnostics; a description of the performance and current status of many machines, including proposed ones such as CLIC, the NLC and TESLA; applications to medical diagnosis and radiotherapy; use in the treatment and sterilisation of materials (including food) and in the reprocessing of radioactive waste; use as potential suppliers of energy.
Foreword

The Eighteenth International Linac Conference (Linac96) was held at the Penta Hotel, Geneva, Switzerland, from August 26 until August 30, 1996. The conference was attended by 319 participants from 16 countries. At the International Organizing Committee meeting held in Dallas in May 1996, there was a strong desire to have an industrial exhibition. This was organized and held in the hotel from Monday morning to Thursday afternoon with ten exhibitors from various countries.

The general format of the programme followed, with slight modifications, the tradition of this conference: no parallel sessions, morning sessions with invited talks and afternoon poster sessions. There were altogether more than 120 proposals for invited talks from the International Advisory Committee and the Programme Committee. That, and in addition the steady extension of the field of electron and ion accelerators, led to the decision to include, besides the traditional 30 minute presentations, also 20 minute talks. This allowed in total 40 invited papers (three in the afternoon before the poster sessions). The electron and ion topics were nearly equally distributed amongst the invited talks and were smoothly mixed in the sessions. In total there were about 230 posters presented.

Following the PAC and ICHEA Conferences in Dallas in 1995 and the EPAC in 1996, we have decided to publish the proceedings in three forms, two of which are being used for the first time at a Linac Conference:

1. The traditional paper version of the Proceedings will be published and distributed to the Conference participants, as well as to selected libraries. This is the official record of the Conference.
2. An electronic version of the Proceedings was available on the World-Wide Web soon after the end of the Conference.
3. A higher quality electronic version of the Proceedings on a CD-ROM will be distributed to the participants.

WWW was used extensively for disseminating the different announcements before the conference.

The last Compendium of Linacs was published in 1976. We intended to produce a new one, an idea that was welcomed by the International Committee. Now, after 20 years, a new and updated version was prepared for the Linac96 Conference. Medical and industrial linacs are not included, the objective of this Compendium being to present all scientific linacs around the world, either in operation, in construction or proposed. We have included 176 “scientific” linacs, distributed over 3 continents (61 in America, 37 in Asia and 78 in Europe).

The Conference started off with a welcome cocktail on Sunday evening (25th August). On Wednesday afternoon we had an excursion to visit the region of Gruyère with different programmes showing typical Swiss landscapes and activities. Participants were free to choose between a visit to the old town of Gruyères with its famous castle and art exhibition, to visit the Nestlé chocolate factory in Broc, to have a walk from the village of Moléson (about 5 km from Gruyères) on the “Sentier des Fromageries” (path of the cheese makers) with a visit to a 17th century cheese-making cottage in Moléson. For good mountain walkers there was a special programme with a tour from the village of Moléson to the top of the Moléson mountain
(2002 m) and descent by cable-car afterwards or the inverse. In the evening, we had a cocktail and dinner in the ancient castle Château d'Oron.

The Companions' Programme included also a variety of activities. It started off on Monday with a Geneva tour through the old town and other important places. Tuesday saw a trip "Salt, bread and wine" with a visit to the "Bread and Wheat House" in Echallens, a visit to a salt mine and to a wine cellar with tasting of regional wines. A boat trip from downtown Geneva to the mediaeval town of Yvoire in France took place on Thursday, in parallel with a full-day excursion to Chamonix, featuring an easy mountain walk from the Plan des Aiguilles (2310 m) to Montenvers (1913 m) beside the magnificent glacier "Mer de Glace".

The traditional conference dinner took place in the Mövenpick Hotel on Thursday evening, starting with a talk by Edward A. Knapp on work done at the Santa Fe Institute, with the title "New Directions for Science". The State of Geneva was represented by Philippe Joye, State Counsellor, and the Commune of Meyrin by its Mayoress, Mrs. Madeleine Bernascon. Swiss music, with typical instruments and songs, was presented by a folklore group. This evening was attended by some 340 participants and companions.

A visit to CERN was arranged on Friday afternoon, with a short introductory talk by Kurt Hübner, the CERN Director of Accelerators. The guided tour presented Linac 2 for protons, Linac 3 for Pb-ions, the LIL linac for electrons and positrons and one of the huge LEP experiments.

The International Organizing Committee met on August 27 and decided that the 20th International Linac Conference will be organized by SLAC in the year 2000 (reminder: the next one, in 1998, will be organised by Argonne). A strong option has been retained for Korea for the year 2002. The rhythm of two conferences in the US and two outside seems to find strong support.

Thanks are due to our sponsors [Alge Elektronik AG (Austria), Leclanché Capacitors (Switzerland), Olivetti SA (Switzerland), Salzgeber-Mechatronik (Austria), Telsa-Electronique SA (Switzerland) and VAT Vakuumventile AG (Switzerland)] and the local authorities (the Commune of Meyrin and the Government of the Republic and Canton of Geneva) who supported us, in particular with the wine for the welcome cocktail, the inauguration of the Industrial Exhibition and the conference dinner. We are grateful to the Programme Committee, the Local Organizing Committee, the PS Secretariat and, of course, to CERN and especially to all those who participated in the publication of these proceedings, for their excellent work.

H.D. Haseroth
Conference Chairman
CONFERENCE ORGANIZATION

Conference Chairman: H.D. Haseroth CERN

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26–30 August 1996
Geneva Switzerland
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Proceedings of the XVIII International Linear Accelerator Conference

August 26–30, 1996
Geneva, Switzerland

Volume 1

EDITORS: C. Hill
M. Vretenar

European Organization for Nuclear Research
Abstract

These Proceedings cover the whole field of linear accelerators, from its original and continuing role in particle physics research to the wide range of applications found today in many other disciplines and technologies. The contributions were deliberately spread among the different conference sessions in order to maintain a broad interest.

The topics covered include: the design, construction and control of linear accelerators and the associated technology; dedicated test facilities, injection, wakefields, bunching, halo, dynamics, radio-frequency (RF), electron and ion accelerators, (laser) ion sources; active alignment, beam steering and spot size; simulation, monitoring and diagnostics; a description of the performance and current status of many machines, including proposed ones such as CLIC, the NLC and TESLA; applications to medical diagnosis and radiotherapy; use in the treatment and sterilisation of materials (including food) and in the reprocessing of radioactive waste; use as potential suppliers of energy.
Foreword

The Eighteenth International Linac Conference (Linac96) was held at the Penta Hotel, Geneva, Switzerland, from August 26 until August 30, 1996. The conference was attended by 319 participants from 16 countries. At the International Organizing Committee meeting held in Dallas in May 1996, there was a strong desire to have an industrial exhibition. This was organized and held in the hotel from Monday morning to Thursday afternoon with ten exhibitors from various countries.

The general format of the programme followed, with slight modifications, the tradition of this conference: no parallel sessions, morning sessions with invited talks and afternoon poster sessions. There were altogether more than 120 proposals for invited talks from the International Advisory Committee and the Programme Committee. That, and in addition the steady extension of the field of electron and ion accelerators, led to the decision to include, besides the traditional 30 minute presentations, also 20 minute talks. This allowed in total 40 invited papers (three in the afternoon before the poster sessions). The electron and ion topics were nearly equally distributed amongst the invited talks and were smoothly mixed in the sessions. In total there were about 230 posters presented.

Following the PAC and ICHEA Conferences in Dallas in 1995 and the EPAC in 1996, we have decided to publish the proceedings in three forms, two of which are being used for the first time at a Linac Conference:

1. The traditional paper version of the Proceedings will be published and distributed to the Conference participants, as well as to selected libraries. This is the official record of the Conference.
2. An electronic version of the Proceedings was available on the World-Wide Web soon after the end of the Conference.
3. A higher quality electronic version of the Proceedings on a CD-ROM will be distributed to the participants.

WWW was used extensively for disseminating the different announcements before the conference.

The last Compendium of Linacs was published in 1976. We intended to produce a new one, an idea that was welcomed by the International Committee. Now, after 20 years, a new and updated version was prepared for the Linac96 Conference. Medical and industrial linacs are not included, the objective of this Compendium being to present all scientific linacs around the world, either in operation, in construction or proposed. We have included 176 “scientific” linacs, distributed over 3 continents (61 in America, 37 in Asia and 78 in Europe).

The Conference started off with a welcome cocktail on Sunday evening (25th August). On Wednesday afternoon we had an excursion to visit the region of Gruyère with different programmes showing typical Swiss landscapes and activities. Participants were free to choose between a visit to the old town of Gruyères with its famous castle and art exhibition, to visit the Nestlé chocolate factory in Broc, to have a walk from the village of Moléson (about 5 km from Gruyères) on the “Sentier des Fromageries” (path of the cheese makers) with a visit to a 17th century cheese-making cottage in Moléson. For good mountain walkers there was a special programme with a tour from the village of Moléson to the top of the Moléson mountain.
(2002 m) and descent by cable-car afterwards or the inverse. In the evening, we had a cocktail and dinner in the ancient castle Château d’Oron.

The Companions’ Programme included also a variety of activities. It started off on Monday with a Geneva tour through the old town and other important places. Tuesday saw a trip “Salt, bread and wine” with a visit to the “Bread and Wheat House” in Echallens, a visit to a salt mine and to a wine cellar with tasting of regional wines. A boat trip from downtown Geneva to the mediaeval town of Yvoire in France took place on Thursday, in parallel with a full-day excursion to Chamonix, featuring an easy mountain walk from the Plan des Aiguilles (2310 m) to Montenvers (1913 m) beside the magnificent glacier “Mer de Glace”.

The traditional conference dinner took place in the Mövenpick Hotel on Thursday evening, starting with a talk by Edward A. Knapp on work done at the Santa Fe Institute, with the title “New Directions for Science”. The State of Geneva was represented by Philippe Joye, State Counsellor, and the Commune of Meyrin by its Mayoress, Mrs. Madeleine Bernasconi. Swiss music, with typical instruments and songs, was presented by a folklore group. This evening was attended by some 340 participants and companions.

A visit to CERN was arranged on Friday afternoon, with a short introductory talk by Kurt Hübner, the CERN Director of Accelerators. The guided tour presented Linac 2 for protons, Linac 3 for Pb-ions, the LIL linac for electrons and positrons and one of the huge LEP experiments.

The International Organizing Committee met on August 27 and decided that the 20th International Linac Conference will be organized by SLAC in the year 2000 (reminder: the next one, in 1998, will be organized by Argonne). A strong option has been retained for Korea for the year 2002. The rhythm of two conferences in the US and two outside seems to find strong support.

Thanks are due to our sponsors [Alge Elektronik AG (Austria), Leclanché Capacitors (Switzerland), Olivetti SA (Switzerland), Salzgeber-Mechatronik (Austria), Telsa-Electronique SA (Switzerland) and VAT Vakuumventile AG (Switzerland)] and the local authorities (the Commune of Meyrin and the Government of the Republic and Canton of Geneva) who supported us, in particular with the wine for the welcome cocktail, the inauguration of the Industrial Exhibition and the conference dinner. We are grateful to the Programme Committee, the Local Organizing Committee, the PS Secretariat and, of course, to CERN and especially to all those who participated in the publication of these proceedings, for their excellent work.

H.D. Haseroth
Conference Chairman
CONFERENCE ORGANIZATION

Conference Chairman: H.D. Haseroth CERN

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M. Inoue         ICR        Y. Yamazaki        KEK
H. Klein         IAP        S. Yu        LBNL
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FR101 High Luminosity Muon Collider Design
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FR102 Advanced RF Power Sources for Linacs
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FR103 Role of Lasers in Linear Accelerators
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INVITED TALK SESSION: Friday, August 30 10:00–12:30
Chairman: G. A. Loew
FR201 Status of ALPI and Related Developments of Superconducting Structures
G. Fortuna, G. Bisoffi, A. Fucco, A. Lombardi, V. Palmieri, A. Pisent, A. M. Porcellato
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Invited Talk Session MO1

Chairman: N. Angert

Monday, August 26, 1996
THE CREATION OF SLAC LEADING TO 30 YEARS OF OPERATION

W.K.H. Panofsky
Stanford Linear Accelerator Center, Stanford University
Stanford, California 94309

The first beam passing through the entire three kilometer length of SLAC was obtained on May 21, 1966. We are therefore commemorating 30 years of operation of that machine. I doubt that this is a record for an accelerator but it is a very long time. Usually when an individual of great age is being asked to what primary factor he attributes his longevity, the normal answer is "virtue and clean living" and most of the time he is lying. I hope that after trying to describe some of the reasons for SLAC's long life I will not be accused of the same. Ever since the original proposal to build SLAC, dated April 1957, was made, I have been asked how long SLAC is apt to endure. My answer has always been: "10–15 years unless somebody has a good idea." Indeed the longevity of SLAC is due to a plethora of good ideas, essentially none of which were anticipated at the time when the machine was originally proposed.

Although SLAC was the outgrowth of a long line of development in the linear accelerator field, the actual proposal to build a machine of this magnitude was a major departure from the customs then prevalent among the practitioners of accelerator construction and the users of accelerators for research in nuclear and particle physics using machines operating at the energy frontier. Indeed SLAC was a direct outgrowth from a series of electron accelerators pioneered by the great physicist William W. Hansen. Hansen's first machine, the MARK I accelerator at Stanford, produced a 6 MeV electron beam and it is famous for having generated the shortest report ever written for a government agency which in its entirety read: "We have accelerated electrons." Then followed the MARK II and MARK III, the former used for nuclear physics, and the latter 100 meters in length, supported a very successful high energy physics program. In parallel there had been the development of hadron linear accelerators, pioneered by the work of Sloan and Lawrence before the war and then converted to practical use by incorporating the drift tube design developed by Alvarez and collaborators.

While SLAC, in terms of its fundamental radiofrequency design, was a simple extrapolation of the disk loaded accelerator concept pioneered by Bill Hansen, it incorporated many concepts that were unprecedented at the time. But it should also be recognized that the 30 years of operation of SLAC covered an installation which underwent many changes. Table 1 shows the sequence of "reincarnations" of the machine which I shall discuss further. Figure 1 shows the initially proposed target area layout and Fig. 2 today's reality. The initial proposal provided for two beams, one to study primary interactions of the electron beam, notably elastic scattering from protons and neutrons. The second was to be a producer of secondary beams for research similar to that then prevalent at hadron accelerators. Indeed this became the minimum mission of SLAC but the facility was amplified by a succession of colliding beam storage rings, and by the linear collider. In addition, the basic performance of the machine was upgraded by the SLAC energy development project (SLED), by a battery of higher power microwave sources and by polarized electrons. In 1969 SLAC carried out an extensive conceptual design study to convert the room temperature structure to a superconducting accelerator a highly premature undertaking. A SLAC proposal, the Recirculating Linear Accelerator (RLA), using the three kilometer structure repeatedly two loops of with recirculating magnets, was not accepted by the sponsoring agency. The RLA was to be both an energy doubler and a duty cycle multiplier at fixed energy.

Table 1: SLAC Major Milestones and Upgrades

<table>
<thead>
<tr>
<th>Year</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957 (Apr)</td>
<td>SLAC proposed to U.S. Government</td>
</tr>
<tr>
<td>1961 (Sept.)</td>
<td>SLAC authorized by U.S Congress</td>
</tr>
<tr>
<td>1962 (July)</td>
<td>Groundbreaking</td>
</tr>
<tr>
<td>1966 (May)</td>
<td>Beam through full length</td>
</tr>
<tr>
<td>1967 (April)</td>
<td>Commence Research Program at SLAC</td>
</tr>
<tr>
<td>1969</td>
<td>Superconducting Conversion Study (not built)</td>
</tr>
<tr>
<td>1971 (June)</td>
<td>Recirculating Linear Accelerator proposed (not built)</td>
</tr>
<tr>
<td>1973</td>
<td>SLED Energy Development (SLED) proposed</td>
</tr>
<tr>
<td>1975–80</td>
<td>SLED installation</td>
</tr>
<tr>
<td>1970</td>
<td>SPEAR construction started</td>
</tr>
<tr>
<td>1972</td>
<td>SPEAR operation started</td>
</tr>
<tr>
<td>1976</td>
<td>PEP construction started</td>
</tr>
<tr>
<td>1980 (April)</td>
<td>PEP operation started</td>
</tr>
<tr>
<td>1973</td>
<td>SSRL started parasitic research</td>
</tr>
<tr>
<td>1979</td>
<td>SSRL started 50–30 SPEAR operation</td>
</tr>
<tr>
<td>1984</td>
<td>SLC started 100% SPEAR operation</td>
</tr>
<tr>
<td>1984</td>
<td>SLC construction started</td>
</tr>
<tr>
<td>1987</td>
<td>SLC full operation</td>
</tr>
<tr>
<td>1987</td>
<td>First polarized electron gun</td>
</tr>
<tr>
<td>1992</td>
<td>First polarized photocathode at SLAC</td>
</tr>
<tr>
<td>1992</td>
<td>Polarization &gt;80% obtained</td>
</tr>
<tr>
<td>1994</td>
<td>B-factory proposed to Government</td>
</tr>
<tr>
<td>1994</td>
<td>B-factory construction started</td>
</tr>
<tr>
<td>1998</td>
<td>B-Facility completion anticipated</td>
</tr>
</tbody>
</table>

Fig. 1 The proposed end station.

But there were other factors which were unprecedented initially. SLAC was probably the first major accelerator whose use was what I called "facility centered." That term described a machine where the research applications were centered on a group of large and generally multipurpose detectors. Prior to SLAC, most particle experiments carried out at proton accelerators were what I might call "building block" experiments; that is experiments where families of small particle detectors were clustered around the target surrounded by a variety of absorbers and analyzing magnets and where time
coincidences provided the major signature for understanding the events produced. This approach was not feasible at SLAC due to the small cross-sections of events of interest, the low duty cycle of the machine which made coincidence observations precarious, and due to the large "soft" background which is generated as a result of the electromagnetic cascade induced by high energy electrons. As a result the construction of the SLAC accelerator proper, which is well documented in the famous "blue book" edited by Richard Neal (1968) was paralleled by the construction of a family of large detectors, listed in Table 2, that became available at the time of initial operation of SLAC. Today in the age of large, almost 4 π steradian detectors surrounding interaction points of colliding beam machines, this mode of operation has become commonplace, but it was a rarity in its day.

![Fig. 2 The end station reality.](image)

**Table 2: Initial complement of experimental facilities at SLAC**

<table>
<thead>
<tr>
<th>INITIAL COMPLEMENT OF EXPERIMENTAL FACILITIES AT SLAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-scattering spectrometers</td>
</tr>
<tr>
<td>20 GeV</td>
</tr>
<tr>
<td>8 GeV</td>
</tr>
<tr>
<td>1.6 GeV</td>
</tr>
<tr>
<td>2-meter streamer chamber</td>
</tr>
<tr>
<td>40&quot; rapid cycling bubble chamber</td>
</tr>
<tr>
<td>General Purpose magnet as hadron spectrometer</td>
</tr>
<tr>
<td>K₁ beam for lepton asymmetry observation</td>
</tr>
<tr>
<td>Beam transport for heavy lepton searches</td>
</tr>
</tbody>
</table>

The second exceptional circumstance accompanying the operation of SLAC was very high peak and also very high average power of the beam (exceeding one megawatt). Thus stopping the beam safely in a manner not generating excessive backgrounds and providing for high power beam collimation resulted in design requirements not hitherto encountered to a significant extent in particle accelerators. Figure 3 shows what happens in a few seconds if the beam strikes a block of copper. The "melt-out" occurs at the maximum of the electron–positron shower. A tungsten block shatters almost instantaneously and concrete disintegrates.

![Fig. 3 Effect of beam on copper target.](image)

The third innovation was the needed emphasis on rapid learning from poor performance and on operational reliability. SLAC in essence is composed of 240 sequential radiofrequency linear accelerators each properly phased to high precision and timed by its pulsing system. While a failure of one of these units does not necessarily lead to loss of beam, the requirement for the simultaneous reliable operation of many subsystems was unprecedented. Let me give one example of how the reliability, and equally important, to be able to learn rapidly from failures, affected a key design choice. We considered the manufacture of the disk loaded microwave structure by two alternative technologies: (1) brazing of rings and disks, which were separately machined, shown in Fig. 4; and (2) electroforming, that is machining a mandrel comprising the space inside the accelerator structure and then electroplating the structure on to this mandrel followed by dissolving the mandrel chemically. A third method (used in the successful MARK III accelerator), shrink-fitting the disks to a cylinder of uniform internal diameter was rejected and developed difficulties after several years of operation due to cold flow of the copper components. The second system was eventually rejected also, not because it would not work, it did. The reason was that any errors made during the manufacture or if future difficulties became manifest during operation, then the feedback for corrective action would be too long. The electroforming of one section required one to two months. However, the technique chosen, joining the links and disks together, required the brazing of 200,000 joints. It speaks well for the quality control of that brazing operation, carried out largely by part-time employees, that over the full 30 years of operations, none of these 200,000 joints has ever leaked. A complex system of fast acting valves, vacuum pumps and microwave windows maintained the vacuum with only five vacuum losses in 30 years.

Precision both in the manufacture of accelerator sections and the alignment were unprecedented in accelerator practice. Machining tolerances in manufacture of accelerator parts were ±0.2 mils and ±0.0 mils and were further improved by individual trimming of sections using radiofrequency measurements. Alignment was provided through a laser beam diffracted by a series of Fresnel lenses that were inserted into the large vacuum pipe supporting the accelerator structure. This system proved very valuable in view of the frequent
ground-motions, depicted in Fig. 5. Groundmotion along the accelerator length continued to move in the same direction, similar to CERN experience. The system saved months of realignment after the big earthquake on October 17, 1989.

Fig. 4 Structure brazening and components.

![Vertical Displacement of Linac Tunnel](chart.png)

**Fig. 5 Background motion.**

SLAC faced a dilemma regarding its control system at the time the laboratory was created: are computers here to stay? As a result the control system was designed using the then computerized systems still in their infancy but with backup systems permitting operation from a multiplicity of manned control points. The backup system was used until suitable computers could be obtained, but was never used thereafter.

Finally there was the transition of operation of linear accelerators from past proprietary machines, run for the benefit of the faculty and staff of a single institution, to a national facility available to any proponent on the basis of merit of a proposed experiment measured by technical feasibility and promise of results. This method of operation is now standard in all the great laboratories of the world, in particular those operated by consortia of universities, or consortia of nations such as CERN. It was the exception in 1957, in particular for laboratories operated by a single university in this case Stanford.

SLAC was unique in technology relevant to the major accelerators then operating at the frontier of energy. There was very little experience in industry on most of the specific technologies required for creating SLAC. We adopted the policy that while we relied on industry to supply many essential components, it was necessary to maintain a limited production capacity in-house to make what SLAC needed. As a result industry did relatively little development but only manufacture SLAC's needs, and SLAC could fill in even for production in case difficulties were encountered when industry either failed to make satisfactory initial proposals or ran into difficulties in producing items of sufficient quality or on schedule.

SLAC was built on schedule, on budget and exceeding the advertised performance. This record is hardly unique in the world of high energy accelerators but it contrasted most favorably with the record of most high technology developments in the United States, particularly in nuclear reactors, major military systems, and space ventures; a record not unnoticed by the government agencies supporting SLAC.

Because of the facility-centered nature of SLAC, we felt it necessary to build up a very strong in-house engineering and scientific team in order to support the construction, operation, and upgrading of the accelerator itself, as well as to support the experimenters. During the early operating period of SLAC, the experimental physics community was generally unfamiliar with the design, construction and management of large experimental facilities, and therefore the inhouse group had to carry a substantially larger part of the burden of experimental facility construction than is the case today with its monster scientific collaborations.

The performance of the SLAC complex is difficult to describe by simple parameters, and the figures of merit for performance shifted during the various phases of operation.

In the original proposal SLAC's energy was to be 10-20 GeV. Shortly after turn-on its energy gradually improved, as shown in Table 3. The only surprise on turn-on was the discovery of multi-section, multi-bunch beam break-up (BBU). This phenomenon was understood almost immediately and remedial measures were taken. Since SLAC is a constant gradient rather than a constant impedance structure, the BBU was less severe since the variable impedance of the structure also implies a gradient in the frequencies of the higher order modes relevant to the beam break-up. Remedies consisted of dispersing the frequency of higher order modes among successive sections, by small deformation of the structure and by strengthening the magnetic focusing system. Figure 6 shows the gain in peak beam current made possible by these measures.

The energy of the machine has been continually increased over the last 30 years. This increase was achieved by improvement in klystron performance, introduction of the SLAC energy development scheme (SLED), and by replacement of the klystrons with three generations of higher power tubes. Peak powers attained by these successive families of klystrons were 24, 36 and 64 megawatts, respectively. Electrical breakdown has not been a factor limiting the attainable energy of the machine.

During its early phases SLAC served only a series of fixed target experiments and the pulse repetition rate was divided among different target areas through a pulsed beam transfer arrangement at the head of the magnetic beam distribution system, called the beam switchyard. This shared pulsed beam delivery system proved very efficient because some experiments were not suited for receiving the full pulse
repetition rate. In particular two major bubble chamber facilities which were used for the first two decades of SLAC operation were suited for a pulse rate of up to 2 per second and up to 15 per second respectively, and thus could receive beams without significant impact on other uses. Each beam could be individually tailored to the experimenters’ need in respect to repetition rate, energy and intensity. Energy variability on a pulse by pulse basis was achieved by triggering each klystron pulse on a programmed basis.

Table 3: Energy records

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Date</th>
</tr>
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<tbody>
<tr>
<td>18.4</td>
<td>June 2, 1966</td>
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<td>19.0</td>
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</tr>
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<td>20.16</td>
<td>January 10, 1967</td>
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<td>August 16, 1968</td>
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<tr>
<td>21.0</td>
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</tr>
<tr>
<td>21.5</td>
<td>April 27, 1969</td>
</tr>
<tr>
<td>22.10</td>
<td>August 23, 1970</td>
</tr>
<tr>
<td>22.28</td>
<td>July 25, 1973</td>
</tr>
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<td>22.74</td>
<td>November 11, 1974</td>
</tr>
<tr>
<td>33.4</td>
<td>March 5, 1980</td>
</tr>
<tr>
<td>53.0</td>
<td>January, 1987</td>
</tr>
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</table>

The increase in energy due to SLED operation was accompanied by a decrease in average beam due to the shortened pulse length inherent in SLED operations. Moreover, average beam delivery has tended to shrink recently, partially due to budget limits which forced operations to lower pulse repetition rates and shortened operating periods.

After the initial operating period solely dedicated to fixed target physics until 1972, operation became even more complex with the advent of storage rings. Construction of SPEAR was started in 1970. SPEAR was never formally authorized as a construction project, but was built in a housing of portable shielding blocks and its hardware was constructed as an internally funded equipment project. SPEAR was possibly the most cost-effective high energy collider ever built leading to extremely important physics with a relatively modest construction effort and only a minor impact on the "pulse economy" of the accelerator. SPEAR was followed by PEP which was a formal construction project housed in an excavated tunnel and provided six interaction halls for experiments. Figure 2 shows the layout of the accelerator with the target area, the two storage rings, and the SLAC Linear Collider, which was to follow.

The beam delivery record of the storage rings is difficult to quantify. SPEAR generally delivered on the order of 100 inverse nanobarns (10^{20} cm^{-2}) per day, and almost an order of magnitude higher per interaction region. After SPEAR was initiated, its usefulness for synchrotron radiation became manifest and a separate Synchrotron Radiation Laboratory was organized to utilize both x-ray beams from the bending magnets as well as to generate higher brightness beams from insertion devices. The use of synchrotron radiation increased sharply and produced extremely valuable results. In consequence it was decided eventually to construct a separate electron synchrotron injector into SPEAR since injection from the main accelerator, which by that time became a 50 GeV linear accelerator, into a 2 GeV storage ring was both inefficient and constituted an undue load on the main machine. SSRL has been a very successful separate operation which is managed as a division of SLAC but no longer interacts technically with the beam delivery of the linear accelerator and its associated storage rings and linear collider.

In 1984 SLAC decided to go beyond the energy region of the two storage rings at SLAC by starting construction of a linear collider (SLC). I will not describe the technical characteristics of that device. It was designed from the beginning to provide collisions between electrons and positrons of 50 GeV each in order to bring the intermediate boson Z^0 under direct investigation. The introduction of the SLC generated a crisis into the continuity of SLAC operations. While the soundness of the fundamental principle of the SLC was never in doubt the detailed difficulties in commissioning the SLC were considerably larger than envisaged. The SLC requires a quality of operation of the SLAC two-mile linear accelerator that is much higher than that incorporated into its basic design. Required emittance volumes of the beam for successful SLC operation are considerably smaller than those needed for fixed target
experiments and also for storage ring injection. The various causes of emittance growth had to be mitigated in steps. Causes of beam jitter had to be investigated and had to be remediated by improvements of power supplies and by the introduction of active feedback systems reducing beam fluctuations. The beam optics of the arc bending magnet system required correction and the final focus system, with its large demagnification was improved. Overall, reliability standards of components had to be improved by a large factor relative to those required for an operation of the linear accelerator in its previous mode. As a result, the quality of beam delivery of the SLC operating at the Z^0 peak has improved; Table 4 shows the record.

A major addition to SLAC’s basic utility was the use of polarized electron beams. This was introduced first in 1970 when a polarized gun was introduced. This device was based on the principle of ionizing electrons from an atomic lithium beam which had been spin-aligned and separated in an inhomogeneous magnetic field. Since 1992 the SLAC linear accelerator and SLAC have been operated almost exclusively with polarized electrons using electrons emitted by a gallium arsenide cathode illuminated by laser light of circular polarization. The amount of polarization attainable from such cathodes has recently been improved to exceed 80 percent by the use of strained gallium arsenide material in which the structure of valence band electrons of the cathode material is no longer degenerate due to the external strain. The availability of a high polarization electron beam has been of enormous value to SLC experiments and has also revitalized the fixed target program by making it possible to isolate spin dependent form factors of the nucleons. Polarized targets are also generally used in such experiments. The performance summary of the SLAC polarized electron source is given in Table 5 and Fig. 7.

Table 4: SLAC SLC/SLD performance for 1992–1995

<table>
<thead>
<tr>
<th></th>
<th>SLD</th>
<th>SLD</th>
<th>SLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp’t Logging</td>
<td>51%</td>
<td>63%</td>
<td>56%</td>
</tr>
<tr>
<td>Machine Develop.</td>
<td>9%</td>
<td>6%</td>
<td>4%</td>
</tr>
<tr>
<td>Alternate Program</td>
<td>1%</td>
<td>1%</td>
<td>4%</td>
</tr>
<tr>
<td>Tuning</td>
<td>19%</td>
<td>11%</td>
<td>10%</td>
</tr>
<tr>
<td>Unsched Down</td>
<td>18%</td>
<td>17%</td>
<td>23%</td>
</tr>
<tr>
<td>Sched. Off</td>
<td>2%</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>Total Hours</td>
<td>2616</td>
<td>4079</td>
<td>5065</td>
</tr>
<tr>
<td>Total Z (x 1000)</td>
<td></td>
<td>10</td>
<td>55.7</td>
</tr>
<tr>
<td>Ave. Lum (Z/hr)</td>
<td>7.5</td>
<td>21.7</td>
<td>35.3</td>
</tr>
<tr>
<td>Approx. Polarization</td>
<td>21%</td>
<td>65%</td>
<td>79%</td>
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Table 5: Performance Summary for the SLAC Polarized Electron Source

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
<th>Cathode Material</th>
<th>Polarization (%)</th>
<th>Hours*</th>
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<tr>
<td>1992</td>
<td>SLD</td>
<td>Ga-As</td>
<td>22</td>
<td>4000</td>
</tr>
<tr>
<td>1992</td>
<td>E142 (n)</td>
<td>Al-Ga-As</td>
<td>40</td>
<td>1100</td>
</tr>
<tr>
<td>1993</td>
<td>SLD</td>
<td>Strained Ga-As</td>
<td>63</td>
<td>5900</td>
</tr>
<tr>
<td>1993/1994</td>
<td>E143 (p)</td>
<td>Strained Ga-As</td>
<td>84</td>
<td>2200</td>
</tr>
<tr>
<td>1994/1995</td>
<td>SLD</td>
<td>Strained Ga-As</td>
<td>77</td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td></td>
<td>18,600</td>
</tr>
</tbody>
</table>

* Availability ≥ 98%

Fig. 7 The polarization versus wavelength for three different cathodes that have run on the SLAC accelerator. The bulk GaAs cathode delivered beam to the SLC in 1992. The AlGaAs cathode was used for a fixed target experiment in 1992. The strained GaAs cathode has been used for both fixed target running and SLC since 1993.

SLAC is currently engaged in converting PEP into a B-factory consisting of a high energy ring storing electrons of 9 GeV and a low energy ring storing positrons of 3 GeV. Stored currents are unusually high, being 0.99 amperes and 2.1 amperes for the high energy ring and low energy ring respectively. The goal is to obtain a luminosity of at least $3 \times 10^{33}$ cm$^{-2}$ sec$^{-1}$. While the B-factory is being undertaken as a construction project, it does not require any modification to the civil engineering environment at SLAC. The B-factory will add a new tool to be available for physics before the end of the century, which hopefully will give another "lease on life" to the laboratory.

The above has been a brief outline of the different phases of operation of SLAC which provided the basis of its longevity. Let me conclude with a brief overview of the experimental results. SLAC has been an unusually productive laboratory both in terms of genuinely new revelations and the accumulation of archival data.

It was only natural that when SLAC was proposed emphasis was given to continuing the work on elastic electron scattering on protons and neutrons, for which Robert Hofstadter had received the Nobel Prize on SLAC's predecessor machine, the MARK III accelerator. As it turned out, elastic scattering using SLAC's facilities worked fine but did not provide any genuinely new insights. Instead, the focus of attention shifted to deep inelastic scattering where cross-sections at high momentum transfers were observed to be very
much larger than anyone had surmised. This work, using three magnetic spectrometers which incorporated the new principle of line to point focusing horizontally, provided data which established "beyond reasonable doubt" evidence for a point-like sub-structure in the nucleons.

The quality and quantity of high energy secondary beams enabled SLAC to become the leading "factory" for bubble chamber pictures for a considerable period of time. The main reason for this preeminence was the high repetition rate of SLAC relative to that provided by the slower cycle of proton synchrotrons. During the peak production period SLAC produced somewhere around six million bubble chamber pictures per year, which tended to saturate the pictorial data analysis capacity of collaborators throughout the world. The 82" chamber at SLAC, using a polarized $\gamma$-ray beam generated by Compton backscattering of laser photons from the electron beam, demonstrated, in addition to many other results, helicity conservation in the photoproduction of vector mesons. The 40" operated in a mode in which photographic picture taking was triggered by an array of counters so that images from only one in 20 to 40 expansions were recorded. The chamber operated for an unprecedented 100 million expansions during its useful life.

One of the surprises from SLAC, but not so surprising to the theorists who predicted the phenomenon, was the large forward intensity of secondary beams. These were exploited for Kaon spectroscopy in a Large Aperture Solenoidal Spectrometer (LASS) and in a streamer chamber. A precision experiment on the muon asymmetry from $K$-decay was performed and various searches for new particles were made in vertical shafts beyond the beam stops.

Then came the results from SPEAR, leading to the November Revolution of 1974 when the $J/\psi$ was co-discovered with the Brookhaven fixed target proton experiments. The unusually clean conditions at SPEAR with the MARK I, and then the MARK II detector, permitted thorough examination of the spectrometry of charmonium and the complete level structure of the psi family was constructed. An important by-product of that work was the discovery of the tau lepton, which was carried out by one of the collaborating groups in the SPEAR experiment. The group "mined the tapes" from that experiment to look for an excess of electron–positron coincidences which were interpreted to be the decay product from heavy lepton pairs, each decaying independently.

Work on the linear collider has also been extremely productive, principally because of the fact that the use of polarized electrons greatly increased the sensitivity in the study of the products of the $Z^0$ decay into various channels. At the same time SLAC has now closed the loop back to the original deep and inelastic scattering experiments. As a result of the energy increase of the accelerator to 50 GeV, and the availability of more than 80 percent polarized electron beams, a new series of electron scattering experiments is in progress which has greatly extended the range of the earlier experiments. While this work is not able to reach the range of momentum transfers and energies of the hadron system attainable at HERA and through the use of the high energy muon beams from proton machines, the precision of these experiments makes it possible to generate form factors which exceed in accuracy measurements using the high energy methods in those kinematic regions where such form factors overlap.

SLAC has been a maverick in high energy physics by pursuing the use of lepton beams as primary sources and using the low duty cycle high intensity character of linear accelerator generated beams. It is now 30 years and three Nobel prizes later than when the first beam was produced in the spring of 1966. Today, with the SLAC Linear Collider, plans for the Next Linear Collider and the construction of the B-factory as well as the rejuvenated fixed target program going strong, I will answer the old question: How long will SLAC continue? with the old reply, "10-15 years unless somebody has a good idea."
MAJOR PROJECTS FOR THE USE OF HIGH POWER LINACS

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Abstract

A review of the major projects for high power linacs is given. The field covers the projects aiming at the transmutation of nuclear waste or the production of tritium, as well as the production of neutrons for hybrid reactors or basic research with neutron sources. The technologies which are common to all the projects are discussed. Comments are made on the technical difficulties encountered by all the projects, and the special problems of the pulsed linacs are mentioned. Elements for a comparison of normal conducting linacs versus superconducting ones are given. Finally the technical developments being made in various laboratories are reviewed.

Introduction

It seems reasonable to place the lower boundary for "High Power Linacs" at the level of 1 MW average power. There is no upper boundary; some projects reach almost 200 MW. Most of these linacs accelerate protons (or H+), with the exceptions of IFMIF (International Fusion Material Irradiation Facility), which is a deuteron accelerator, and of a CW electron linac designed for PNC (Power Reactor and Nuclear Fuel Development Corporation in Japan) [1].

The main purpose of these proton or deuteron linacs is the production of neutrons, by spallation for the proton linacs, or by breaking the deuteron for IFMIF. As far as spallation is concerned, there is a possible trade off of beam current against energy. Above 1 GeV, the number of produced neutrons is roughly proportional to the beam power.

The neutrons are intended to be used in 4 main classes of applications:
1. For transmutation [2], either for treating nuclear waste or for producing tritium. Transmutation requires beams with a power above some tens of MW. For such a power the CW mode is the most convenient and the chosen energy varies from one project to another from 600 MeV to 1.7 GeV, depending of the neutron flux needed and the technology chosen for the high energy part of the accelerator (normal conducting or superconducting cavities). The beam spot is enlarged from the centimeter size at the linac exit to the meter size on the target. For such a large magnification, non linear optics is usually preferred to other systems like raster scanning or linear optics. A non linear optics can give an almost homogeneous power deposit on the target area and is less sensitive to beam displacements at the linac output.
2. Future hybrid reactors are subcritical reactors where the deficit in neutrons is compensated by the neutrons produced by a proton beam shooting directly into the reactor core. Here a CW beam is required, with a power in the range of 10 to 30 MW. On the low side of this range, cyclotrons may be competitors to linacs [3].
3. For basic research with neutrons [4]. Here one needs pulsed neutrons, with a pulse length of about 1 μs. The so-called research reactors have up to now produced abundant continuous neutron fluxes for research in physics. These neutrons have the advantage of being thermalized at a temperature which can be chosen to some extent. But it is very difficult to get pulsed neutrons from reactors (an essential feature for time of flight measurements) without reducing drastically the averaged flux. Most proposed neutron sources are based on accelerators, which can easily produce pulsed beams. In addition, it is not so difficult to obtain the needed public acceptance for a new accelerator than it is for a new reactor. There is no criticiy risk with accelerators, and they do not produce long lived radioactive waste in the spallation target. Even if a pulsed mode of operation is more natural for accelerators than with reactors, one cannot get at once from a linac a large average power in very short pulses. This is the reason why a rather long linac pulse is injected into a synchrotron or a storage ring in a multturn injection mode, then extracted on one turn. The ring behaves as a compressor, or an accelerator-compressor. An efficient multturn injection requires a non-Liouvillean mechanism: the linac accelerates H+ which are converted into proton when passing through a stripping foil.
4. Irradiation of materials. IFMIF is designed to evaluate the damages in materials created by 14 MeV neutrons, those which are created in the deuterium-tritium reaction of the future fusion reactors. This neutron energy is the reason for the choice of 30 to 40 MeV for the accelerator. To get the required neutron flux, one has to accelerate a rather large beam current.

Regarding the project of the electron linac mentioned above, it is intended to produce a large photon flux for the treatment of nuclear waste by photo-reactions.

There are common features to all the linac projects (except the electron linac to which the rest of this text does not apply). They consist of an ion source, a RFQ, a DTL section (more or less modified) leading to roughly 100 MeV, and a high energy part, usually referred to as CCL (coupled cavity linac). When the beam current at the linac output is in excess of 100 mA for protons, (or below for H+), the first part of the linac (ion source, RFQ and sometimes a part of the DTL section) is doubled. The two beams are then mixed in a funneling process, which consists in interleaving the bunches with the help of an alternate radial deviation produced by an RF cavity. When funneling is used, it is mandatory that the cavities after the funneling use a frequency being an even multiple of the cavities before the funneling (usually twice).

Normal conducting versus superconducting cavities

As pointed out by R. Jameson [8], "The age of adventure (high risk) in SC is over... Projects can decide to use RT or SC technology on the basis of their performance, cost, availability, flexibility, and upgradability requirements". One will see below that almost all the major projects of high
power linacs considered using SC. Most projects are based on
RT cavities, with SC as an option, with the exception of the
Japanese project that is now rather based on SC. For projects
with superconducting cavities, the RFQ and DTL section still
in standard room temperature technology. Only the high
energy part involves superconducting cavities (but this high
energy part represents 90% of the investment). However, SC
low energy cavities are being considered for IFMIP as an
alternative solution (a Toshiba design, see [8]).

It may not be unuseful to summarize here the classical
arguments in favor of SC or against it, since they apply to
almost all the projects described below.

1. With the same beam hole, the accelerating gradient may be
larger than for RT, reducing significantly the linac length. But
actually the usable gradient is not as high as one could think,
because the possibility of entering a large amount of RF
power per unit length along the linac is limited.

2. Alternatively, with the same gradient one can chose a much
larger beam hole, hence a reduced risk of cavity activation.

3. SC cavities are usually short, due to the limited power
passing through a single RF coupler. Therefore the cavities
have a large velocity acceptance. The same cell length can be
applied to large parts of the linac, offering the possibility of
having spare cavities.

4. The needed RF power is less for SC as it is for RT, since
there are only small losses in the cavity walls. But these
losses occur at very low temperature (2 K or 4 K) and cost
about 1000 times more at 2 K (or 300 at 4 K) to be evacuated
as compared to the same losses at room temperature, requiring
powerful cryogenic plants.

5. SC cavities must have thin walls to be efficiently cooled.
Lorentz forces mechanically deforms the structure when
operated at high gradient. This is a problem especially for
pulsed linacs.

6. RF couplers for SC cavities is a subject of concern.

7. Investment cost is not larger for SC than for RT (possibly
smaller).

8. Operating cost is smaller for SC.

9. Reasonable prices for CW RF power can be obtained only
with large (1 MW) units. Therefore the power must be split
between several cavities (4 or 8). This applies for both SC and
RT, but RF level and phase is more difficult to control for SC
cavities when several of them are fed by a single RF source.

10. SC offers the possibility of upgrading the linac to higher
energy and current as the performance of couplers and windows
is improved.

SC clearly appears as an emergent technology, but a
quantitative study of cost and risk benefits has yet to be done
[8]. It appears that the weight of each of the arguments above
is evaluated for each project depending of the local context.

The European Spallation Source

The first phase of the studies for a European Spallation
Source is now reaching its term, that is to say that a choice
has been made between several possibilities [4–7]. The chosen
configuration, at room temperature, is shown on Fig. 1. It
consists of a 1.33 GeV H⁺ linac and two compression rings.

The requirements for the proton beam on the target are the
following:

- 1 μs long proton beam on the target
- 50 Hz repetition rate
- 5 MW average power
- (actually there will be a second target accepting 1 MW at
10 Hz)

![Fig. 1] ESS LINAC, 1.33 GeV, 5 MW.

It may be noted that each proton pulse carries an energy of
100 kJ, which is the subject of some concern with the
building of stress waves in the target, and the reason for
choosing a liquid (Hg) target.

The linac beam pulse is 1.2 ms long, working at 50 Hz.
The injection into the rings must be made in such a way that
the rings are not homogeneously filled (40% of the
circumference is void), a condition necessary for an efficient
extraction. So the 1.2 ms pulse is sliced in 360 ns long
micropulses, separated by 240 ns gaps.

As one can see on figure 1, it has been impossible to avoid a
funnel, which takes place at the level of 5 to 7 MeV.
With the present state of the art for H⁺ sources, it would be too
difficult to get the required peak current of 100 mA at the linac
output with a single ion source. Moreover, the RFQ behaves
better for moderate currents. The DTL section is a classical
one. The quadrupoles are pulsed in the first cavity to ease the
cooling problem in very short drift tubes. An accelerating
gradient $E_0 T$ of 2.8 MV/m and a synchronous phase of 25° are
chosen. It must be noted that such a gradient is substantially
higher than the gradients chosen for CW RT linacs, which
usually stay at the 1 MV/m level. But the 6% ESS duty cycle
allows a gradient comparable to injector linacs, where the
disposed in the walls can be easily evacuated.

The RF system for the high energy part of the linac
consists of 66 4 MW peak power klystrons feeding 264
cavities. That is to say that 1 MW is available for each cavity.
The power going into the beam and the cavity wall amounts to
0.75 MW. Field and phase stabilization respectively at 1% and
1° require the 0.25 MW extra power. This is particular to
pulsed linacs, where the transient behavior requires a sizable
percentage of the total RF power to be correctly mastered.

Side coupled or disk and washer cavities are proposed for
the high energy part of the linac. The cavity length (1.27 m to
1.95 m) is short enough to allow a constant cell length inside
a cavity. Transverse focusing is provided by doublets located
every second cavity. Doublets are favored over slingsets as they
give a more circular and smaller diameter beam.
Even if RT is the base line design, the ESS project considered the possibility of a SC linac from 150 MeV up to 1.33 GeV, or even 2.5 GeV with a halved current. Figure 2 shows a SC module which consists of a couple of 2 cell cavities. The chosen frequency is 352 MHz, hence the working temperature is 4 K. Several possibilities have been contemplated, with accelerating gradients in the range of 8 to 10 MV/m, RF power per input coupler from 300 to 300 kW and 200 to 300 cavities. The whole energy range can be covered with 20 different structures (20 different β).

**Fig. 2** Cryomodule for the ESS LINAC.

**Other Spallation Sources**

There is a large number of spallation source projects around the world [8, 9]. Most of them do not enter in the scope of this paper for various reasons: too low power linac, no linac at all. However it seems useful to mention of few of them:

1. The IPNS project (Intense Pulsed Neutron Source) at Argonne consists of a 400 MeV H⁺ linac with an average power of 400 kW and one RCS (Rapid Cycling Synchrotron) boosting the energy up to 2 GeV, or two RCS in cascade reaching 10 GeV. The average power on the target amounts respectively to 1 MW and 5 MW.
2. The 1 MW level is being reached on a spallation target at PSI near Zürich with a cyclotron.
3. LAMPF has been operating at Los Alamos with an average beam power exceeding 1 MW. It has been proposed [10, 11], to upgrade LAMPF for injecting into a accumulator/compressor ring. A single turn extraction would allow to obtain a 1 MW average power short pulse spallation source (SPSS). The LAMPF modification would consist in replacing the old part below 100 MeV by a new one including a 100 EkeV H⁺ injector, RFQ and DTL sections, the side coupled cavity section being unchanged.
4. It must be noted that the Japanese high power proton linac project (see section 5) includes the possibility of injecting into a storage ring to obtain a short beam pulse to be sent onto a spallation target.

**The Japanese project**

JAERI proposed in 1984 a Neutron Science Research Program (NSRP) [13, 14]. At the core of this program is a 1.5 GeV proton linac with an average current of several mA. This program covers OMEGA (transmutation of minor actinides), basic neutron researches, nuclear energy related technologies on material science, neutron irradiation, radioactive beams, etc. JAERI originally proposed a pulsed linac with a 100 mA peak current and 10% duty cycle. An important R/D work has been made for the front end portion of this linac (see section 9). JAERI has now modified the original proposal to meet new requirements. Figure 3 shows the conceptual diagram of the accelerator as it is now. One can see that the high energy part of the linac, above 100 MeV, uses SC cavities. The linac will be operated first in a pulse mode for a spallation neutron source, with a 1 mA average beam current in 2 ms long pulses at 50 Hz, and a H⁺ source. In a second stage the linac will be operated in a CW mode, the current being raised progressively up to 10 mA in protons. An ultimate goal could be several tens of mA.

**Fig. 3** The Japanese Project.

In addition to the classical advantages in favor of SC (see section 2) there is here an other one: the linac length can be substantially reduced, an important point knowing the limited space available at Tokai-Mura. One drawback in shifting to SC is the necessity to modify the front end design to accept a CW operation. Presently the RFQ is designed to work with a 10% duty cycle and the hot test model of the DTL for 20%. For a reliable operation in a CW mode, the maximum electric field will be reduced from 1.68 EK (Kilparick limit) down to 1.43 EK.

The chosen frequencies are 200 MHz for the RFQ and the DTL and 600 MHz for the SC section. The EIMAC tetrode tube used for the front end has an output peak power of the order of 1 MW. The conceptual design work for high power CW tetrodes and klystrons has been started, taking into account the two modes of operation, pulsed and CW.

Figure 4 shows the schematic drawing of the SC cryomodule. For a maximum electric field of 16 MV/m and an iris radius of 7.5 cm, the accelerating field $E_z$ is (in MV/m):

1. $2.90$ at $\beta = 0.45$
2. $5.67$ at $\beta = 0.73$
3. $7.18$ at $\beta = 0.88$

**Fig. 4** Half of a cryomodule for the Japanese Project.
With a synchronous phase angle of 30° the total active length is of the order of 250 to 300 m, for a physical total length of 650 to 750 m.

IFMIF

IFMIF is the project of an International Fusion Material Irradiation Facility. The main motivation for IFMIF is to test the behavior of materials which could be used for DEMO, the Tokomak to come after ITER, presently being studied. The neutron flux should produce 50 dpa (displacement per atom) per year in a volume of 0.1 litre and 1 dpa/year in 10 litres. The IFMIF requirements will be met by two 125 mA, 40 MeV CW deuterion linacs operating in parallel. The target will be a curtain of molten lithium flowing with a speed of 15 m/s.

The IFMIF accelerator is shown on Fig. 5. A dual ion source (one operating, one in stand-by) generates a 140 mA deuterion beam at 100 keV. Then an RFQ accelerates 125 mA up to 8 MeV. The final section of the accelerator consists of DTL cavities. Both the RFQ and the DTL are operated at the relatively low frequency of 125 MHz, a conservative approach to minimize the beam losses. There will be ten 1 MW RF power units per linac.

The 8 MeV RFQ is 11.7 m long. It is segmented in 3 longitudinal RF segments that are resonantly coupled through irises in the intermediate end walls. This gives a fair separation of the operating mode from the unwanted longitudinal modes of the RFQ. Each of the 3 RF segments is made from 4 physical pieces. The needed RF power is about 3 MW. All the losses (from 140 mA to 125 mA) occur below 2 MeV.

The DTL section consists of 7 Alvarez cavities with post couplers, each fed by a 1 MW unit. The control of the resonant frequency will be made by controlling the temperature of the cooling water. The inner diameter of the drift tubes is 3 cm, the goal for current losses being 3 nA/m. It should be noted that the accelerator may be operated with no acceleration in the last (or the two last) cavity, providing a selectable output energy of 30, 35 or 40 MeV.

The accelerator will be operated with H₂⁺ to avoid activation during testing periods, and pulsed for tune-up and start-up. The beam calibration station (see Fig. 5) will accept the full intensity only with a duty factor < 2%.

The high energy beam transport is basically a FODO channel including "momentum compactor" cavities to fulfill the requirement that the energy dispersion on the target be limited to + and - 0.5 MeV. The beam spot on the target must be 5 * 20 cm² with a flat top uniformity of + and - 5%. So there is a beam expander section which comprises 2 octupoles separated by 2 quadrupoles. An energy dispersion cavity broadens the beam energy distribution in order to spread the Bragg peak and reduce the maximum power density in the lithium curtain. To prevent beam scraping throughout the channel, a large beam pipe radius is chosen (12 cm). In addition to the achromatic 90° bend that can be seen on figure 5, there will be a 10° kick so as to shield as much of the final optics from the backstreaming neutrons as possible.

A thorough RAM (Reliability, Availability, Maintainability) study has been made for IFMIF. The expected availability of the accelerator itself is 88%. It is estimated that the accelerator is designed with sufficient derating but no significant upgrade capability. Additional beam current, if desired, would be provided by adding other 125 mA modules.

TRISPAL

TRISPAL (TRIium, SPALlation) is the French project for the production of tritium by spallation. The parameters have been changed since a previous presentation [16]. It is now estimated that the amount of tritium to be produced per year will be covered by a 600 MeV proton accelerator with a 400 mA beam operating in the CW mode. The design of the accelerator is deliberately conservative, for a number of reasons. The goal is here to convince that an accelerator is as reliable as a nuclear reactor. The key words are: feasibility, reliability, proven off the shelf technology, existing RF tube. This is the reason for a CW low current, low energy accelerator instead of a higher energy, higher current shorter pulsed accelerator, a single RF frequency for which klystrons do exist (350 MHz), of course no funneling, and RT technology, even is a SC version is envisaged as an option.

Figure 6 shows the general lay out of the accelerator, which consists of an ECR proton source, a 5 MeV RFQ working at 1.7 EK, a DTL section up to about 100 MeV, and a CCL section. Then there is a transport channel to the 2 targets, only one being used at a time. The system includes an 82° bend, a FODO channel, a non linear expander and a final 8° bend to avoid backscattered neutrons. The beam spot on the target is a square with a side of 60 to 80 cm.

The chosen CCL uses the slot coupled structure working at the π mode, similar to the LEP RT cavities or the ESRF
cavities, with adequate cell length according to the $\beta$. Several comments must be made on this choice. First on the frequency: it seems that a 750 MHz CCL would offer a shunt impedance better by a factor $\sqrt{2}$; this is untrue if one keeps the beam hole the same at 750 MHz as it is at 350 MHz; in that case one can show [17] that, on the average from 100 to 600 MeV, the effective shunt impedance is roughly the same in both cases; what is lost in $Z_g$ is gained on $T$ and $Z_gT^2$ is conserved. The second comment is about the chosen structure; the choice has been made between several possibilities on the ground of construction cost; moreover, there was some suspicion on the behavior of on axis coupling structures under heavy beam loading (the field in the coupling cells may cause multipactoring problems); the fact that the $\pi$ mode has a zero group velocity is a question of concern for long cavities, but not here for 5 to 7 cells cavities (same cell length inside a cavity). Coming to the RF system, a single 1 MW klystron feeds 8 cavities working at an average effective field $E_T$ of 1.12 MV/m. There will be 40 klystrons, for an active length of 500 m. It may be noted that here is here some derating of the klystrons: for a nominal 1.3 MW power, they will be operated at 1 MW for a better reliability.

There is no serious feasibility problem for the DTL section, even if lodging DC quadrupoles in the first drift tubes is not easy. However one can have second thought about the necessity of quadrupoles inside the drift tubes. It is a technology which is rather expensive due to the mechanical difficulties of feeding and cooling the quadrupoles, but also the stringent radial tolerance on the drift tube positioning. The tolerance could be substantially relaxed were it not for the quadrupoles. Structures with quadrupoles outside of the drift tubes have been proposed at Los Alamos (see section 8). The TRISPAL project has a somewhat different approach. It is well known that the effective shunt impedance for DTL is better for long cavities where the end walls have a small relative contribution to the losses. This is true, but if one compares a good long cavity with quadrupoles inside the drift tubes to a short cavity (let say 5 cell) with drift tube shape optimized without worrying for a quadrupole inside, then one ends up with a better effective shunt impedance for the short cavity [17]. This is what is being investigated now as a possibility for optimizing the TRISPAL construction cost.

**APT**

APT, the Accelerator for Production of Tritium, is the advanced project of a family of accelerators studied at Los Alamos for several years (transmutation of waste, plutonium burning, energy production [2]). The present base line is a RT 1.3 GeV proton linac; there are two versions, depending on the quantity of tritium to be produced per year: one with a 100 mA beam, the other with 134 mA; in the latter case there are two front end accelerators and a funnel. Figure 7 gives the main parameters. It is worthwhile to point out to that the classical Alvarez DTL section has been replaced by a CCDTL section (Coupèd Cavity Drift Tube Linac) [18, 19]. This structure is the solution chosen by Los Alamos to the problem mentioned above (see section 7), after imagining and rejecting an other solution, the BCDTL (Bridge Coupled Drift Tube Linac). One can almost say that the construction of the front end part (RFQ, CCDTL) has already begun under the name of LEDA (see section 9). The CCL section consists of side-coupled cavities. It is estimated that the RT CCL technology is very mature; only a modest effort will be needed to carry out the conceptual design of this base line high energy part of the linac.

**Fig. 7** APT room temperature linac (baseline).

But it is also believed that an SC solution should be emphasized for this high energy section. One can see on figure 8 the two versions of this SC linac: same front end part as RT, SC from 100 MeV up to 1.3 GeV or 1.7 GeV depending on the quantity of tritium. In both versions there is a 100 mA beam, hence no funnel. Cryomodules have been designed for two or four 4 cells cavities, the cavities are equipped with stiffeners to reduce mechanical vibrations. The decision of SC becoming the base line will be taken when electrical and mechanical performance of single cell cavities are confirmed, and when questions concerning the radiation tolerance of niobium are answered. Single cell cavities are now being fabricated and an experimental program for the niobium behavior under radiation has been started.

**Fig. 8** APT superconducting linac.

RFQs have been one of the major breakthrough in accelerator technology. They do work perfectly well in CW mode for low currents, as cyclotron injectors, for instance. Or for high pulsed currents as synchrotron injectors. However their reliability when applied to large CW currents has to be confirmed. It is the nature of RFQ that the focusing field cannot be tuned separately from the accelerating field. High current means strong focusing, high fields, high power density.
in the walls; a CW operation brings the difficulties of cooling the structure and avoid sparking between the vanes. There is little experience around the world with the operation of CW RFQs and DTLs [20, 21]. So it would be unwise to start the construction of a large CW linac without a deeper acquaintance with the technology of CW RFQs and DTLs, and also their daily behavior. This is the reason why several laboratories decided to build a front end part of a future large linac.

The Japanese started at Tokai-Mura an important program consisting of a proton source and an RFQ working at 10% duty cycle, and a DTL hot model without beam [22, 23]. The proton source has given 140 mA, of which 120 mA are protons, and the RFQ accelerated 70 mA with a duty cycle reduced to 7%. The measured transparency was 70% for a design value of 95% [14]. This front end was tailored to a pulsed project which is now shifted to CW (see section 5), so it has to be accordingly modified.

At Los Alamos, where RFQ tradition is strong, an "Accelerator Performance Demonstration Facility" has been proposed [24, 25]. A new version, LEDA (Low Energy Demonstration Accelerator) is now under construction. It is intended to provide design confirmation and operational experience. LEDA will be a nearly exact replica of the APT accelerator front end, 100 mA CW, but will include extra diagnostics and instrumentation. It consists of a proton source, a 6.7 MeV RFQ and a 20 to 40 MeV CCDTL, with an "almost seamless" transition between the RFQ and the CCDTL section. The 8 m long RFQ is made of 4 segments stabilized by resonant coupling.

At Saclay an ion source named SILHI is being constructed. Oriented for TRISPAL and IFMIF, it will be able to deliver CW currents of 100 mA in protons or 140 mA in deuterons. It has been decided recently to go further: the new authorized IPHI program will consist of a 7 m long RFQ plus a 6 m long DTL, accelerating protons up to 12 MeV. Of course the RFQ and DTL design will benefit from the studies made for TRISPAL.

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Invited Talk Session MO2

Chairman: P. Lapostolle

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JEFFERSON LAB, A STATUS REPORT

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Abstract

Thomas Jefferson National Accelerator Facility (Jefferson Lab; formerly known as CEBAF), operates a 4 GeV, 200 μA continuous wave (CW) electron accelerator that re-circulates the beam five times through two superconducting 400 MeV linacs. Electrons can be extracted from any of the five recirculation passes and beam can be simultaneously delivered to the three experimental halls.

As the commissioning stage nears completion, the accelerator is becoming a fully operational machine. Experiments in Hall C have been underway since November 1995 with beam powers of over 300 kW at various energies. Hall A has received beam for spectrometer commissioning, while Hall B is expected to receive its first beam in the fall of 1996. Accelerator availability of greater than 70% during physics runs and excellent beam quality have contributed to making Jefferson Lab a world class laboratory for accelerator-based electromagnetic nuclear physics. With the high performance of the superconducting RF cavities, machine upgrades to 6 GeV, and eventually 8 to 10 GeV are now in the planning stages. Operational and commissioning details concerning all aspects of the machine will be discussed.

Introduction

As the commissioning process at the Jefferson Lab comes to an end, the emphasis is shifting from just making the machine work to making it work reliably and reproducibly. The physics experiments scheduled at the three end stations demand that the accelerator have the flexibility to provide a wide range of beam parameters and to do so with high precision and a minimum of downtime. These parameters range from currents as low as a few nanoamps to Hall B to over 100 μA to Halls A and C; beam energies from 0.5 to 4.0 GeV; small energy spread; tight control over beam stability; and all of the halls want highly polarized beam for many of the planned experiments. The accelerator must be able to provide beam to all three halls simultaneously as well as be able to switch to performing accelerator development tasks whenever the beam is not needed and then to return the beam on target as soon possible. The accelerator has been designed, built, and commissioned with these demands in mind.

The accelerator is a CW machine consisting of a 45 MeV injector capable of producing three beams, two 400 MeV superconducting linacs, nine recirculation arcs, a beam switchyard, and three experimental halls. The three beams have independently controllable current at 499 MHz that fills alternating buckets in the 1497 MHz accelerating field of the superconducting cavities. The beams are split by 499 MHz room temperature RF separator cavities which deflect bunches from any recirculation pass either to the beam switchyard or for further recirculation around the accelerator.

Important components of the accelerator are individual klystrons and control modules for each superconducting cavity, multiple beam capability, polarized beam capability, the EPICS (Experimental Physics and Industrial Control System) control system, and a highly reliable central helium refrigerator. The individual rf systems allow each cavity to be run at its optimal level and provide precise control over phase and gradient. The multiple and polarized beam capabilities are important for performing experiments simultaneously in the three end stations. The use of EPICS has proven to be a good choice in terms of reliability and flexibility for machine control. The high availability of the accelerator so far would not have been possible without the excellent performance of the central helium refrigerator.

Many details of the accelerator design have been discussed in previous conferences [1,2]. Here, the status of various subsystems will be reviewed, including the most recent progress. Since the accelerator at the Jefferson Lab is now a production machine for the nuclear physics community, the efforts, both present and planned, to make it highly reliable and flexible will be covered.

System Status

The accelerator consists of two superconducting linacs with a nominal energy gain of 400 MeV per pass and nine recirculation arcs. With up to five passes, the accelerator can deliver beams with energies in discrete steps between 845 and 4045 MeV. The magnet system and beam optics have not changed substantially since the last conference [2].

The injector is a unique system that must deliver three interleaved 499 MHz beams with each beam having individually adjustable current to match the requirements of the three experimental halls. The injector has been thoroughly modeled with PARMELA with excellent agreement. Several special diagnostics unique to the injector will be discussed later. The three beams can be extracted to separate experimental halls using normal conducting, highly efficient 499 MHz rf separator cavities [3,4]. The kick generated by the cavities is amplified by quadrupoles and septum magnets to either deflect the beam to an experimental hall or to recirculate. The geometry dictates that only one beam per

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pass can be extracted to an end station, except for the highest energy pass, where all three beams can be sent to the halls simultaneously.

Since more than half of the planned experiments require the use of polarized electrons, the polarized electron source is becoming the focus for much attention. The polarized photocathode electron source, developed at the University of Illinois, has been installed in the injector region of the tunnel and integrated into the control system. A highly stable diode laser [5] locks to the master oscillator at 499 MHz drives the photocathode and produces a pre-chopped, polarized beam. A precision spin manipulator using electrostatic deflectors [6] allows the spin to be set to an arbitrary angle which can be varied to give the maximum polarization at the target. Another important feature under development is a 5 MeV Mott polarimeter for precisely measuring the polarization. With the first experiment using polarized beam planned for February 1997, much work remains to be done.

The superconducting RF system consists of 338 cavities in 42 cryomodules and a quarter-cryomodule in the injector. This presently represents the largest installation of superconducting cavities in the world. A klystron drives each individual cavity, and each has its own low level RF controller. Having individual controls allows each to be run at its optimal level with precise control over the phase and gradient. The cavity performance has considerably exceeded the design goal of 5 MeV/m [7]. The entire RF system can be controlled and monitored from a single control system screen [8] that provides the operators with the ability to quickly locate problems. During commissioning, the klystrons have been operated at a voltage of 7 kV instead of their nominal 11.6 kV setting to save on the power bill. This has limited the total linac beam current to less than 400 μA versus the design value of 1 mA. As higher beam currents are sent to the end stations, the high voltage of selected klystrons is increased to support increased beam loading.

The central helium refrigerator continues to provide 2.08 K helium to the cavities with outstanding performance, achieving over 95% availability during the scheduled accelerator running period. The system, which can support 4800 W, presently operates with a constant heat load of about 3100 W, of which 1500 W is the actual RF heat load.

EPICS performs the difficult task of controlling and monitoring the numerous systems on the accelerator [9]. With over 40,000 control points and 120,000 database records, the accelerator has one of the largest installations in the world. EPICS is supported by an international effort and sharing between these groups reduces redundant software development. The open system architecture makes it possible to access the control system using more familiar programs such as Mathematica, Tcl/Tk, UNIX, and C. Thus much of the high-level application programming development can be done by accelerator scientists, leaving the controls group to focus on the difficult low-level work. As commissioning of the accelerator and the control system nears completion, the controls group can now concentrate on making the high-level applications more robust and reliable.

The very high average beam powers make machine protection an important issue. An initial system based on photomultiplier tubes proved to be cumbersome to set up and not always reliable. A new system, the beam loss accounting system [10] uses the "what goes in must come out" principle to measure beam loss in the accelerator. Stainless steel pillbox cavities at 1497 MHz pick up the beam current at the end of the injector and immediately before all of the experimental halls and beam dumps. The cavities are cross calibrated and will trip the beam off if the beam loss is greater than preset limits. These limits are presently an integrated beam loss of over 2.5 μA, or an instantaneous loss of 2500 μA-μs beyond a 2.5 μA threshold. This new beam loss accounting system is a major improvement in the setup and operation of the machine in a safe manner.

**Machine Reliability and Reproducibility**

To maintain our present goal of over 70% (and ultimately higher) uptime during physics runs, machine reliability and reproducibility are very important issues. Improving reliability and reproducibility covers a broad scope of topics, some of which are described here.

With over 2000 magnets, over 300 RF cavities, and 120,000 database records, keeping track of all of the operationally important settings is a difficult task. An operator-friendly interface that allows machine settings to be saved, restored, or compared [11] performs this task. Particularly useful is the ability to compare the present machine state to previous settings to find values that have gone off nominal.

In the early days, rebooting the IOC’s (Input-Output Controllers) that run the EPICS control system caused great consternation in the control room as the beam would never come back exactly as before. To alleviate this problem, a system for saving before and restoring after a reboot was implemented. All of the volatile signals on each IOC have been determined and are saved and then restored in the appropriate order. One particularly pernicious problem was magnet irreproducibility. The only way to return the machine to its pre-reboot state was to cycle each magnet on that IOC through its hysteresis loop. A multidisciplinary group was dispatched to solve the problem and discovered that zero current was being sent to the magnets briefly during the reboot, thus causing them to fall off their hysteresis loop temporarily without informing the alarm handler. The problem was fixed and the machine reproducibility greatly improved.

As was mentioned earlier, the high average beam powers require a tight control over the beam to limit accidental beam strikes. One way to do this is to provide a security system to keep unauthorized persons from changing any control system parameters. Such a system has been implemented in EPICS and presently gives access only to the accelerator operations staff. Others may be granted access for testing or other purposes by request to the control room. While the security system cannot stop malicious damage, most unintentional
changes will be caught. In addition to machine protection, the security system provides another way to increase machine reliability during physics runs.

The EPICS alarm handler provides an efficient way to monitor systems to ensure that they stay within prescribed limits. A good example is the alarm handler for the magnet system. Numerous problems are monitored, with the mismatch condition and the off-loop condition being the most important. A magnet mismatch alarm occurs whenever the desired setpoint differs from the readback by a specific amount implying a hardware problem, while the off-loop alarm occurs whenever the software determines that the magnet has gone off its predetermined hysteresis loop. A new application of the alarm handler is its use in configuration control. Configuration control refers to a particular machine setup that is considered fixed and should not be changed by the operations staff. For example, a configuration alarm system has been implemented in the injector that includes settings for magnets, RF gradients and phases, and beam position monitor calibration factors. If any of these settings stray from their fixed values for whatever reason (operator error, computer error, etc.) an alarm will inform the operators.

Setting up the machine in a reproducible fashion can be hampered when different people do the work in slightly different ways, even when following the same written procedure. To improve stability, an “auto turn-on” sequence is being developed that will guide the operator through the task of turning on the machine, and automate the procedure as much as possible. For some systems which are not fully incorporated into the control system, automation is not yet possible and the program will present a list of tasks to perform. Eventually, the “auto turn-on” will become a “one button turn-on”, thus reducing the person-to-person variability in machine setup.

A final topic for improving machine reliability is hardware tracking. Tracking hardware problems can show trends and identify common problems that need attention. A simple interface [8] allows operators and technicians to note hardware problems for RF cavities and control modules, beam position monitors, or magnets. A log of the problems for each item is kept and can easily be examined and compared to others. Another tracking system is the downtime logger. Whenever the beam is off for an extended time, the downtime logger is invoked and an operator enters the reason for the downtime. The operator then notifies the logger when the problem is resolved and the beam has been returned to its target. This system makes it easy to find the total up time, down time and tune time for the accelerator, as well as providing a simple mechanism for finding recurring faults that are limiting uptime.

Operational Issues

The setup and operation of an accelerator with such a large number of individual elements requires careful attention to written procedures that make use of quick, effective diagnostic methods. During commissioning, these procedures were developed by accelerator physicists and carried out by the operations staff. As mistakes were found and methods improved, the procedures were updated to reflect the improvements. All of the knowledge gained during the debugging of the machine setup was not forgotten, but turned into a trouble-shooting guide. The trouble-shooting guides are on-line information that guide the operators through a sequence of symptoms and solutions. The accelerator experts are thus relieved of having to respond to every crisis that occurs, leaving them more time to work on machine improvement and development.

To facilitate machine setup and to verify that the accelerator meets the necessary specifications, a number of useful diagnostic tools have been developed, some of which are described below.

One of the more important machine parameters is energy spread (specified to be $< 10^{-4}$, 1σ). The beam emittance (specified to be $\varepsilon_{\text{rms}} < 2\times10^{-9}$ m at 1 GeV) is typically lower than what is required by the end stations and is not an issue, except for betatron matching between accelerator sections. The origin of the energy spread is in the injector. If all of the cavities in the accelerator are perfectly crested, the injector must provide a bunch length of less than 2° (3.6 ps). The nominal bunch length for the injector (1°) is lower than this. The bunch length is measured and monitored using several different methods (see D.X. Wang, this conference, for more details).

The first method uses a 6 GHz pickup cavity to measure the time of flight for small slices of the bunch as it is swept across a slit in the beam chopper[12]. A plot of the input phase versus the output phase at the pickup cavity yields the bunch length. An operator interface can carry out the measurement in about 10 seconds, and after a few iterations, the phases of the injector RF components can be set to within 0.1° by matching the measured phase space to the optimum configuration as determined by PARMELA simulations. By doing a harmonic analysis of the data, the amount of phase change necessary to bring the phase space to its ideal configuration can be calculated and the whole process automated [13]. The disadvantage of this phase transfer method is that it cannot be carried out during normal beam operations, and that it is sensitive to space charge effects.

A new method based on coherent synchrotron radiation (CSR) has recently been developed [14]. A magnetic chicane separates the injector from the linac, and a special diode sensitive to a wavelength corresponding to the nominal bunch length is positioned after the first dipole in the chicane to pick up the coherent synchrotron radiation. The radiated power at constant beam current is inversely proportional to the bunch length and can be calibrated against a backphasing measurement. The CSR method provides a non-destructive measure of the bunch length and can operate in pulsed or CW mode. The CSR signal is presently being incorporated into the control system.

Two other important parameters affecting the energy spread are the path length and the $M_{\text{str}}$, or the change in path...
length with energy change. Both of these parameters are measured using sensitive phase detection methods. For the first pass in the accelerator, the maximum energy is set by phasing the rf cavities in each linac. For the upper passes, the phasing cannot be altered, and the path length through each arc is set by using "dogleg" magnets [15]. The path length from pass to pass is measured by detecting the phase difference in a 1497 MHz cavity in the line common to all of the passes. The signal from the first pass is used as a reference, and the phase error signal between the first pass and other passes gives a measure of the path length difference with an accuracy of 0.05°. The dogleg magnets can then be adjusted to zero the phase error. The whole measurement process has been incorporated into the control system and an operator can measure and correct the path length for all passes in less than ten minutes.

The recirculation arcs are designed to be achromatic and isochronous, implying that the M_{55} matrix element should be zero. With a non-zero M_{55}, the energy spread across the bunch will cause it to debunch through the arc, thus increasing the energy spread for the next arc. The same cavities used for measuring the path length are also used to measure M_{55}. By modulating the beam energy before entering an arc, and picking up the phase error signal after the arc, the M_{55} can be measured to within an accuracy of 10 cm in 2 minutes. The M_{55} can then be set to zero by measuring it as a function of quadrupole scaling for a family of quadrupoles in the arc proper and choosing the scale factor that minimizes M_{55}.

All of the above measurements are difficult to perform unless all of the accelerating cavities are operating near their crest in phase. In the early stages of commissioning, this was a time consuming task requiring the operators to phase each cavity manually. Such methods are clearly not acceptable for an operational machine where machine time is at a premium. The energy of the beam can be calculated to 2x10^{-3} by fitting the beam orbit through an arc to the machine model. Each cavity can then be automatically set by a program [16] which varies the phase of the cavity by ±30° and measures the fitted energy at several phase points. By fitting the results to a sinusoidal curve, the phase providing the maximum energy can be found. Each cavity requires 1 to 2 minutes to set with a resolution of 1-2°.

### Results

The accelerator provided beam for its first nuclear physics experiment in November of 1995, culminating over 10 years of design, construction, and commissioning. Highlights of the accelerator operation include:

- the completion of 3 experimental programs in Hall C
- delivering 25 μA, CW beam at five discrete energies in an 8 hour period
- delivering beam from the polarized source to an end station
- delivering CW beam to Hall A (5 μA) and Hall C (60 μA) simultaneously
- running at greater than 1 GeV for one pass
- maintaining an average accelerator availability of over 70% during physics runs [17], and
- delivering beam with a maximum power of over 300 kW.

The maximum delivered single beam current (see Table 1) for various energies are listed below.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Max Current (μA)</th>
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<tbody>
<tr>
<td>45</td>
<td>200</td>
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<tr>
<td>845</td>
<td>135</td>
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<tr>
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<td>4045</td>
<td>80</td>
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### Long Term Plans

In response to the needs of the nuclear physics community, several longer term programs are under way to provide the wide range of beam parameters necessary for all of the planned experiments. These programs cover multiple guns, the ability to easily run the accelerator at any allowable energy, and future energy upgrades.

The present injector has the capability of delivering three unpolarized beams with currents covering a dynamic range of about 1:2,000. It can also deliver one polarized beam (not at the same time as unpolarized). While this situation has been adequate for commissioning, it will not fulfill all of the upcoming experimental requirements. Hall B will require a few nanoamps when it comes on line and Halls A and C often need over 100 μA. All of the halls want polarized beam, and beams with the maximum polarization cannot be delivered to all three halls simultaneously for an arbitrary energy from one gun [18]. All of these requirements point to the need for multiple guns and an injector to merge the beams into alternating rf buckets. Work is under way to design an injector that will cover the whole range of current, polarization, and pulse structure needed for the planned physics program.

During commissioning, the energy of the injector has been set to an energy of 45 MeV, and the linacs to 400 MeV, giving deliverable energies from 845 MeV to 4.045 GeV, and the beam optics have been optimized for this setup. Work on a momentum management system has begun which will set both the distribution of rf gradients based on the total desired energy and current and the optical lattice. Preliminary tests of this system were performed in a 1 GeV, single pass test, but much work remains to be done. For example, it is not yet known if simply scaling the magnet settings with the momentum change will work, or if a model based system will provide better results.
The last major aspect of the long range planning is an upgrade to push the maximum available energy above 4 GeV. The outstanding operation of the superconducting cavities makes running at energies approaching 6 GeV a possibility in the near future, requiring only upgraded dipole magnet power supplies. Ways to push to energies beyond this are also being studied, but will require considerably more time and money.

Conclusion

As the commissioning stage nears completion, the accelerator at the Jefferson Lab is becoming a fully operational machine. Experiments in Hall C have been underway since November 1995 with beam powers over 300 kW at various energies. Hall A has received beam for spectrometer commissioning, and beam to Hall B is expected in the fall of 1996. Accelerator availability of greater than 70% during physics runs and excellent beam quality have contributed to making Jefferson Lab a world class laboratory for accelerator-based electromagnetic nuclear physics.

Considerable effort has gone into improving the reliability and reproducibility of the machine by concentrating on the many subsystems that make up the accelerator. This includes topics such as automation, trouble-shooting guides, useful alarm handlers, fast and efficient diagnostics, tight control over computer reboots, hardware tracking, and control system security. All of these topics not only improve the operability of the machine, but also give the operations staff the ability to efficiently run the machine without continual input from the accelerator scientists.

Operational highlights include: delivering 25 μA CW beam at five discrete energies in an eight hour period; delivering beam from the polarized source to an experimental hall; running at greater than 1 GeV for a single pass; delivering 4.0 GeV, 80 μA CW beam to an experimental hall; delivering rf separated beam to Hall A and Hall C simultaneously; and sending three separate 60 μA CW beams to a dump.

Plans for the future include a number of topics of interest to the users. To provide the widely varying beam requirements of the three experimental halls, the injector will be expanded to have multiple guns that can operate simultaneously. Improvements of the accelerator as a whole to further increase machine reliability are a must. Finally, a plan is being developed to upgrade the maximum beam energy to 5-6 GeV, and eventually to 8-10 GeV as feasible.

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Abstract

The proposed accelerator production of tritium (APT) project requires an accelerator that provides a cw proton beam of 100 mA at 1300 MeV. Since the majority of the technical risk of a high-current cw (continuous-wave, 100% DF) accelerator resides in the low-energy section, Los Alamos is building a 20 MeV duplicate of the accelerator front end to confirm design codes, beam performance, and demonstrate operational reliability. We report on design details of this low-energy demonstration accelerator (LEDA) and discuss the integrated design of the full accelerator for the APT plant. LEDA's proton injector is under test and has produced more than 130 mA at 75 keV. Fabrication is proceeding on a 6.7-MeV, 8-meter-long RFQ, and detailed design is underway on coupled-cavity drift-tube linac (CCDTL) structures. In addition, detailed design and technology experiments are underway on medium-beta superconducting cavities to assess the feasibility of replacing the conventional (room-temperature copper) high-energy linac with a linac made of niobium superconducting RF cavities.

Introduction

A source of large numbers of neutrons has many applications [1], including the production of tritium. Nuclear fission reactors are traditional sources of neutrons, but a spallation process in which 1 GeV protons produce multiple neutrons, is an alternative that avoids a critical assembly and circumvents the environmental and safety challenges of a reactor. A suitable target/blanket design permits the creation of about 42 neutrons for every incident proton (at 1300 MeV).

The U.S. Department of Energy (DOE) is funding development of an accelerator-driven process (accelerator production of tritium, APT) for tritium production. Conceptual design of this production facility is being led by Los Alamos National Laboratory (LANL), with assistance by several other National Laboratories.

The proton driver for this APT facility is expected to be a cw (100% duty factor), 100 mA beam at 1300 MeV. Beam energy or current may be upgraded to 1700 MeV or 135 mA, respectively, to provide a 50% increase in neutron production. The unprecedented beam power of 130 (or 170) MW means that particular attention must be paid to structure cooling and to extremely low beam losses (less than 0.2 nA/m, above 100 MeV) to minimize component activation and permit "hands-on" maintenance of the linac.

In addition to the design of the entire accelerator, target/blanket assembly and tritium-extraction system, Los Alamos is proceeding with the design, setup and testing of a full-current prototype at approximately 20 MeV to confirm operational reliability of the accelerator front end. This low-energy demonstration accelerator (LEDA) will permit a full-power proton-beam test of the new, low-beta accelerating structures used on APT.

Design Description

A majority (from about 100 MeV to the final energy) of the APT accelerator may be a conventional coupled-cavity linac (CCL) or side-coupled linac structure. Alternatively, a super-conducting linac assembly [2] could replace most of the CCL structure, to effect power savings and provide improved operational flexibility.

A conventional proton injector, including a number of enhancements described below, is used to create a 75 keV, 115 mA beam. A radio-frequency quadrupole (RFQ) will be used to extend the energy to about 6.7 MeV. A relatively new structure, the coupled-cavity, drift-tube linac (CCDTL) [1] that combines the features of a conventional DTL and the CCL will accelerate the protons to approximately 100 MeV.

Low-Energy Demonstration Accelerator (LEDA)

LEDA will be constructed, assembled and tested at Los Alamos, and will be virtually identical to the first approximately 20 MeV of the APT accelerator. One of the few differences is that LEDA may have additional diagnostics to enable us to better characterize operation and measure details of the accelerated beam.

Beam tests will be done in a sequential fashion, as each linac structure is completed. Beam testing, commissioning and operation will extend over several years. Meanwhile, injector beam tests have been underway for more than a year. The RFQ should be completed and ready for beam about April, 1998. Beam operation with the first section of the CCDTL should start in the fall of 1998. Additional sections of the CCDTL will be added over the next couple of years and reliability testing and operations may extend past the turn of the century.

LEDA is intended to reduce risk in the design of the APT accelerator. Most of this risk reduction will be achieved by increasing our confidence in accelerator design and simulation codes, providing an improved basis for cost estimates, reducing uncertainty on beam-loss levels, verifying beam quality and performance, and in giving data on operational reliability. Table I indicates the primary objectives for the several stages of testing.

In addition, LEDA will provide an earlier opportunity for operator training, will serve as a "hot" spare for major low-energy components, and can be available as a prototype test bed.

Figure 1 shows a 20 MeV LEDA configuration, which will be the primary emphasis for the first few years of operation. However, we intend to assemble a full 40 MeV accelerator for better testing CCDTL matching halo formation, and the use of RF "super-modules". In the event the APT accelerator is a room-temperature structure and more neutrons are required, LEDA may be used to test a configuration with a beam funnel, increasing the beam current to about 135 mA.
Fig. 1. Proposed LEDA configuration for testing the first 20 MeV of a 100 mA cw proton linac. Circles beneath the RFQ and CCDTL structures depict the 1-MW rf systems.

Table 1
LEDA Technical Objectives

Stage 1 -- Operation of injector beam
- Detailed measure of beam at RFQ match point
- Match beam into the CRITS RFQ
- Show fault recovery
- Demonstrate long-term operation
- Demonstrate variable current (and beam pulsing)

Stage 2 -- Characterize 6.7 MeV RFQ beam
- Demonstrate integrated cw operation of injector and RFQ
- Confirm beam performance and benchmark simulations
- Evaluate reliability and long-term operation
- First test of klystron redundancy concept

Stage 3a -- Operation of 11 MeV CCDTL Beam
- Characterizes match between RFQ and CCDTL
- Confirm beam performance and benchmark simulations
- First use of 700 MHz rf power tube

Stage 3b -- Operate 17 MeV beam test
- Confirms matching across different structures
  - Tests multiple 700 MHz rf sources
  - Tests all critical beam dynamics

Stage 4. Operation with 40 MeV beam test
- Allows test of full rf “super module”
- Confirms formation of beam halo and control mechanisms
- Confirms design parameters of high-energy linac
- Measures beam performance through 3-gap and 2-gap structures.

Stage 5. Beam funnel demo -- (reqd for RT 3 kg option only)
- Is the most cost-effective means of increasing beam current by 50–100%.
- Allows measure of impact on beam quality by funnel.

LEDA will be assembled and tested in the former GTA (ground test accelerator) facility; this is being modified with the addition of more ac power and upgraded water-cooling systems.

An environmental assessment (EA) was prepared for LEDA and a FONSI (finding of no significant impact) was issued in April, 1996.

Figure 2 shows (by calendar year) the top-level schedule for the several LEDA experimental activities. The primary immediate focus of the LEDA program is to assemble and test the RFQ (stage 2, above). An equally important milestone for us is the testing of the first section of CCDTL, confirming the beam match and proper operation of the new 700 MHz klystrons.

Fig. 2. Top-level LEDA schedule for major assembly and beam testing.

Ion Injector

The LEDA injector was designed and partially assembled with funding from a former program [3,4]. However, all testing and refinements have been done with APT support. Figure 3 shows the present configuration for testing.

Fig. 3. The LEDA injector test stand, showing (at left) the microwave feed into the ion source, the two-solenoid transport, and emittance measuring gear at the far right.

The ion source for this LEDA injector was designed and built by a team at the Chalk River Laboratory (CRL) in Ontario, and is virtually identical to that used successfully on their cw proton accelerator program [5]. This source is particularly appealing because it has no filament, requires very little power =600 W of 2.45 GHz microwaves), has very high gas efficiency (requires <0.1 torr l/s), is very stable, and has a high proton fraction (>90%). These excellent operating parameters lead us to speculate that this source can be far more reliable [6] than any previous cw proton source.

The LEDA beam extractor is very similar to one developed on the FMIT (Fusion Materials Irradiation Test) facility [7] at Los Alamos in the early 1980s. Detailed beam and extraction simulations are done with the PBGUNS code that self-consistently solves for the plasma-emission surface.

The low-energy beam transport (LEBT) and RFQ matching section are very similar to the two-solenoid system used on the GTA (ground test accelerator) [8] to provide a high-quality, tunable beam for RFQ injection. Space-charge neutralization in most of the transport region compensates for 98% of the beam space charge. In addition to vacuum pumps and non- interceptive diagnostics, the LEBT will include steering and
focus magnets, an insertable beam stop, a variable iris for current control, and a fast deflector for beam pulsing.

Operation with the pictured injector test stand has demonstrated the required cw (DC) 75 keV beams with more than 110 mA of protons, with a normalized transverse emittance of 0.2 \( \pi \) mm-mrad. Design and testing details of the LEDA injector are covered in a companion paper [9] at this conference.

RFQ

Although the RFQ is by now a commonplace accelerator, the APT and LEDA RFQ differ from previous structures in a few important respects. LEDA's eight-meter-long, 350-MHz RFQ will be built in eight sections, configured as four separately tunable segments. Structurally, it is a solid brazed structure with two minor vanes and two major vanes. Predicted rf power losses on the interior surfaces of this solid copper (OFE) assembly are 1.27 MW, necessitating very effective water cooling. Full-current beam acceleration will require a total of 2.0 MW, so either two or three 1.0 MW rf klystrons will be needed to supply rf power. Static slug tuners will be adjusted during final tuning, then custom machined to size and bolted into place. During operation, resonance control will be through control of cooling water temperature.

A full-scale (8-meter long), low-power, “cold-model” was built and used to verify structure tunability and to confirm the details of the vane undercutts. In addition, a short length of an “engineering model” was built, brazed and tested to confirm the stackup of errors and to measure the structural rigidity.

![Photo of the 8-m long aluminum RFQ cold model, used to develop tuning procedures and tailor the design codes.](image)

The LEDA RFQ is in concurrent detailed design and fabrication. Machining is nearly complete on the first of eight sections (Fig. 5); most vane skirts have been roughed out, samples of the sixteen different vane tips were completed, and a start was made on the brazing cycles.

![APL/LEDA RFQ SCHEMATIC](image)

A1 A2 B1 B2 C1 C2 D1 D2

Fig. 5. Depiction of the eight sections of the LEDA RFQ. Each is nominally one meter in length.

![3-D depiction of the first of eight RFQ sections.](image)

![Cross-section of the LEDA RFQ, showing locations of cooling channels and braze joints.](image)

![Adequate cooling is imperative for this cw, high-power RFQ. A controlled-temperature water flow of 1300 gpm (82 l/s) is needed for RFQ cooling. After initial tuning, RFQ section resonance is adjusted by control of the cooling-water temperature.](image)

Of the eight RFQ sections shown in Figure 5, three (A1, A2 & C2) will have 12-each vacuum pumping ports, three other sections (B1, C1 & D1) will support four-each rf coupling ports and irises, while two sections (B2 & D2) will include neither vacuum nor rf ports. Power from each of the nominal 1–1.3 MW rf klystrons will be split four ways to keep the power applied to each rf window to a conservative 250 kW. Each of the four major copper structures in each of the eight sections will require 5 major machining steps and three braze steps.

CCDTL

Design details and advantages of the 700-MHz coupled-cavity drift-tube linac are described in [10]. The CCDTL was invented to capture the major benefits of both the DTL structure and the ubiquitous CCL (coupled-cavity linac), both of which have seen extensive operation. The CCDTL promises to provide a higher shunt impedance than the DTL and has all transverse focusing magnets outside the accelerating cavities, relaxing alignment tolerances on the cavities. This configuration also allows many cells to be brazed into a solid one-piece structure, again with resonance control effected by cooling-water temperature control.

Both a half-scale and a full-scale cold model of several contiguous CCDTL cells have been constructed to permit code comparisons, refinement of tuning procedures, and optimizing
coupling-cell configuration. Our standard design codes, including PARMILA, have been modified [11] (and benchmarked) to accommodate the symmetric CCDTL accelerating cavities.

LEDA will provide the first opportunity to test the CCDTL structure with high rf power and with beam. Like the RFQ, the CCDTL will be made of solid OFE copper. Singlet electromagnetic quadrupoles will be assembled in a split configuration to facilitate installation on the structure without breaking vacuum. Bipolar steering windings will be added on the quads, and used with beam-position monitors (BPMs) inside the magnet bore to facilitate beam steering through the linac.

![Cutaway of the CCDTL structure, showing two drift tubes in each cell.](image)

Fig. 8. Cutaway of the CCDTL structure, showing two drift tubes in each cell.

Longitudinal matching (Fig. 9) between the RFQ and CCDTL will be done by adjustment of the synchronous phase in the last few RFQ cells and the first several CCDTL cells. The two structures will abut, creating a maximum drift distance without acceleration of only 2.5 μλ. This matching feature is just one of many designed to control halo growth in the accelerated beam. [12]

![Configuration of the match between the LEDA RFQ and the first section of the CCDTL.](image)

Fig. 9. Configuration of the match between the LEDA RFQ and the first section of the CCDTL.

Higher energies, bore-to-rms beam ratios are at least 25:1 for the room-temperature structure and 40:1 for the superconducting structure. These simulation results increase our confidence that beam losses will not exceed 10 nA/m, and that “hands-on” maintenance will be feasible.

**LEDA Beam Commissioning**

Development of beam commissioning procedures will be an important part of LEDA. Primary LEDA commissioning objectives include:

- Verification of all design and simulation codes and models.
- Determination of best conditioning and turn-on procedures.
- Demonstration of beam performance; current, quality, stability.
- Measure of halo formation, causes and elimination.
- Measure of operational reliability and failure predictions.
- Monitoring of matching between structures.
- Determination of what diagnostics are needed in what locations.
- Development of optimum commissioning procedures for use in a plant or production accelerator.

Initial beam commissioning will be started at a low duty factor, at a rep rate of 5 or 10 pps, and with pulse lengths of only about 100 μs. This will help prevent equipment damage, accelerator activation and will facilitate use of conventional diagnostics for initial tune-up. We expect to use a cw mode with variable current (starting at about 1 mA) for start-up of the operational beam. On-line diagnostics with the operational cw beam will be limited to use of non-interceptive diagnostics, relying heavily on video-profile cameras and BPMs (beam-position monitors) sensitive to the 350 MHz fundamental modulation.

**CCL**

A 700-MHz standard-configuration side-coupled linac will be used from the end of the CCDTL (about 100 MeV) to either the end of the accelerator, or to the match point into a superconducting structure. Based on preliminary optimizations, the favored transition point to the SCRF structure is about 217 MeV (Figure 10).

**Super-Condecting Structure Option**

A superconducting section of accelerator is being considered for use from approximately 217 MeV to the final APT energy. Use of a superconducting linac structure will dramatically reduce the required rf power for the plant, and also promises operational advantages in terms of stability and flexibility. One expected advantage is operational availability, as any single non-functioning module can be detuned and taken out of service. Details of the proposed superconducting structure are given in a companion paper [14].

The proposed complete APT accelerator configuration is shown in Fig 10. The exact transition point between the low-energy room-temperature structures and the high-energy superconducting structures will be made later, after a full optimization trade is made between cost savings, operational advantages, beam quality and design risk. Detailed discussions are given in reference [2].
Fig. 10. APT's proposed configuration of accelerating structures to provide a 100 mA proton beam at either 1300 or 1700 MeV.

Acknowledgments

Support for all of the APT program (including LEDA) is provided by the US Department of Energy, Defense Programs (DP) Office. Design of the APT accelerator is being led by a team at Los Alamos National Laboratory, mainly from AOT (Accelerator Operations and Technology) and ESA (Engineering Services and Analysis) divisions. Assistance is provided by Lawrence Livermore National Laboratory (LLNL), Brookhaven National Laboratory (BNL) and Sandia National Laboratory (SNL). A partnering and much of the balance-of-plant (BOP) work is done by personnel from the Savannah River Site (SRS). SRS is the preferred site for the APT production plant, if APT is the selected technology. At the time of publication, a selection is scheduled for choice of a Prime contractor, who will be responsible for preliminary and final design and construction of the APT plant.

Design efforts on APT and LEDA benefit greatly from previous programs, especially the FMIT (Fusion Materials Irradiation Test) and ground test accelerator (GTA) development at Los Alamos, and the cw proton development at Chalk River Laboratories (CRL). We wish to express our sincere appreciation to all those who shared their knowledge from cw linac development.

I want to specially acknowledge the key task leaders on the major LEDA systems. Joe Sherman is responsible for the development of the proton injector. Dale Schrage is pushing the design and fabrication of the RFQ. Rick Wood is leading the construction of the CCDTL. Dan Rees is overseeing the procurement, design, assembly and testing of the high-power rf systems. Jim Stovall is leading the beam dynamics simulations and preparing a beam commissioning plan. Without the hard work and dedication of these folks and many others doing equally important, smaller tasks, LEDA would not be possible.

References

HALO SIMULATION IN A REALISTIC PROTON LINAC DESIGN

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Abstract

A critical part of the design of a high intensity linear accelerator is to keep activation caused by particle loss below an acceptable limit. For bunch currents up to 200 mA it is possible to make a technical layout of a proton linac which allows operation in a non-space charge dominated regime. As a consequence almost no rms emittance increase is obtained in all three planes and the production of halo particles is reduced. A cylindrical bunch stays cylindrical. To examine the process of particles moving from the core into the halo, Monte Carlo simulations with large number of macroparticles are necessary. Strong transverse-longitudinal coupling is observed. The simulation results are used also to study the effect of halo scraping.

Introduction

High intensity proton linacs can either be pulsed $^1$H$^-$ – accelerators up to 5 MW average beam power [1] or cw H$^+$ – accelerators up to 130 MW beam power [2]. The major design problem is to reduce the particle loss along the linac down to 1 W/m which corresponds to a loss rate below $10^{-7}$/m. Losses above this limit prevent hands on maintenance. Therefore the linac design is determined by approaching these loss figures.

Particle loss is caused by a small number of particles outside the dense beam core, called the beam halo. The origin and the formation of the halo and its dynamics is an important issue for understanding the particle loss. There exist two different approaches. The first is a theoretical one based on simplified particle distributions and transport channels. Significant progress has been made in recent years on the basis of the so-called ‘particle-core model’ [3]. However, it is not obvious how to transform those results into loss rates for realistic linac designs where the beam is bunched and accelerated. The other approach is to first set up a realistic linac design based on technical parameters. With the help of Monte Carlo simulations such a design is checked against particle loss.

High Current Proton Linac Design

For this investigation of halo properties the underlying realistic high current linac design is the linac of the European Spallation Source (ESS) [4]. The layout of the linac [5] is shown in Fig. 1.

The low energy part consists of two $^1$H$^-$ – ion sources with 70 mA peak current each, two RFQs separated by a 2 MeV bunched beam transfer line for installing a fast chopping device and a 5 MeV funneling line after the second RFQ. The drift tube linac (DTL) operates at 350 MHz and accelerates a bunch current of 107 mA up to 70 MeV. The coupled cavity linac (CCL) has a frequency of 700 MHz resulting in an effective bunch current of 214 mA [6]. The CCL accelerates the beam up to 1.334 GeV. It is followed by a transfer line to the two compressor rings. The linac operates at 50 Hz and 6% duty cycle.

Fig. 1 ESS linac layout: IS: ion source, CH: chopper, FU: funneling, BR: bunch rotator

The main task of the linac design is to reduce the losses along the linac and at ring injection [7]. For low loss ring injection the low energy chopper and a bunch rotator in the transfer line are foreseen. The transverse losses along the linac have to be minimized by choosing appropriate parameters.

Beam currents of 107 mA in the DTL and 214 mA in the CCL are considered to be high and therefore it is expected that the beam is space charge dominated. Nevertheless, despite the high current it is possible to set the parameters for the CCL such that the beam dynamics is not space charge dominated, which reduces the sensitivity against mismatch and tolerances.

Fig. 2 Designed tunes for 214 mA effective beam current along the ESS-CCL. Upper curve is for transverse direction, lower one for longitudinal direction

To get a non-space charge dominated design the transverse tune has to be decreased along the CCL with increasing energy. This increases the beam dimensions at higher energies giving a smaller space charge density. As a consequence longitudinal focusing is still effective at high energies. The energy dependence of the transverse tune $\sigma$, in the CCL is shown in Fig. 2. The transverse tune has been chosen to decrease like
Here $\gamma$ is the relativistic factor and the index $o$ refers to the input energy of 70 MeV. Other underlying numbers are the effective beam current of 214 mA, a transverse rms input emittance of $0.6 \pi$ mm-mrad and a longitudinal rms input emittance of $1.2 \pi$ $\mu$ MeV. Transverse focusing is provided by doublets.

The tune ratios $\sigma_{L}/\sigma_{x}$ stay rather constant around 0.8 in the transverse and the longitudinal direction. The value 0.8 is indicative of the non-space charge dominated design. Not shown is the zero current tune $\sigma_{0o}$. For the CCL design $\sigma_{10}$ starts at 105° at 70 MeV. However, $\sigma_{10}$ decreases quite fast. At 105 MeV its value has fallen below 90°. The longitudinal zero current tune $\sigma_{0o}$ is always below 90°.

The equipartition ratio in the bunch system, the ratio between transverse and longitudinal energy, is around 0.5 at the input. As a function of energy the ratio first increases up to 0.9 and then falls down to 0.5 at the high energy end. A ratio of 1 at high energies would be possible by doubling the transverse tune and therefore reducing the transverse beam radius. The increasing space charge density would shift the design parameters into a space charge dominated regime [8], which we try to avoid.

Monte Carlo simulation with up to 200000 particles have been carried through for the DTL and CCL. Hereby the DTL and CCL have been simulated as whole. No effect can be associated with the frequency jump and the change from a singlet to a doublet focusing system. The rms emittances along the CCL are shown in Fig. 3. Less than 10% rms emittance growth is observed. This indicates that no dangerous resonances are present and no temperature exchange takes place between the transverse and the longitudinal direction.

![Fig. 3](image-url) Transverse and longitudinal rms emittance as a function of energy in the ESS CCL

Real space projections at the beginning and at the end of the CCL are shown in Fig. 4. At the input into the DTL the transverse and longitudinal phase space is filled independently with waterbag distributions. This is a reasonable assumption for the particle distribution produced by the preceding RFQ. The resulting cylindrical bunch shape is conserved along the linac. The forces of such a distribution can be calculated analytically [9].

Fig. 4 $(\Delta \phi, y)$-projections at input and output of the CCL

The transverse mismatch factor, which is not shown, has an average value of 0.3. Sources of mismatch are the changes of cell length and number of cells from cavity to cavity. The mismatch causes no rms emittance growth.

In summary it can be said that the ESS linac is an example of a high current linac designed in the non-space charge dominated regime. This results in small rms emittance growth, conservation of the bunch shape and in less sensitivity against mismatch.

Properties of the Halo

It is understood that the halo consist of only a small number of particles outside the beam core. Small means that less than $10^{-3}$ particles are forming the halo. To understand the properties and dynamic of the halo particles one should try to answer questions about the halo production mechanism and the single particle motion.

To answer these questions Monte-Carlo simulations with a large number of particles have been made for the ESS Linac, a realistically designed linear accelerator. Results presented here refer to the CCL. The output distribution of the preceding DTL was transferred into the CCL. Space charge calculations are fully three dimensional and no symmetries have been assumed. Projections of the input distribution are shown in Fig. 5. Examining the distribution one can see that no halo has developed up to the end of the DTL. This is no longer true at the end of the CCL, see Fig. 6. Transversely less than 0.1% of the particles have entered the halo. A filamentation is seen in the longitudinal phase space which contains less than 1% of the particles.

The evolution in the longitudinal phase space is shown in Fig. 7 at four different energies along the linac. The boundary of the longitudinal distribution at input differs slightly from an elliptical one. This is due to a 20 % rms emittance increase in the DTL. In order to study the sensitivity against longitudinal mismatch we have not corrected the injection parameters longitudinally. The non-elliptical distribution is connected with nonlinear forces which causes the filamentation in the longitudinal phase space. The mismatch enhances the development of a halo. This agrees with investigations made before [10]. Monte Carlo simulations with a longitudinally matched beam show much less filamentation [11].

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filamentation is acceptable for the linac, it cannot be ignored in a following high \( \beta \) transfer line either to a compressor ring or to a target station [12].

While we studied the filamentation in the longitudinal phase space, transversely we are interested in the particle motion of the radially outermost particles. The particle-core model assumes that halo particles are oscillating through the beam core [13,14]. For a space charge dominated beam, chaotic particle trajectories have been found [15,16]. Analytical models for halo formation have been developed by different groups [17,18,19] and are confirmed by numerical simulations [19,20].

In order to compare the particle-core model with the results of the Monte Carlo simulation presented here Fig. 8 shows the real space \((x,y)\) at four different energies. 200 selected particles are plotted, the outermost ones at the CCL output. Tracing those particles backwards one sees that the particles are inside the beam core around 1264 MeV. They are in the halo around 1166 MeV and again in the beam core at 1117 MeV. This corresponds to a full betatron oscillation consistent with a design tune design tune \( \sigma_t \) is around 15° at this energy range. This confirms the particle oscillation predicted by the particle-core model.

Information about the halo production mechanism can be obtained if the position of halo particles at the CCL input are studied. Again the 200 outermost particles in the \((x,y)\)-space at the end of the CCL are investigated, see Fig. 9. Their positions in phase space at injection are shown in Fig. 10. Comparing Fig. 9 and 10 several conclusions can be made.

Halo particles in \((x,y)\)-space at the end of the CCL come from the boundary of the longitudinal distribution and transversely mainly from the inner part of beam at injection, see Fig. 10. The conclusion cannot simply be reversed. Not every particle which is initially located at the boundary of the longitudinal distribution and inside the beam will become later on a halo particle. All six initial coordinates in the whole phase space have to be considered. At the end of the CCL the same halo particles are found inside the longitudinal phase space distribution forming some clusters, see Fig. 9. In the transverse phase space the particles are uniformly distributed inside the core, see again Fig. 9.

These observations lead to the following conclusion.

![Figure 5](image1.png)

**Fig. 5** Phase space projection at the input of the CCL (70 MeV)

![Figure 6](image2.png)

**Fig. 6** Phase space projection at the end of the CCL (1.334 GeV)

![Figure 7](image3.png)

**Fig. 7** The evolution of the longitudinal phase space distribution along the CCL.

![Figure 8](image4.png)

**Fig. 8** Demonstration of the halo particles traversing the beam core, as predicted by the particle-core model.
dial halo particles are driven out of the beam by a transverse-longitudinal coupling force. Initially they are located at the boundary of the longitudinal phase space projection. The coupling causes the particles to enter the halo in (x,y)-space and at the same time the particles move inwards into the longitudinal distribution. Details of the amount of halo particles in the (x,y)-space at the end of the linac are correlated to the precise knowledge of the longitudinal input distribution.

Beam Scraping at Medium Energies

Beam envelopes in y-direction are plotted along the linac in Fig. 11. There are less than $10^{-4}$ particles outside ±10 mm for all parts of the linac, except for two 'hot spots' at around 1150 and 1250 MeV. The envelope of the outermost particle, representing the $10^{-5}$ level, reaches values up ±15 mm. The pipe radius is 22 mm along the CCL.

Scraping away some particles in the halo at medium energies is tried for the CCL. Around 800 MeV scrapers in the x and y directions are positioned at two places. The distance from the axis is set to be 9 mm. The maximum absorbed beam power is limited to less than 0.5 kW on each scraping device. This corresponds to 30 particles at 800 MeV in a Monte Carlo simulation with 200000 particles.

Fig. 9 Phase space projections of the 200 outermost particles in (x,y)-space the end of the CCL

Fig. 10 Phase space distributions of the same particles as in Fig. 9 at the beginning of the CCL

Fig. 11 Beam envelopes in y-direction along the CCL. The different envelopes corresponds to (inward to outward) 90, 99, 99.9, 99.99 and 100% of the particles

Fig. 12 Beam envelope of the outermost particle without and with two scrapers. The two outer curves (filled circles) correspond to the unscraped beam, the two inner ones (open squares) correspond to the scraped beam.

In Fig. 12 the envelope of the outermost particle in y-direction is plotted above 800 MeV. Less than $10^{-3}$ particles in total are scraped away. Also shown is the effect of using two scrapers which are separated by about 40° in beta-
tron oscillation. Quite obvious is the limitation of the beam envelope to about ±10 mm at most positions. At the two hot spots the number of particles outside ±10 mm and the maximum amplitude are reduced.

The two scrapers are positioned to get an overall 'global' effect on the beam envelope. For reducing the hot spots other scraper positions and probably more than two might be necessary. For the ESS CCL 6 to 8 scrapers in the x and y direction each are considered in every second diagnostic section, which are separated by about 20° in betatron oscillation. With this arrangement it should be possible to have less than 10⁻⁵ particles outside ±10 mm all along the linac after scraping, which is a reduction by one order of magnitude.

Acknowledgment

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OVERVIEW OF LINAC APPLICATIONS AT FUTURE RADIOACTIVE BEAM FACILITIES

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Abstract

There is considerable interest worldwide in the research which could be done at a next generation, advanced radioactive beam facility. To generate high quality, intense beams of accelerated radionuclides via the "isotope separator on-line" (ISOL) method requires two major accelerator components: a high power (100 kW) driver device to produce radionuclides in a production target/ion source complex, and a secondary beam accelerator to produce beams of radioactive ions up to energies on the order of 10 MeV per nucleon over a broad mass range. In reviewing the technological challenges of such a facility, several types of modern linear accelerators appear well suited. This paper reviews the properties of the linacs currently under construction and those proposed for future facilities for use either as the driver device or the radioactive beam post-accelerator. Other choices of accelerators, such as cyclotrons, for either the driver or secondary beam devices of a radioactive beam complex will also be compared. Issues to be addressed for the production accelerator include the choice of ion beam types to be used for cost-effective production of radionuclides. For the post-accelerator the choice of ion source technology is critical and dictates the charge-to-mass requirements at the injection stage.

Introduction

There are about 20 nuclear physics laboratories around the world which are either currently active in basic research with accelerated radioactive beams or are proposing new facilities for such research. Two major studies have been carried out recently to consider the research opportunities and technical options for future radioactive beam facilities, one by a North American committee [1] and the other by a European committee [2]. In the recently completed 1996 Long Range Plan for nuclear physics in the United States, the Nuclear Science Advisory Committee has recommended high priority for investment by the National Science Foundation and the Department of Energy in accelerator facilities to create advanced capabilities for research with radioactive beams.

One method of generating energetic beams of short-lived isotopes is via peripheral nuclear reactions with primary beams of stable heavy ions which are directly accelerated to energies per nucleon in the range of 50–1000 MeV. At such high energies the kinematics of these reactions are such that the secondary beams have relatively good transverse and longitudinal emittances and, after separation in the beamlines via magnetic rigidity and differential energy loss in absorbers, are appropriate for a variety of nuclear reaction studies. There are several laboratories which are currently doing research with radioactive beams generated via this fragmentation mechanism; examples are GSI near Darmstadt in Germany,GANIL in Caen, France, NSCL in East Lansing, Michigan, and RIKEN near Tokyo, Japan.

A variation on the fragmentation method is to create secondary beams of radioactive ions in the beamline at lower energies via nuclear transfer reactions utilizing inverse kinematics. The details of producing a beam of the short-lived radionuclide $^{12}_7$F via this method for nuclear astrophysics studies at ATLAS are given in a contribution to this conference [3].

A second general method of generating radioactive beams is known as the two-accelerator or ISOL (Isotope Separator Online) method. The ISOL technique has been used for over thirty years to produce, ionize, mass separate, and study short-lived nuclear isotopes. ISOLDE [4] at CERN is a premier example of a facility based on this technique. At ISOLDE radionuclides are produced via nuclear spallation reactions with 1 GeV proton beams from the Booster synchrotron which is part of the high energy accelerator chain at CERN. Other ISOL facilities are based at research reactors and use thermal neutron fission of $^{235}$U as the radionuclide production mechanism; the OSIRIS facility at the reactor in Studsvik, Sweden is an example of this type. Using the ISOL method for the production of radioactive beams at energies high enough for nuclear reaction studies is a relatively new concept which has not been used extensively to date. Pioneering work to develop accelerated radioactive beams using this method has been carried out at Louvin-la-Neuve [5]. The present paper addresses the issues involved in selecting appropriate accelerators for both the driver and secondary beams for ISOL-type facilities.

Typical ISOL-type Radioactive Beam Facilities

An ISOL-type accelerated radioactive beam facility comprises several major components: the primary beam (driver) accelerator or reactor to create the radionuclides, the target/ion source complex, a high resolution mass separator, the secondary beam accelerator, and a variety of experimental areas and apparatus for the research program. A schematic technical layout of such a facility as envisioned by the IsoSpin Laboratory study [1] was presented by J.M. Nitschke [6].

Of the several laboratories around the world which are either constructing or proposing new radioactive beam facilities there is a wide variety of choices of primary and secondary beam accelerators. In most cases radioactive beam facilities are evolving via upgrades or modifications to existing nuclear physics laboratories by adapting and utilizing one or more existing accelerators. In some cases the radioactive beam facilities are attached to production accelerators or reactors which exist primarily for other applications.
Table 1

Configurations of a few selected ISOL-type radioactive beam facilities, under construction and proposed

<table>
<thead>
<tr>
<th>Project/Laboratory</th>
<th>Location</th>
<th>Primary beam accelerator</th>
<th>Secondary beam accelerator</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRIBF</td>
<td>Oak Ridge</td>
<td>Cyclotron, k = 100 MeV</td>
<td>Tandem, 25 MV</td>
<td>Commission, ’96</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cyclotron, k = 200–250 p</td>
<td>Tandem + SC Booster, 50 MV</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>INS</td>
<td>Tokyo</td>
<td>Cyclotron, k = 67 MeV</td>
<td>RFQ + IH Linac, 14 MV</td>
<td>Test, 1996</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Synchrotron, 3 GeV p</td>
<td>RFQ + IH Linac</td>
<td>JHP future</td>
</tr>
<tr>
<td>ARENAS</td>
<td>Tsukuba</td>
<td>Cyclotron, k = 110 MeV</td>
<td>Cyclotron, k = 44 MeV</td>
<td>Constr./1998</td>
</tr>
<tr>
<td>SPIRAL/GANIL</td>
<td>Louvain-la-Neuve</td>
<td>Cyclotrons, k = 400 (H)</td>
<td>Cyclotron, k = 265 MeV</td>
<td>Constr./1998</td>
</tr>
<tr>
<td>REX-ISOLDE</td>
<td>CERN</td>
<td>Synchrotron, 1 GeV p</td>
<td>RFQ + IH Linac, 16 MV</td>
<td>Constr./1998</td>
</tr>
<tr>
<td>ISAC/TRIUMF</td>
<td>Vancouver</td>
<td>Cyclotron, k = 500 (H')</td>
<td>RFQ + IH Linac, 13 MV</td>
<td>Constr./2000</td>
</tr>
<tr>
<td>PIAFE</td>
<td>Grenoble</td>
<td>Reactor, thermal n</td>
<td>Cyclotrons, k = 88, 160 MeV</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>ATLAS</td>
<td>Argonne</td>
<td>Linac, 245 MV</td>
<td>RFQ + SC Linac, 70 MV</td>
<td>R&amp;D</td>
</tr>
</tbody>
</table>

To illustrate some of this variety, the configurations of a few ISOL-type radioactive facilities are listed in Table 1. A review of these new projects and others, including fragmentation-type facilities, was given by A. Mueller [7]; progress reports on several specific facilities will be included in the proceedings of the recent Fourth International Conference on Radioactive Nuclear Beams. Some of the challenges to be confronted in developing powerful, broadband ISOL-type radioactive beam facilities are:

- High intensity radioactive beams,
- Cost effective solutions,
- exotic beams/ far from stable isotopes,
- Excellent beam quality and energy variability,
- Broad mass range of secondary beams,
- High resolution isobar separation,
- Diagnostics for tuning weak exotic beams,
- Target/ion sources for high power primary beams,
- Shielding and remote handling at production target.

Below, in separate sections, primary and secondary beam accelerators are discussed.

**Driver Accelerators**

A general-purpose facility for producing intense accelerated radioactive nuclear beams must incorporate a powerful driver device to generate large quantities of radionuclides. Some ISOL facilities have been located at high-flux research reactors to produce and study the neutron-rich isotopes produced via thermal neutron-induced fission of $^{235}$U. The new radioactive beam project PIAFE [8], listed in Table 1, will utilize the ILL reactor at Grenoble as the production device. All other present projects are using or planning to use some type of accelerator as the driver device; either a synchrotron, cyclotron, or linac in various implementations. Essentially all existing or proposed radioactive beam facilities utilize either a pre-existing driver device or post accelerator, or both. The only proposed "green field" facility listed in Table 1 is that planned as part of the Japanese Hadron Project. Even in this case, however, the radioactive beam capability will coexist with other major research interests in an extensive accelerator complex.

**Radionuclide-Production Mechanisms**

The choice of driver device for a radioactive beam facility is intimately related to the overall goals of the laboratory and the capabilities of the secondary beam accelerator. In many instances, as mentioned above, the driver device is pre-existing and the other components must be adapted to its capabilities. For example, a reactor is a prolific source of medium-mass, neutron-rich radionuclides which result from thermal neutron fission. Hence, Phase II of the new PIAFE facility will be dedicated to the acceleration and study of nuclear reactions with this class of radionuclides. On the other hand, high energy proton synchrotrons can prolifically produce both proton-rich and neutron-rich isotopes over a broad mass range via the spallation reaction mechanism. The REX-ISOLDE collaboration [9] is constructing a secondary beam accelerator at ISOLDE to utilize the existing synchrotron and ion source infrastructure at that facility.

However, the costs of reactors and GeV energy proton synchrotrons probably exclude them from consideration as dedicated drivers for future radioactive beam facilities. For the production of radionuclides there are a variety of nuclear reaction mechanisms at the disposal of designers. With primary beams of protons and heavy ions in the energy range of 10's to 100's of MeV per nucleon several reaction mechanisms can be utilized: compound nucleus/fusion-evaporation reactions, primarily for proton-rich products; light-ion induced fission, primarily for medium mass, neutron-rich products; spallation reactions with intermediate energy (~100 MeV per nucleon) heavy ions; and fragmentation of heavy ions such as $^{14}$O. A desirable driver accelerator for an advanced radioactive beam facility is one capable of delivering a variety of beam types over a range of beam energies. Such flexibility permits selecting a beam/target combination and an associated reaction mechanism to selectively populate radionuclides in a specific mass region.

**A Proposed Heavy-Ion Linac Driver**

A driver accelerator with a beam power of up to 100 kW would be desirable for radioactive beam production. Most experience to date is with up to a few kilowatts of beam power.
and improvements in target/ion source technology are expected to lead to higher beam powers being feasible. A linear accelerator capable of delivering a variety of ion species with beam power up to 100 kW at energies per nucleon of 100 MeV is shown schematically in Fig. 1. This is the type of driver accelerator suggested by the Argonne group in a working paper [10]. To accelerate light ions, such as $^1$H, $^2$H, and $^3$He, a multicusp or microwave ion source and a light-ion RFQ would be used in the injector. Whereas, for heavy ions, such as $^{16}$O, would require an ECR ion source operating with an m/q of 6, pre-acceleration in an RFQ and ion linac to an energy per nucleon of 5 MeV for stripping a higher charge state for further acceleration to 100 MeV per nucleon.

**Fig. 1.** Schematic view of a high-beam-power linac to deliver a variety of ion beams for radionuclide production.

### Conventional Linac Option

The driver shown schematically in Fig. 1 could be implemented as a conventional linac with the parameters indicated in Table 2. The linac main stage could be a conventional DTL or possibly a CCDTL structure [11]. A preliminary physics design study of the DTL configuration for the heavy ions has been carried out by AccSys Technology, Inc. [12]. As indicated in Table 2 the beam currents for the heavy ions would be limited by the ion sources rather than by the linac beam power capability, due to the high peak current requirement.

### Superconducting Linac Option

An alternative to the conventional DTL or CCDTL linac discussed above is a superconducting linear accelerator. This would involve the extension of the well-established technology now used for low energy heavy ion linacs to higher beam currents and to a somewhat higher velocity regime. Two technical advantages of a superconducting linac with CW beams are: (a) the continuous beam would eliminate a potential problem with voltage ripple at the production target/ion source, and (b) the heavy ion beam intensities available from a DC ion source would permit the achievement of much higher beam powers than with the low duty cycle conventional linac (as indicated in Table 2). Furthermore, the superconducting option is likely to be significantly less expensive to operate, by an estimated $2M/year, due to a much lower electrical power requirement and the elimination of the maintenance of the set of high-peak-power klystrons required for the conventional linac.

By using independently phased two- or three-gap superconducting resonators the velocity range possible with such structures would permit the nominally 200 MV linac to deliver beams of 200 MeV protons as well as the 100 MeV per nucleon heavy ions with m/q=2 as discussed above; this is a very useful additional beam for radionuclide production purposes. There are several well established superconducting structures for ion velocities up to about 0.15c [13], but this application would require the extension of this technology up to v = 0.55c. Prototypes of structures which could possibly be modified for operation in this velocity regime have been developed and tested by Delayen, *et al.* [14], one of which is illustrated in Fig. 2. Alternate geometries, including a "spoke" structure, have been proposed by Delayen, *et al.* [15].

### Table 2

Parameters of a Conventional Drift Tube Production Linac

<table>
<thead>
<tr>
<th>Linac Specifications:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Output Beam Energy: 100 MeV per nucleon</td>
<td></td>
</tr>
<tr>
<td>Max Output Beam Power: 100 kW</td>
<td></td>
</tr>
<tr>
<td>Typical Light Ions: $^1$H, $^2$H, $^3$He (microwave ion source)</td>
<td></td>
</tr>
<tr>
<td>Typical Heavy Ions: $^{12}$C, $^{16}$O, $^{20}$Ne, $^{38}$Ar (pulsed ECR ion source)</td>
<td></td>
</tr>
<tr>
<td>Typical Max. Currents: $^1$H, 1 mA; $^2$H, 0.5 mA; $^3$He, 0.25 mA (Light Ions @100 kW)</td>
<td></td>
</tr>
<tr>
<td>Typical Max. Currents: $^{16}$O, 55 µA; $^{36}$Ar, 28 µA (Heavy Ions @100 kW)</td>
<td></td>
</tr>
<tr>
<td>Typical Ion Currents: $^{16}$O, 20 µA; $^{36}$Ar, 3 µA (Source/Stripping Limits)</td>
<td></td>
</tr>
</tbody>
</table>

**Linac Specifications:**

- Injector RFQ/Linac: 5 MeV/u output @q/m = 1/6, (30 MV)
- Main Linac: 100 MeV/u out @q/m = 8/18, (215 MV)
- Duty Cycle: 2.5% @ 120 Hz
- Input Power: 1.75 MW
- Output Energy Variation: 15% increments
- Controls: Pulse-pulse ion source and energy variation possible

**Fig. 2.** A two-gap superconducting niobium resonator which was constructed and tested at ANL by Delayen, *et al.* [14].

Papers presented at this conference by K.C. Chan and G. Geschenke discuss possible uses of superconducting linear accelerators for very high power applications, such as for neutron spallation sources, transmutation of waste, and production of tritium. To date these applications are
considering superconducting structures for velocities above 0.5c, to be operated at higher frequencies and lower temperatures. For the radioactive beam driver accelerator application it seems desirable to keep the frequency below about 400 MHz so that operation at 4.5 K is economically feasible. To keep the capital cost of a superconducting driver competitive with that of a conventional linac, efficient fabrication methods for structures in this low-velocity regime will have to be developed [16].

Other Driver Accelerator Options.

As indicated in Table 1 above several radioactive beam projects are using synchrotrons or cyclotrons as the driver accelerators. Synchrotrons are generally used in projects which share the accelerator with other applications, typically for high energy physics research, as in the case of ISOLDE and the Japanese Hadron Project. There is also the possibility that there will be a proposal to use the rapid cycling synchrotron of the ISIS facility at the Rutherford Appleton Laboratory in Great Britain as the driver for a future radioactive beam facility [17]. These synchrotrons use high energy protons to produce radionuclides via spallation reactions.

The cyclotrons at GANIL will be used with beam power up to 6 kW and a variety of species from deuterons to heavy ions at energies up to 100 MeV per nucleon to produce radionuclides for the new SPIRAL facility [18] via various production mechanisms including fragmentation and light ion induced fission. The cyclotrons at GANIL have been in operation for several years for basic research in nuclear physics including the production of radioactive beams via the fragmentation mechanism. The SPIRAL project is an upgrade which gives the laboratory the option to produce radioactive beams via both fragmentation and the ISOL-method. Similarly, the existing 500-MeV H⁺ cyclotron at TRIUMF will be used as the driver for the new ISAC radioactive beam project [19]. The initial plans are to use beam currents up to 10 μA, and to increase to higher currents as the target/ion source technology permits.

The HRIBF project [20], currently in commissioning stages at ORNL, is using the existing ORIC cyclotron as the driver, but there are plans to possibly upgrade to an advanced radioactive beam facility in the future, which would involve the addition of a more powerful driver accelerator. Various types of cyclotron are currently under consideration, including compact superconducting and conventional separated sector styles [21], either of which could deliver 250 MeV proton beams at currents of 100–200 μA. A review of cyclotrons which could be constructed for use as drivers was given recently by Y. Jongen [22].

Post-Accelerators

The requirements of the post-accelerator of an advanced radioactive beam facility are to a large extent dictated by the choice of ion source for the secondary beams. Two common classes of ion source are the standard ISOL-type 1+ sources as used at ISOLDE [4], GSI [23], and other on-line isotope separator facilities, and higher charge-state sources as are planned for use, for example, at SPIRAL [18]. The ISOL-type 1+ ion sources have been developed to have high efficiencies and excellent emittances for a broad range of elements, but place great demands on the post-accelerator due to the very low q/m values for heavy masses. ECR ion sources generally have worse emittances, but have been demonstrated to have good efficiencies for noble gases, and are under development for other elements [24]. Other developments are in progress to use ISOL-type ion sources in combination with an ion trap plus an EBIS device [9] or with an ECR “catcher” [25] to increase the charge states.

Post-Accelerators Based on Linacs.

The Argonne Post-Accelerator Proposal. The Argonne concept for an advanced radioactive beam facility [10] is to build on the present capability of the ATLAS superconducting linacs to deliver beams from protons to uranium with excellent transverse and longitudinal beam quality [26]. The injector stage of the post-accelerator is being designed [27] to start with 1+ ions with masses up to about 200 from ISOL-type ion sources; a schematic layout is shown in Fig. 3. The design of a CW, low-frequency RFQ for the first stage of this injector was presented at this conference [28]. This concept involves stripping of the 1+ ions to 2+ or 3+ after the first stage RFQ. High stripping efficiencies with very low multiple scattering (<1 m) have been demonstrated for Kr, Xe, and Pb ions using a low-pressure windowless gas cell [29]; charge-state fractions for 1-MeV Pb ions in helium and nitrogen are shown in Fig. 4.

Pre-acceleration and stripping of 1+ ions for injection into ATLAS

Fig. 3. Block diagram of the ANL concept for a radioactive beam pre-accelerator beginning with 1+, mass 132 ions from an ISOL-type ion source.

RFQ + IH-Linac Combinations. Several radioactive beam facilities [19, 30, 9, 31] are using normally conducting low-frequency RFQ structures followed by IH-linacs to take advantage of the high shunt impedances obtainable with such structures. Two of these [19, 31] will operate CW.
Other Post-Accelerator Options.

**Cyclotrons.** The SPIRAL [18], ARENAS [5], and PIANE [8] projects will all use cyclotrons as the radioactive beam post-accelerators. The CIME cyclotron, currently nearing completion at GANIL for the SPIRAL project is shown schematically in Fig. 5. A specific advantage of cyclotrons over linacs is that being isochronous and with high turn numbers they are m/q selective with resolutions up to 10,000. A disadvantage is that, to achieve high beam energies, ions with relatively high q/m values are required.

**Tandems.** The HRIBF facility at Oak Ridge is using the existing 25 MV tandem as the post accelerator [20]. It produces beams with low transverse emittance at energies useful for nuclear physics over a broad mass range for any ion species which can be either directly extracted as or charge exchanged into a negative ion.

This research was supported by the US DOE Nuclear Physics Division under contract W-31-109-ENG-38.

References

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Invited Talk Session MO3

Chairman: V. Teplyakov

Monday, August 26, 1996
Performance of the Argonne Wakefield Accelerator Facility and Initial Experimental Results

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Abstract

The Argonne Wakefield Accelerator (AWA) facility has begun its experimental program. This unique facility is designed to address advanced acceleration research which requires very short, intense electron bunches. The facility incorporates two photocathode based electron sources. One produces up to 100 nC, multi-kiloamp 'drive' bunches which are used to excite wakefields in dielectric loaded structures and in plasma. The second source produces much lower intensity 'witness' pulses which are used to probe the fields produced by the drive. The drive and witness pulses can be precisely timed as well as laterally positioned with respect to each other. We discuss commissioning, initial experiments, and outline plans for a proposed 1 GeV demonstration accelerator.

1. Overview of the AWA Facility

The generation of high gradients (> 100 MV/m) in wakefield structures requires a short pulse, high intensity electron drive beam. The main technological challenge of the AWA program is the development of a photo injector capable of fulfilling these requirements. The goal of the AWA is to demonstrate high gradient and sustained acceleration of charged particle beam by using wakefield method. In the past year we have made considerable progress towards attaining the design goals of the AWA.

Fig.1 shows the schematic diagram of the AWA facility, consisting of 3 major components: 1) an L-band rf photocathode and Linac capable of producing a 100 nC electron drive beam; 2) a second L-Band photocathode gun generates a low emittance and low charge beam which probes the wakefield produced by the intense drive beam and 3) An experimental test section for wakefield experiments.

AWA Facility Schematic Layout

Figure 1. Schematic layout of the AWA facility.

A picosecond UV laser with up to 8 mJ/pulse output is used to illuminate the photocathode for both guns.

In this paper we present detailed descriptions of the facility and initial characterization of its performance. The preliminary results of dielectric and plasma wakefield experiments are discussed. The near and long term plans for experiments and facility upgrades will be described.

2. Photocathode Gun and Drive Linac System

The gun and drive linac are shown in Fig. 2. The laser photocathode sources was designed to deliver 100 nC bunches at 2 MeV to the drive linac. The photocathode gun is a single cell standing wave cavity with designed peak field of 90 MV/m on the cathode [1]. Some of the novel features incorporated into the gun to attain high intensities include a large (2 cm diameter) cathode, the use of a curved laser wave front and nonlinear focusing solenoids matched to the angle-energy correlation computed for the 100 nC bunch. So far, only flat laser pulses have been used for the experiment. However, for most AWA experiments, only 40 – 60 nC pulses are needed as discussed below.

The AWA drive linac [2] consists of two sections of $\pi/2$ standing wave structures. Each section is about a meter long. The linac is designed to deliver 18 MeV electron beam with 5 - 10 % of energy spread at 100 nC.

3. Witness Gun

The witness gun a six-cell, copper, iris loaded, rf photocathode operating at 1.3 GHz in a p/2 standing wave mode. A low charge, low emittance witness beam (0.1 nC charge, 1 p mm-mrad 90% physical emittance) is produced to probe (i.e. witness) the wakefields left behind by the drive beam. The witness gun is a scaled down version of the s-band Mark IV accelerator that was used at SLAC, as described in reference [3]. Since the Mark IV Accelerator was a linac, some adjustments were made to turn it into a photocathode gun using the rf design code URMEL. The witness gun has a photocathode in the first 1/2 cell, a coupling iris in the fourth full cell and a beam exit hole in the last half cell.

In order to probe the test devices properly, the witness beam must have a kinetic energy of 4 MeV, a physical emittance of 1 p mm-mrad, an energy spread of less than 1% and a bunch length of about 5 ps. Extensive simulations with PARMELA have shown the Mark IV type gun to be capable of achieving the design parameters. Using a 1.5 mm spot size and a phase launch of 65 degrees we obtain the following results:

<table>
<thead>
<tr>
<th>Energy</th>
<th>90% Emittance</th>
<th>Energy Spread</th>
<th>Bunch Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.53 MeV</td>
<td>0.76 p mm-mrad</td>
<td>0.5% FW</td>
<td>5.6 psec</td>
</tr>
</tbody>
</table>

4. Lasers and Control

The picosecond KrF laser system

The laser consists of a front end that produces picosecond pulses at 248 nm and a final KrF amplifier. The central component of the front end is a synchronously pumped mode locked dye oscillator (Coherent 702). The dye laser is tuned to the desired wavelength of 497 nm by a single-plate birefringence filter. Coumarin 102 dissolved in benzyl alcohol and ethylene glycol is the lasing medium, and DOCl dissolved in benzyl alcohol and ethylene glycol is the saturable absorber. A harmonic tripled mode locked Nd:YAG laser is used to pump the dye laser. The frequency of the mode locker is 40.625 MHz of which the 32nd harmonic is exactly 1.3 GHz.

A single pulse from the dye laser output train is amplified to 300 $\mu$J through a three-stage amplifier. The dye amplifier is Lambda-Physik FL2003 pumped by 100 mJ, 308 nm pulses from a Lambda-Physik LPX105i excimer laser. The duration of the pump pulse is shortened to 10 ns so only one pulse from the dye oscillator can be amplified. The output from the dye amplifier is frequency doubled in a 3x3x7mm angle matched BBO crystal. Output at 248 nm is typically 25 - 30 $\mu$J. Because the length of this doubling crystal, temporal broadening of the input pulse is expected.

Amplification of the ultra-short UV pulses is done in a single stage KrF excimer laser (Lambda-Physik LPX105i). The input pulses pass through the amplifier twice in order to fully utilize its stored energy. Typical output of 8 - 10 mJ is obtained routinely. The length of the final pulse is measured by a Hamamatsu streak camera (model C1587) which has resolution of 2 ps. The typical measured pulse length (FWHM) is 3 - 4 ps. No satellite pulses observed. Repetition rate of the laser can be as high as 35 Hz.

In order to have certain flexibility of the experiment, we can run the Coherent 702 dye laser in a single jet mode. In the single jet mode, the laser is capable of producing pulse length from 5 ps to 30 ps. We have verified the laser pulses length by using the autocorrelator and streak camera. The laser energy is from 5 - 7 mJ/pulse with nominal fluctuation of 10% for the long laser pulses.

Controls and data acquisition

The design of the AWA control system[6] is based in part on the experience gained at the Advanced Accelerator Test Facility (AATF), and also on more extensive data acquisition systems used for high energy physics experiments. The goal of the AWA system is to provide easy selection and adjustment of accelerator and beamline parameters, as well as the online analysis of diagnostic and physics data.

At the core of the system is an HP-750 RISC workstation using the UNIX operating system. The workstation is interfaced to VMEbus via a high speed adapter with dual port RAM. A 68060 CPU board on the VMEbus handles command requests from the
workstation and provides auxiliary processing capabilities. Most of the control and monitoring functions are handled through a VME-CAMAC parallel bus interface. Video signals from beam position monitors and from the streak camera, comprising the actual physics data from the experiment, are acquired using a high resolution VME-based frame grabber. The AWA control software was developed in house and is based on the Tcl/Tk scripting language. The various codes comprising the system are written in C and FORTRAN77.

5. Initial Characterizations of the drive and witness beam

Detailed characterization of the both AWA drive and witness beam is currently underway. We have made an initial measurement of the beam properties at the exit of the Linac. Attempts were made to measure the pulse length and emittance vs the charge.

One unexpected problem encountered during the experiment was the low observed quantum efficiency of Magnesium photocathode, compared to measurements reported in the literature [4]. The QE found for Mg is 1~ 1.5x10^4. Hence almost all the available laser energy is required to generate a 100 nC beam. However, a higher intensity laser pulse generally induces the photocathode to emit electron continuously ("explosive mode") [5]. Therefore, our initial measurements were made with charges generally less than 100 nC.

A diagnostic port at the exit of the Linac consists of an insertable pepper pot and a phosphor screen for emittance measurements. A calibrated integrated current transformer (ICT) device is used here for online nondestructive charge monitoring and a thin quartz (1 mm thick) plate is used as a Cherenkov radiator for pulse length measurement.

High Charge Generation

A 20-27 nC beam can be produced by 1 mJ laser pulse regardless the laser pulse length. It appears that we run into the space charge limit when we increase the laser power to 2 - 3mJ for short laser (5 ps). The maximum charge produced is 55 nC with 5 mJ of laser power. Increasing the laser pulse length resulted in higher charges as expected. A 100nC per pulse were observed, and 90nC pulses can be reached consistently with 5mJ laser power.

Pulse Length Measurement

The electron pulse length is measured by using a streak camera situated in the laser room. The Cherenkov light from the quartz plate in the diagnostic port is collected and transported to the laser room. The Cherenkov light transport line was carefully built to ensure that no electron beam information can be lost.

![Fig 3 Electron pulse length vs charge](image)

Results of the measurement are summarized in Figure 4. Because the electron pulse is not a gaussian, all the data were characterized by the full width half maximum (FWHM). The bunch length has a strong dependence on the charge. The shortest bunch length is 11 ps for 18 nC beam. At each charge, we average several data points to minimize the “random error” due to the pulse to pulse charge fluctuations. For 80 nC beam (with long laser pulse length), the measured electron pulse length is 48 ps, longer than the design goal (100 nC, 30ps). We are in the process of setting up an experiment for further investigation to attempt to reduce the bunch length. Note that while the Linac focusing is optimized for the curved laser bunch, only planar wavefront laser beam have been used.

Emittance Measurement

A “pepper pot” with 0.5 mm holes and 2.5 mm spacing with a phosphor plate placed 40 cm downstream used for emittance measurement. Because of the small electron beam spot and relatively large holes of the pepper pot, and the resolution is about 10 mm mrad. Therefore, we have only estimated an upper limit on the emittance.

The following table summarizes the results of several measurements.
<table>
<thead>
<tr>
<th>Charge</th>
<th>Measured rms physical emittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>20nC</td>
<td>10 mm mmrad</td>
</tr>
<tr>
<td>55nC</td>
<td>13 mm mmrad</td>
</tr>
<tr>
<td>70nC</td>
<td>20 mm mmrad</td>
</tr>
</tbody>
</table>

**The Witness Beam**

The witness gun and its associated beam lines were recently installed and commissioned. Properties of the witness beam are being studied. The charge produced in the witness gun ranges from 0.1 - 3 nC. The beam energy is 4 MeV. The beam has been used for the initial dielectric wakefield measurements. Emittance measurements using a quadrupole scan technique and bunch length measurements using Cherenkov radiation are underway.

**Synchronization of the drive and witness beam**

Once the drive beam and the witness beam are generated, both beams are transported to the experimental section and combined. Since both the drive and witness beam are generated using the same laser pulse, a laser beam splitter is used to reflect a small amount of the laser beam through an adjustable delayed. Time delay between the two beams can be adjusted precisely using a mirror mounted on a movable stage for the witness laser beam line, while at the sametime, adjusting the rf phase to the witness gun to maintain a constant laser injection phase. The typical delay range used in the wakefield experiments is -50 ps to 400 ps. Delays up to 10 ns are possible using this system limited only by the adjustable stage.

6. Initial Wakefield Experiment Results

We have performed several collinear wakefield experiments to verify the performance of the AWA facility. Initial choice of the wakefield device were dielectric structure fabricated from Borosilicate glass. This material has a sufficiently large DC conductivity to minimize charging effects during beam tuning when scraping of the drive beam is worst.

**Dielectric Wakefield Experiment**

We have measured the wake field in two different dielectric structures (7 and 15 GHz). The results for the 7 GHz structure are shown in Figure 4. The wake amplitude is 1.5 MV/m for 20 nC drive beam. The structure has an inner radius of 1.25 cm and an outer radius of 1.6 cm with dielectric constant of 4. The measured wakefield amplitude and frequencies agree well the theory. This directly tested all the components of the AWA facility, and the results are satisfactory.

Another dielectric tube with inner radius 5 mm and outer radius 7.7 mm was also studied in the wakefield experiments. The resonant frequency for this tube is 15 GHz. A wakefield amplitude of > 5 MV/m was observed. Further tuning of the drive beam (more charge and shorter pulse length) should produce a wakefield in the excess of 15 MV/m in this structure.

![Wake Field Data for 7 GHz Dielectric Structures](image)

Figure 4. Measured longitudinal wakefield for the 7 GHz dielectric wakefield structure. The peak corresponds to 1.5 MV/m.

**Plasma Wakefield Acceleration and Focusing Experiment**

In collaboration with an UCLA group, we have performed several preliminary experiments to study the plasma wakefield acceleration in the blowout regime. The first set of experiments demonstrated acceleration of a witness beam as a result of the plasma wave excitation caused by the drive beam. There is a current effort to study the self focusing of the drive beam. In order for the drive beam energy to be optimally coupled to the plasma wave, the drive beam must be focused to a very small spot, and the radius of a significant part of the beam must be kept nearly constant by the plasma’s focusing force for the length of the plasma. The aim of the current experiment is to quantify this focusing and propagation, which depends greatly on the beam’s emittance, charge and initial matching, as well as on the plasma properties.

7. Future Planned Experiment

**Near term plans**
a). Fully characterize the AWA beams, particularly the drive beam. Studying the beam properties (bunch length and emittance vs charge) dependence on the machine parameters.

b). High gradient collinear wakefield experiments using a dielectric structures. Generation of an electron pulse train and test the step-up transformer concepts. Ultimately to test the dielectric breakdown of the dielectric materials.

c). Continuation of nonlinear plasma focusing and acceleration experiments.

d). Collinear Wakefield Plasma Experiment. This experiment will be very similar to the AATF experiment [6]. Since the drive beam charge from the AWA is much higher than the charge from AATF, one should expect much more intense wakefield. Although this experiment will be in the non-blowout regime, we still believe it is very interesting. We can scan the charge from 2 nC ~ 40 nC in the range of plasma densities of $10^{15} - 5 \times 10^{13}$. The justification of this experiment is that although PWFA has been a subject of the intense theoretical investigations, no one has experimentally studied PWFA in detail. Since we have the capability of mapping out the wakefields, this experiment should be straightforward to carry out. The expected acceleration gradient produced in the plasma would be in the range of 10 - 50 MV/m.

Long term plan

Its well know that a major constraint of collinear wakefield acceleration is the transformer ratio. To overcome this difficulty, an accelerating field step-up transformer scheme of the dielectric wakefield accelerator was proposed[7]. The approach is to extract rf power from an intense drive beam traveling in a relatively large diameter dielectric wake field tube (stage I). This power is then transferred to a smaller diameter dielectric loaded guide (stage II) where the enhanced axial electric field is used to accelerate electrons. Field enhancement results both from a lower group velocity in stage II than in stage I (longitudinal compression), and from geometrical effects made possible by the use of the dielectric loaded guide (transverse compression). High net acceleration can be realized if one uses a train of large number (10 - 20) electron pulses. The spacing of the drive pulses can be arranged in such way that a long rf pulse is generated to fill stage II. This also permits us to identify less stringent parameters for the drive beam than previously described. Using this new procedure we predict that Phase-I of the AWA (20 MeV drive beam) can accelerate a witness beam to over 100 MeV in a meter or less.

The current plans for the AWA (phase I) is to generate 40 nC, 20 ps long electron pulse train consisting of 10 -20 pulses. Further upgrade of the drive beam energy in excess of 100 MeV (phase II) without changing any of other parameters would enable us to achieve net acceleration of the witness beam to 1 GeV energy in a less of 10 meters. Therefore, successful demonstration of the multiple pulse driven step-up transformer is critical.

8. Summary

Installation of the AWA Phase I facility has been completed. The facility was successfully commissioned. The drive gun and Linac has produced up to 100 nC beam with maximum pulse length of 50 ps (FWHM). The witness gun has produced high quality beams being used for the wakefield experiments. More detailed characterizations of both beams are currently underway. Initial collinear dielectric wakefield experiments verified the new wakefield measurement system. High gradient wakefield acceleration experiments in dielectric structures and in plasma are being pursued.

We would like to thank L. Balka, A. Caired, C. Keyser, B. Taylor and K. Wood for their technical support. This work is supported by the Department of Energy, Division of the High Energy Physics, Contract No. W-31-109-ENG-38.

References

Poster Session MO

Chairman: V. Teplyakov

Monday, August 26, 1996
RFQ-, CHOPPING- AND FUNNELING-STUDIES FOR THE ESS-INJECTOR-LINAC*  
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Abstract

The front end of the ESS Linac has to provide a bunched high current H-beam with a special time structure for injection into the following DTL. This can be achieved by a system of two 175 MHz RFQ lines, each with a current of 54 mA, whose beams will be combined in a funnel section to a 107 mA beam with a bunch repetition rate of 350 MHz. For a proper operation of the compressor rings the linac beam must be chopped with a 60 % duty factor at the ring revolution frequency of 1.67 MHz which implies beam pulses of 360 ns and gaps of 240 ns during the macro pulse of 1.2 ms. A layout of the chopping line will be presented. A new concept for beam funnelling using a two-beam RFQ and a multigap funneling deflector will be discussed.

Introduction

The RFQ (Radio Frequency Qruadrupole) injector for the ESS linac provides a bunched beam of 107 mA at 5 MeV. This will be achieved by a system of two 175 MHz RFQ lines, each with a current of 54 mA, whose beams will be combined in a funnel section. For proper operation of the compressor rings the linac beam must be chopped with a 60 % duty factor at the ring revolution frequency of 1.67 MHz which implies beam pulses of 360 ns and gaps of 240 ns during the macro pulse of 1.2 ms. The chopping system shall also be used to achieve sharp edges at the head and the end of the macropulse.

RFQ

Each RFQ line is split into two sections with the chopping line between the two RFQs to enable chopping with an unneutralised, bunched beam at a moderate energy to reduce the required chopping voltages but at an energy high enough so that the beam can be transported through the line with a minimum emittance growth. Figure 1 shows a schematic drawing of the ESS RFQ injector system.

Table 1: Main parameters of the ESS RFQs.

<table>
<thead>
<tr>
<th></th>
<th>RFQ 1</th>
<th>RFQ 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0$ [MHz]</td>
<td>175</td>
<td>175</td>
</tr>
<tr>
<td>$E_{ip}$ [MeV]</td>
<td>0.05</td>
<td>2.0</td>
</tr>
<tr>
<td>$E_{cut}$ [MeV]</td>
<td>2.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Length [m]</td>
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<td>5.1</td>
</tr>
<tr>
<td>$N_{gap}$ [kw]</td>
<td>360</td>
<td>700</td>
</tr>
<tr>
<td>$N_{beam}$ [kw]</td>
<td>132</td>
<td>169.5</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic drawing of the ESS RFQ injector system.

The design of the first RFQ has been optimised for a total normalised input emittance of $1\pi$ mm mrad with respect to a small output emittance and a reduced output divergence of the beam to match to the chopping line. The operating frequency of the RFQs will be 175 MHz in order to be well below the current limit. In table 1, the main parameters of the ESS RFQs are shown.

Chopping

A fast beam chopper has to be included into the injector to create voids for a loss free extraction from the compressor rings. In addition the head and the tails of the macro bunches could be cut away, where the beam intensity may vary due to space charge neutralisation effects. In the EHFs-proposal [1] the layout of such a chopping line was presented, which could be adapted to the ESS requirements in a first step. Beam dynamics calculations showed high transmission (< 95 %) at a transverse emittance growth of 50 %. The bunch width could be kept smaller than ±45° [2]. Nevertheless the length of the line is about 7 m and the transverse beam dimensions become inbetween rather large, therefore the investigation of a more compact line has been started [3].

The chopping line has been designed with the chopper and the beam dump placed in the same drift section. It consists of single quadrupoles and buncher cavities. The beam dump will be in front of the third buncher cavity, where enough space for cooling is available. A drawing of the chopping line is shown in figure 2.

The chopper structure will be a pulsed electrostatic deflector, based on the BNL design [4], with deflection plates segmented into strips transversal to the beam direction. They are connected by coaxial delay lines, so that the pulse velocity along the beam direction is matched to the beam.
velocity. One set of strips above and below the beam will halve the magnitude of the voltage needed for deflection. A drawing of the chopper structure is shown in figure 3.

![Figure 3. Schematic drawing of the chopper structure.](image)

To avoid that bunches at the head or the end of the macropulse are not totally filled, the chopping voltage must rise in less than one rf-cycle. So the rise and fall time of the chopping voltage of 2 kV has to be less than 4.5 ns to achieve a clean chopping and this seems to be within technical possibilities. Beam dynamics calculations for this layout have been done with the PARMTRI-code using an rz-Poisson-solver and a beam current of 59.5 mA. The results show a transmission of 99% through the chopping line. The separation of the chopped and the unchopped beam at the position of the beam dump is about 5 mm. Figure 6 shows the transversal behaviour of the unchopped and figure 7 of the chopped beam along the chopping line. The particle distributions both for the chopped and unchopped beam at the position of the beam dump are plotted in figure 8 and figure 9.

![Figure 4. Particle input distribution of the chopping line.](image)

![Figure 5. Particle output distribution of the chopping line.](image)

![Figure 6. Transversal behaviour of the unchopped beam along the chopping line.](image)

![Figure 7. Transversal behaviour of the chopped beam along the chopping line.](image)
Funneling

To achieve the required beam current of 107 mA two identically bunched beams have to be combined into a single beam with twice the frequency, current and brightness. This so called funneling, proposed first by Montague and Bongardt [5], has to be done with a well bunched beam, which is needed for low emittance growth in a system of dipoles, quadrupoles, rebunchers and a deflector. Figure 10 shows the principle of funneling.

Now a new system with a two-beam RFQ and a resonator driven deflector has been investigated. A first two-beam funneling experiment includes a two-beam RFQ where the beams are bunched and accelerated with a phase shift of $180^\circ$ between each bunch. In the two-beam RFQ the beam separation is kept small. Therefore the rf-funneling deflector system can operate at low voltages. The new concept, based on a resonator driven multi-gap deflector, where the ions are deflected several times, facilitates some constraints in beam funneling like the limitation of the electric field by rf-sparking. To study the properties of the new two-beam RFQ, different types of prototype resonators were built and tested. Also calculations with the electrodynamics CAD program MAFIA have been done for comparison with the low-level measurements. A combination of a two-beam RFQ, which joins the two separated RFQ 2-resonators, and a single- or multi-gap deflector will be used for the ESS linac. Figure 11 shows a scheme of the ESS funneling section and table 2 the main parameters of the two-beam RFQ and the rf-deflector.

![Figure 11: Scheme of the ESS funneling section.](image)

| Table 2: Main parameters of the two-beam RFQ and the rf-deflector. |
|-------------------|-----------------|
| **two-beam RFQ**  |                  |
| $f_0$ [MHz]       | 175             |
| $E_{in}$ [MeV]    | 5               |
| $E_{res}$ [MeV]   | 5               |
| Length [m]        | 1               |
| $N_{fin}$ [kw]    | 250             |
| Angle between beam axes [mrad] | 284 |
| **rf-deflector**  |                  |
| $f_0$ [MHz]       | 175             |
| Voltage [kV]      | 500             |
| Length [cm]       | 8.8             |
| $N_{fin}$ [kw]    | 65              |
| Beam separation at input [mm] | 12.6 |

References

RF-PROPERTIES OF THE VE-RFQ-INJECTOR FOR THE ISL-CYCLOTRON*

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Abstract

The separated sector cyclotron at the ISL (Ionen-Strahl-Labor, Berlin) will get a new injector. The RFQ-part of the injector consists of two closely coupled VE- (Variable Energy) RFQs with an input energy range of 15 to 30 keV/n and an output energy range of 90 to 360 keV/n. For direct injection into the cyclotron a small energy spread and a duty factor of 100 % are needed, which is difficult for RFQs. Calculated and measured rf-properties of the RFQs will be discussed.

Introduction

The scientific program at the ISL, the former VICKSI-(Van de Graaff Isochron Cyclotron Kombination für Schwere Ionen) facility has changed from nuclear physics to solid state physics [2]. The VICKSI-facility consists of two external injection beamlines, a Van-de-Graaff and a Tandem injector with a separated sector cyclotron as postaccelerator. To meet the demands of the solid state physics users the Tandem injector will be replaced by a combination of an ECR source mounted on a 200 kV platform and a two stage VE-RFQ. The ECR-RFQ-combination will accelerate the ions to energies between 0.09 and 0.36 MeV/n to cover the range of final energies out of the cyclotron between 1.5 and 6 MeV/n.

The VE-RFQ-Structure

In an RFQ structure [3] the accelerating longitudinal fields are achieved by a geometrical modulation of the quadrupole electrodes, as shown in figure 1. The shape of the electrodes is characterized by the parameters aperture radius a, modulation m and the cell length L.

![Fig. 1: The shape of the modulated electrodes.](image)

Due to the Wideroe resonance condition [4], where $\beta_*$ is the normalized particle velocity, $v_*$ the particle velocity and $f$ the frequency:

$$L = \frac{\beta_* \lambda}{2} = \frac{v_*}{2f},$$

(1)

the fixed particle velocity profile can only be varied by either changing the cell length or the frequency. The second possibility is the way which has been used for RFQs with variable energy [5]. For this reason it is possible to change the output energy $E_{out}$ using the same electrode system: $v_* = v_0$. $E_{out} = v_0^2$.

To change the frequency of the 4-Rod RFQ, a type of resonator developed in Frankfurt [6], the resonator can be tuned capacitively or inductively. Figure 2 shows the inductive tuning by a movable tuning plate, which varies the effective length of the stems.

![Fig. 2: Scheme of the VE-RFQ.](image)

In Frankfurt the VE-RFQ was developed at first for the application as a cluster postaccelerator at the 0.5 MV Cockroft-Walton facility at the IPNL (Institut Physique Nucleaire Lyon, France) [7, 8]. This accelerator is designed for an input energy between $E_{in} = 5$ keV/n and 10 keV/n and an output energy between $E_{out} = 50$ keV/n and 100 keV/n.

Based on the positive experiences of this project, a first combination of an ECR source with a VE-RFQ has been built for the IKF (Institut für Kernphysik, Frankfurt). The RFQ is designed for a minimum charge-to-mass-ratio of 0.15, an output energy of $E_{out} = 100$-200 keV/n, a maximum electrode voltage of 70 kV and has a structure length of 1.5 m.

The RFQ-concept for the ISL-cyclotron

To inject into a cyclotron, the RFQ has to provide a bunched beam at a well defined injection energy determined by the inner radius of the cyclotron. The energy variability of the separated sector cyclotron will be kept by using an injector which has a variable energy and a variable frequency like the

* Work supported by the BMBF.
VE-RFQ. The operating frequency of the RFQs must be synchronized with the cyclotron frequency. RFQs have a fixed ratio of input to output energy given by the cell length of the first and last acceleration cell. This is similar to the energy gain factor of a cyclotron. For these reasons a VE-RFQ is well suited as an injector for a cyclotron [9].

The new injector consisting of an ECR source and a VE-RFQ has to fit into the existing Tandem beamline. To stretch the energy range of the injector the RFQ will be split into two RFQ stages, mounted in one vacuum-chamber. Each stage with a length of 1.5 m consists of a ten stem 4-Rod RFQ-structure. With a power consumption of 20 kW per stage an electrode voltage of 45 kV will be possible.

The RFQs will be driven in two different modes of operation. In the high energy mode both RFQs accelerate, the output energy of the cyclotron is between \( E_w = 3 \) MeV/n and \( E_w = 6 \) MeV/n with a harmonic number of 5 for the cyclotron. In the low energy mode the second RFQ has a detuned phase and works as a quadrupole transport channel. The energy range of the cyclotron in this mode is between \( E_w = 1.5 \) MeV/n and \( E_w = 3 \) MeV/n. The cyclotron works on the harmonic number 7. In both modes the frequency of the RFQ is tuned to the eighth harmonic of the cyclotron frequency. Parameters are given in table 1.

<table>
<thead>
<tr>
<th>RFQ:</th>
<th>min. / max. ( E_w )</th>
<th>15 / 30 [keV/n]</th>
</tr>
</thead>
<tbody>
<tr>
<td>min. / max. ( E_{\text{comb}} ) RFQ1</td>
<td>90 / 180 [keV/n]</td>
<td></td>
</tr>
<tr>
<td>min. / max. ( E_{\text{comb}} ) RFQ2</td>
<td>180 / 360 [keV/n]</td>
<td></td>
</tr>
<tr>
<td>energy gain factor RFQ1</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>energy gain factor RFQ2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>charge to mass-ratio</td>
<td>1/5 - 1/8</td>
<td></td>
</tr>
<tr>
<td>frequency</td>
<td>85 - 120 [MHz]</td>
<td></td>
</tr>
<tr>
<td>max. electrode voltage</td>
<td>45 [kV]</td>
<td></td>
</tr>
<tr>
<td>length / diameter</td>
<td>3 / 0.5 [m]</td>
<td></td>
</tr>
</tbody>
</table>

Cyclotron:

<table>
<thead>
<tr>
<th></th>
<th>0.43 [m]</th>
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<tbody>
<tr>
<td>injection radius</td>
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</tr>
<tr>
<td>extraction radius</td>
<td>1.8 [m]</td>
</tr>
<tr>
<td>frequency</td>
<td>10 - 20 [MHz]</td>
</tr>
<tr>
<td>max. dee-voltage</td>
<td>140 [kV] (peak)</td>
</tr>
<tr>
<td>energy gain factor</td>
<td>16.8 - 18.6</td>
</tr>
</tbody>
</table>

The RFQ output emittance depends largely on the input conditions. For matched input beams with an energy spread \( \Delta E/E < 1.5 \% \), a normalized emittance \( \epsilon_c < 0.5 \pi \text{ mm mrad} \) and a bunch length \( \Delta t < 1 \text{ ns} \) a transmission of 100 % is expected. To reach this beam quality it is necessary to have a buncher-chopper system between the ECR and the RFQs [10].

The ECR source is mounted on the 200 kV platform formerly used for the Tandem (see figure 3).

**Fig. 3: ECR source mounted on the platform.**

The vertical beam is bent by 90° passes through the buncher-chopper system and will be injected into the RFQs. The final matching into RFQ, will be done by a triplet lens. The beam from RFQ, is transported into the injection beamline of the cyclotron, to which a rebuncher has been added to make a proper time focus for the cyclotron.

**Rf-Properties**

The rf-properties were calculated with the code MAFIA Ver. 3.2 [11], to check several structural details. The main point of interest is the relation between the tuning plate position and the frequency as well as the dependance of the shunt impedance and the Q-value on the frequency, as shown in figure 4.

**Fig. 4: Relation between the position of the tuning plate and the rf parameters.**
Another point of interest is the electrode voltage along the RFQ (flatness), which should be constant. Calculations have shown that the flatness is a function of the frequency. The value of 3% at the highest frequency is non-critical, at lower frequencies it decreases, as shown in figure 5.

![Flatness graph](image)

**Fig. 5: Flatness.**

With MAFIA the loss distribution at the different RFQ-components has been calculated. Results show that 64% of the power will be lost at the stems (at 85 MHz). At 120 MHz the losses are: electrodes 31%, tuning plate 19% and electrode supports 12%.

The duty factor of 100% and the maximum power consumption of 20 kW together with the calculated losses at the different components were the arguments for a modified electrode material with an integrated cooling channel.

To compensate the frequency shift caused by thermal effects at high power level an additional tuning element is required. The effect of the slow tuner to the frequency varies with the resonance frequency as shown in figure 6.

![Frequency graph](image)

**Fig. 6: Frequency to tuner position.**

### Status and schedule

The vacuum chamber is copper plated and leak tested, the stems are aligned and mounted in the cavity. The components (tuning plate, vacuum pumps, etc.) are installed (figure 7).

![Resonator view](image)

**Fig. 7: View of the resonator.**

The electrodes and their supports are manufactured and will be brazed together with the water cooling. First low level measurements are scheduled for September 1996, the high power tests at NTG" will start in October 1996.

### References


* Neue Technologien, Im Steinigen Graben 12-14, 63571 Geinhausen

52
DESIGN OF COMPACT RFQS*

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Abstract

New features have been put into the design of RFQ accelerators, which result in small emittance growth, reduce the length of the RFQ structure and can be used to improve the matching to the following linac, buncher, chopper or funneling line. Design examples are presented for the new high current linac at GSI, for the ESS study, and for the HIIF injectors.

Introduction

The interest in high intensity particle beams has been pushed by high energy and heavy ion physics demands as well as by applications like neutron sources, military material testing, and inertial confinement fusion. The work on ion sources, injectors and accelerator structures has increased the pulse as well as the average current significantly.

Injectors are a combination of an ion source, a low energy beam transport line (LEBT), a preaccelerator, mostly an RFQ, and an intermediate matching section (IMS) which matches the beam to a following structure e.g. an IH or an Alvarez accelerator. Despite being relatively short, the injector defines the phase space density for the following stages in which the effective emittance can only grow. The development of the RFQ (Radio Frequency Quadrupole)-structure was a major step for the improvement of injectors [1,2]. It is giving the option of high overall transmission from the ion source dc-beam to a well bunched beam.

The variety of RFQ-accelerators covers the full ion mass range from H to U, frequency range from 5-500 MHz and duty factors from below 0.01 up to 100% [3,4]. The physics of transport and acceleration of high current ion beams in RFQs have been solved to such extent, that the best beams, which can be produced by ion sources and transported in a LEBT, can be captured and transmitted with very small emittance growth by RFQs.

![Image](image.jpg)

Fig. 1 Scheme of RFQ electrodes.

The RFQ basically is a homogeneous transport channel with additional acceleration. The mechanical modulation of the electrodes, as indicated in figure 1, adds an accelerating axial field component, resulting in a linear structure which accelerates and focuses with the same rf fields. For a given injection energy and frequency the focusing gradient \( G = \frac{X \cdot U_{0}}{a^2} \); \( X < 1 \) for modulated electrodes determines the acceptance in a low current application. A maximum voltage \( U_0 \) has to be applied at a minimum beam aperture \( a \), if the radial focusing strength is the limiting factor. The highest possible operating frequency should be chosen to keep the structure short and compact. Besides the choice of \( U_0 \) and operating frequency \( f \) of the "RFQ design", the values of aperture \( a \), modulation \( m \) and the length \( L_c \) along the RFQ, determine the electrode shape (pole tips) and the beam properties.

The principles of "RFQ design" are based on early work at ITEP and LANL. The spatial homogeneoues focusing and adiabatic bunching AB, where the beam is continuously bunched and accelerated with small axial fields, are basic ingredients of the RFQ to which sections for the radial- RM and axial matching (shaper) SH to the dc-beam have been added. The last part of the RFQ is the accelerator section ACC where the synchronous phase and the modulation or the axial field are kept constant like in a normal linac.

This is the basic content of the RFQGEN and RFQUICK codes and its relatives which generate parameter sets for the RFQ electrodes and the input for the simulation code PARMTEQ [5], which is a reference multiparticle code to study the transport of the beam through the cells of an RFQ and check emittances and losses. These successful tools have been used with some minor variations for a number of injectors and for the generation and studies of space charge dominated beams.

For low current heavy ion beams first major changes have been introduced. For the MSI injector and later on for the second injector at SATURNE a prebuncher with only a few cells followed by a short drift has been put into the first part of the RFQ without adiabatic bunching to reduce the length and power consumption of this injector. Also current limits or tune depressions have been used as design criteria along the RFQ rather than synchrotron frequencies to increase the overall currents [6].

In the development for the GSI-HLI-RFQ designs have been studied, in which basically all parameters were varied adiabatically with a decreasing radial \( \sigma_r \) and longitudinal \( \sigma_z \) like a broad hill resulting in short RFQs with rather low long emittances and a very small radial emittance growth without shaper, adiabatic bunching and ACC sections [7]. Surprisingly this method could also be applied for high current proton RFQs resulting in beam properties, which

* supported by the BMBF
could be achieved only with rather long classical designs. It should be mentioned, that these designs are independent of the kind of RFQ rf-structures used.

In the following examples of RFQs are presented, which make use of these design features. In addition new accelerator sections are added, which give an improved matching to the following IMS and accelerator stages.

**The GSI High Current RFQ**

The GSI accelerator facility consists of the 18 Tm Heavy Ion Synchrotron (SIS) and the Experimental Storage Ring (ESR). In order to feed these rings up to their space-charge limit a new High Current Injector (HSI – Hochstrominjektor) is under construction now [8], consisting of a 36 MHz RFQ and a IH linac from 120 keV/u to 1.4 MeV/u as shown in Fig. 2.

The HSI-RFQ electrode design follows the method used for the Spiral-RFQ prototype which has been built for rf-testing as well as for beam experiments [9, 10]. A very short IMS line to the IH-linac with an RFQ-lens has been selected to provide the special shape of the beam to the IH-linac with radially and longitudinally converging beam ellipses. To produce the longitudinal profile the beam has to drift first and then has to be rebunched. To reduce the IMS length the accelerator section of the RFQ has been modified in a way that in the last cells the stable phase was shifted to zero, to accelerate the beam without restoring force. The electrode parameters are shown in fig. 3, the output distribution for the design input current of 16.5 mA for U⁴⁺ is shown in fig. 4, with only 10% emittance growth in the RFQ.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>( E_{in}, E_{out} ) [keV/u]</td>
<td>2.2, 120</td>
</tr>
<tr>
<td>( U_0 ) [kV]</td>
<td>125</td>
</tr>
<tr>
<td>( N_{cell}, ) Length [m]</td>
<td>356, 9.22</td>
</tr>
<tr>
<td>( \delta_{in, out} ) [( \pi ) mm mrad]</td>
<td>0.05, 0.055</td>
</tr>
<tr>
<td>( I_{in, I_{design}} ) [mA]</td>
<td>( U^{+}, 15 )</td>
</tr>
</tbody>
</table>

**Two beam RFQ**

For a given emittance of an ion beam the current limit for rf-accelerators is proportional to the ion velocity and to the rf-wavelength, assuming rf-electrical focusing and field strength limitations. Due to the limited perrance of the ion sources a significant increase in beam current can be achieved e.g. by funnelling, which in an ideal case, doubles the ion beam without increase of emittance by a zipper like combining of bunches and doubling of the accelerator frequency. Examples where funnelling is essential are the spallation sources studies e.g. ESS [11] and Heavy Ion Inertial Fusion- (HIF-) injector schemes which have the typical tree of injectors. For the first funnelling stage a new two-beam RFQ, where two beams are bunched and accelerated in a single rf cavity has been proposed, as shown Fig. 5.
The two-beam RFQ consists of two sets of convergent quadrupole electrodes driven by one resonant structure. This brings the two beams very close together while they are still radially and longitudinally focused. A short funneling deflector at a rather low voltage placed directly behind the twin beam RFQ will combine the beams.

Matching to the funnel deflector will be done with the RFQ. The emittance growth in an rf-funnel deflector is minimal for a point-like bunch. So a $x,y$ focus is in the midth of the funnel deflector, while the axial focus should be somewhat later to match also to a transport line to the next accelerator stage. This has been achieved by a modified ACC section of the RFQs: A drift section DS with a number of cells with reduced synchrotron phase and focusing strength is followed by refocusing cells RF, rebunching cells RB and a matching out MO section.

![Output particle distribution for the twin beam RFQ](image)

Fig. 6: Output particle distribution for the twin beam RFQ.

Fig. 6 shows results for the beam distribution at the funnel location. The simulation was done for a He$^+$ beam funneling experiment under way at the IAP [12]. The beam is converging in the $x,y,z$ planes, although not totally symmetric. This beam shaping facilitates the funneling and should reduce emittance growth in the funneling line. It can be adopted e.g. to a high current chopping line as well, where the beam has to drift in the deflector without focusing [11].

**Other work**

Beam dynamics design procedures have been investigated by many authors, with mostly small deviations from the basic approach given by the ITEP and LANL groups, where the main work concentrated on high flying RFQs, emittance growth mechanism, halo formation and beam losses. The smooth parameter variation approach discussed above does not help in all cases but e.g. surprisingly helps keeping equipartitioning in the RFQ and small emittance growth [13,14]. The adding of a debuncher section was first done for the first SATURNE-RFQ [15] (no space charge), resulting in a rather long RFQ-structure. The short second SATURNE-RFQ worked with an internal prebuncher, like the MSI-RFQ, and an external debuncher [16]. The new designs for the HSI and the Two beam experiment have a DS incorporated into the ACC-section, and the radial focusing for both planes is added in the twin-beam structure example.

The smooth parameter variation design procedures also are used to reduce the power requirements of ion RFQs, which is an important parameter for applications. In low current applications the power has been reduced by more than 50% with only small reduction in acceptance and transmission [17].

**Acknowledgements**

I want to acknowledge the members of my group for support and help in beam dynamics as well as in computer questions, and especially H. Deitinghoff as reference point in beam dynamics, and colleagues from collaborations who always ask for more for less.

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EXPERIMENTS WITH HEAVY-ION BEAMS AND RF-TESTS WITH THE 27 MHZ HIGH-CURRENT SPIRAL-RFQ-PROTOTYPE *

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Abstract

A Spiral-RFQ has been built and operated with Ar\(^+\) beams up to 8 mA. In rf-tests very high electrode voltages were reached at design duty factor. The aim of the experiments was the test of the Spiral-RFQ for the High Current Injector (HSI), which is planned at GSI to fill the Heavy Ion Synchrotron (SIS) up to its space charge limit. This Spiral-RFQ, a prototype for the HSI-RFQ, covers the crucial matching and bunching section of the electrodes. It is capable to produce ion beams of high brilliance. The results of recent beam experiments with Ar\(^+\) and rf-tests will be presented together with work for future plasma physics experiments.

Introduction

In 1990 the 18 Tm Heavy Ion Synchrotron SIS and the storage/cooler ring ESR went into operation. The linear accelerator UNILAC however, serving as injector for the SIS, had not been changed until then. To improve the UNILAC in a way of being able to fill the SIS up to its space charge limit several modification studies have been undertaken.

One possible solution is the combination of an ion source and a 27 MHz-Four-Rod-Spiral-RFQ with a length of 35 m, known as HSI (Hochstrominjektor) replacing the first Wideroe section of the UNILAC [1]. This RFQ should be capable to accelerate heavy ion beams of 25 mA U\(^{2+}\) from particle energies of 2.2 keV/u up to 216 keV/u. The particle charge would then be increased to U\(^{10+}\) by a gas stripper, further acceleration by the remaining second UNILAC Wideroe section would follow. At 1.4 MeV/u the ion charge would again be increased to U\(^{28+}\), and with postacceleration in the final UNILAC sections the beam would be ready for injection into the SIS.

Later studies deal with a layout for U\(^{1+}\) [2], where one stripper could be omitted. The RFQ-prototype could well be used for these ions, too. For even higher performance the rod-electrodes would simply have to be changed.

The Spiral-RFQ Prototype

A prototype for the U\(^{2+}\)-layout of the Spiral-RFQ has been built for both, rf-testing and beam experiments [3, 4]. It is only 4 m long but consists of the first 231 resonator cells, a third of the total HSI cell number. Nevertheless, the most critical part of the electrodes where the beam is matched and bunched is totally covered.

The resonator structure is mounted in a rectangular vacuum chamber made of aluminium. The structure itself can be easily accessed by eight lids in the side wall of the chamber. It consists of 20 spirally shaped copper stems; onto these the electrodes are mounted. The electrode alignment is achieved by precisely milled washers, it has been checked via an opto-mechanical system and is as precise as ±0.1 mm, less than 3 % of the aperture radius.

Table 1 gives an overview on the main parameters of the RFQ-prototype, Fig. 1 shows a schematic view of a 4-stem Four-Rod-Spiral-RFQ structure.

![Fig. 1: Schematic view of a Four-Rod-Spiral-RFQ-Structure with four stems.](image)

<table>
<thead>
<tr>
<th>Parameters of the Spiral-RFQ-Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Operating frequency</td>
</tr>
<tr>
<td>Cell number</td>
</tr>
<tr>
<td>Input energy</td>
</tr>
<tr>
<td>Output energy</td>
</tr>
<tr>
<td>Synchronous phase</td>
</tr>
<tr>
<td>Aperture radius</td>
</tr>
<tr>
<td>Max. electrode modulation</td>
</tr>
<tr>
<td>Normalized acceptance</td>
</tr>
<tr>
<td>Electrode voltage</td>
</tr>
<tr>
<td>RF-power consumption</td>
</tr>
<tr>
<td>Space charge limit</td>
</tr>
</tbody>
</table>

* Work supported by BMBF and GSI
Beam Experiments

After having accelerated a He$^+$-beam of 980 μA at the IAP Frankfurt (Institut für Angewandte Physik) – however, due to a mismatched injection, at twice the design rf-level – further beam tests with heavier ions were done at GSI. The ion beam was extracted from a CHORDIS (Cold or Hot Reflex Discharge Ion Source) and focused for RFQ injection by one magnetic quadrupole doublet lens and one magnetic quadrupole triplet lens. Therefore an optimized matching could be achieved. For beam measurement three beam transformers (behind the ion source, in front of and behind the RFQ), two fast Faraday cups as well as an emittance measurement device were available. Fig. 2 shows a photograph of the experimental setup.

![Photograph of experimental setup](image)

Fig. 2: Experimental setup.

The quadrupole parameters of the injection system were optimized with numerical methods. The actual input beam quality could be observed by mounting an emittance measurement device in place of the RFQ. The results confirmed the computer simulation well.

With Ar$^+$-ions a maximum pulse beam current of 8 mA could be reached at design-rf-level; this is the space charge limit for the RFQ calculated with PARMTEQ (Phase and Radial Motion in Transverse Electric Quadrupoles) assuming ideal electric field distribution. The peak bunch current was 30 mA. Extrapolation to U$^{24+}$-ions would lead to a pulse beam current of 24 mA (i.e. a peak bunch current of 90 mA). Fig. 3 shows the pulse beam current at RFQ input (upper) and RFQ output (lower); the scale is 2 mA/div. vertically and 1 ms/div. horizontally. The peak bunch current is shown in Fig. 4; the scale is 10 mA/div. vertically and 10 ns/div. horizontally.

![Diagram of pulse beam current](image)

Fig. 3: Pulse beam current at RFQ input (upper) and RFQ output (lower). The scale is 2 mA/div. vertically and 1 ms/div. horizontally.

![Diagram of bunch current at RFQ output](image)

Fig. 4: Bunch current at RFQ output. The scale is 10 mA/div. vertically and 10 ns/div. horizontally.

The measured transverse emittance was 50 μm·mm·mrad, the energy spread was ±1.5%, again well-corresponding to computer simulations. Fig. 5 shows the output emittance after 530 mm drift in the $xx'$-plane (left) and the $yy'$-plane (right).

![Diagram of emittance](image)

Fig. 5: $xx'$- and $yy'$-emittance behind the RFQ and a drift of 530 mm.
Rf-Experiments

For accelerating ions with yet a higher mass-to-charge ratio higher electrode voltages (and so rf-levels) are required. The ability of the RFQ to operate under such conditions has been tested. After a considerable time of conditioning the maximum applied rf-power was as high as 260 kW at a duty-cycle of 0.4% / 50 Hz. The electrode voltage, measured with an rf-pickup probe calibrated with Ar²-beam, was 185 kV. This leads to a very high maximum field gradient of 340 kV/cm, corresponding to a Kilpatrick value of about 3. The \( R_p \)-value (= shunt impedance) is 520 kΩ·m, which confirms previous low-level measurements [3]. The RFQ behaved stable, no excessive sparking and no ponderomotive effects could be observed. Adequate cooling of the RFQ-structure ensured that the resonance frequency showed no drift. Higher rf-levels could not be applied due to the limited rf-amplifier power.

Forthcoming Plasma Experiments

Further use of the 27 MHz-Spiral-RFQ-Prototype will be providing a high-current He²-beam (0.8 mA) for experiments in plasma physics. The beam will be fed onto a luminescent target, allowing the bunch structure being observed with high time-resolution by a streak-camera. Another planned experiment is the interaction of the ion beam with thin plasmas for space charge neutralisation purposes.

The ion beam will be extracted from a CHORDIS source and will be injected into the Spiral-RFQ via two solenoid lenses. The final focus will be achieved by a magnetic quadrupole triplet lens. For beam current and bunch structure observation there are beam transformers and Faraday cups installed.

The work for setup of the experiment is almost completed so that first beam measurements are scheduled for September 1996.

Conclusions

The objective of the recent experiments, proving the capability of the Four-Rod-Spiral-RFQ serving as an injector providing highly brilliant high-current heavy-ion beams, could be fully achieved. Beam current as well as the rf-parameters were in very good correspondance to PARMTEQ simulations. Therefore the Spiral-RFQ-prototype can supply high-current ion-beams for experiments in plasma physics as well as working as a compact implanter for singly charged heavy ions like O⁺, P⁺, As⁺, up to Kr⁺.

References


A NOVEL DESIGN FOR ION BEAM FUNNELING BY THE USE OF A TWO-BEAM RFQ AND A MULTIGAP-DEFLECTOR*

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Abstract

Heavy ion inertial fusion (HIIF) injector linacs start with a set of low frequency radio-frequency quadrupoles (RFQs), because of the small values of the current limits of linear accelerators in the low energy part. For a higher ion energy, the frequency is increased to reach a better accelerator efficiency. The accumulation of ion beam current in such a driver linac is done by multiple stages of funneling: in each stage the accelerator frequency is doubled and two beams with 180 degrees phase shift are combined to fill all the r.f.-buckets of the high frequency accelerator stage. In the ideal case, there is no change of the emittance and the beam current and brightness are doubled.

For the first funneling stage a two-beam RFQ, where two beams are bunched and accelerated in a single r.f. cavity and a novel scheme for an r.f. funneling deflector operating at low voltages has been developed. With the use of convergent beams, a short funneling structure placed around the beam crossing position seems to be possible.

Introduction

A heavy ion inertial fusion (HIIF) driver could start with a set of low frequency radio-frequency quadrupoles (RFQs) which employs electrical r.f. focussing and provides bunched ion beams with high transmission[1,2]. The layout of a HIIF injector is shown in Figure 1.

![Diagram of a HIIF injector system](image)

Initial funneling experiments have been done with systems of discrete elements such as quadrupole doublets and triplets, debunchers, defectors and bending magnets [3,4,5]. Another solution for beam funneling is the use of an accelerator structure which provides two beams within one cavity and a single r.f. deflector structure which bends the two beams to one common axis.

The two-beam RFQ

The two-beam RFQ consists of two sets of quadrupole electrodes driven by one resonant structure. For this reason the new two-beam RFQ brings the two beams very close together while they are still radially and longitudinally focussed. For the beam funneling experiment an electrode geometry of the two-beam RFQ that gives identical radial beam orientations is favourable. The two possible electrode geometries are shown in Figure 2.

![Diagram of two-beam RFQ geometries](image)

Fig. 2. Different electrode geometries for the two-beam RFQ.  
a) the standard geometry for a 4-rod RFQ,  
b) the preferred geometry for the two-beam RFQ.

The electrode capacity should be as small as possible to achieve an efficient r.f. structure. Therefore the inner electrodes of the two quadrupoles have the identical r.f. phase. With such an electrode geometry a smaller beam separation and convergent beam axes have become possible. For the support of the chosen electrode geometry (Figure 2 b) an RFQ structure with symmetric stems from the bottom to the top of the cavity is taken to minimise the dipole effects.

To study the properties of the new two-beam RFQ resonator, various kinds of prototype resonators were built and tested [6,7]. Also calculations with the MAFIA code were done for comparison with the low level measurements. A prototype resonator with a reduced length and parallel beam axis has been designed and built. The resonator consists of two pairs of electrodes with a length of 100 cm supported by four symmetric stems in linear arrangement. In high power tests the maximum r.f. input power in pulsed mode was limited to 12 kW by the r.f. power amplifier. At this

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* Work supported by the BMBF.
power an electrode voltage of 27 kV was measured. For the beam funnelling experiments a two-beam RFQ 2 m long with convergent beam axes is under construction. Figure 3 shows a view of the two-beam RFQ.

![View of the two-beam RFQ](image)

**Fig. 3. View of the two-beam RFQ.**

### The multigap deflector structure

The electrode geometry of the multigap deflector consists of some deflector plates divided by spaces or sections with larger aperture with equal length. In this geometry, the particles will see the deflecting field in one direction several times but the deflection in the opposite direction is always less. The length of the capacitors have to be proportional to the particle velocity and to the inverse of the frequency of the deflector system. Figure 4 shows a scheme of the electrode geometry and the behaviour of the particles along the multigap deflector.

![Scheme of the multigap deflector](image)

**Fig. 4. Scheme of the multigap deflector.**

For beam funnelling, the frequency of the deflector has to be the same as the accelerator frequency, so that the bunches from different beam axes will see opposite field directions because of the phase shift of 180° between each bunch. If the two incoming beams are parallel, the cell length of the deflector has to be $\beta \lambda$ ($\beta = \frac{v}{c}$ with $c =$ speed of light and $\lambda =$ wavelength of the deflector frequency) to get a displacement only. If the two beams are not parallel, the cell length has to be $\beta \lambda / 2$ to reach a maximum change of the beam angle [8]. The r.f. resonator for the multi-gap deflector will be a structure as it is used for 4-Rod-RFQs with two stems. Each stem is electrically contacted with one of the deflector electrodes and will sustain the other electrode by a ceramic support. For longer electrodes it is possible to use an rf structure with more stems to preserve mechanical stability. Figure 5 shows a view of the multigap deflector.

![View of the multigap funnelling deflector](image)

**Fig. 5. View of the multigap funnelling deflector.**

### The two-beam funnelling experiment

The funnelling experiments will be carried out with $\text{He}^+$ ions to facilitate ion source operation and beam diagnostics. Two small multicusp ion sources and electrostatic lenses, built by LBNL [9,10], will be used. A IGUN [11] simulation of one lens is plotted in figure 6.

![IGUN simulation of the electrostatic lense](image)

**Fig. 6. IGUN simulation of the electrostatic lense.**

The ion sources and injection lens will be attached directly on the front of the RFQ with an angle of 76 mrad, the angle of the beam axes of the two-beam RFQ. Figure 7 shows a photograph of the multicusp ion source attached to the injection system.

With this angle of 76 mrad the distance between the two beams at the RFQ input will be more than 160 mm and about 40 mm at the output. The electrodes are supported by eight flat stems. To achieve a proper voltage distribution along the electrodes, the distance between the supports has to be reduced along the resonator. The RFQ electrode design is in progress with the use of the PARMTEQ code. For the phase shift of 180° between the bunches of each beam, two different electrode designs with different electrode lengths are required.
Behind the RFQ the funnelling deflector will be placed before the beam crossing. Figure 8 shows the experimental set-up of the funnelling experiment. Beam diagnostics in front of and behind the RFQ and behind the funnelling deflector are in preparation. The funnelling resonator is under construction and a prototype for r.f. measurements has been finished.

In Table 1 the main parameters of the planned experiment with He\(^+\) and the design parameters of a first HIIF funnelling stage for Bi\(^+\) are shown.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>He(^+)</th>
<th>Bi(^+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-beam RFQ f(_0) [MHz]</td>
<td>54</td>
<td>27</td>
</tr>
<tr>
<td>Voltage [kV]</td>
<td>10.5</td>
<td>180</td>
</tr>
<tr>
<td>R(_e)-value [kOhm-m]</td>
<td>150</td>
<td>250</td>
</tr>
<tr>
<td>Q(_e)-Value</td>
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<td>3000</td>
</tr>
<tr>
<td>T(_m) [keV]</td>
<td>4</td>
<td>230</td>
</tr>
<tr>
<td>T(_\text{min}) [MeV]</td>
<td>0.16</td>
<td>12.54</td>
</tr>
<tr>
<td>Length [m]</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>Angle between beam axes [mrad]</td>
<td>76</td>
<td>76</td>
</tr>
<tr>
<td>Multigap funnelling deflector f(_0) [MHz]</td>
<td>54</td>
<td>27</td>
</tr>
<tr>
<td>Voltage [kV]</td>
<td>6</td>
<td>273</td>
</tr>
<tr>
<td>Length [cm]</td>
<td>54</td>
<td>233</td>
</tr>
</tbody>
</table>

**Conclusions**

The experiments and results achieved by building and evaluating the two-beam RFQ prototype resonators have provided the needed knowledge to proceed with the final design of the two-beam RFQ resonator for funnelling. The MAFIA calculations for the RFQ structure and the PARMTEQ calculations for the electrode design are finished. A multigap deflector for funnelling is under development. A first deflector prototype for low level measurements has been built. The ion sources and injection systems are manufactured and are running on a test stand. Next steps are the assembly of the experimental setup and the synchronisation of the two ion sources.

**References**

BEAM DYNAMICS CALCULATIONS FOR THE ACCELERATION OF DIFFERENT IONS IN A HEAVY ION LINAC

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Abstract

Heavy ion linear accelerators are well suited as driver in heavy ion inertial fusion facilities. In present scenarios the acceleration of different ion species or the simultaneous acceleration of different isotopes in the same linac are discussed. Beam dynamics calculations have been performed to check the beam behaviour and the conditions for such a kind of operation in RFQ and DTL.

Introduction

Heavy ion inertial confinement fusion is considered to be an attractive method to create a future powerful source of energy. Several studies are underway to design a driver facility for the generation of the required very intense heavy ion beams for pellet ignition.

One possible way is an rf-linac / storage-ring approach [1,2], where the beam is accelerated in a long main linac to the final energy and then injected into the rings for storage and compression. In all parts severe limitations exist due to space charge effects and emittance growth.

While the first driver proposals dealt with the acceleration of only one ion species, like Bi⁺, recently the use of different ion species or isotopes has been suggested to overcome especially space charge limits.

In the proposal for a charge symmetric driver [3], the simultaneous acceleration of the four main isotopes of Pt, both positively and negatively charged, is foreseen to increase the current limit in the final transport channel by space charge neutralisation. The idea of telescoping of ion bunches [4] propagates the non-Liouvillean time overlap of bunches of ions with different masses but same momentum, which allows the use of the same final focusing channel.

In the latter proposal the ion species changes in the accelerator from macropulse to micropulse, which may allow the switching of the linac parameters from pulse to pulse (already routine operation for the UNILAC of GSI at low currents [5]), while in the case of the space charge neutralised driver the ion species is changing from micropulse to micropulse, i.e. only simultaneous acceleration is possible.

Proposed Driver Layout

In the main linac of the driver facility, heavy ion currents in the range of some hundreds of mA up to some A must be accelerated to meet the power requirements for pellet ignition. Limitations for the accumulation of such intense ion beams at low particle energies are the maximum current that can be extracted from a single ion source and the current transport capability of LEBT and RFQ. Therefore in all rf linac designs a funneling scheme [6] is under consideration, in which the beams of 8 or 16 ion sources are bunched and pre-accelerated and then bent together in successive steps, where the rf frequency is doubled in each step.

In the MRTI – ITEP (Moscow) proposal [7] the linac transports 4 ion sources producing positively charged Pt ions of the isotope masses $A = 192, 194, 196$ and 198 and another 4 sources for negatively charged Pt ions. The beams with identical current and emittances are bunched and accelerated by $4 \times 8$ Radio Frequency Quadrupoles (RFQs) and then merged into one main linac, consisting of Widoreic and Alvarez type Drift Tube Linacs (DTLs). It is proposed to design all RFQs for an average mass number 195; in this case, transmission and output emittances for the 4 isotopes accelerated with the same electrode voltage differ only slightly at low beam currents [8]. For a design current near the theoretical current limit, this is still investigated.

As another example, the beam behaviour for the 4 positively charged Pt isotopes has been examined for the first part of an Alvarez DTL, following the MRTI proposal. Again the linac parameters were chosen for the intermediate mass 195 (Table 1); the generation of the linac for particle dynamics calculations has been done with the code packages CLAS, GENLIN and ADAPT.

<table>
<thead>
<tr>
<th>Parameters for Alvarez-1 from MRTI [7].</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
</tr>
<tr>
<td>Energy</td>
</tr>
<tr>
<td>Cell length ($B\lambda$)</td>
</tr>
<tr>
<td>Gap length ($B\lambda/5$)</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>E-field gradient</td>
</tr>
<tr>
<td>Bore radius</td>
</tr>
<tr>
<td>Synchronous phase</td>
</tr>
<tr>
<td>Total length</td>
</tr>
</tbody>
</table>

The tank radius and the drift tube outer diameters were optimized with CLAS in order to get the right frequency for both the first and last cell of the linac. Then results were interpolated with GENLIN in order to get the features of all the intermediate cells. The quadrupole lengths were set to 92% of the tube lengths and their gradients were computed with ADAPT for the first 250 cells of the linac (86.9 m), corresponding to an energy range from 600.0 to 798.3 MeV. Each focusing period is formed by 5 lenses of the same sign fol-

* Work performed in Frankfurt in the framework of INTAS 94-1713.
ollowed by 5 lenses of the opposite one (i.e. FFFFFDDDD), in order to limit the maximum gradient, which is now between 34.2 and 28.5 T/m, smoothly decreasing from a quadrupole to the next one, though it was found that using the same value for all the 5 quadrupoles of the same sign within a period gives nearly identical output results.

For the beam input, the following parameters were used:

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam input parameters for Alvarez-1 from MRTI [7].</td>
</tr>
<tr>
<td>Horiz. beam size</td>
</tr>
<tr>
<td>Vert. beam size</td>
</tr>
<tr>
<td>Horiz. emittance</td>
</tr>
<tr>
<td>Vert. emittance</td>
</tr>
<tr>
<td>Bunch length</td>
</tr>
<tr>
<td>Momentum spread (dp/p)</td>
</tr>
<tr>
<td>Current</td>
</tr>
</tbody>
</table>

The quoted emittances are full values, not normalized; rms normalized emittances may be obtained dividing by 5 and multiplying by \( \beta y \). The Twiss parameters \( \beta_{x,y} \) are obtained from the emittances and the beam size values, assuming \( \alpha_{x,y} = 0 \). Similarly, the longitudinal emittance is the product of bunch length and momentum spread, while \( \beta_z \) is obtained from the emittance and the bunch length values, assuming \( \alpha_z = 0 \). Calculations were started at low current, that was then raised stepwise to pulse currents of 30–40 mA (total current 400–500 mA), which are presently available from heavy ion sources.

The acceptance of such a linac was computed running MAPRO for the first 250 cells only (due to limited storage and computing time), using the above input values. It was then possible to adjust \( \alpha_{x,y} \) in order to match the acceptances and maximize the number of transmitted particles.

**Preliminary Results**

With the input Twiss parameters above, an input distribution for 2000 particles was generated, using a 4-dim waterbag random distribution in both transverse planes and, independently, a 2-dim waterbag distribution in the longitudinal one (Fig. 1). Then particle dynamics calculations were performed with MAPRO on the linac structure generated by CLAS, GENLIN and ADAPT, for the intermediate atomic mass \( A = 195 \) and for the 4 isotopes (\( A = 192, 194, 196 \) and 198) with positive charge only, where matching of the beam and reduction of emittance growth turned out to be rather time consuming.

Preliminary results show that it is possible to accelerate different isotopes in the considered part of the linac: for all masses, the transmission is higher than 97% and the emittance growth is similar, as shown in Table 3 (full emittance) and Table 4 (95% emittance).

The output emittances are given in Figures 2 to 4.

![Fig. 1 Input emittances.](image1)

<table>
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<td>Output parameters for Alvarez-1 from MAPRO.</td>
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![Fig. 2 Output emittances for A = 192.](image2)

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<td>Output parameters for Alvarez-1 from MAPRO (for 95% emittance).</td>
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Conclusions

The acceleration of different ions in the same linac with a fixed parameter setting is proposed in new heavy ion fusion driver design. For a perfect neutralisation of the beam current in the final focus transport line, beams of identical current and bunch dimensions must be delivered from the driver linac. In a first attempt, beam dynamics calculations indicated that variation of beam current and emittances within a few percentages can be achieved for the simultaneous acceleration of different masses. More work will be done for lower emittance growth and higher beam currents.

References

A Study of Beam Chopping Options for the ATLAS Positive Ion Linac
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Abstract

Unbunched beam components from the injection beam bunching system must be removed prior to acceleration in the ATLAS Positive Ion Injector Linac (PII). A sine-wave chopper has been used for this purpose up to now. Such a device can have a significant detrimental effect on the longitudinal and transverse beam emittance of heavy-ion beams which can be sufficiently severe to limit the overall beam quality from the ATLAS accelerator.

A study of the optimum chopper configuration and chopper type was undertaken as part of a new ion source project for ATLAS. A transmission-line chopper and a two-harmonic chopper were investigated as alternatives to the conventional sine-wave chopper. This paper reports the results of that investigation and discusses the design of the selected transmission-line chopper.

Introduction

The acceleration of heavy-ion beams in the ATLAS superconducting linac[1] is accomplished with a minimum of emittance growth. In order to achieve heavy-ion beams possessing the lowest possible emittance, a two-stage bunching system is used to convert the continuous (DC) beam from the ion sources into a sharply pulsed beam for injection into the linac. The bunching system is 60-70% efficient in this process. The remaining unbunched portion of the beam must be removed to avoid increased emittance and secondary partial bunches interspersed among the intended beam bunches.

Removing the unbunched beam components is presently accomplished with a 'sine-wave' RF chopper which deflects particles with significant time errors vertically, alternately 'up' and then 'down'. The chopper is installed in the low energy beam transport section of the PII where the particle velocity is typically 0.0085c.

'Sine-wave' choppers introduce beam degradation by causing emittance growth through increased beam divergence in the deflection plane and by adding additional energy spread to the off-axis particles. Keeping the beam well bunched and physically small reduces these negative effects, but the reality of beam transport systems does not usually allow the chopper to be placed in the most desirable location from this viewpoint.

As part of a new ion source project for ATLAS[2], a design review of the injection bunching and chopping system for the ATLAS Positive Ion Injector (PII) has been undertaken with a goal of improved performance with regard to space charge limitations and to the performance of the chopping system. The bunching system study has been published previously[3]. In this paper, the present 'sine-wave' chopper performance is compared to what appears to be an attractive alternative - a segmented transmission-line square-wave chopper. The results of this study come from calculations of the chopper electric field components using the program POISSON[4] and ray-tracing particles through those fields using MATHCAD[5].

Chopper Options Considered

Sine-Wave Chopper

The resonant sine-wave chopper is a simple, cheap, low power alternative for such applications. In a number of situations, it is possible to find configurations which reduce the detrimental effects of the sine-wave deflection. In most applications, such as the present ATLAS implementation for the tandem and the PII injector, beam transmission occurs at the zero-crossing point of the waveform. The chopper operates at half the bunching frequency, alternately deflecting unwanted beam components in opposite directions. At ATLAS the deflection plane is the vertical plane.

Because of the finite size of the chopper plates and the continuous waveform of the resonant chopper, all particles see some electric field as they traverse the plate region. The result is that they emerge from the chopper with an additional divergence and position offset that is almost linearly proportional to time error relative to the bunch center. Since the initial divergence of a particle is assumed to be independent of time, this induced chopper divergence is uncorrelated with the transverse emittance and therefore adds in quadrature to the original value. For a well bunched beam, the divergence will be increased by from 10 to 40%. If the beam optics make it desirable to place the chopper far from a time waist, then the emittance, especially longitudinal, can be increased much more than this value.

Even more important than the transverse emittance growth, a significant increase in energy spread will generally occur for all particles which are off-axis. Since the chopper plates will not be at a waist, this effect can be quite significant.
This growth results from the plate fringing fields yielding an accelerating/de-accelerating field component which is phased additively at the entrance and exit of the plates. In addition, alternate bunches are accelerated/de-accelerated doubling the effect when averaged over many bunches. For the ATLAS PI2 geometry, this effect can produce an energy spread at ±1 cm off-axis which is comparable to the bunching-induced energy spread and in total exceeds the buncher voltage when the effect from alternate bunches is considered. Since this energy spread is time correlated in a highly nonlinear manner and has a strong radial dependence, it functions as a longitudinal emittance growth.

**Two Harmonic Chopper**

The effect of adding an additional frequency to the sine-wave chopper was investigated. This approach can be beneficial to limiting emittance growth when the transit time of a particle is a small fraction of the chopper period and when the beam is well bunched in the chopper plates. Neither situation is realized for the ATLAS PI2 injector. The beam transit time through the buncher field is a total of 65° and we wish to use the chopper at a location some distance from the buncher waist, so the time width of the transmitted beam will be the equivalent of 30° in chopper phase. Under these conditions flattening of the sine-wave at 90° cannot be extended over a sufficiently large phase range to significantly alter the effect on emittance of the chopper. Ray-tracing calculations showed no significant reduction in emittance growth compared to the single frequency chopper.

**Transmission-line Chopper**

The transmission-line chopper is a series of short pairs of electrodes which can be biased to a high voltage, deflecting all ions sufficiently to be stopped on a downstream aperture or slit system. The electrodes are arranged in a "parallel strip-line" configuration allowing an impedance matched system for fast time response. When transmission of a beam bunch is desired, the electrode voltage is pulsed to zero while the beam bunch traverses the electrode. The voltage pulse transmits downstream to the other electrodes in the chopper system delayed sufficiently so as to stay in phase with the beam bunch. Similar chopper electrode systems have been employed by others[6,7] but with different transmission requirements and electronic implementations.

The transmission-line chopper is a non-resonant system, so the details of the waveform can be varied with a sufficiently sophisticated pulse generator. This allows the function of a chopper, described in the introduction, to be combined with that of a beam sweeper - a device which removes some bunches from the bunch train created by the injection bunching system. This feature is needed for some of the experimental program supported by ATLAS and is now accomplished with a separate set of deflection electrodes and electronics.

The attractive feature of this implementation of the transmission-line chopper is that the electrode geometry indicated in figure 1 can be chosen, in the limit of a sharp field boundary, so that the main body of the transmitted particles see no deflecting field. Therefore, the emittance growth in transverse and longitudinal phase space can be significantly reduced. Only the fringe particles of a bunch, which constitute the transition region from full transmission to full cut-off, experience a transverse kick or an energy change.

The angular deflection which particle 'i' in the transition group with charge q, mass A, and velocity βi experiences is given simply by:

\[
\theta_i = 0.322 \cdot \left( \frac{q}{A \cdot \beta_i} \right) \cdot E_y \cdot dt_i
\]

where \( dt_i \) (which is designed to be less than \( l_i/\beta_i \)) is the time spent in the field region of length \( l_i \). The number of electrode pairs is chosen so that the maximum deflection is similar to the maximum deflection in the present sine-wave chopper - 6 to 8 mm. The detrimental effect on the beam emittance is much reduced because the deflection is in only one direction, not equally in two directions, and the chopper geometry can be designed so that \( dt_i \) is zero for the main transmitted body of the ensemble. As an example when using a cutoff point of ±5 ns, the deflection seen by particles at ±2.5 ns is only 35% to 50% in a transmission-line chopper compared to a sine-wave chopper.

![Calculated Chopper Fields](image)

**Fig. 1.** Calculated transmission-line chopper electric field profile for pulse transmission condition. The biased DC clamp electrodes limit the extent of the fringing fields. The blue lines show the strip-line geometry assumed.

The induced energy spread from the transmission-line chopper is significantly less than that seen in the sine-wave chopper. There is no phase flip while the particles are in the chopper plates nor do alternate bunches see opposing field patterns which double the ensemble effect compared to any one bunch. The main component of the ensemble sees little or no electric field; only a small acceleration from the residual fringe field is observed.

For the transition group particles, the leading particles see an accelerating (let us say) field, while the those trailing see a de-accelerating field. These residual acceleration fields act as additional bunching components but they have an
undersirable radial dependence (essentially a spherical aberration). Overall the energy spread increase in a typical case is less than 25% of that experienced in a sine-wave chopper.

The most compact geometry which gives the minimum emittance growth to the beam is one in which each electrode is approximately the width of an individual bunch and is separated by a similar width field-free (nearly) gap which serves as a 'staging' region for the bunch while the previous electrode turns 'on' and the next electrode turns 'off'. Multiple sections of parallel strip-line deflectors are arranged transverse to the beam path. Figure 2 is a cartoon schematic of the geometry and electrical properties of the transmission-line chopper. Each strip-line section will be 1.5 cm wide in the beam direction by 5.0 cm long transversely with 3.6 cm total vertical gap required by the beam size in the chopper region. Between the strip-line sections will be 1 cm wide DC biased, or grounded, electrodes which will serve to clamp the fringing fields as indicated in Figure 1. The physical strip-line period is 4.5 cm long.

Fig 2. Schematic picture of the symmetric parallel plate transmission-line chopper electrode structure. The plates will be driven symmetrically by separate pulse generators synchronized off the master oscillator. The transmission-line will consist of ten deflection regions spaced as indicated in figure 1 requiring a pulse delay of approximately 17 ns.

Strip-line sections terminate in a lumped constant delay line which matches the deflection pulse propagation to the arrival time of a beam bunch at the next strip-line section. The complete traveling wave deflector will have 10 sections and operate at a pulse rate of 12.125 MHz and a maximum voltage of ±1000 volts. Frequency response will have to be better than 100 MHz to produce pulse rise times of 5 ns.

The deflector sections have an extreme geometry which results in a large vertical space between two narrow strip-line halves. Transmission-line impedance is therefore dominated by edge effects and surrounding structures. A test strip-line has been constructed with the requisite dimensions, but 46 cm long. Measurements indicate each strip-line half has an impedance of 200 Ω and overall bandwidth of 3.0 GHz.

Each strip-line deflector is connected in series to the next deflector through an impedance matched delay line section that provides the strip-line propagation delay of 17.6 ns required to match the bunch arrival time at the next section. The voltage-off pulse width has been chosen, at this time, to also be 17.6 ns. This means the transition to the transmission state for the next deflector section occurs when the pulse is at the midpoint between deflectors. Shorter voltage-off times are possible, narrowing the pulse acceptance, but with some additional detrimental effects on beam emittance and energy spread. The coaxial spiral delay line[8] chosen is a coaxial transmission-line with a helical inner conductor. The axial wavelength is very long compared to the diameter which produces the desired compact length necessary for this application. The entire strip-line and delay line system will be mounted in the beam vacuum.

Construction of a prototype chopper electrode structure is underway. Beam tests of the structure are expected to occur by the end of 1996.

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References

A LOW-FREQUENCY RFQ FOR A LOW-CHARGE-STATE INJECTOR FOR ATLAS

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Abstract

A design for a split-coaxial, normally-conducting, 12 MHz RFQ structure is being developed to accelerate singly charged ions of mass 132 and heavier to a velocity v/c = 0.008, suitable for injection into the ATLAS superconducting heavy-ion linac. Numerical studies have shown that a transverse (normalized) acceptance of 0.25 π mm-mrad can be achieved while maintaining a longitudinal emittance as small as a few keV-nsec. A novel feature is the use of drift-tubes at the entrance and exit of the RFQ which make use of the voltage offsets intrinsic to the split-coaxial structure to increase the voltage gain by about 30%. A half-scale model of the RFQ has been built and tested. The model, with no provision for cooling, was not operable cw but was pulsed to vane-vane voltages as high as 59 kV for periods of several milliseconds. The achieved level, limited by arcing in an rf feedthrough and so not a fundamental limit for the structure, corresponds to 1.2 times the (frequency and gap dependent) Kilpatrick limit. Assuming the model results scale, a 2 meter long 12 MHz RFQ, with 8 mm minimum aperture radius, will operate at 100 kV intervale voltage with an RF input of slightly less than 25 kW. Design and construction status of a full-scale prototype is discussed.

Introduction

This paper discusses the ongoing development of a low-frequency RFQ as the initial element of a secondary beam linac for an ISOL-type radioactive beam facility. The proposed facility would upgrade the existing ATLAS superconducting heavy-ion linac for the acceleration of radioactive beams [1,2]. In its present form, ATLAS can accelerate any ion with a sufficiently high charge state (q/A > 0.1). For efficient production of most radioactive beams, much lower charge states must be accelerated, at least for the first few MV of the linac. Adapting ATLAS to radioactive beams, therefore, requires development of a low-charge-state injector which can maintain the good features of ATLAS, i.e. large transverse acceptance, flexibility in configuration, and most particularly, excellent beam quality [2,3]. To meet these goals, it is necessary to maintain substantially smaller longitudinal emittance than is typical for RFQ implementations. Several features of the RFQ discussed here ensure this result.

The RFQ should operate at as low a frequency as is practicable both to minimize longitudinal emittance growth and also to maximize the transverse acceptance. The split-coaxial RFQ geometry is appropriate for this frequency range; RFQ structures have already been developed that operate near the frequency and fields required[4].

Injecting the RFQ with a pre-bunched beam maintains the longitudinal emittance at a smaller value than is practicable using adiabatic bunching within the RFQ structure [5]. Also, by removing the bunching function, the length of the RFQ is reduced and the efficiency enhanced. A suitable bunching system exists: the 12 MHz gridded-gap, four-harmonic system which is presently in use on the ATLAS accelerator can bunch 70% of a dc beam into 1 nsec bunches[6]. The efficiency can be further improved by development of a finer grid structure, which should be straightforward for the very low beam currents anticipated.

Placing the RFQ on a variable voltage platform (350 kV) allows operation at a constant velocity profile for a wide range of ion masses and also increases the velocity at the entrance of the RFQ, thus increasing the transverse acceptance.

RFQ Design and Numerical Modeling

We have analyzed an RFQ structure configured for beams of charge to mass ratio of 1/132 [2]. Ions of higher charge state are accommodated by scaling the platform voltage to maintain a constant injection velocity and the RFQ voltage as the ratio of mass to charge. The RFQ parameters are as follows:

- Operating frequency: 12.125 MHz
- Resonant Structure: split-coaxial
- Vane-vane voltage: 100 kV
- Maximum Electric field: 12.8 MV/m (1.2 KP)
- Minimum Aperture: 8.00 mm radius
- Modulation factor: 1.5
- Entrance Velocity: 0.00247 c
- Exit Velocity: 0.00493 c
- Number of cells: 44
- Length: 222 cm
- Synchronous phase: -30 degrees

The split-coaxial structure is characterized by a voltage offset of ½ the vane-vane voltage (Vv) at both entrance and exit. We make use of this offset to provide accelerating potential by attaching a drift tube to the high-voltage vane pair at both the entrance and exit of the RFQ. The energy gain provided by the two drift tubes is somewhat greater than twice Vv and, as shown below, increases the voltage gain through the RFQ by more than 20%.

The electric fields near the vane tips have been numerically modeled using TOSCA and also RELAX3D.
The vane geometry used has a constant radius of curvature of 10 mm, 1.25 times the minimum aperture radius. At entrance and exit the vanes are tapered over a 4 cm interval.

Figure 2 shows the transverse and longitudinal dimensions of a beam bunch numerically traced through the RFQ and includes matching electrostatic triplets at the entrance and exit. Some parameters for the beam shown are:

Species
Sn$^{122}$
Charge state
1+
Entrance Velocity
0.00247 (378 keV)
Exit velocity
0.00493 (1508 keV)
Emittance (normalized)

Input:
Transverse
0.27 π mm-mrad
Longitudinal
4.7 π keV-nsec

Output:
Transverse
0.27 π mm-mrad
Longitudinal
6.1 π keV-nsec

The small increase in longitudinal emittance through the RFQ indicates that beam quality in this system will be determined primarily by the bunching system. It should be noted that the transverse acceptance projected above is substantially greater than required for the ISOL - type ion sources contemplated for this machine. In fact, for the vane voltage assumed above, it is possible to accelerate singly charged uranium ions and achieve similarly small longitudinal emittance values by reducing the RFQ modulation factor from 1.5 to 1.3, and the transverse acceptance from 0.27 to 0.17 π mm-mrad.

Hardware Modeling and Tests

An roughly half-scale model (19.6 MHz) of the RFQ with unmodulated vanes, has been constructed of copper and aluminum. Measurements of the electromagnetic fields in the model yielded the following results (where we have scaled both the structure size and the observed RF surface resistance to 12.125 MHz) for $V_r = 100$ kV:

RF Input Power $= 23.6$ kW
Peak surface electric field $= 12.3$ MV/m
RF Energy $= 2.3$ joules

Even though no efforts at vibration isolation were made, the effects of ambient mechanical vibrations on the RF eigen-frequency were much less than the intrinsic resonator bandwidth and should pose no operational problem.

The model was so constructed that it was possible to evacuate the resonator and operate it at high fields. No provision for water cooling was made, however, so that high-field operation was limited to periods of a few milliseconds at a repetition rate of a few pulses per second.

An rf pickup loop to monitor the vane voltage was calibrated by three different methods. The first method, using the results of perturbation measurements of the field together with direct measurements of the rf energy content of the resonator, gave values for $V_r$ in good agreement with a direct...
measurement using a high-impedance probe. The third method was to observe the high-energy cutoff energy for bremsstrahlung produced during high-field tests: this indicated voltages some 20% higher than the voltage determined by the two previously mentioned methods. This may be due to bremsstrahlung resulting from electron trajectories which traverse an appreciable portion of the length of the RFQ while traveling between vane pairs. In the split-coaxial structure, such trajectories can yield voltages greater than \( V_c \). The calibration for the results discussed here was from the first two methods discussed.

On operation following initial pumpdown, the structure exhibited low-level multipacting, which conditioned away in less than an hour. High power operation was with pulses of a few milliseconds duration, and with a duty factor less than 1%. At higher field levels, the structure arced between the RFQ vanes repeatedly but within a few hours had conditioned to \( V_c = 59 \) kV. At this level the input power was limited (at approximately 15 kW) by arcing in a vacuum feedthrough to the power coupling loop.

Figure 3 shows the results of this test, in the context of the Kilpatrick model for limiting electric fields in RF structures\(^7\). It should be noted that for most RFQ implementations, the rf frequency is sufficiently high that for practical vane-vane spacing, the Kilpatrick limit is in the asymptotic limit of large gap, and the gap dependence is generally ignored. For the present case of a very low frequency RFQ, however, we are not in the asymptotic region for the Kilpatrick model, and the gap dependence is quite important. This is born out by the experimental result for the 19 MHz model shown in Figure 3, which is nearly three times the asymptotic Kilpatrick limit for this frequency, but only 1.23 times the Kilpatrick limit when the gap dependence is included. Using the complete Kilpatrick model to scale the present result to a 12 MHz structure, it appears that operation at an intervane voltage of 100 kV is feasible.

**Conclusions**

By operating at low frequency, and by pre-bunching the beam, it seems feasible to provide good transverse acceptance and excellent longitudinal beam quality in an RFQ structure for singly-charged ions heavier than mass 132. It should be noted that two two-meter sections of 12 MHz RFQ will be required for an injector for ATLAS. This paper has focused on the critical entrance section, as subsequent sections are similar, but technically less demanding.

A two-meter section of 12 MHz RFQ is presently under construction. Tests are planned initially to be with unmodulated vanes, for the purpose of demonstrating cw operation and determining voltage limits. Subsequently, the vanes will be modulated and tests with beam performed.

**Acknowledgements**

The authors gratefully acknowledge numerous helpful conversations with Rolf Muller, Jerry Nolen, and John Staples. John Vincent, John Brandon, and other staff members of the National Cyclotron Laboratory made possible the high power RF tests, which were performed at Michigan State University. We also thank Michael Bruns for performing the RELAX 3D calculations.

**References**

Plasma Modified Production of High-current, High-purity cw H⁺, D⁺, and H⁻ Beams from Microwave-driven Sources

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Abstract

We have recently reported [1] the production of cw proton beams from magnetically-confined microwave-driven sources, operating under non-resonant (non-ECR) conditions, with proton fractions greater than 0.95, the remaining fraction consisting of H₂⁺ (0.05) with no H₃⁺. We achieve this by the addition of H₂O to the plasma at molecular concentrations of ~1.0% and about 700 W 2.45 GHz RF power to the source. High-current (45 mA) high-power (45 kV) beams of >92% proton purity have been produced using this technique [2]. Additional impurity ions, O⁺ at 4 parts per thousand (ppt) and OH⁺ and H₂O at < 1 ppt are produced. We report further progress using this technique and similar results we have achieved for cw D⁺ beams with D₂O and H₂O additives. Finally, we report progress we have made in the direct extraction of cw H⁻ beams from microwave-driven sources in terms of ion source surface material and confining magnetic field configurations. Mechanisms are discussed.

Introduction

High-current cw proton sources of high reliability are a current requirement for several proposed accelerator applications, including spallation neutron sources and accelerator production of tritium. A desirable property of such sources is that the proton fraction of the extracted beam be as high as possible so as to avoid the need for selection of the desired ion, i.e., to enable direct injection into an accelerating structure. A number of sources have been described in the literature that yield proton fractions on the order of 80% of the extracted beam, the other unwanted components being H₂⁺ and H₂⁺[3,4,5]. Techniques to enhance the proton fraction above 80% are highly desirable.

Similarly, high current H⁺ sources are a requirement for advanced spallation sources based on circular accelerators and other circular proton accelerators that use stripping injection, and for tandem accelerators.

Background

It has long been known that addition of minor constituents to microwave-generated plasmas can modify the species composition of the plasma and can increase atomic neutral fractions relative to molecular species. Systematic studies of atomic hydrogen fractions from microwave-driven plasmas have produced atomic hydrogen beams with close to 100% purity[6], leading us to recognize that this may be a viable technique for the production of high purity ion beams.

In the case of H⁺ production, pioneering studies by Hall et al. [7] demonstrated the effectiveness of freshly evaporated tantataum surfaces in producing copious quantities of vibrationally excited molecular hydrogen (a required precursor to H⁺ formation). The observations of Hall et al. appear to never have been deliberately, or successfully, applied to the production of high-current cw H⁺ beams.

Apparatus, Diagnostics, and Experimental Techniques

Figure 1: Schematic of apparatus including modifications necessary for production of H.

The major components of our apparatus shown in Fig. 1 include a magnetically-confined microwave-driven (ECR) source purchased from AECL powered by a 2.45 GHz microwave generator (2 kW). The microwave generator is coupled to the source via a circulator and a four-stub autotuner. The ion source is attached to a large high-vacuum oil-free diagnostic chamber with a base pressure of 1x10⁻⁶ Torr.

Ion beams extracted at a few hundred volts from the 5 mm source aperture by an accel-decel arrangement are primarily collected on the decel electrode that is in the configuration of a faraday cup. A 0.5 mm aperture in the decel electrode allows a small portion of the beam to be transported to a quadrupole mass spectrometer (QMS) via an electrostatic zoom lens for quantitative beam composition measurement. Light from the ion source is monitored by an optical monochromator by a clear line-of-sight through the QMS (sapphire window). The monochromator continuously monitors the atomic hydrogen
Balmer $\alpha$ radiation (656 nm) to give a measure of the atom concentration in the source under varying conditions.

Additives, in this case H$_2$O and D$_2$O (gas), are introduced into the source along with the H$_2$ or D$_2$ via a micrometer leak valve. The composition of gas in the source (H$_2$, D$_2$, H$_2$O, D$_2$O, etc.) is monitored by a residual gas analyzer (RGA) mounted in the diagnostic chamber.

**Results**

Most of the measurements reported here are conducted with the ECR source operating slightly off-resonance, as chosen by the magnitude of the magnetic confining field. Although operation off-resonance usually produces a smaller fraction of protons in the extracted beam, such is not the case in the present experiments with H$_2$O as an additive.

A) Proton production

![Mass spectrum of positive ion beam with H$_2$O additive.](image)

Figure 2 shows a beam composition obtained with -1% H$_2$O added to the source for 1 sccm H$_2$ flow and 700 W microwave power. In this case, the proton fraction of the total beam (consisting of H$^+$ + H$_2$$^+$) is slightly higher than 0.95. Under similar conditions with no H$_2$O, the proton fraction of the total beam (consisting of H$^+$ + H$_2$$^+$ + D$_2$$^+$) is about 0.75, consistent with the measurements of Taylor and Wills [3] obtained under similar non-resonant conditions.

Figure 3 shows the proton fraction (H$^+/(H^+ + H^+_2 + H^+_2)$) and H$_2$O atom emission from the source versus percent H$_2$O added to the plasma. As expected, the proton fraction extracted tracks the concentration of H atoms in the source. The hysteresis in the two sets of curves occurs because the measurements were taken under increasing and decreasing amounts of H$_2$O, which takes a finite time (minutes) to reach equilibrium.

![Proton fraction and light vs percent water in the source.](image)

Figure 4 displays the proton fraction (H$^+/(H^+ + H^+_2 + H^+_2)$) and H$_2$ emission from source with -1% H$_2$O additive vs magnetic field. Light and proton fraction do not correlate well around the resonance condition. Indeed, maximum proton fraction is obtained at the resonance condition indicated by the arrow, where light is at a minimum. This probably occurs because efficient ionization of H atoms at resonance reduces their concentration and hence the intensity of H$_2$ emission.

b) Deuteron Production

Although not illustrated here, similar increases can be achieved in the deuteron fraction (D$^+/(D^+ + D^+_2 + D^+_2)$) by addition of H$_2$O or D$_2$O to D$_2$ plasmas, though this increase is less than in the case of H$_2$ as already high deuteron fraction can be obtained in pure D$_2$. Maximum deuteron fractions of about 0.93 are obtained. D$_2$O and H$_2$O are equally effective, although the use of H$_2$O results in minor impurities (H$^+$, HD$^+$) from ion-molecule reactions in the source.
c) H⁺ Production

Production of H⁺ ions in ion sources is known to occur by dissociative electron attachment of slow electrons to vibrationally excited hydrogen, H₂(v).

\[ e^{-}_{\text{slow}} + H_2(v) \rightarrow H^+_2 \rightarrow H + H^+ \]  (1)

where H₂⁺ is an intermediate temporary negative ion state. It is generally accepted that H₂(v) may be formed by the reaction

\[ H_2 + e^{-}_{\text{fast}} \rightarrow H_2(v) + e^{-}_{\text{fast}} \]  (2)

Attempts at direct extraction of negative ions from the standard magnetically-confined microwave-driven ion source described above by ourselves and others [8] have proved fruitless.

This probably arises from several causes. First, the mean energy of the electrons is generally low (~20 eV, Taylor and Wills [3]) and is not conducive to production of H₂(v) via equation (2). Second, the electrons in the source are magnetically confined along the axis between the extraction aperture and the microwave window. Thus, even if the weakly bound (0.75 eV) H⁺ species were formed in the source, it likely would be destroyed by collisional detachment by the 20 eV electrons.

However, Hall et. al. [7] have demonstrated alternative techniques for producing H₂(v), the precursor for H⁺. They find that H₂(v) may be generated in copious quantities by recombinative desorption of H atoms at surfaces coated with tantalum atoms. We have made use of this observation of Hall et al. to achieve the first direct extraction of H⁺ ions from a magnetically confined microwave driven ion source.

In order to produce H₂(v), the precursor of H⁺, we have lined the inside of our source with a tantalum sheet to produce H₂(v), via the reaction

\[ H + H + \text{tantalum surface} \rightarrow H_2(v) \]  (3)

In order to reduce the flux of 20 eV electrons at the extraction aperture, the source solenoids were moved back from being centered on the source to being centered on the microwave window. This results in the magnetic field diverging and thus diverting electrons at the extraction aperture. Immediate extraction of H⁺ ions was achieved as measured by the QMS.

Electrons necessarily extracted along with the negative ions were removed from the beam prior to mass analysis by a weak (~30 Gauss) transverse magnetic field in the region of the accel-decel electrodes. About 100 mA of extracted electrons were collected on these electrodes.

Shown in Figure 5 is a mass spectrum of H⁺ extracted from the source. Based on the ratio of total H⁺ extracted to H⁺ sampled by the mass spectrometer, we estimate this first successful attempt to produce H⁺ resulted in a total H⁺ current of 4-5 mA being extracted from the 5 mm diameter source aperture.

![Figure 5: Mass spectrum of H⁺ extracted from the modified source.](image)

This first data was obtained on August 20, 1996, and so optimal conditions for H⁺ production have not yet been achieved. Effects of additives have not yet been studied.

Acknowledgments

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References

THE ANL 50 MeV H' INJECTOR - 35 YEAR ANNIVERSARY

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Abstract

The H' Injector at ANL consists of a 750 keV Cockcroft-Walton preaccelerator and a Alvarez type 50 MeV Linac. The accelerator was originally constructed as the source of protons for the Zero Gradient Synchrotron (ZGS). The first proton beam was extracted from the preaccelerator in 1961. The accelerator is presently used as the injector for the Intense Pulsed Neutron Source (IPNS), a 500 MeV rapid cycling synchrotron with a spallation-neutron target. During most of the time since turn-on over 15 years ago, the IPNS facility availability has rarely dropped below 90% and has averaged 95% over the last ten years. During the same period, the 50 MeV injector availability has averaged 99%. Performance and improvements over the 35 year period is discussed.

Introduction

The ANL 50 MeV Injector has proven itself to be a very versatile and reliable machine. The linac has been used as a source of protons, H' ions, polarized protons, polarized deuterons, and neutral particle beams during it's many years of operation. Ground was broken for the injector in June 1959. The first 750 keV proton beam was obtained in December 1961. The first 50 MeV protons were accelerated in the linac ten months later in October 1962. The injector was used as the proton source for the ZGS 12.5 GeV synchrotron until 1976 when the ZGS became the first accelerator to utilize direct injection of H' ions as a normal mode of operation. The last two years before the ZGS was shut down in October 1979, were dedicated to the acceleration of polarized protons. A Rapid Cycling Synchrotron (RCS)[1] was developed and constructed in the mid 1970's as a proposed booster for the ZGS. Due to the scheduled shutdown of the ZGS the booster concept was abandoned. However, the RCS evolved into the 500 MeV accelerator for injecting protons to the IPNS spallation-neutron target. The linac has now supplied H' ions at a 30Hz rate to the RCS for over 15 years. We expect to inject the 5 billionth pulse into the RCS in late November of this year.

Injector General Description

The layout of the IPNS accelerator system including linac, RCS, and the spallation target is shown in Figure 1. The preaccelerator houses the 750 kV Cockcroft-Walton power supply, the H' ion source, and the high gradient accelerating column. The H' ion source is a magnetron type[2] in which negative ions are extracted directly from the hydrogen plasma on the surface of the cathode. The extractor electrode and magnet poles are at terminal ground and the source, including the pulsed arc supply, pulsed hydrogen supply, and cesium supply are pulsed to a negative 20 kV potential. After extraction, the beam is bent 90° by a magnetic dipole, focussed by three quadrupole magnets, and injected into the high gradient column. The 750 keV beam is transported 6 m to the linac in a beamline containing two quadrupole triplets for beam focussing, a vertical and horizontal steering magnet, one 200 MHz buncher, and a fast beam chopper for beam shaping. The linac cavity is a copper clad structure 0.94 m in diameter and 33.5 m long operating at 200.070 MHz. It was constructed in eleven sections, which are bolted together. The linac contains 124 drift tubes, each containing a dc quadrupole magnet. RF power is supplied to the linac via a rectangular waveguide to a single feedloop in the center of the cavity. A 50 MeV beam line transports the H' beam 38 m to the RCS accelerator. Beam steering and focussing is provided by a total of eight horizontal and two vertical dipole magnets and sixteen quadrupole magnets.

Figure 1. Layout of the IPNS accelerator.
System Evolution

Preaccelerator

The 750 kV power supply for the preaccelerator is a standard four stage Cockcroft-Walton. The input transformers to the four stage multiplier are driven with a 400 Hz motor generator set. There have been no failures of the high voltage transformers, rectifiers, or capacitors since construction. Parts of the regulating system have been updated but some of the amplifiers are still original.

The original ion source used to supply protons to the ZGS was a standard duoplasmatron which produced enough beam current to supply the synchrotron with a 20 mA, 100 µs pulse at a one-pulse-every-four-second rate. When we switched to H+ injection, a modified duoplasmatron with a hydrogen charge exchange cell[3] was used. This source was quite adequate for supplying the ZGS with enough beam current but the RCS was close to being input limited. Also, the hydrogen flow needed in the charge exchange cell required two 30,000 l/s bulk titanium sublimator vacuum pumps in the high voltage terminal. The titanium slugs in these pumps had to be replenished every two or three weeks requiring many man-hours of maintenance. In 1983 the magnetron type H+ ion source was installed. This source produces 45-50 mA, 70 µs beam pulses at a 30 Hz rate, which is more than sufficient to supply the RCS 50 MeV input requirement of 10 mA. The source has been very reliable, requiring only disassembly and cleaning after several thousand hours of operation.

The original accelerating column was a multi-gapped low gradient structure and required frequent cleaning to enable it to hold the 750 kV. In 1970 a single gap high gradient column was developed and installed, increasing the linac output capability from 20 mA to over 40 mA. A six megohm resistor in series between the 750 kV supply and the column results in only a few second trip during a column arc. The column arc rate averages about four per hour. The column hasn’t required disassembly and cleaning in nearly ten years.

Linac RF System

The rf system was the first linac amplifier built utilizing the 7835 triode. It was the first and only amplifier to transport the rf from the power amplifier to the cavity via a rectangular waveguide. The 7835 cavity is not pressurized, but we have had very few problems with voltage breakdown. We have had continuing problems with blocking capacitor voltage punch-through. These failures seem to come in bunches every several years. Presumably the cause is a void or foreign particle in the irathene insulation. Besides upgrading most of the power supplies to accomodate the 30 Hz rep-rate, the only major changes in the rf system have been with the plate modulator for the 7835. The modulator has been redesigned and replaced twice due to problems with output switch tube voltage holding capabilities. The tube we have been using for the past 15 years is the ML7560. The tube lifetime has been excellant, over 25,000 hours, and the arc through rate is maybe one per week.

Linac Cavity

The ANL linac was patterned after the 50 MeV Brookhaven Alternating Gradient Synchrotron (AGS) linac, with the main difference being that the quadrupole magnets in the 124 drift tubes are dc instead of pulsed. Originally each magnet had a transistorized shunt attached for individual control. Presently, transistorized shunts are utilized on only the first 58 magnets. The cavity vacuum system started out with nine 2000 l/s ion pumps and one 20" mercury diffusion pump for pump-down. The present system uses seven ion pumps, two cryo-pumps and a 1500 l/s turbo-pump. The ion pumps in use are the original pumps. We try to overhaul at least one per year which means each pump operates about 7 years before removal and cleaning.

To keep gas stripping of the H+ beam at a minimum, we try to keep the cavity vacuum below $5 \times 10^{-7}$ Torr. We have an ongoing problem involving water leaks into the linac high vacuum system. There are 57 water cooled tuning balls mounted along the length of the linac. These are 14 cm diameter copper balls both threaded and silver soldered to a 2.54 cm stainless tube which extends through the cavity wall. A smaller diameter water distributor tube runs down the center of the 2.54 cm tube to supply water for cooling the copper ball. Water leaks (apparently through the threaded and silver soldered joints) into the cavity vacuum have developed over the years in 15 of these tuning balls. A method of repairing these leaks without removing the tuning ball or breaking the linac vacuum was developed. A smaller diameter cooling tube is placed inside the original tube making good thermal contact with the inside of the ball to allow for sufficient heat removal. The space between the tubes, which now contains the leak, is evacuated, virtually eliminating what would now be an air leak into the cavity. We presently have a water leak in one of the tuning balls so small that we have yet to locate it.

Polarized Beams

In 1973, the first high energy polarized proton beam[4] was developed at the ZGS. It operated very successfully until 1979 when the ZGS was shut down permanently. The source was installed in a new preaccelerator located just west of the original as shown in Figure 1. To house the large polarized proton source, a high voltage terminal 2.5 m x 3.5 m x 4.5 m in size was required. The terminal was built by a company that manufactures campers. The source weighed over 4,500 kg and consumed over 35 kW of electrical power. It contained three rf systems; six magnets; six beam line elements; and nine vacuum pumps including diffusion, ion, turbo-molecular, sublimator, and mechanical. A pulsed bending magnet at the high energy end of the linac allowed both a polarized proton pulse to be injected to the ZGS, and a burst of H+ beam pulses to be injected to the RCS.
In 1978 the first ever high energy polarized deuteron beam[5] was accelerated. The deuterons were accelerated to 375 keV in the preaccelerator and to 25 MeV by the 50 MeV linac. The rf level and quadrupole magnet currents used for accelerating deuterons in the 2βλ mode were essentially the same as normally used for protons. Normal tuneup resulted in a deuteron transmission through the linac of about 25%.

Neutral Particle Beams

Proton Therapy

In 1983 the H⁺ beam resulting from gas stripping at the high energy end of the linac was studied as a possible proton therapy facility at Argonne[6]. The H⁺ beam was separated from the H⁰ beam by a bending magnet and the H⁺ beam drifted through the beamline to the previous ZGS area. An intensity collimator and halo foil reduced the lower energy components produced by gas stripping earlier in the linac. The beam was then converted to H⁻ by passing through a thin foil. It then passed through a spectrometer magnet into the experimental enclosure.

Strategic Defense Initiative

One of the objectives of the Strategic Defense Initiative (SDI) was to put a medium energy (50-200 MeV) H⁺ linac into space to evaluate the promise of Neutral Particle Beam (NPB) devices. The beam intensity and quality requirements were far beyond those of any operating linac so a great deal of research was required. The only operating H⁺ linac in this energy range was at IPNS, so the Neutral Particle Beam Test Stand (NPBTS)[7] was developed in 1986. Two beam lines were constructed in the old ZGS tunnel. The first line provided basic physics information on beam diagnostics and high energy neutralization devices. The second line was used to study the magnetic optics required to produce large diameter beams with low divergence.

Accelerator Operations

Figure 2 shows the availability ratio (ratio of beam hours available to beam hours scheduled) for the entire RCS accelerator system. As can be seen the yearly average is around 95%. The availability of the linac alone averages above 99%. Scheduled and operating time are shown in Figure 3. For several years budget constraints have limited operation to less than 20 weeks per year. The Scientific Facilities Initiative (SFI) funding included in the FY 1996 budget provides for an increase in operating time in 1996 to 25 weeks and should eventually result in an operating schedule of up to 32 weeks per year.

Acknowledgements

The authors wish to thank the entire linac crew for their diligent machine maintenance and improvements. Without their efforts, the continuing high availability numbers for the linac would be impossible.

References


THE CEBAF RF SEPARATOR SYSTEM∗

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Abstract

The 4 GeV CEBAF accelerator at Thomas Jefferson National Accelerator Facility (Jefferson Lab) is arranged in a five-pass racetrack configuration, with two superconducting radio-frequency (SRF) linacs joined by independent magnetic transport arcs. The 1497 MHz continuous electron beam is composed of three interlaced variable-intensity 499 MHz beams that can be independently directed from any of the five passes to any of the three experimental halls. Beam extraction is made possible by a system of nine warm sub-harmonic separator cavities capable of delivering a 100 μrad kick to any pass at a maximum machine energy of 6 GeV. Each separator cavity is a half-wavelength, two cell design with a high transverse shunt impedance and a small transverse dimension. The cavities are powered by 1 kW solid state amplifiers operating at 499 MHz. Cavity phase and gradient control are provided through a modified version of the same control module used for the CEBAF SRF cavity controls. The system has recently been tested while delivering beam to Hall C. In this paper we present a description of the RF separator system and recent test results with beam.

Introduction

The 4 GeV CEBAF accelerator is arranged in a five pass racetrack configuration, with two superconducting radio-frequency (SRF) linacs joined by independent magnetic 180° transport arcs. The continuous electron beam is composed of three interlaced variable intensity beams that can be independently directed from any of the five passes to any of the three experimental halls. This allows three simultaneous experiments at the same or different energies and currents. Electrons are emitted through a thermionic cathode or a polarized laser cathode that is being commissioned. Presently only one experimental hall is fully operational, Hall C, with Hall A in the final commissioning stages.

To develop the three independent beams the CEBAF accelerator uses a chopping cavity system in conjunction with separator cavities operated at the third subharmonic (499 MHz) of the accelerating cavities. The separator cavities are positioned in each of the five passes and allow for different combinations of energy to be delivered to the experimental halls. The accelerator can deliver only a single lower energy (845, 1645, 2445, 3245 MeV) to any one hall at a time or the maximum energy (4 GeV) to one, two or all three experimental halls. Each pass has been designed to deliver the 100 μrad kick necessary to extract the beam. The separator phase arrangements for the first through fourth pass and fifth pass are shown in Fig. 1.

![2 Way Beam Split](image1)

![3 Way Beam Split](image2)

Fig. 1: Separator Cavity Phasing.

The nine cavities are arranged in the following fashion: pass one and two each have one cavity, pass three and four each have two cavities and the final fifth pass has three cavities (Fig. 2). The reason is that it was more economical to build cavities than to buy high power amplifiers. In addition the arrangement allows for energy upgrade in the future without the addition of hardware.

![RF Separator System](image3)

Fig. 2: RF Separator System.

The cavities are powered by six solid state amplifiers that can be manually switched to any cavity in any pass. The most

∗ Work supported by the Department of Energy, contract DE-AC05-84ER40150.
amplifiers that will be needed at any one time is five, so one acts as a hot spare. Eventually it is envisioned to have an electromechanical switch matrix for drive and probe cables so that one can switch remotely between passes.

**Cavities**

The CEBAF separator cavity is a new design which achieves a high transverse shunt impedance in a package with compact transverse physical dimensions [1]. Two B field coupled λ/2 cells make up each separator cavity. Each cell is a resonant cylindrical cavity with four internal coplanar field perturbing rods that are parallel to the cavity axis (Fig. 3). As reported in other papers the cavity is operated in a TEM dipole type mode at 499 MHz and the beam path is along the cavity axis [1, 2]. The frequency of each cell is adjusted by a manually operated capacitive frequency tuner. Power is delivered to the separator cavity by a critically coupled inductive copper loop probe mounted to a 1 5/8" coaxial EIA adapter. Cavity gradient is measured by a small highly undercoupled monitor loop probe.

![Fig. 3: Two Cell Separator Cavity.](image)

The separator cavity is constructed from two cylinder body assemblies, one center flange/rod assembly and two end flange/rod assemblies. These parts are then joined together using Conflat vacuum hardware.

The flange/rod assemblies are quite intricate [3]. The rods are made from a tellurium copper alloy for strength and are brazed into an OFHC copper end slug. The end slug is brazed to a stainless steel collar which is then electron beam welded to a stainless steel Conflat flange (Fig 4). The entire assembly is then copper plated. Water channels in each flange assembly deliver coolant to the rods, which are hollow and fitted with septum plates. A water channel also surrounds each cylinder body.

An interesting feature of the cavity is that the stainless steel cylinder body does not require copper plating. The fields and therefore the currents are very weak at the cavity perimeter, making plating irrelevant. Tests made during prototyping showed that copper plating the cylinder body resulted in less than a 5% increase in the intrinsic $Q$. This amounted to a substantial cost savings in manufacturing the cavity.

![Fig. 4: End Flange and Rod Assembly.](image)

<table>
<thead>
<tr>
<th>CEBAF Separator Cell</th>
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<tbody>
<tr>
<td>Length</td>
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<tr>
<td>Radius</td>
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<tr>
<td>Beam pipe diameter</td>
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<tr>
<td>Rod diameter</td>
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<tr>
<td>Rod gap longitudinal</td>
<td>2 cm</td>
</tr>
<tr>
<td>Rod center transverse spacing</td>
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<tr>
<td>Cavity resonant frequency</td>
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<tr>
<td>Cavity loaded $Q$</td>
<td>2500</td>
</tr>
<tr>
<td>Transverse shunt Impedance</td>
<td>350 MΩ/m</td>
</tr>
</tbody>
</table>

**Separator Cavity Transverse Shunt Impedance**

The transverse shunt impedance is an important figure of merit for a deflecting cavity, and we have determined this value through three separate means. The first method was to perform a MAFIA code simulation of the cavity. Next we conducted a beam test with an installed separator in the accelerator, where we measured the beam deflection. Finally, a bead pull measurement was conducted in the lab [4]. Given the complicated geometry we believe the MAFIA results are in fairly good agreement with the other two methods.

| MAFIA$^*$ | $R_{\perp} = \frac{V^2}{P_t} = 175 \ \text{M}\Omega$ |
| Beam Test$^*$ | $R_{\perp} = \frac{V^2}{P_t} = \left(\frac{845 \text{MeV} \cdot 131 \mu\text{rad} \cdot 2/3}{26 \text{ W}}\right)^2 = 208 \ \text{M}\Omega$ |
| Bead Pull$^*$ | $R_{\perp} = \frac{V^2}{P_t} = \frac{Q_0 \left(\int \sqrt{\Delta f \cdot \cos \frac{\omega c}{\omega}} \, dz\right)^2}{2\pi f^2 r^1 e_{\text{a}}} = 212 \ \text{M}\Omega$ |

**Amplifiers**

The amplifiers for the system were built by a private company on contract with Jefferson Lab. They are of a

$^*$ includes transit time effects
modular design that moves away from the traditional chassis style used by many high power solid state amplifiers. The amplifiers are capable of 1300 W of saturated power and 1 kW of linear power. The amplifiers are modeled after broadcast amplifiers where quick repairs are a necessity. Each amplifier has four (250 W) power modules that can easily be removed for repair. In addition the power modules can be removed and the amplifier operated with one, two, or three modules to reduce the power consumption. Each power module is identical and can be switched between amplifiers if necessary. The amplifiers can be controlled either locally for maintenance or remotely through the CEBAF control system during operation. Interlocks consist of a load-missing fault for personnel safety and over temperature to protect the unit.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Amplifier Specifications</th>
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<tr>
<td>Power out (linear)</td>
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<tr>
<td>Power out (saturated)</td>
<td>1.3 kW</td>
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<tr>
<td>Frequency</td>
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<td>Class</td>
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<tr>
<td>Gain</td>
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<tr>
<td>VSWR (in/out)</td>
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</tr>
<tr>
<td>Noise figure</td>
<td>&lt; 8.0 dB</td>
</tr>
</tbody>
</table>

Cavity Control

Cavity control is accomplished through a modified superconducting (SC) cavity control module [5]. In a superconducting mode the cavity provides the first pole in the feedback system. In the normal conducting case that is not feasible since the cavity's bandwidth is 200 kHz. Therefore the control modules have been designed to include a removable artificial pole at 10 Hz. This allows high gain (30 dB) operation without the possibility of oscillation. The control system is based on a traditional phase and amplitude system that controls each individually. The signal processing components were chosen to minimize AM to PM and vice versa. We have not had problems with the SC cavities and therefore do not foresee any problems with normal conducting cavities.

Calibration

The RF control modules are unique in that each is calibrated in an environmental chamber. The modules are completely characterized to remove offsets, phase shifts, and amplitude shifts. A complete record of temperature drifts is then downloaded into the control module where custom algorithms use the information to compensate for them. Local operational information such as cable attenuations and cavity coupling parameters are downloaded to the control module in situ.

Software control

The EPICs control platform provides the user interface in the form of control displays and state machine logic [6]. Because there are only six RF control modules and nine separator cavities, operators must have ability to switch RF controllers between the cavities. This posed a dilemma for the RF controls because each RF control module needs to have operational data (cable attenuations, cavity Q) specific for each cavity. To facilitate this a matrix database has been developed that allows operators to download any operational information to any RF control module.

Interlocks

The CEBAF accelerator is set up so that any experimental hall can have a number of different options of beam energy and current. Hall B in particular will require currents three to four orders of magnitude lower than the other halls. Any beam reaching this hall that is larger than 1 pA could destroy the target; therefore an interlock is needed such that the separator phase cannot slip 120°. In addition directly downstream are very thin septa magnets that are susceptible to beam burn through. A phase slip of 20 degrees could put the beam onto one of the thin septa, causing a vacuum accident. Therefore a fast shutdown system that compares the chopping cavity phases to the separator cavity phase is being installed and tested.

Status

Presently all of the cavities are installed and have been tested to 1 kW. The phase slip interlock is undergoing beta testing and it is expected to be fully operational by January 1997. Operations with beam have also been successful. The system has been used to deliver 4 GeV, 70 μA beam to Hall C while concurrently delivering 845 MeV, 5 μA beam to Hall A. Multibeam delivery to all three experimental halls is planned for early 1997.

References

Investigation of Space Charge Compensated Transport by Use of a Gabor Plasma Lens

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Abstract

Low energy beam transport (LEBT) of high perveance ion beams suffers from high space charge forces. Space charge compensation reduces the necessary focusing force of the lenses and the radius of the beam in the lenses and thence from the emittance growth due to aberrations and self fields. The use of electrostatic lenses is restricted due to decompensation by the electric fields. On the other side magnetic lenses suffer, for high mass ions, from the necessary high magnetic fields and the resulting technical problems. A different approach for LEBT is a lens using a static non neutral plasma confined in a magnetic and electrostatic field configuration allowing strong electrostatic focusing with only small influence on space charge compensation. Modeling of the plasma in respect to low lens aberrations is very difficult and there is no closed theory available. New measurements at low residual gas pressure as well as theoretical work will be discussed.

Introduction

For prediction of the transport capabilities of a low energy transport line using compensated transport it is necessary to know the density distributions of the compensating particles and the beam particles. So far the distribution of the compensating particles can only be calculated in a selfconsistent way, in a drift region [1,2,3]. This is not possible inside magnetic structures now. The theory for determination of the electron density (for positive ions) in compensated transport might benefit from the theory of charge density distribution in a Gabor plasma lens (GPL) where the electron enclosure is performed by magnetic and electrostatic fields. The advantages of a Gabor lens for measurements are higher electron densities and therefore enhanced influence on the beam. Therefore solving the density distribution problem for the GPL might be a step forward for description of compensated transport. An indication therefore give [4,5] where some aberrations in compensated transport are explained by a high electron density on axis. Apart from the forecast of self fields in compensated transport the GPL is still a very promising candidate for a LEBT line.

Theory

The theory of electron density in a Gabor lens was originally given by [6]. The maximum density is only determined by the (homogeneous) magnetic field and given by

$$\rho_{\text{max}} = \frac{e \cdot \varepsilon_0 \cdot B^2}{2 \cdot m_e}$$

(1)

Other studies [7,8] assume that the focal strength of a Gabor lens is linear with the applied electric potential of the center electrode. Results of numerical calculations using eq. (1) for the radial electron enclosure density and a Poisson solver for the longitudinal confinement by the electrode potential assuming a homogeneous filled cylinder of 106 mm length and 35 mm diameter (this is the free space inside the Frankfurt Gabor lens) is shown in fig. 1. The maximum electron density is a function of the free external field parameters. This calculated theoretical maximum density might not be reached in an experiment. Furthermore a homogeneous density distribution was assumed which has to be proven experimentally.

Experimental set up

Two experiments have been set up. One for determination of the electron density by examination of the light emitted by the plasma. This radiation is produced by collisions between the residual gas and the captured electrons. A second experiment was set up to measure the focusing capabilities of the GPL using a 10 keV He+ beam. The results will be compared with numerical simulations.

Density measurements

The set up for the measurement of the radial density distribution is shown in fig. 2. The GPL was mounted on a turbo molecular pump with an adjustable valve for residual gas pressure control. The plasma is produced by a gas discharge below the Paschen limit. The emitted light was measured by a CCD camera installed on top of the lens. Therefore the measured light intensity is integrated along the z axis. The results are used to determine the electron density distribution. The pressure was adjusted to be comparable to the beam experiments. Helium, argon and hydrogen were used as residual gas.

Beam measurements

The set up for the measurement of the focusing capabilities is shown in fig. 3. The ion beam (He+, 10 keV, 4 mA, DC, p=7*10^-5 hPa) was extracted from a HIEFS [9] like ion source and
Fig. 2: Experimental set up for the measurement of the light.

Fig. 3: Experimental set up for beam measurements.

A parallel beam of approx. 40 mm diameter at the entrance of the Gabor lens was formed by the LEBT consisting of two solenoids. The Gabor lens was followed by a diagnostic tank (profile, beam potential and emittance measurements).

**Experimental results**

**Density measurements**

Fig. 4 shows a result of a light intensity measurement. The intensity of the emitted light is strongly peaked on the lens axis and therefore the electron density is assumed to be distributed in a similar way. In fig. 5 the radial light intensity distribution is shown as a function of the potential on the center electrode, the form of the radial density distribution seems to be constant and the height grows linear in a first approximation except for the lowest fields where the gas discharge is off. In fig. 6 the light intensity is shown as a function of the external field. The intensity

Fig. 4: Intensity of the emitted light as a function of $x$ and $y$ for a CCD exposure time of 5 s and a lens potential of 3 kV and a magnetic field strength of 105 G.

Fig. 5: Radial density distribution of the emitted light as a function of the electrode potential for a fixed magnetic field of 105 G.

Fig. 6: Radial density distribution of the emitted light as a function of the magnetic field for a fixed lens potential of 3 kV.

Fig. 7: Maximum and minimum intensity of the emitted light as a function of the electric and magnetic field.

Rises more than linear for low fields and then levels off. In fig. 7 the maximum (upper graph) and the minimum (lower graph)
light intensity of the profiles is shown as a function of the external parameters electrode potential and magnetic field strength. The contour of these light intensity plots are similar to the pattern of the theoretical expected maximum electron densities (fig. 1).

**Beam measurements**

The results of the emittance measurements behind the Gabor lens are shown in fig. 8 and 9. Fig. 8 shows the emittance with the lens off, fig. 9 with the lens in operation. Fig. 10 - 12 show numerical calculations of the transport capabilities of the lens. In fig. 10 the emittance in front of the lens is shown. This was calculated from the measured emittance behind the lens (fig. 8) using 250 beams and neglecting the space charge of the beam (degree of compensation in the measurements was > 90 %). Fig. 11 shows the result of a transport calculation for operational lens starting with this emittance (fig.10). A homogeneous electron density distribution calculated from the radial limitation criteria for the lens (\(n_e=38*10^{-6} \text{ As/m}^3\)) was assumed. The beam space charge was neglected. Fig. 12 shows the result of a transport calculation using the 'peaked' electron distribution from the CCD measurements scaled to the same density in the maximum (\(n_{e_{max}}=38*10^{-6} \text{ As/m}^3\)).

**Conclusions**

Comparison between the measured emittance and the calculated emittances show in focusing strength and in aberration forecast a better result for the peaked than for the homogeneous distribution. Nevertheless the experiments indicate that the electron density is between these two cases. This could be explained by additional electrons produced by the beam traveling through the lens and the influence of the beam potential on the plasma. The principle for the electron concentration on the axis is unknown. Therefore theoretical work using selfconsistent density distributions for the thermalized electrons will be done.

**References**


**Acknowledgment**

We thank L. Wicke and Dr. M. Sarstedt from the IAP for the use of the CCD camera.
INVESTIGATION OF SPACE-CHARGE COMPENSATION WITH RESIDUAL-GAS-ION ENERGY ANALYSER

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Abstract

Low energy beam transport of high perveance beams with magnetic quadrupole focusing requires a high degree of space-charge compensation. Furthermore the build-up time of space-charge compensation has to be short compared to the beam-pulse duration. In order to study the space-charge compensation in the drift sections between the focusing elements of the existing GSI UNILAC injector, the energy spectrum of the residual gas ions produced by the beam and accelerated radially by the space-charge potential can be measured. Here-to a compact electrostatic energy analyser of the Hughes-Rojansky type [1] has been built allowing for time integrated as well as time resolved measurements. First measurements in time integrating mode have been performed.

Introduction

Residual gas ions (RGI) are created locally by collisions of beam ions (BI) with residual gas atoms (RGA) proportional to beam current density \( j_{\text{BI}}(r) \) and to the cross section of the production of RGI \( \sigma_{\text{RGI}} \) and the density of RGA \( n_{\text{RGA}} \). (A thinning of the residual gas by that interaction only takes place at beam densities not reached under our experimental conditions.) Under the assumptions of 1-dim. cylindrical symmetry, positive beam potential \( \Phi(r) \) and RGI created at rest, the RGI are accelerated outwards radially in the beam potential. The energy distribution of the RGI \( dT_{\text{RGI}}/dW \) (with \( T_{\text{RGI}}(W) \) the line current of RGI with energies below \( W \)) contains information on \( j_{\text{BI}}(r) \), \( \Phi(r) \) and \( \sigma_{\text{RGI}} n_{\text{RGA}} \) in a folded form. It can be evaluated from measurements with an RGI spectrometer, taking into account the spectral sensitivity of the instrument. E. g. the radial potential distribution \( \Phi(r) \) of a compensated DC beam has been reconstructed from \( dT_{\text{RGI}}/dW \) and \( j_{\text{BI}}(r) \). For a decompensated DC beam \( j_{\text{BI}}(r) \) and \( \Phi(r) \) have been derived directly from the RGI energy spectrum \( dT_{\text{RGI}}/dW \) and the total beam current \( I_{\text{BI}} \) via an analytical inversion [2].

Time resolved measurements of the build-up of space-charge compensation can be performed with a spectrometer using a channeltron detector and a multi-channel scaler [3].

Quality of Measured RGI Energy Spectra

Besides the energy resolution of the spectrometer given by slit width and acceptance angle (here: 1.6 % due to slit width, ±0.4 % due to acceptance angle) some effects can deteriorate the quality of measured RGI energy spectra.

1-dim. cylindrical symmetry is essential for a simple interpretation of RGI energy spectra. The symmetry of the beam potential is supported by a cylindrical drift tube of sufficient length surrounding the beam at the axial position of the spectrometer. Disturbing external electric fields are minimised by it but the effect of an asymmetry of the beam cannot be suppressed.

An asymmetry of the beam (or total charge configuration) as well as charging of isolating surface layers in drift tube and spectrometer or external magnetic fields can diminish the number of RGI arriving at the spectrometer under proper angles.

The detected RGI current is lowered in the same way due to the non-radial movement of RGI created with non-zero energies. For the given geometry and thermal start energies this is significant only for detected RGI energies below 3 eV and can be corrected to some extent [2].

The space charge of RGI on the way from the drift tube to the entrance slit of the spectrometer causes a widening of the RGI "beam". This can be significant because it is not unusual that the perveance of the RGI "beam" exceeds that of the ion beam. The resultant decrease of detected RGI intensity is strongly chromatic. Hence the spectrometer has to be positioned as near as possible to the cylindrical drift tube.

In the case of strong production of secondary electrons by the beam, a negative signal is superimposed at the low energy end (up to a few eV) of the RGI energy spectrum. This is due to secondary electrons irregularly passing the spectrometer by multiple reflexions.

Fluctuations of beam current or beam diameter can result in a broadening of the RGI energy spectra. (An indication for the quality of a spectrum is a sharp decrease at the high-energy end.)

The build-up of space-charge compensation with time results in a broadening of spectra measured time integrated at pulsed beams.

Electrostatic Energy Analyser

An electrostatic energy analyser with an energy resolution of 2 % at an acceptance angle of ± 6° for both directions has been built (Fig. 1). It has been operated with Faraday cup and electrometer amplifier for time integrated absolute measurements. Operation with channeltron in single particle counting mode for time resolved measurements [3] and measurements at low intensities is foreseen. (The channeltron is not mounted yet.) The RGI flux has to be adjustable to the
pulse counting capability of the channeltron (10^6 s^-1). This is provided by accelerating the RGI to an electrode (the bottom of the Faraday cup) and detecting the secondary electrons. The secondary electron flux to the entrance of the channeltron is controlled by a (second) variable accelerating voltage. Both modes of operation can be performed without changes of the spectrometer.

The RGI energy analyser was mounted in a standard diagnostic box in the GSI injector after the mass separating dipole magnet (Fig. 2). A drift tube of 100 mm inner diameter and 270 mm length was inserted into the box. A pulsed Ne^+ beam of 232 keV, approx. 16 mA, 25 Hz repetition rate and 0.67 ms pulse duration was used. The 22Ne^+ fraction was adjusted to the axis of the beam tube with a diameter of approx. 10 mm. A 10% 22Ne^+ fraction hit the drift tube approximately at the axial position of the RGI energy analyser (Fig. 3).

Fig. 1. RGI energy analyser and drift tube.

The spectrometer is well shielded against irregular particles but no measures are taken to prevent secondary electrons from irregularly passing it by multiple reflections at the deflector plates.

Electric heating of the spectrometer is possible in order to prevent gaseous surface layers. Due to a separate heat shield and a mounting with low thermal conductivity, only 12 watt are required to maintain a temperature of 200 °C (more seems possible). At the same time the channeltron which is mounted in a separate housing stays below 50 °C. Non-magnetic material was used throughout. All stainless steel parts are annealed at 1000 °C. The analyser is mountable in a tube of 100 mm diameter.

20 cm downstream of the RGI energy analyser the beam passed between the two electrodes of a motorised slit (spacing 55 mm). These could be biased positively in order to decompensate the beam. 1.3 meter further downstream (after a quadrupole doublet) the beam was stopped without secondary electron suppression.
First Measurements

The influence of an increase of residual gas pressure on the RGI energy spectra is shown in Fig. 4. The maximum beam potential decreases as well as the potential drop inside the beam which falls from approx. 20 V to below 5 V. Compared to a theoretically estimated maximum potential of approx. 500 V and a potential difference of approx. 100 V in the decompensated beam this indicates high degrees of space-charge compensation. At $7 \times 10^{-7}$ hPa the steep decrease at the high-energy end of the spectrum points to a build-up time shorter than the theoretical build-up time $\tau = (\sigma_{\text{RGI}} n_{\text{RGA}} V_{\text{DE}})^{-1}$ of approx. 200 $\mu$s ($v_{\text{BE}}$ velocity of Bi).

Nevertheless, caution has to be taken with this interpretation because two anomalous facts were observed: 1. Generally at low pressure or with decompensated beam the beam position had an unusual strong influence on the spectra. 2. At high decompensation voltages the maximum of observed RGI energies was far below the theoretically expected 500 eV. This effect persisted even if the decompensating electrode was moved into the beam. Up to now these effects are not fully understood. A possible reason is the disturbed symmetry due to the space charge of the $^{22}$Ne$^+$ fraction and the secondary electrons produced by it. If this is confirmed by experiments with a pure $^{20}$Ne$^+$ beam or a He$^+$ beam the RGI energy analyser will be shifted to another location.

Planned Experiments

The influence of beam parameters as diameter, pulse length, current and current fluctuations and of residual gas pressure on the space-charge compensation will be studied. As well time resolved measurements (time resolution 2 $\mu$s) of the build-up of space-charge compensation in the pulsed UNILAC beam are planned for the near future. The hard- and software for channeltron operation and data analysis are in preparation.

References

Design and construction of standing wave accelerating structures at TUE

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Abstract

Two standing wave accelerating structures have been built for the operation of two AVF racetrack microtrons (RTM). For the first RTM a 3 cell 1.3 GHz on axis coupled standing wave structure has been designed to accelerate a 50 A peak current beam in 9 steps from the injection energy of 6 MeV to a final energy of 25 MeV. The beam will be used as drive beam for the free electron laser TEUFEL. The second structure accelerates a 7.5 mA beam in 13 steps from the injection energy of 10 MeV, to a maximum energy of 75 MeV. This 9 cell on-axis coupled structure operates at 3 GHz and was designed with a relatively large aperture radius (8 mm) in order to avoid limitations on the RTM's acceptance. Design, fabrication and testing of the structures have been done in house. For the design of the structures the combination of the codes Superfish and Mafia has been used. Low and high power tests proved that the structures live up to the demands. With the experiences gained a design for the accelerating structure of the H⁻ linac of the ESS project has been made. The design of the cells as well as a novel type of single cell bridge coupler will be presented.

Introduction

The Racetrack Microtron Eindhoven (RTME) has been designed to accelerate a pulsed 7.5 mA electron beam from the injection energy of 10 MeV to the final energy of 75 MeV [1]. The acceleration is achieved in 13 subsequent passages by a 5 MeV, 3 GHz standing wave on-axis coupled cavity, see sec. .

The free electron laser project TEUFEL is a cooperation between the Dutch universities of Eindhoven and Twente. Part of this project is a 25 MeV racetrack microtron which is being built at Eindhoven [2]. The microtron cavity is a standing wave on-axis coupled structure that consists of three accelerating cells and two coupling cells, see sec. .

The linac of the accelerator based neutron spallation source ESS project will accelerate a 100 mA H⁻ beam over 660 m length from 70 to 1334 MeV. This paper describes the cell and bridge coupler design in sec. .

The RTME cavity

Fig. 1 depicts a schematic lay-out of the on-axis coupled RTME cavity. Table 1 lists some of the measured and related parameters of this cavity [3].

Table 1: Measured and related parameters of the RTME cavity, \( T_{\text{Cue}} = 288 \) K.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>resonant frequency (MHz)</td>
<td>2998.70</td>
</tr>
<tr>
<td>stopband (MHz)</td>
<td>-0.06</td>
</tr>
<tr>
<td>accelerating voltage (MV)</td>
<td>5.0</td>
</tr>
<tr>
<td>coupling coefficient (%)</td>
<td>-4.61</td>
</tr>
<tr>
<td>direct coupling coefficient (%)</td>
<td>-0.24</td>
</tr>
<tr>
<td>loaded quality factor</td>
<td>4125</td>
</tr>
<tr>
<td>coupling ratio ( \beta )</td>
<td>2.35</td>
</tr>
<tr>
<td>cavity length (m)</td>
<td>0.45</td>
</tr>
<tr>
<td>eff. shunt impedance (MΩ/m)</td>
<td>62.3</td>
</tr>
<tr>
<td>dissipated power (MW)</td>
<td>0.90</td>
</tr>
<tr>
<td>beam power (MW) @ 7.5 mA</td>
<td>0.50</td>
</tr>
</tbody>
</table>

The 9 accelerating and 8 coupling cells are formed by stacking 18 accurately fabricated square bricks of OFHC-Cu. These square bricks are used for a repetitive mounting on the lathe and for the alignment of the total cavity in a ridge. Here the pieces are kept together with a force of \( \sim 3000 \) N by a multi-spring based clamping mechanism.

For the tuning the parts are mainly stacked in sets of 2 and 4 terminated with plates forming respectively 3 and 5 coupled resonators with 3 and 5 mode frequencies. From the three mode frequencies the accelerating and coupling cell resonant frequencies and the coupling coefficient are obtained. From the five mode frequencies also the direct coupling coefficient for the accelerating cells is obtained.

To tune the end parts they are stacked with their two tuned nearest neighbour parts. This structure is covered with a plate. The \( \pi/2 \)-mode resonant frequency of this structure is adapted to the tuning frequency by adapting the frequency of the end part.
Figure 2: The measured electric field profile in the RTME cavity.

The dimensions of the waveguide-cavity coupling iris are determined by repetitive VSWR measurements in the waveguide.

Since in a perfectly tuned structure there will only flow major RF currents on the outer surface of the accelerating cells, it was decided to only join the two halves of the accelerating cells by brazing, whereas the two halves of the coupling cells are joined by O-rings. As brazing material Ag72Pd28Cu29.8 with a melting temperature of 780°C has been used. After constitution of the different parts in the ridge no vacuum leaks could be detected.

After the completion of the structure the electric field profile of the π/2-mode has been determined by means of the perturbing ball method, see fig. 2. The standard deviation in the measured field amplitudes corresponds with 1% of the average amplitudes in the cells, indicating that the structure is properly tuned. It is not possible to quantify the magnitude of the electric fields in the coupling cells.

The high power tests have been done with a 2 MW EEL M5125 magnetron that was connected to the cavity via a 4-port circulator. By means of an EH-tuner located after the second port of the circulator the amount of power sent to the cavity at the third port could be regulated [3]. At most as much as 1.6 MW of power was sent to the cavity, implying an energy gain of 6.1 MeV for the electrons. This means operation at a maximum field surface strength of 1.17 Kilpatrick field limit. At this field strength hardly any voltage breakdowns occurred and no sign of multipactoring was observed.

The TEUFEL cavity

The fabrication of the TEUFEL cavity was done similarly as the RTME cavity. Table 2 lists some characteristics of the TEUFEL cavity [4].

Due to the high peak currents in the cavity the structure will operate under high beam loading conditions. Therefore the coupling ratio is relatively high, $\beta = 6.7$. The precise beam current to be accelerated in the microtron is not known yet. The generator and reflected power in dependence of the macro pulse current

<table>
<thead>
<tr>
<th>Table 2: Accelerating cavity parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>resonant frequency (MHz)</td>
</tr>
<tr>
<td>stopband (MHz)</td>
</tr>
<tr>
<td>accelerating voltage (MV)</td>
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<tr>
<td>coupling coefficient (%)</td>
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<tr>
<td>direct coupling coefficient (%)</td>
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<tr>
<td>loaded quality factor</td>
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<tr>
<td>coupling ratio $\beta$</td>
</tr>
<tr>
<td>cavity length (m)</td>
</tr>
<tr>
<td>eff. shunt impedance (MΩ/m)</td>
</tr>
<tr>
<td>dissipated power (MW)</td>
</tr>
</tbody>
</table>

is depicted in fig. 3. This was calculated with formula[5]

$$r = \frac{(1 + p - \beta)^2}{4\beta} + \frac{(1 + \beta)^2}{4\beta} \left( \tan \phi - \tan \psi_0 \right)^2,$$  \hspace{1cm} (1)

where $r$ is the normalized reflected power (normalized w.r.t. the wall losses), $p$ is the normalized beam power, $\tan \psi = -2Q_0(\omega - \omega_0)/\omega_0$, $\tan \psi_0 = -p \tan \phi/(1 + \beta)$, $\omega$ is the RF frequency and $\phi$ is the accelerating phase.

The ESS linac

The proposed lay-out of the linac of the European Spallation Source (ESS) project [6] has two front ends, each with a H-source (70 mA, 50 kV, 10% d.c.), low energy beam transport, an RFQ, a beam chopper and a second RFQ. Funneling is at 5 MeV. A drift tube linac (DTL) operating at 350 MHz accelerates the beam up to 70 MeV. In the reference design a 700 MHz normal conducting side coupled cavity linac (CCL) further accelerates the beam to 1.334 GeV to feed the rings [7].

In the CCL a single 2 MW klystron will feed 2 tanks connected via a bridge coupler. The tank length is determined by limiting the peak power per tank to 0.75 MW. It then varies from 1.27 (16 cells at 70 MeV) to 1.95 m (10 cells at 1.334 GeV), short enough to allow constant cell length in one tank (the phase slip per tank is 4 deg.). The intertank gaps have a length of $5/2\beta/\lambda$.
and \(3/2 \beta/\lambda\). Over the shorter gap the two tanks are connected via a bridge coupler.

In the design of the CCL first the shunt impedance and the transit time of the individual cavities is maximised. Various parameters determining the shape of a cell are of importance. The shunt impedance increases with decreasing bore hole radius, web thickness between cells and nose cone thickness.

Fig. 4 depicts the values for the shunt impedance as optimised with Superfish. It is reasonable to lower this value by 20% to account for the losses due to the coupling slots between accelerating and coupling cells and manufacturing imperfections. In previous designs of long side coupled CCL’s the outer diameter of the cells has been kept constant in order to minimise fabrication costs. With modern machining techniques, as programmable lathes, this is no longer necessary. The extra costs due to the varying outer diameter will not imply a significant cost increase. The diameter will be kept constant within a single tank.

For the calculation of the cell geometries we have the availability of the accurate 2D code Superfish and the less accurate 3D code Mafia. For the calculation of the coupling coefficient between the accelerating and coupling cells we need accurate 3D results. Therefore for this calculation the combination of the codes Superfish and Mafia has been used as described in ref. [8]. By varying the offset of the symmetry axis of the coupling cells to the symmetry axis of the accelerating cells the coupling coefficient can be varied between 2 and 8%.

Due to the varying length of the bridge couplers a number of higher order modes in these bridge couplers are within the passband of the accelerating tanks [9]. At lower energies the \(\text{TE}_{111}\) mode crosses the passband. This mode can easily be expelled from the passband by placing two round disks with a diameter of about half the coupler diameter at the end of the coupler at the locations where the electric field is maximum. At higher energies the \(\text{TE}_{112}\) mode crosses the passband. This mode is expelled from the passband by placing two rings in the coupler where the amplitude of the \(\text{TE}_{112}\) mode is maximum. The rings are large enough to expel the perturbing mode from the passband, but small enough to assure that the resonator still operates as a single cell resonator. Mafia calculations on the combination of two accelerating cells that are connected via coupling cells to the bridge coupler show that the method works. One has to assure however that the shifted mode is well outside the passband to avoid mixing with one of the chain modes.

References

ELECTROMAGNETIC FIELDS IN PERIODIC LINEAR TRAVELLING-WAVE STRUCTURES

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Abstract

An analytical description of the electromagnetic field in a periodically disk-loaded circular waveguide is given. The field is expressed in terms of the waveguide modes. The main advantage of this approach is that each mode matches the boundary conditions in the empty waveguide. These modes have convenient orthogonality properties. First, a single diaphragm in the waveguide is considered and the reflection problem arising from one incident waveguide mode is solved with the mode-matching technique. Then a matrix eigenvalue equation is derived for the periodically loaded waveguide. The solution of this equation yields the dispersion curve for the structure and leads to the full field description for a given operating mode of the accelerator.

TM0n modes of a circular waveguide

A circular waveguide of radius \( b \), centered around the \( z \)-axis is considered. For the acceleration of particles in the disk-loaded waveguide, only the transverse magnetic (TM) modes of the electromagnetic field are of interest. A time dependence of \( e^{j\omega t} \) and a \( z \) dependence of \( e^{-\Gamma_n z} \) is assumed and substituted into Maxwell’s equations. The axially symmetric \( TM_{0n} \) mode solutions are:

\[
\begin{align*}
e_{zn} & = \pm \frac{\sqrt{2\alpha_n}}{b \Gamma_n} J_1(\alpha_n b) e^{\Gamma_n z}, \\
e_{rn} & = \frac{\sqrt{2}}{b J_1(\alpha_n b)} J_1(\alpha_n r) e^{\Gamma_n z}, \\
h_{\varphi n} & = \pm Y_n \phi_n e^{\Gamma_n z}, \\
\alpha_n^2 & = \Gamma_n^2 - \frac{\omega^2}{c^2}.
\end{align*}
\]

For the \( n \)th mode, the \( r \)-component of the electric field is \( e_{zn} \), the radial electric field- and azimuthal magnetic field components are \( e_{rn} \) and \( h_{\varphi n} \) respectively. The wave admittance \( Y_n = \frac{\phi_n}{\Gamma_n} \) and \( \alpha_n \) is the \( n \)th root of the Bessel function \( J_0(x) \). The functions \( \phi_n \) defined in equation (2) are orthonormal:

\[
\int_0^b \phi_n \phi_m r dr = \delta_{nm}.
\]

The mode-matching technique discussed in the next section makes use of this orthonormality. For linear travelling wave accelerating structures it is customary to choose the radius \( b \) and the frequency \( \omega \) in such a way that only the propagation constant \( \Gamma_1 \) is imaginary. All other \( \{\Gamma_n\} \) are real and represent attenuating modes.

*Corresponding author

Reflection from a single diaphragm

In the circular waveguide of radius \( b \), an infinitely thin diaphragm with a circular aperture of radius \( a \) is placed at \( z = 0 \), see Fig. 1.

\[
\begin{align*}
& \rightarrow a_m \quad \rightarrow a_m \quad \rightarrow a_m \\
& \rightarrow 0 \quad \rightarrow 0 \quad \rightarrow 0
\end{align*}
\]

Figure 1: reflection at a diaphragm

The coefficients of the incident modes are \( a_{im} \) so a general incident field is given by:

\[
\sum_{m=1}^{\infty} a_{im} \phi_m e^{-\Gamma_m z}.
\]

Here, the reflection problem is solved for one incident propagating mode: \( a_{11} = 1 \) and all other \( a_{im} \) are zero. At the diaphragm, there will be an infinite number of reflected and transmitted modes with coefficients \( a_{rn} \) and \( a'_{rn} \) respectively, because at \( z = 0 \) a linear combination of all the modes is needed to satisfy the boundary conditions at the diaphragm. The total radial electric field \( E_r \) and azimuthal magnetic field \( H_\varphi \) are:

For \( z < 0 \):

\[
E_r = \phi_1 e^{-\Gamma_1 z} + \sum_{m=1}^{\infty} a_{rn} \phi_m e^{\Gamma_m z},
\]

\[
H_\varphi = Y_1 \phi_1 e^{-\Gamma_1 z} - \sum_{m=1}^{\infty} Y_m a_{rn} \phi_m e^{\Gamma_m z}.
\]

For \( z > 0 \):

\[
E'_r = \sum_{m=1}^{\infty} a'_{rn} \phi_m e^{-\Gamma_m z},
\]

\[
H'_\varphi = \sum_{m=1}^{\infty} Y_m a'_{rn} \phi_m e^{-\Gamma_m z}.
\]

By using the boundary condition \( E_r = E'_r = 0 \) at the diaphragm for \( a < r < b \) and the continuity of the tangential field components in the aperture (\( z = 0 \)):

\( E_r = E'_r \) and \( H_\varphi = H'_\varphi \).
for $0 \leq r \leq a$, a matrix equation can be derived, whose solution yields the coefficients $a_{rm}$ and $a'_{rm}$. In the derivation, the orthonormality of the $\phi_n$ functions is used. This procedure is known as the mode-matching technique, see Masterman [1].

To obtain a matrix equation of finite size, the series of reflected and transmitted modes have to be truncated; therefore only a finite number of coefficients are calculated. Once the coefficients $a_{rm}$ and $a'_{rm}$ are found, the total field can be calculated at every position in the waveguide. The most important coefficients are $a_{r1}$ and $a'_{r1}$. These are better known as the reflection coefficient $R$ and transmission coefficient $T$. The coefficients are in general complex numbers, and as a measure for $R$, the susceptance $B$ is defined as:

$$ B = \frac{2iR}{1 + R} $$

(11)

$B$ is a real-valued quantity [2]. The susceptance $B$ has been calculated as a function of the frequency $\omega$, see Fig. 2. The solid line is calculated by using the mode-matching technique and the dashed line represents an approximation for the susceptance given by an analytical formula derived with the small-aperture theory [3]:

$$ B = \frac{3\pi J_1(\alpha_1) b^4 k}{2a^2} \frac{b^4}{a^3}, $$

(12)

where $ik = \Gamma_1$. This formula was derived by assuming that the aperture diameter is small compared to the guide wavelength $\lambda_g = \frac{2\pi}{k}$. Calculations for smaller aperture radii show an even better agreement between the mode-matching solution and the approximation formula [2].

The periodic structure

In Fig. 3, a section of an infinitely long periodic structure is shown. The structure consists of an empty waveguide with radius $b$, containing diaphragms with aperture radius $a$, equally spaced at a distance $d$. It is assumed that the decaying modes excited at the diaphragms decrease to a negligible value at the neighbouring diaphragms and that only the reflected and transmitted propagating mode is of importance [2]. Once the coefficients for the back and forth propagating modes are found, the coefficients of the decaying modes can be calculated from the single-diaphragm theory discussed in the previous section.

![Figure 3: A section of the infinitely long periodic structure.](image)

The radial electric field of the propagating modes is:

For $-d < z < 0$:

$$ E_r^1 = a'_1\phi_1e^{-ikz} + b'_1\phi_1e^{ikz}. $$

(13)

For $0 < z < d$:

$$ E_r^2 = a'_2\phi_1e^{-ikz} + b'_2\phi_1e^{ikz}. $$

(14)

Similar equations can be found for the azimuthal magnetic field. In the expression for $E_r^1$, the term $a'_1\phi_1e^{-ikz}$ represents the field of the mode propagating in the positive $z$-direction. When $a'_1e^{-ikz}$ is seen as an effective coefficient for this mode, the coefficient at the diaphragm ($z = 0$) is $a'_1$, see Fig. 3. The coefficient at $z = -\frac{d}{2}$ is called $a_1$ and is given by:

$$ a_1 = a'_1e^{ik\frac{d}{2}}. $$

(15)

The other coefficients are defined in a similar way. The coefficients $a'_1$ and $b'_1$ are linked to $a_2$ and $b_2$ in the following way:

$$ a'_2 = Rb'_2 + Ta'_1, $$

(16)

$$ b'_1 = Ra'_1 + Tb'_2. $$

(17)

By using equations (16) and (17) together with equation (15) and similar equations for the other coefficients, a transfer matrix can be found which connects the coefficients $a_1$ and $b_1$ at $z = -\frac{d}{2}$ with the coefficients $a_2$ and $b_2$ at $z = \frac{d}{2}$:

$$ \begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \begin{bmatrix} \frac{1}{T}e^{ik\frac{d}{2}} & \frac{-R}{T} \\ \frac{R}{T} & (T - \frac{R^2}{T})e^{-ik\frac{d}{2}} \end{bmatrix} \begin{bmatrix} a_2 \\ b_2 \end{bmatrix}. $$

(18)

The Floquet theorem, see Collin [3], links the fields at position $z = -\frac{d}{2}$ to the fields at position $z = \frac{d}{2}$:

$$ \begin{bmatrix} a_2 \\ b_2 \end{bmatrix} = e^{-i\beta d} \begin{bmatrix} a_1 \\ b_1 \end{bmatrix}, $$

(19)

where $\beta d = \phi$ is the phase shift per cell. With this equation, a phase velocity can be defined, because at the time $\omega t = \beta d$ the...
fields at \( z + d \) are the same as the fields at position \( z \) for \( t = 0 \). This gives a phase-velocity:

\[ v_p = \frac{\omega}{d} \]  

(20)

By combining equations (18) and (19), a matrix eigenvalue equation can be derived, which has the characteristic equation:

\[ \cos \beta d = \cos kd - \frac{B}{2} \sin kd. \]  

(21)

With \( B \) the susceptance. From equation (21) it can be observed that the phase shift per cell \( \phi = \beta d \) can also be negative, which yields a solution for waves travelling in the negative \( z \)-direction.

Since \( B \) has been calculated as a function of \( \omega \) and \( k \) is also known as a function of \( \omega \) from equation (4), the phase shift per cell \( \phi \) can be calculated as a function of \( \omega \), see Fig. 4. This figure was made using the parameters of the periodic structure of a 10 MeV linear travelling-wave electron accelerator with an operation mode \( \phi = \frac{2\pi}{3} \). From Fig. 4, the frequency of this \( \frac{2\pi}{3} \) mode can be deduced. Once the frequency has been found, the eigenvalue problem can be solved and the coefficients of the propagating modes are obtained. With these, the coefficients of the decaying modes can be calculated by using the single diaphragm theory. For a phase shift of \( \frac{2\pi}{3} \) per cell, three cells are needed for the field description. Figure 5 shows the total longitudinal electric field on the \( z \)-axis in the three cells. The dashed line represents the field calculated from the Fourier coefficients of the \( \frac{2\pi}{3} \) mode given by the computer code Superfish [4].

Figure 4: The frequency \( \omega \) as a function of the phase shift \( \phi \) per cell, using \( a \approx 10 \text{ mm} \), \( b \approx 39 \text{ mm} \) and \( d \approx 33.33 \text{ mm} \).

Figure 5: The \( E_z \)-field on the axis for the \( \frac{2\pi}{3} \) mode. The solid line is the field calculated with the theory and the dashed line represents the field calculated with Superfish.

To obtain more accurate results, the theory could be extended to include diaphragms of finite thickness [2] [5] and also to a description of aperiodic structures [6], which is important for the design of low-energy travelling-wave linacs.

**References**


**Concluding remarks**

The empty waveguide modes are a useful tool for the description of the electromagnetic field in periodically disk-loaded waveguides. With the mode-matching technique, the reflection of waves from an infinitely thin diaphragm is described accurately. The dispersion curve of the infinitely long periodic structure can be calculated and the calculated fields for a given frequency \( \omega \) agree reasonably well with the fields calculated by Superfish.
THE 75 MeV RACETRACK MICROTRON EINDHOVEN

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Abstract

The 10–75 MeV Racetrack Microtron Eindhoven (RTME) is designed to serve as injector for the electron storage ring EURERPE. In RTME electrons are injected at 10 MeV by a traveling wave linac. The microtron’s 5 MeV standing wave cavity, which is synchronized with the linac, accelerates the electrons 13 times. The main RTME magnets are two-sector magnets, which are tilted in their median planes, to provide strong focusing forces for optimal electron optical properties. Closed orbit conditions are fulfilled with the help of small correction dipoles located in the microtron drift space; these dipoles are adjusted on the basis of beam position measurements. Isochronous acceleration is accomplished by position and phase measurements. An elaborate diagnostic system will be used for efficient commissioning of the combination of the 10 MeV linac and RTME.

Basic Design

The design of the microtron is basically dictated by the two resonance conditions. First, the revolution time of the first orbit, \( t_1 \), is an integer multiple, \( \mu \), of the RF-period \( 1/f \) (\( t_1 = \mu / f \)). Second, each revolution time must exceed the preceding one by another multiple (\( \Delta t = t_n - t_{n-1} = \nu / f \)). From these resonance conditions two basic relations for a racetrack microtron are derived:

\[
E_r = \left( \frac{\nu}{\mu - \nu - 2L/\lambda} \right) E_{inj},
\]

and

\[
B_r = \frac{2\pi f E_r}{ec^2} \nu,
\]

where \( \lambda = c/f \), \( E_{inj} \) is the injection energy, \( L \) is the field-free region between the magnets and \( B_r \) is the resonant or isochronous magnetic field, corresponding to the energy gain per turn, \( E_r \). The maximum energy is given by \( NE_r + E_{inj} \), with \( N \) the number of cavity passages.

The RF-frequency of the RTME cavity, \( f \), must be the same as the RF-frequency of the 10 MeV linac. The mode number, \( \nu \), and the number of orbits, \( N \), should be as small as possible to maximize the phase acceptance and to minimize phase errors due to imperfections of the construction [3]. The field-free region must be large enough to place the microtron’s cavity. As we want to use normal conducting magnets, the magnetic field strength in the air gaps is limited by the maximum field strength in the iron (about 2 T for ordinary steel). The basic parameters that have been chosen for RTME are summarized in table 1.

<table>
<thead>
<tr>
<th>Basic microtron parameters</th>
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<tbody>
<tr>
<td>Kinetic energy at injection [MeV]</td>
</tr>
<tr>
<td>Kinetic energy at extraction [MeV]</td>
</tr>
<tr>
<td>Energy gain per turn [MeV]</td>
</tr>
<tr>
<td>Number of orbits</td>
</tr>
<tr>
<td>RF-frequency [MHz]</td>
</tr>
<tr>
<td>Resonant magnetic field [T]</td>
</tr>
<tr>
<td>Mode number</td>
</tr>
<tr>
<td>Mode number ( \nu )</td>
</tr>
<tr>
<td>Distance between magnets [m]</td>
</tr>
</tbody>
</table>

Two-Sector Bending Magnets

The main bending magnets of RTME have two magnetic field sectors to provide strong focusing forces. Sector 1 and 2 have magnetic field strengths of \( B_L \) and \( B_H = aB_L (a > 1) \), respectively. The trajectories in the bending magnets consist of two circular arcs, defined by their centres \( M_1 \) and \( M_2 \), radii \( \rho \) and \( \rho/a \).
and angles $2\Theta$ and $(\pi - 2\Theta)$, respectively (see figure 2). The tilt angle, $\tau$, is retrieved from geometrical considerations:

$$\tan \tau = \frac{\sin 2\Theta}{\frac{1}{\cos 2\Theta} - \cos 2\Theta}.$$  \hspace{1cm} (3)

The magnetic field $B_L$ is to be chosen:

$$B_L = \left( \frac{1}{a} + \frac{1}{\pi} \left( 1 - \frac{1}{a} \right) (2\Theta + \sin 2\Theta) \right) B_r,$$ \hspace{1cm} (4)

such that resonant acceleration is not violated.

![Two-sector magnets](image)

Figure 2: Two-sector magnets.

The parameters $a$ and $\Theta$, not prescribed so far, determine the focusing properties of RTME. Therefore, the transversal acceptance of RTME has been calculated for many combinations of $a$ and $\Theta$, where estimations for the fringing fields of the bending magnets with their field clamps have been taken into account [4]. Consequently, $a = 1.17$ and $\Theta = 45^\circ$ have been chosen, which give a horizontal and vertical acceptance of 40 mm-mrad and 10 mm-mrad, respectively. With eq.(3) this yields $\tau = 4.45^\circ$.

The racetrack microtron with two-sector bending magnets has been compared with a microtron with homogeneous magnets. For both types of microtrons the trajectories in the horizontal and vertical plane are plotted both for a parallel and a divergent beam at injection (see figure 3). The main difference is the periodicity of the betatron oscillations.

For the horizontal plane motion the tune of the two-sector option is 1.15 for the first and 1.07 for the final orbit. For the homogeneous option these numbers are 1.10 and 1.04, respectively. This leads to a smaller beam size in case of the two-sector magnets.

The stronger focusing would also lead to smaller vertical beam sizes if the defocusing of the fringing fields would be less. However, the fringing fields lead to a blow-up of the beam in the first turn (the trace of the matrix is larger than 2 [5]). The tune of the two-sector option is 0.22 for the second and 0.30 for the final orbit. For the homogeneous option these numbers are 0.09 and 0.05, respectively.

![Trajectories](image)

Figure 3: Trajectories in the horizontal and vertical plane for a parallel beam and for a divergent beam at injection. Homogeneous option: (a) $x_0 = -1..+1$ mm, $x'_0 = 0$, (b) $x_0 = 0$, $x'_0 = -1..+1$ mrad, (c) $x_0 = -1..+1$ mm, $x'_0 = 0$, (d) $x_0 = 0$, $x'_0 = -1..+1$ mrad. Two-sector option: (e) $x_0 = -1..+1$ mm, $x'_0 = 0$, (f) $x_0 = 0$, $x'_0 = -1..+1$ mrad, (g) $x_0 = -1..+1$ mm, $x'_0 = 0$, (h) $x_0 = 0$, $x'_0 = -1..+1$ mrad [2].

**Misalignments and Magnetic Field Imperfections**

Because of the strong focusing forces provided by the main bending magnets RTME operates further from integer resonances than conventional microtrons. Therefore the sensitivity for misalignments of the bending magnets is smaller. It has been investigated that all alignment tolerances can be met by mechanical alignment except for the tilt angle, $\tau$.

Furthermore, the magnetic field maps of the main bending magnets have been measured. These field maps have been used for numerical orbit calculations, which have shown that it is not possible to obtain 180° bends for all orbits, simultaneously.

However, the effects of the alignment error of the tilt angle as well as the magnetic field imperfections can both be counteracted by an array of correction dipoles that is located in the field–free region halfway the two dipoles.

**Diagnostics**

An elaborate diagnostic system will be used for efficient commissioning of the combination of the 10 MeV linac and the 10–75 MeV racetrack microtron [6]. The commissioning will take place in two stages.

In the first stage the cavity will be replaced by a temporary beamline with a quadrupole and an OTR-set-up, which are used to measure the shape of transversal emittances [7]. Consequently, the emittance of the injected beam can be matched.
to the calculated acceptance of the microtron by adjusting the quadrupoles in the beam guiding system between the 10 MeV linac and RTME [8].

In the second stage the combination of the linac and RTME will further be assembled. Then the energy of the injected electrons, the cavity potential and the phase difference between the accelerating voltage of the linac and the cavity are adjusted. The energy of the beam is measured by means of the left RTME bending magnet, see figure 4. This is done for several different positions of the phase-shifter, which determines the phase difference of the accelerating voltage between the linac and the RTME cavity. Consequently, the energy will appear as a sine-like function of the position of the phase-shifter:

\[ E = E_{inj} + E_{cav} \cos \phi, \]

(5)

where \( E_{inj} \) is the energy of the injected beam, \( E_{cav} \) is the cavity potential and \( \phi \) is the phase difference between linac and cavity. The mean of this function is the injection energy; the amplitude of the harmonic part is the cavity potential. Further, the measurement yields a calibration for the phase-shifter.

In the microtron many stripline beam position monitors (BPM's) are used to adjust the array of correction dipoles discussed in the previous section [9]. A phase-probe measures the phase difference between the cavity voltage and the first harmonic of the electron bunches in the field-free region of the microtron. This phase-probe can be placed in each of the twelve orbits. The phase-measurements as well as the beam position-measurements are used to optimize the adjustable microtron parameters.

References


Figure 4: Left-hand RTME magnet used as spectrometer.
OPERATIONAL STATUS OF PLS 2-GeV ELECTRON LINAC

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Abstract

The PLS 2-GeV electron linac at the Pohang Accelerator Laboratory (PAL) has been served as a full energy injector to the storage ring called the Pohang Light Source (PLS) since September 1994. The linac uses eleven 80-MW klystrons driven by 200-MW modulators. There are 42 constant gradient accelerating sections and 6 quadrupole triplets. During the period from September 1994 to December 1995, the accumulated beam operation exceeded 4,000 hours. However, the average operation time of individual klystron reached to 17,200 hours as of December 1995. This time was counted after the installation of individual klystron starting from November 1992. We have lost one klystron which was the oldest one placed at the module #2 during the summer maintenance period in 1995. The expected beam operation in 1996 is about 5,000 hours. We report the current status of the linac and several upgrades - mostly computer control system and beam diagnostics - based on our operational experiences achieved during the commissioning and normal operations.

Introduction

The PLS 2-GeV linac was completed at the end of June 1994 as a full energy injector to the storage ring. The PLS, a third generation synchrotron radiation source, is designed to serve as a low emittance light source for various research such as basic science, applied science, and industrial and medical applications [1]. The 2-GeV linac consists of 11 klystrons and modulators, 10 pulse compressors, and 42 accelerating sections including those for the preinjector.

The electron beam is generated from the thermionic e-gun applied with DC 80 kV. The pulse length of the electron beam is 1-ns and its repetition rate is 10 Hz. Electron beams from the e-gun are then entered to the bunching system which consists of a prebuncher and a buncher. The prebuncher is a re-entrant type, standing-wave cavity, and the buncher is a traveling structure with four cavities including the input and output coupler cavities. The bunched beam is then accelerated to 2-GeV by passing through 42 accelerating sections. The accelerating section has a SLAC-type constant gradient structure with $2\pi/3$ operating mode. Its length is 3.072 m. The RF frequency used is 2,856 MHz.

In order to obtain 2-GeV beam with 42 accelerating sections, the accelerating gradient of the linac should be at least 15.5 MV/m. If we take one or two klystrons as stand-by, this number is increased to 17.5 or 19.5 MV/m, respectively. In order to achieve this requirement, we adopt high power klystrons of 80-MW maximum output and SLAC-type pulse compressors with $TE_{015}$ operation mode. In addition, the RF pulse length should be at least 4 μs for a higher energy multiplication factor from pulse compressor cavities. Major parameters of the PLS linac are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Major parameters of the PLS linac</th>
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<tbody>
<tr>
<td>Beam Energy</td>
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<tr>
<td>Machine Length</td>
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<tr>
<td>Energy Spread</td>
</tr>
<tr>
<td>E-Gun</td>
</tr>
<tr>
<td>RF frequency</td>
</tr>
<tr>
<td>Length of Accelerating Section</td>
</tr>
<tr>
<td>Operating Mode</td>
</tr>
<tr>
<td>Repetition Rate</td>
</tr>
<tr>
<td>No. of Klystrons</td>
</tr>
<tr>
<td>No. of Pulse Compressors</td>
</tr>
<tr>
<td>No. of Accelerating Sections</td>
</tr>
<tr>
<td>No. of Quadrupole Triplets</td>
</tr>
<tr>
<td>Beam Exit</td>
</tr>
<tr>
<td>2 GeV</td>
</tr>
<tr>
<td>150 m</td>
</tr>
<tr>
<td>± 0.3 % or less</td>
</tr>
<tr>
<td>&gt; 2 A / 1, 2, or 40 ns</td>
</tr>
<tr>
<td>2,856 MHz</td>
</tr>
<tr>
<td>3.072 m</td>
</tr>
<tr>
<td>2π/3</td>
</tr>
<tr>
<td>60 Hz (max.)</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>42</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>0.1, 1, 2 GeV</td>
</tr>
</tbody>
</table>

The beam transport line (BTL) which connects the storage ring and the linac consists of 5 bending magnets, 24 quadrupoles, 5 vertical correctors and 8 horizontal correctors. The 2-GeV electron beam leaving the linac is bent 20 degrees horizontally by two bending magnets toward the injection area of the storage ring. After the beam travels about 65-m from the end of the linac, the beam is bent upward to the beam plane of storage ring which is 6-m higher than that of the linac.

Subsystems of the PLS 2-GeV Linac

The PLS 2-GeV linac consists of several subsystems such as klystron-modulator, vacuum, control, and cooling system. Here, we report the performance of individual subsystems.

Klystron and Modulator System

The klystron-modulator system provides high-power microwave to accelerate electron beams. One module of the klystron-modulator system consists of a s-band (2,856-MHz) klystron of which maximum output is 80-MW and a matching modulator which supplies 200-MW peak power with a repetition rate of maximum 60-Hz. The pulse length of the modulator output is about 7 μs [2].

Run-time data of the klystron tube are shown in Fig. 1. The first failure in eleven klystrons using in the linac occurred at #2 klystron after 18,800-hour operation time. The cause of
this failure was a faulty lead connector of the focusing solenoid. Even though this unit is not able to provide designed output, it is still being used in the test lab as an RF source to the resonant ring. Thyatron tubes installed in the PLS 200-MW modulator are originally F-303 type from ITT. We had a few problems such as a high infant failure (which occurs in less than 500 hours of run-time), frequent self-firing phenomena, and premature turn-off symptoms. However, six tubes out of 11 are still running, and they reached over 18,000 hours of run-time. The most frequent failure of the klystron-modulator system comes from thyatron switch tubes.

General failures occurred during the linac operation are summarized in Fig. 2.

**Accumulated HV Run Time Statistics**

![Accumulated HV Run Time Statistics](image)

**Fig.1:** Accumulated run time of klystrons.

**RF Drive System**

There are three parts in the drive system; the signal source to drive the first klystron, the main drive line to transmit the drive power to remaining 10 klystrons, and IPA (isolator, phase shifter, and attenuator) units to adjust the power level and the phase angle of the drive power to the klystron. A high precision synthesized signal generator is used as a master oscillator. The frequency stability of the master oscillator is \(5 \times 10^{-9}/\text{day}\). A solid-state amplifier boosts the input RF power of 1-W CW coming from the PSK (phase shift key) unit to the maximum 720-W. The PSK is a phase reverse unit required to the pulse compressor.

The main drive line is an \(1\&5/8''\) coaxial line. It transmits the 2,856 MHz RF power from the cross coupler waveguide located in the preinjector waveguide system to the remaining klystrons. Approximately, 120-kW RF power is supplied to the main drive line. The output power of each directional coupler located at about 14 meter interval is in the range of 2 to 3 kW.

The IPA unit provides an isolation of the main drive signal from the reflected drive signal at each klystron as well as best conditions of the drive RF signal in phase and amplitude. The IPA unit consists of an RF unit and a controller unit. There are two key components in the RF unit; a phase shifter and an attenuator. The phase shifter is a rotary-field type. It is digitally controllable from 0° to 360° with a step of 1.4°. The attenuation of the attenuator is variable from 0 to 20dB and it is controlled by a DC motor. The remote control of this unit is made by a VME computer system.

**Vacuum System**

The vacuum system of the PLS linac maintains the average pressure at about \(2.0 \times 10^{-8}\) Torr under high-power microwave loading of average 54 MW peak power per module with a pulse width of 4.1 μs and a repetition rate of 30 Hz. The base pressure is \(1.0 \times 10^{-8}\) Torr without 45°C cooling water supply. With cooling water, this pressure increases up to \(1.8 \times 10^{-8}\) Torr. The outgassing rate of this system has decreased from \(2.0 \times 10^{-12}\) Torr-l/sec-cm² at the end of 1994 to \(9.5 \times 10^{-13}\) Torr-l/sec-cm² at present.

**Control System**

The linac control system is based on the VME realtime control system linked with the SUN UNIX workstation as an operator interface to the linac. There are two important features added after the commissioning of the linac. During the summer maintenance period of 1995, a feature of automatic report generation was added. Since then, most of the activities done by duty operators can be recorded in the report. As an additional beam diagnostic system, 53 beam loss monitors are installed and linked to the main control system [3].

**Cooling System**

The cooling system for precision temperature control of \(45 \pm 0.2°C\) is in operation with the total flow rate of 180 m³/hr and the pump output pressure of 3.5 kg/cm². The temperature
of accelerating sections and pulse compressors are precisely controlled by this system. The normal water cooling system of about 32°C for solenoids and other conventional components is maintained with the total flow rate of 85 m³/hr and the pump output pressure of 6.0 kgc/m².

The heat dissipation rate for normal operation is about 225,000 kcal/hr, which is about 85% of the design capacity of the heat exchanger.

Operation Results

As an injector to the storage ring, primary duty of the PLS linac is to provide stable beams with an energy of 2-GeV precisely. The beam energy depends on the RF power and the phase between RF and the electron bunches. The RF phase influences not only the beam energy but also the beam qualities such as the energy spread, the beam emittance and the current delivery ratio. The RF phase of high power is controlled by adjusting the RF phase of the driving signal for the klystron by the IPA system. Either the prebuncher or the buncher influences the beam quality significantly. Throughout the normal operation in 1995 - 1996 period, we improve the relation between the RF phase and electron bunches. Thus, we can get same 2-GeV beams with less RF power [4]. This condition reduces the required high voltage in the modulator system and it provides more stable beam operations.

The operational parameters of the PLS linac and the BTL are summarized in Table 2.

<table>
<thead>
<tr>
<th>Table 2 : Operation parameters of the PLS linac</th>
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<tbody>
<tr>
<td>Normal Beam Energy</td>
</tr>
<tr>
<td>Accumulated Operation Time</td>
</tr>
<tr>
<td>Accelerating Gradient</td>
</tr>
<tr>
<td>Beam Pulse Length</td>
</tr>
<tr>
<td>E-Gun High Voltage</td>
</tr>
<tr>
<td>Energy Spread</td>
</tr>
<tr>
<td>Klystron Output Power</td>
</tr>
<tr>
<td>Pulse Compressor Gain Factor</td>
</tr>
<tr>
<td>Beam Delivery Rate BTL</td>
</tr>
</tbody>
</table>

There are 13 beam-current-monitors (BCM) and 12 beam profile monitors (BPRM) for the beam diagnostics in the PLS linac and the BTL. There are also two beam analyzing stations in the linac. The delivery ratio of the beam current depends mainly on the beam optics. This ratio was less than 20% in the linac and 60% in the BTL at the early stage of the operation. Currently, it becomes more than 60% in the linac and 90% in the BTL by improving the optics.

There are 42 beam loss monitors in the linac and 11 units in the BTL to measure the loss of electrons during the acceleration. The loss monitor consists of an air dielectric coaxial cable placed inside an aluminum case. A voltage of 500-V DC is applied between the inner and the outer conductor to detect the particles ionized by radiation resulting from the lost electrons. The ionized particles are accumulated for about 100 ms.

Summary and Future Plans

The PLS 2-GeV linac is served as a full energy injector to the storage ring of the Pohang Light Source (PLS) since September 1, 1994. The beam operation was carried out for 192 days in 1995 and 82 days in the first half of 1996. The total operation time is about 7,000 hours by the end of June 1996. The average availability of RF system was about 85% in the first half of 1995, and it increased to 90% in the latter half of the year by improving the protection circuits. The accumulated operation times of most klystrons reached over 20,000 hours.

Most of vacuum troubles occurred at the high power dummy loads because of severe outgassing. Also, troubles occurred occasionally at the ceramic windows of the pulse compressors due to the vacuum leak from very small crack. This problem was normally cured by applying the vacuum seal.

We have a plan to install one more klystron and four accelerating sections just after the end of the linac. At present, this section is a part of BTL. This extra section will provide the electron beam to 2.5-GeV. Also, we are planning to replace current high power loads to newer and better performed ones.

Acknowledgments

We are grateful to thank to the team of the linac division for their endless efforts to improve the performance of the linac operation. This work is supported by Ministry of Science and Technology and Pohang Iron & Steel Company.

References

CURRENT STATUS OF CONTROL SYSTEM FOR PLS 2-GeV LINAC

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Abstract

The PLS 2-GeV electron linac at the Pohang Accelerator Laboratory (PAL) has been served as a full energy injector to the storage ring called the Pohang Light Source (PLS) since September 1994. The linac uses eleven 80-MW klystrons driven by 200-MW modulators. There are 42 constant gradient accelerating sections and 6 quadrupole triplets. A graphic-based real-time control system has been developed and used for the commissioning and the normal operation since 1994. The system has three layers of hierarchy; operator interface for machine control, device interface for data acquisition, and the supervisory layer which provides effective data processing and networking. After providing basic skeleton of machine control system, we added several features such as modulator control windows and RF signal display windows. Also, for beam diagnostics, beam loss monitors are added in the linac and the beam transport line. In this paper, we report the current status of the control system and upgrades during 1995-1996 period.

Introduction

Pohang Accelerator Laboratory (PAL) has completed the 2-GeV synchrotron radiation source named Pohang Light Source (PLS) by the end of 1994 [1]. The PLS consists of a 2-GeV electron linear accelerator as a full energy injector and a 2-GeV storage ring. The PLS project was started from April 1988, and its construction was completed in December 1994. After the successful commissioning of the linac and the storage ring, the PLS has started its service as a low-emittance light source from September 1, 1995 for various research areas such as material science, surface physics, biology, and semiconductor applications using X-ray lithography.

When the PLS opened to the public service, there were only two beamlines; one for vacuum ultra-violet (VUV) application and one for X-ray application. However, by the end of August 1996, there are four more beamlines constructed; one NIM (normal incident monochromator) beamline, one XAFS beamline, one lithography beamline belong to the company named LG electronics, and one white beamline. The first undulator beamline will be ready in 1997. The number of beamlines will be increased drastically in next several years.

The 2-GeV linac employs 11 klystrons and modulators in the ground floor and 42 accelerating sections in the tunnel. Its overall length is 150-m and the average accelerating gradient is 15 ~ 20 MV/m. In order to achieve such a high accelerating gradient, 80-MW klystron and SLAC-type RF pulse compressor are used. There are also many magnet power supplies (MPS), vacuum monitors, and various beam diagnostics devices. The circumference of the storage ring is 280.56-m. The storage ring lattice is based on the triple-bend-achromat (TBA) with a 12-fold symmetry. There are 36 bending magnets, 144 quadrupoles, and 48 sextupoles. There are three re-entrant type RF cavities with 60-kW klystron per each cavity. In order to correct the beam orbit, there are 108 beam position monitors and corrector magnets around the storage ring. There is a 96-m long beam transport line (BTL) to connect the linac and the storage ring.

Even though the control systems of the linac and the storage ring are developed by different teams, there are three common factors. Each system has a three-level hierarchy structure and a VME-based system with OS-9 operating system. And all custom-made codes are written by C-language.

The linac control system includes the main linac and the whole beam transport line (BTL) except the Lambertson DC septum magnet which is located at the injection straight section of the storage ring. There are also two beam analyzing stations (BAS) to analyze the properties of electron beams up to 100-MeV and 2-GeV, respectively. The structure of control system was finalized by January 1993. At this stage, it was decided that we would use commercial products for all hardware such as CPU boards and I/O boards and concentrate our effort to develop necessary software with the help of commercial development toolkit named RTworks. Before starting the major work, we made the signal list and the design manual for the linac control system [2,3]. The actual S/W development started from May, 1993, and the initial phase of the control system was completed by the end of June, 1994. It played an important role during the commissioning of the 2-GeV linac which started at the beginning of January, 1994.

At present, the linac control system provides a reliable function in daily operations [4]. However, it is obvious that the linac control system is continuously being upgraded based on operational experiences and diagnostic equipment added.
Hierarchy of Linac Control System

Our aim for the linac control system is to provide a reliable, fast-acting, distributed real-time system. There are three layers in the control hierarchy; operator interface layer, data process layer, and data acquisition layer. Last two layers are based on the VME realtime system. There are also three subsystems divided into their own functional characteristics; modulators and microwave system (MK), magnet power supplies (MG), and beam diagnostic (BM) subsystems. Several special systems are connected directly to the data process layer. These layers are linked with four independent eternets.

Device Interface Computer (DIC)

This layer is directly connected to the individual devices to be controlled or monitored. The local computer connected to the individual devices is called the device interface computer (DIC). There are eleven units for the modulator and microwave control systems (MK), three units for magnet power supplies (MG). There are also two units of beam profile monitors and other diagnostic equipment in the linac and the BTL. All DICs are located in the klystron gallery.

Each DIC is consisted of an ELTEC E-16 CPU board, a 14" EGA graphic monitor, a draw-type keyboard, and several I/O boards mounted on the standard 19" rack. The E-16 board includes a Motorola 68030 CPU, 4 MDRAM, an EGA compatible video port, and an ethernet port. There is an extra memory board with 4 MDRAM in each DIC. All of the I/O boards used in the VME system are commercially available. The operating system is OS-9 with the MGR graphic development tool. On-demand local computer control is available to all DICs. This feature is extremely useful for the local commissioning and testing of an individual device, especially 200-MW modulators. Each modulator is now controlled by its own DIC such as the self-recovery from various dynamic interlocks.

Supervisory Control Computer (SCC)

In order to avoid heavy work loads on the main computer, we divide the linac control system into three subsystems; modulators and microwave system (MK), magnet power supplies (MG), and beam diagnostics (BM). The role of SCCs is an intermediate data manager for the assigned subsystem. Thus, there are three units assigned to their own functions.

Each SCC unit consists of an ELTEC E-7 CPU board, a 19" monitor mounted on the sub-control console, a 3.5" floppy disk, a 900-MB hard disk, and a streaming tape backup system. The E-7 board has a Motorola 68040 CPU, 16 MDRAM, a workstation graphic board. And there are two ethernet ports in each SCC; one for the data acquisition layer and one for the operator interface layer.

All SCCs are installed in one standard 19" rack in the sub-control room which locates next to the main control room only separated by large glass windows.

Three more such units are installed in another standard rack in the same room. Even though the major role of these extra units is to develop the system software without disturbing the main control system, these can provide backup functions for the main SCCs in case of troubles.

Operator Interface Computer (OIC)

This is the main computer for the PLS linac control system. The OICs are actually one SUN-4 sparcstation and two X-terminals connected to this SUN workstation. They are located on the main console. A duplicated system is placed in the sub-control room. This is the backup system which is normally used for the development work along with backup SCCs. The operating system is UNIX, and RTworks is intensively used to optimize graphics and data handling between the UNIX system and the OS-9 system.

There is one more SUN-4 workstation in the main control room for physics-related researches. Accelerator physicists can develop various simulation codes and apply their results to real operations later.

Software

In parallel with the hardware structure, we use three layers in the S/W structure. Subsystems such as MK, MG, and BM are monitored and controlled by an individual task running on the appropriate layer. There are two important features in the linac control S/W; the client/server routines to exchange data and commands between layers, and the separation of monitor/control tasks. When the operator selects a command from an appropriate window, it sends down to the designated device via control client/server routines in the realtime system. The data collected by a given command returns to the operator's window through a separate route. The communication between layers is made by TCP/IP protocol.

Data Acquisition Layer

The major roles of the data acquisition task in DICs are as following; to store monitored data from individual devices to the designated buffer (m_buffer) regularly, and to send updated data to the SCC upon request. For the control command from the SCC, the corresponding control task sends data or messages to control individual device in realtime through proper I/O ports. Other important roles of the data acquisition task are to monitor any malfunction of
connected devices and to provide emergency cures if possible, and to report the status to the SCC.

**Data Processing Layer**

The major role of the data process task is to collect the updated data from attached DICs and to store them in the realtime database. These data are sent to the RTdaq running on the OIC upon requests made by the operator. Also a corresponding task sends control commands to the proper DIC in realtime. All the required application software are running in realtime in this layer including client/server routines for the ethernet communications. Every data in the linac operation are stored in the RAM area temporarily and hard/floppy disk for permanent records.

**Operator Interface Layer**

A commercial S/W package named RTworks is used to develop graphic-based operator interfaces. The RTworks is actually an integrated development toolkit for an optimum data handling between client/server systems. Using this toolkit, it is possible for one S/W engineer to develop all required operator interfaces for the linac control in a year.

The data received in the RTdaq from realtime CPUs are sent to the RTserver by inter-processing communications, and they are displayed in the monitoring windows by RThci routine. A command selected by a mouse action drawn by an operator is sent to the SCC through user defined processes.

There are several windows for operators to control and monitor individual system such as MPS, bunchers, IPAs (isolator, phase shifter, and attenuator to provide best microwave condition to electron beams), and modulators. Each window has a value display area and a control sub-window. All the control action can be made by selecting areas with a mouse or select items from pull-down menus. The main control window includes the status of 11 modulators and phase angles for IPAs. Subsystems such as magnet control and monitoring windows can be started by selecting proper commands from the pull-down menu.

**Upgraded Features and Future Plans**

As of the end of June 1994, most of the linac control system was completed [5]. It has been used for the commissioning to obtain 2-GeV beams and for the routine operations to provide beams to the storage ring being commissioned in 1995. Since then, there have been several features added in the linac control system.

During the summer maintenance period in 1995, a feature of the automatic report generation was added in the linac control system. So, duty operators can report activities carried out during their duty period. This report includes various setting values of magnet power supplies and phase angles and amplitudes of IPAs.

In April 1996, the control subsystem for beam loss monitors (BLM) were completed. Now, the BLM signals from 42 detectors in the linac and 11 detectors in the BTL are displayed in the main control window.

Signals from beam current monitors are about to ready to display in the main console. This work involves a fast signal processing due to the 1-ns pulse duration of the electron beam. At present, necessary electronics including fast sample/hold circuits for BCM are completed. Full tests of BCM electronics and data acquisition routines was also carried out in June 1996. However, due to the huge amount of digitized data coming from 13 BCMs, the current OIC is not adequate to handle these data properly. Thus, the main computer of OIC is required to upgrade to faster and larger one. This upgrade will be done in next year.

The timing system will be incorporated to the main control system after completing the optical communication circuit between the individual time delay unit located at the sub-control room and the corresponding modulator in the klystron gallery. At present, new optical network is installed but not tested yet. New timing system will be tested in 1997. There will also be a new e-gun control system.

**Acknowledgments**

We are grateful to thank to the team of linac operations, especially to M. G. Kim, K. W. Kim, N. S. Sung, H. S. Kang, and S. W. Kang for their valuable helps and suggestions in developing the linac control system. This work is supported by Ministry of Science and Technology and Pohang Iron & Steel Company.

**References**

KLYSTRON-MODULATOR SYSTEM AVAILABILITY OF PLS 2 GEV ELECTRON LINAC

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Abstract

PLS Linac has been injecting 2 GeV electron beams to the Pohang Light Source (PLS) storage ring since September 1994. PLS 2 GeV linac employs 11 sets of high power klystron-modulator (K&M) system for the main RF source for the beam acceleration. The klystron has rated output peak power of 80 MW at 4 microsec pulse width and at 60 pps. The matching modulator has 200 MW peak output power. The total accumulated high voltage run time of the oldest unit has reached beyond 23,000 hour and the sum of all the high voltage run time is approximately 230,000 hour as of May 1996. In this paper, we review overall system performance of the high-power K&M system. A special attention is paid on the analysis of all failures and troubles of the K&M system which affected the linac high power RF operations as well as beam injection operations for the period of 1994 to May 1996.

K&M System Performance

The key features of the K&M system design include the 3-phase SCR controlled AC-line power control, resonant charging of the PFN, resistive De-Qing, end-of-line clipper with thyrite disks, pulse transformer with 1:17 step-up turn ratio, and high power thyatron tube switching. The major operational parameters of the PLS-200-MW K&M system are listed in Table 1.

For the fault free stable operation of the system, the thyatron tube is one of the most important active components which require continuous maintenance and adjustments.

Table 1. Operational parameters of K&M systems.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak beam power</td>
<td>~150 MW (200 MW max.)</td>
</tr>
<tr>
<td>Pulse width</td>
<td>ESW 7.5μs, 4.4μs flat-top</td>
</tr>
<tr>
<td>Pulse rep. rate</td>
<td>30 pps (120 pps max.)</td>
</tr>
<tr>
<td>PFN impedance</td>
<td>2.64Ω (3% positive mismatch)</td>
</tr>
<tr>
<td>Voltage stabilization</td>
<td>SCR, DC feedback &amp; 5% De-Q'ing</td>
</tr>
<tr>
<td>Pulse transformer</td>
<td>1:17 (turn ratio), Lc=1.3μH, Cc=69nF</td>
</tr>
<tr>
<td>Thyatron switching loading</td>
<td>Heating factor: 46.8x10⁻⁹, 8.5 kA peak anode current</td>
</tr>
<tr>
<td>Klystron tube</td>
<td>Drive power: ~300 W, gain: ~53dB, peak power: 80/65 MW (currently running at 50 to 65 MW)</td>
</tr>
</tbody>
</table>

The thyatron tubes which meet the PLS-200-MW system specifications are listed in Table 2 together with their specifications. Three types of thyatron tubes, ITT/F-303, Litton/L-4888, and EEV/CX-1836A are installed in our system, and the performance evaluations are underway. This effort is initiated to improve the system from the frequent occurring faults (see Fig.3) caused by the irregular recovery action of the thyatrons, which strongly depends upon the reservoir control.

There are three types of system interlocks, namely dynamic, static, and personal protection interlocks. All the static fault activation is initiated by the relay logic circuit, and the dynamic faults which require a fast action response are activated using the electronic comparator circuit. When the system operation is interrupted by the static fault, it can be recovered either by the remote control computer or manual reset. However, we have been performing all manual resets till July 1995 for the purpose of the experience accumulation.
such as to find the type of troubles and system bugs which could provide ideas of the system improvement.

Table 2. Comparison of the thyatron tubes.

<table>
<thead>
<tr>
<th>ITEM</th>
<th>ITT F-303</th>
<th>Litton L-4888</th>
<th>EEV CX-1836A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater(Vₑ/A) max</td>
<td>6.6 / 80</td>
<td>6.7 / 90</td>
<td>6.6 / 90</td>
</tr>
<tr>
<td>Reservoir(Vₑ/A) max</td>
<td>6.0 / 20</td>
<td>5.5 / 40</td>
<td>6.6 / 7</td>
</tr>
<tr>
<td>Peak anode(kV/kA) for</td>
<td>50 / 15</td>
<td>50 / 10</td>
<td>50 / 10</td>
</tr>
<tr>
<td>Peak anode vol.(kV) inv</td>
<td>50</td>
<td>n/c</td>
<td>50</td>
</tr>
<tr>
<td>Avg. anode cur.(A) max</td>
<td>8</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>min DC anode vol.(kV)</td>
<td>2</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Heating factor(x10⁶) max</td>
<td>300</td>
<td>400</td>
<td>n/c</td>
</tr>
<tr>
<td>dI/dt(kA/µs) max</td>
<td>50</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Anode delay(µs) max</td>
<td>0.3</td>
<td>0.4</td>
<td>0.35</td>
</tr>
<tr>
<td>Trigger jitter(ns) max</td>
<td>2</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Fig. 1. Accumulated run times of the K&M systems.

The statistical analysis of the machine availability presented in this paper is applied to two different periods. One period is based on the operational method of the manual reset mode by the maintenance crew only for the period of September 1994 to May 1995. The other is based on automatic reset mode by the remote computer control for the period of May 1995 to May 1996. The major circuit change for the computer controlled reset mode is the CB trip interlock modification; instead of CB trip activates SCR gate hold and the soft start of the DC high voltage.

System Availability Statistics

Since the completion of the PLS 2 GeV linac installation in December 1993, all the K&M systems have been in operation continuously except scheduled short-term shut downs. Fig.1 shows the total accumulated times of klystron and thyatron heater operation, and the high voltage run. Sum of the high voltage run time of each modulator has reached over 230,000 hour, and the experience accumulated so far provides the valuable information for the stable operation. Fig. 2 shows the monthly failure and down time statistics for the period of September 1994 to May 1995 (manual reset) and the period of May 1995 to May 1996 (auto reset).

Machine availability analysis has been performed based on the data using the techniques described in detail in reference[3]. Fig.3 is the monthly availability and MTBF (mean time between failure) statistics of klystron-modulator system. The table 3. is the summary of the average fault analysis data. The MTBF calculated by dividing the sum of the accumulated modulator run time with the total fault count(MTBF=N*TO/FC). The MTTR(mean time to repair) is equal to the total down time divided by total fault counts (MTTR=TD/FC).

One can see in table 3, approximately 76% of the machine availability(A=1-MTTR*FC/TO) has been improved to approximately 96% by applying auto reset mode operation.
with the simple CB trip modification, which is also shown in Fig. 2 & 3. It indicates most of the system troubles are not so serious, and in many cases they are easily recoverable.

Fig. 4. Interlock status of klystron-modulator system for the period of September 1994 to May 1995.

Table 3. Fault analysis of klystron-modulator system for PLS.

<table>
<thead>
<tr>
<th>Item</th>
<th>94.9-95.5</th>
<th>95.5-96.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of modulators, N</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Spare no. of modulators</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Operation time(hr)(^1), TO</td>
<td>6000</td>
<td>7560</td>
</tr>
<tr>
<td>Total failure counts, FC</td>
<td>226</td>
<td>115</td>
</tr>
<tr>
<td>Total down time(hr)</td>
<td>1468</td>
<td>344</td>
</tr>
<tr>
<td>MTBF(hr)</td>
<td>26.5</td>
<td>65.7</td>
</tr>
<tr>
<td>MTTR(hr/failure count)</td>
<td>6.5</td>
<td>2.998</td>
</tr>
<tr>
<td>System availability, A</td>
<td>0.76</td>
<td>0.96</td>
</tr>
</tbody>
</table>

\(^1\) Operation time for the statistical analysis.

Fig. 4 shows the total systems static fault count data collected during the period of September 1994 to May 1995. Fig. 5 is the total system static fault count data collected for the period of Jun 1995 to May 1996. From Fig. 4 & 5 one can see the significant decrease in CB trip count by the CB trip modification and the apparent relative increase in klystron troubles as the accumulated run time increases.

Summary

It is approximately 2 years since the PLS 2 GeV linac has started its operation. We have analyzed the klystron-modulator systems performance record for the period. It is observed that the reliability of klystron is well over our expectations compared with other components in the modulators. The life time of thyatron tubes appears to be reasonable except the occurrence of infant failures. However, the major improvement is necessary for the reservoir control which is the main source of system troubles. The machine availability statistics of the K&M system for the manual reset mode is calculated to be approximately 76%. It appears to us that there are still lots of rooms for the improvement toward the availability more than 96% with proper choices of the protection circuits and the automatic reset mode. During the period of Jun 1995 to May 1996 we have modified our OCR (over current relay) interlock not to interrupt main CB but SCR gate with static fault action as an attempt to reduce major source of static fault. During the period no system damage has been occurred, and we have activated remote reset control in the case of static fault. Just one year old statistics shows an excellent system's availability of approximately 96%.

Fig. 5. Interlock status of klystron-modulator system for the period of Jun 1995 to May 1996. (1) CB trip, (2) klystron vacuum, (3) fan, (4) magnet flow low, (5) SCR ac over current, (6) magnet temp. high, (7) cooling temp., (8) thyatron heater, (9) triaxial cable, (10) klystron heater, (11) magnet current low, (12) EOLC, (13) core bias current low, (14) core bias current high, (15) key switch, (16) thyatron driver, (17) thyatron grid circuit, (18) replaced charging inductor, (19) replaced klystron, (20) replaced thyatron, (21) replaced MPS, (22) replaced ion pump controller, (23) PPN RC snubber, (24) De-Qing fault.

Acknowledgments

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References

CONCLUSIONS FROM THE LISA SUPERCONDUCTING LINAC EXPERIENCE

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Abstract

The commissioning of the experimental superconducting (SC) RF linac LISA (working at 4 K) has been completed and conclusions can be drawn regarding the performance of this low energy (25 MeV), high average power machine.

The illustration of the difficulties encountered in commissioning and operating this rather compact accelerator with few people can give suggestions for improvements to those interested in the application of such machines (as FEL drivers, gamma and neutron generators, etc) in a non specialized environment.

1. Introduction

The INFN Frascati National Laboratories (LNF) started the LISA project, concerning the construction of an SC-RF linac in 1988, in the mainframe of an effort to promote activities in the field of SC-RF technology applied to accelerators.

At the beginning of the '90s however INFN decided the construction of the DAFNE Phi-factory to become the first priority of the Laboratories, thereby moving RF-SC activities and the LISA project to a lower priority level. The construction of the machine, started at the end of 1989, was nevertheless completed in 1993.

LISA has been described in various conferences [1]. For ease of the reader we recall that the SC linac is composed of four independent cryostats, each housing a 4-cell 500 MHz cavity of the Desy-Hera design. We report the parameters of the machine in Table 1, where achieved and design values are shown. Question marks regard parameters that could not be measured for lack of specific instruments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Bunch length (mm)</td>
<td>?</td>
<td>2</td>
</tr>
<tr>
<td>Peak current (A)</td>
<td>?</td>
<td>5</td>
</tr>
<tr>
<td>Duty cycle (%)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Macropulse current (mA)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Invariant emittance (nmrd)</td>
<td>10^-5</td>
<td>10^-5</td>
</tr>
<tr>
<td>Energy spread</td>
<td>2 x 10^-3</td>
<td>2 x 10^-3</td>
</tr>
<tr>
<td>Micropulse frequency (MHz)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Macropulse frequency (Hz)</td>
<td>3</td>
<td>10</td>
</tr>
</tbody>
</table>

In the following two years the commissioning of LISA has been concluded with the limited forces of our small group (6 graduates and 3 technicians) and the support of external industries for maintenance and repairing of apparatus.

This has been possible thanks to the high degree of automation of the whole machine and to the easy use of the Apple Macintosh man-machine interface. This experience should encourage those who are doubtful about installing a SC linac in University or research Lab environment that cannot afford a numerous team of specialized personnel.

On the other hand, a limited number of operators implies a careful organization of shifts in order to keep the machine running for long periods, as is necessary for an efficient use. In fact, as it takes about three days to cool-down the cavities and one day to warm-up, to which are possibly to be added a couple of days to recover the cold state in case of a transient electrical power failure, it is evident that the running period should not be less than one month. This can be achieved if an efficient automatic system of He gas recovery is provided, so that permanent presence of experienced personnel on the site is not required. In our case, in the absence of such a system, the compressor had to be restarted by an operator in a few tens of minutes, otherwise the gas was lost in air through the exhaust valves. This fact limited the running periods of LISA to about two weeks, which resulted in a very lengthy and inefficient commissioning.

2. Commissioning of the linac

The most difficult problem we had to face during commissioning, and which ultimately limited the performance of the machine, was the presence of cavity vibrations in the cold machine, due to thermo-acoustic oscillations in the refrigerator-cryostat system. They seem to be mainly due to the close interconnection of the gas circuits of the cryostats through the common return line between valve box and refrigerator. In fact a relevant reduction of vibrations has been achieved by closing partially the gas return lines from the cryostats to the valve box, thus decoupling somehow the circuits [2]. In other similar structures (JAERI, Japan,) where each cryostat carries on top its small refrigerator, no such vibrations have been detected.

A centralized scheme like ours is therefore not to be recommended. One should at least decouple each cryostat from the system by a local phase separator.

Two of the cavities show much stronger vibrations than the others. This may be due to some internal defect of insulation between the 4 K body and the 70 k shield. When ultimately we succeeded in limiting the vibrations of these cavities so that the corresponding frequency deviation was within the loaded bandwidth, it was evident that the voltage and phase stabilizing systems have to work at their best in order to keep the beam energy fluctuations below 1%.

The phase feedback is the more critical as it has to cope with ±45 degrees deviations. The corrections require supplementary power from the klystrons, setting a limit to the voltage obtainable from these two cavities and therefore the maximum stable beam energy (15 MeV, well below the 20 MeV peak achieved).

All cavities show structure deformations and consequent field unflatness as deduced from the measurements of their dispersion curves [3]. The maximum deviations of the inter-cell coupling factors Kq from their average are shown in
Table 2 for the two worst Lisa cavities in comparison with a well tuned Desy cavity of which the field unflatness has been measured. It is therefore to be expected that in our cavities the field unflatness is of the same order (i.e. 70%).

<table>
<thead>
<tr>
<th></th>
<th>CAV-1</th>
<th>CAV-4</th>
<th>DESY NOT TUNED</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{π/4}$</td>
<td>1.91%</td>
<td>1.91%</td>
<td>2%</td>
</tr>
<tr>
<td>$K_{π/2}$</td>
<td>2.32%</td>
<td>2.27%</td>
<td>2.17%</td>
</tr>
<tr>
<td>$K_{3π/4}$</td>
<td>3.27%</td>
<td>3.16%</td>
<td>2.89%</td>
</tr>
<tr>
<td>$&lt;K&gt;$</td>
<td>2.5%</td>
<td>2.45%</td>
<td>2.35%</td>
</tr>
<tr>
<td>$\delta K/&lt;K&gt;$</td>
<td>54%</td>
<td>51%</td>
<td>38%</td>
</tr>
<tr>
<td>$E_{max}/E_{min}$</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All cavities show also Q degradation with respect to the values originally measured at the factory in horizontal tests on the cavity fully assembled in the cryostat. As shown in Fig.1, there is a decrease of the low field Q by about a factor 2, and a decrease of the field emission threshold by about 30%.

![Graph](image)

**Fig. 1- Typical Q vs E curve (empty dots are factory values).**

This however has not been the ultimate energy limiting factor, as the pulsed regime (with several % duty cycle) is widely compatible with the cooling power of the refrigerator. Quench has rarely occurred for gradients well above 5 MV/m.

After the original degradation following the installation on the accelerator, the cavities have suffered no apparent further deterioration even though their inner walls have been hit frequently by the beam and moreover no laminar flow clean air has been employed during the frequent disassembly operations on the vacuum chamber. The machine has shown to be much sturdier in handling than feared at first.

**3. Diagnostics issues.**

Beam diagnostics have played an important role in the commissioning of the accelerator. The types of devices used are: toroids for average macropulse current, strip-lines for transverse position and beam time structure, fluorescent and OTR targets for both transverse position and shape.

Strip-lines are essential for a good beam transport through the 1 MeV arc where no fluorescent targets are available. The data acquisition system allows to display a trajectory on line (see Fig. 2), so that manual corrections can be made to minimize the distance of the trajectory from the axis. The automation of this process has not been implemented due to lack of control software manpower.

![Graph](image)

**Fig. 2 - BPM measurement of the relative beam displacement in the arc varying the bending field of -2% (square points) and -4% (dot points)**

The drawbacks found in the strip-lines system are scarce sensitivity, so that the readings are reliable only above 1 mA beam current, and thermal drifts that oblige to perform frequent offset calibrations. The experienced acquired in Lisa has however allowed us to design better electronics for the Desy-TTF experiment [4].

Strip-lines have also been employed in an unusual way as broadband detectors to obtain information on the time structure of the beam. The shape of the envelope of the 50 MHz lines spectrum of the signal induced by the beam on the strips gives information on the proper settings of inflector, chopper and prebuncher parameters (see Fig. 3) [5]. A proper time structure is essential for a good capture of the beam by the SC cavities.

![Graph](image)

**Fig. 3 - Normalized square amplitude of spectrum envelopes vs frequency. The outer full line is the ideal one (only 500 MHz buckets evenly filled), the inner full line is a good one (mainly 500 MHz buckets filled). The dashed line is a bad one, with many 2500 MHz side buckets filled.**

As to fluorescent targets, in order to avoid saturation, it was found very useful to use simple oxidized Aluminium ones in the lower energy part of the injector. Optical Transition Radiation foils, originally planned only to test the prototypes for the Desy-TTF experiment, have shown to be a very effective instrument for the beam transverse charge distribution measurement at higher energies.

Measurement of bunch length, which is expected to be a few ps, was not possible because of lack of specific
instruments. A tentative to use the traditional indirect method consisting in detecting energy spectrum variations vs the RF phase of one of the cavities [6] failed because the beam after the SC cavities was not stable enough over long periods. We have however prepared the hardware for a measurement on the 1 MeV injector beam, which is sufficiently stable, based on coherent transition radiation specturm [7] and we hope to perform it in the near future.

4. Reliability.

A question that is often posed by potential users of SC linacs is about the reliability of operation of such a machine. Only the non traditional parts will be discussed here. It must be stated first that the operation has been too discontinuous to allow for statistics and that this machine was not intended for users. The various sectors have worked for about two months per year (in 4 shifts of two weeks each) from 1992 to 1995. Only in the last two years the machine has been commissioned as a whole.

The hardware of the SC cavities has behaved well. No discarces were detected in the main couplers, due to their large oversizing, and we did not need to use the antenna cooling system. No troubles came from the HOM suppressors, which were left unterminated, due to the negligible interaction of the beam with HOMs.

The refrigeration system has performed well. We had only to substitute, after the first two years, the gas exhaust valves on the cavity LHe container, which had lost their tightness due to frequent blowing in preliminary manoeuvres. Occasional interruption of operation during the shifts was mainly caused by electrical power failure due to thunderstorms.

Another peculiar accident connected with the high charge of the beam pulse regards the glass windows through which the cameras look at the fluorescent targets. Several of these windows were broken due to charge accumulating on the surface. We solved the problem by a metalization of the surface itself.

5. Conclusions

Regarding general features of the accelerator, it is to be remarked that the 1 MeV injection energy is too low for a good beam capture efficiency by the SC cavities. A few more MeV would be advisable. It would also be better to place the injector on axis with the cavities, to avoid beam position fluctuations due to imperfections in the achromaticity of the arc in connection with injector beam energy variations (in our design the arc was required by the planned recirculating beam transport after the FEL interaction for energy recovering).

In conclusion, the correction of the defects of two of the cavities and some modifications of the LHe distribution system would allow LISA to attain the design goals. It is the priority given to other projects that has stopped the work on this machine. In fact many potential uses of this machine have been proposed besides the original FEL application.

The intense, high quality beam of this machine, that has allowed us to detect OTR radiation without difficulty even at 1 MeV [8], is a precious source, and many experiments have been proposed, among which the generation of high brillance monochromatic X rays through channelling in crystals, a medium intensity cold neutron source, and the test of coherent inverse Compton scattering.

References.

    Physical Review Letters 73, 1994, N.7
[8] - M. Castellano et al.
A High Current Proton Linac with 352 MHz SC CAVITIES

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Abstract

A proposal for a 10–120 mA proton linac employing superconducting beta-graded, CERN type, four cell cavities at 352 MHz is presented.

The high energy part (100 MeV-1 GeV) of the machine is split in three β-graded sections, and transverse focusing is provided via a periodic doublet array. All the parameters, like power in the couplers and accelerating fields in the cavities, are within the state of the art, achieved in operating machines.

A first stage of operation at 30 mA beam current is proposed, while the upgrade of the machine to 120 mA operation can be obtained increasing the number of klystrons and couplers per cavity. The additional coupler ports, up to four, will be integrated in the cavity design. Preliminary calculations indicate that beam transport is feasible, given the wide aperture of the 352 MHz structures.

A capital cost of less than 100 M$ at 10 mA, reaching up to 280 M$ for the 120 mA extension, has been estimated for the superconducting high energy section (100 MeV-1 GeV).

The high efficiency of the proposed machine, reaching 50% at 15 mA, makes it a good candidate for proposed nuclear waste incineration facilities and Energy Amplifier studies [1, 2].

Choice of the 352 MHz Frequency

Our design is based mainly on the choice of a low RF frequency for the SC linac. A wide experience in the design, construction and operation of 352 MHz cavities and RF systems is available at CERN [3]. The 352 MHz frequency at moderate gradient operation (around 5 MV/m) allows for large geometrical irises and lower beam current densities. A critical issue for such a machine will be the control of the beam halo growth [4], and the choice of a low frequency allows to lower both the space charge tune depression and the ratio of the beam (core) size with respect to the beam line aperture.

Another important issue, the future availability of several 1.3 MW CW klystrons of the CERN LEP RF system, that will be decommissioned before year 2000, gives an economical incentive for the investigation of a scheme based on the LEP 352 MHz frequency. Moreover, we have also to take into account the experience of several European companies for cavities production and the cavity tooling machines already available at the companies [3].

In our view the development of new β-graded structures [5, 2], with up to four coupler ports, at 352 MHz could allow to reach a beam current of 120 mA employing present technological RF components (simply by incrementing the number of klystrons and couplers/cavity, limiting the power per coupler to approximately 200 kW).

In the following we present a preliminary parameter set for the high energy part (100 MeV-1 GeV) of the machine, as presented to C. Rubbia in the framework of a possible INFN collaboration to the Energy Amplifier and waste transmutation project. The low energy part should be composed of two sections: an RFQ [2] (up to ≈ 7 MeV) and a conventional DTL linac (up to ≈ 100 MeV). This design has been recently included as the candidate for the high energy accelerator section of the Energy Amplifier proposal [6], and work is in progress for a full optimization of the optics and for the development of the RF cavities.

The β-graded structures for the high energy section

We have chosen to cover the energy range from 100 MeV to 1 GeV with three different families of β-graded four cell cavities at 352 MHz, with cell length defined as $L_{cell} = \beta \lambda_{RF}/2$. Four cell cavities have been chosen in order to reduce the number of cavities and the physical structure length, that has to include cut-off tubes, coupler and HOM ports.

This choice of three energy ranges (and consequently of three $\beta$ values for the different sections) allows to keep the transit time factor of a particle in each cavity always greater than 0.9, along the whole machine. The main characteristics of the cavities in each section are given in Table 1.

Table 1: Energy range, design β, active length and length of the focusing period, for the three families of 4 cell cavities.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$\beta$</th>
<th>$L_{active}$ (m)</th>
<th>$L_{FIDO}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100–185</td>
<td>0.47</td>
<td>0.800</td>
<td>7.5</td>
</tr>
<tr>
<td>185–360</td>
<td>0.60</td>
<td>1.022</td>
<td>8.4</td>
</tr>
<tr>
<td>360–1000</td>
<td>0.76</td>
<td>1.294</td>
<td>9.5</td>
</tr>
</tbody>
</table>

The energy gain in each cavity is given by:

$$\Delta T_{eav}(MeV) = L_{active}(m)E_{acc}(MV/m)g\left(\frac{\beta}{\beta_{0}}\right)\cos(\phi_{RF})$$

where $L_{active} = NL_{cell}$ is the active cavity length (in Table 1), $E_{acc}$ is the accelerating field in the cavity, $g(\beta/\beta_{0})$ is the transit time factor of the cavity, depending on the design $\beta$ and the actual beam $\beta$, and $\phi_{RF}$ is the operating RF phase.

In our design, considering the requirement of phase stability, we have chosen $\phi_{RF} = -30^\circ$, and $g > 0.9$ all over the machine.
The role of the transit time factor $g$ can be seen in Figure 1, where we plot the energy gain of each cavity along the machine. Here we chose a constant $E_{acc}$ in each section (the values are given in Table 2); as an alternative approach one can individually set the cavity gradients to provide a constant energy gain in the sections.

Figure 1: Energy gain along the three linac sections, as a function of the cavity number, keeping the nominal accelerating gradient fixed in each section (see text for details).

The basic accelerating cell of each linac section consists of one cryomodule containing four cavities, transverse focusing is provided by quadrupole doublets every cryomodule.

**Focusing Structure**

The focusing structure is a FIDA cell, where the beam acceleration is provided by four RF cavities, in one cryomodule, between successive quadrupole doublets, as seen in Figure 2. The possible use of quadrupole triplets to allow for 'rounder' beams will also be considered.

Figure 2: Focusing structure of the linac.

The three sections of the linac have different cell lengths. The active cavity length and the corresponding lattice periodicity in the three sections are indicated in Table 1.

The quadrupole integrated field $G_1$ ranges from 1 to 3.5 T along the machine, hence it is possible to place warm normal conducting quadrupoles between the cryomodules.

For this reference design the zero current maximal phase advance per cell has been set to $90^\circ$, although a value close to $60^\circ$ or $72^\circ$ should be more appropriate. In the first unit of the first section there is a strong longitudinal phase advance and a reduction of $E_{acc}$ will be investigated.

Preliminary calculations with the linear space charge code TRACE-3D [7] in the current range of 10-120 mA show that beam transport with a beam radius/aperture ratio in the range 10–50 along the machine is possible.

**Section details**

In Table 2 we report the main characteristics of the three sections of the high energy part of the linac, including RF power distribution. The maximum RF power in the couplers is approximately 200 kW, the current upgrade would require the insertion of additional couplers (up to four) in each cavity. The four coupler ports should be integrated from the beginning in the cavity design.

<table>
<thead>
<tr>
<th></th>
<th>S. 1</th>
<th>S. 2</th>
<th>S. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>N. of structures</td>
<td>24</td>
<td>36</td>
<td>96</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.47</td>
<td>0.60</td>
<td>0.76</td>
</tr>
<tr>
<td>$E_{acc}$ (MV/m)</td>
<td>5.2</td>
<td>5.8</td>
<td>6.0</td>
</tr>
<tr>
<td>Section length (m)</td>
<td>45</td>
<td>76</td>
<td>226</td>
</tr>
<tr>
<td>10 mA beam current</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF Power/section (MW)</td>
<td>0.85</td>
<td>1.81</td>
<td>6.35</td>
</tr>
<tr>
<td>RF Power/cavity (kW)</td>
<td>35.4</td>
<td>50.3</td>
<td>66.1</td>
</tr>
<tr>
<td>couplers/cavity</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Klystron/section</td>
<td>1</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>120 mA beam current</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF Power/section (MW)</td>
<td>10.2</td>
<td>21.72</td>
<td>76.2</td>
</tr>
<tr>
<td>RF Power/coupler (kW)</td>
<td>212</td>
<td>201</td>
<td>198</td>
</tr>
<tr>
<td>couplers/cavity</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Klystron/section</td>
<td>$\approx$10</td>
<td>$\approx$20</td>
<td>$\approx$80</td>
</tr>
</tbody>
</table>

A total of 156 cavities and 350 m of physical length are required for the three sections of the superconducting linac, in this reference design. These two numbers could slightly increase in the final design, in order to: decrease the cavity gradient, employ quadrupole triplets focusing, include beam diagnostic elements inside the cryomodules or matching elements between sections.

**Cost of the linac, and efficiency considerations**

The capital cost of the superconducting linac, excluding the RF power costs, is approximately 72.5 M$\$, and the cost breakdown is indicated in Table 3.

**Estimated RF Capital Cost**

Assuming, 1.5 M$\$ per klystron (1.3 MW, CW with power supplies) and 50 k$\$ per coupler (including the RF distribution), in Figure 3 we plot the total capital cost of the linac (including the RF system), and the total capital cost per MW of beam power, as a function of the beam current (in mA).
Table 3: Capital cost of the SC linac.

<table>
<thead>
<tr>
<th>Item</th>
<th>Number</th>
<th>$M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavities (with tuners)</td>
<td>156</td>
<td>39.0</td>
</tr>
<tr>
<td>Quadrupoles</td>
<td>78</td>
<td>3.1</td>
</tr>
<tr>
<td>RF Controls</td>
<td>156</td>
<td>4.2</td>
</tr>
<tr>
<td>Vacuum Pumps</td>
<td>40</td>
<td>1.0</td>
</tr>
<tr>
<td>Vacuum Valves</td>
<td>78</td>
<td>1.0</td>
</tr>
<tr>
<td>Cryostats</td>
<td>39</td>
<td>8.0</td>
</tr>
<tr>
<td>Beam Monitors</td>
<td>80</td>
<td>0.8</td>
</tr>
<tr>
<td>Controls</td>
<td>1</td>
<td>3.0</td>
</tr>
<tr>
<td>Cryopiant Cost (8 kW @ 4.2 K)</td>
<td>1</td>
<td>8.9</td>
</tr>
<tr>
<td>Ancillary Equip. (350 m)</td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td><strong>72.5</strong></td>
</tr>
</tbody>
</table>

Overall Linac Efficiency vs. Beam Current

Assuming a klystron efficiency of 58%, a refrigeration power of approximately 2.5 MW and a contingency power of 1 MW dedicated to the ancillary components of the linac, the overall efficiency of the machine as a function of the beam current is presented in Figure 4. Note that 50% plug efficiency is reached at 15 mA operation. The operation at the full 120 mA current would allow to reach nearly the nominal klystron efficiency.

Conclusions

A preliminary study for a low frequency, high current superconducting proton linac for nuclear waste incineration and energy amplifier applications has been proposed. The machine operates at the 352 MHz of the LEP RF system with three sections of β-graded superconducting cavities.

Preliminary calculations indicate that beam transport at high current is possible, and further studies to address cavity design, both from the electromagnetic and the engineering point of view, and beam halo formation are in the starting phase.

The choice of the RF frequency and of the machine parameters provides a very good plug efficiency at high beam current, a crucial issue for the proposed applications.

Figure 4: Overall linac plug efficiency vs. beam current (mA)

Acknowledgements

We are grateful to Carlo Rubbia who stimulated this work.

References


PRELIMINARY RESULTS ON NIOBIUM SPUTTERED FILMS INSIDE TESLA TYPE CAVITIES

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Abstract

In the framework of the ARES project and as a possible application for TESLA [1] we realized a test set-up to study the deposition of Nb films inside a single-cell TESLA type cavity. The plasma confinement was obtained with two external coils centered on the cavity axis in a magnetic bottle configuration. The system is operational and optimization of the discharge parameters is in progress: samples are being produced to test the film quality.

This paper covers a brief description of the test set-up and preliminary results on samples (thickness, RRR, and XRD measurements).

Introduction

The Nb coated copper cavities provide higher stability against quench respect to cavities traditionally made of Nb sheet. This is a very important characteristics for high acceleration field application, because quenching is still a field limitation above 10MV/m for high frequency cavities [2].

Sputtering is a well known [3] and useful technique for coating copper RF cavities with superconducting thin films [4], [5].

Magnetron sputtering to coat accelerating cavities with superconducting film was developed at CERN for 500 MHz cavities, and is at present used in industry to coat 350 MHz copper cavities for LEP with Nb films [6]: the magnetic field is produced by a coil placed inside the cylindrical cathode and displaced in steps along the cavity axis to achieve a uniform coating.

Because our setup is designed to coat 1.3 GHz cavities for TESLA that are 3 times smaller than the CERN ones, external coils placed on the outside of the cavity cut-off pipes (see Fig.1) and producing a magnetic mirror field configuration have been adopted, so as to preserve full control over the field shape and intensity.

The two coils are contained in a soft iron shield (low carbon contents) 4 mm thick realized so as to be taken down completely and changed according to needs. This configuration has the aim to obtain a magnetic field concentrated along the axis of cavity with a minimum at center of about 200 Gauss and a mirror ratio (\(B_{\text{min}} / B_{\text{max}}\)) of about 2.

The field simulation has been obtained with Poisson-Superfish program, on which is based the whole coil design.

The Sputtering System

The sputtering system is schematically shown in Fig.1; we have different stainless steel TESLA type cavities [7] in the inner walls of which, along all cavity profile, we can place small copper and sapphire (Al2O3) samples that allow us to make a complete film diagnostic. We can characterize the Nb film through RRR (Residual Resistivity Ratio), \(T_c\) thickness and XRD (X Ray Diffraction) measurements.

![Diagram of the sputtering system](image)

**Fig.1** Sputtering system scheme

The vacuum on the system is performed by an ultracleaned pumping group consisting in a 4 m³/h diaphragm pump for the primary vacuum and two on fast turbo molecular pumps (nominal pumping speed respectively 180
l/sec and 300 l/sec) one of which is provided with magnetic bearing, in this way we have a very good compression ratio for hydrogen besides a good ultimate pressure ($\sim 10^{-10}$ mbar) and total absence of hydrocarbons.

The system is provided of a residual gas analyzer (RGA) which besides finding the ultimate pressure gas composition, permits to check, during sputtering process, the percentage of gas produced, as for instance hydrogen, that damages the film structure if it is over a certain threshold. To use the RGA during sputtering process, due to relatively high operating pressure ($\sim 10^{-5}$ mbar), we need a differential pumping, i.e. the RGA communicates with cavity through a diaphragm of 0.6 mm and it is provided with another pumping system in such way as to decrease the pressure of 3 order of magnitude respect to the pressure of the cavity vacuum chamber.

The cathode consists of a vacuum tight stainless steel tube (17 mm inner diameter) surrounded by a niobium liner (20/24 mm inner/outer diameters). The liner is an high purity Nb tube (RRR value better than 150) without welding. The stainless steel tube is provided of an inner support that holds and centers 7 SamCo permanent magnets (small cylinders 8 mm diameter 16 mm long) along all the cavity length that will be cooled through a liquid freon circuit to take away about 2 KW of power. We have performed the preliminary tests to optimize discharge parameters; in those preliminary tests we used magnetic bottle configuration without permanent magnets inside cathode.

**Discharge parameters optimization**

To characterize our system we produced I versus V curves for different pressures, typical curves are shown in Fig. 2.

![Fig. 2. Discharge characteristics at different pressures](image)

The current in our coils was 80 A and the distance between the coils 17.5cm. After a coil shields optimization and coils distance reduction (10.8cm) to increase plasma confinement, we could work at lower pressure (3×10^{-3} Torr) and higher current (1.5 A) with same voltage; we obtained the I versus V curves showed on Fig. 3.

![Fig. 3. Discharge characteristics at different pressures with new magnetic shields configuration](image)

We produced 4 samples, the discharge parameters for each sample are listed on table 1. The sample 4* is produced with new magnetic shield configuration.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Current [A]</th>
<th>Power [W]</th>
<th>Pressure [mTorr]</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>400</td>
<td>4.5</td>
<td>60'</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>400</td>
<td>4.5</td>
<td>60'</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>480</td>
<td>5.1</td>
<td>60'</td>
</tr>
<tr>
<td>4*</td>
<td>1.5</td>
<td>600</td>
<td>3.0</td>
<td>50'</td>
</tr>
</tbody>
</table>

*Table 1: Discharge parameters*

As one can observe the discharge current for last sample was increased at lower pressure due to a better plasma confinement with new magnetic field configuration.

**Measurements on samples**

The crystalline quality of the samples has been investigated by means of x-ray diffraction in the 0-2θ mode using Cu Kα₂ radiation. Diffraction data from sample 4* are shown in Fig 4.

Indexing of the lines allowed the identification of three different orientations, namely (110), (211), (321), the latter being barely discernible as a bump in the experimental data. The lattice constant $d_0$ has been estimated by careful extrapolation in order to minimize systematic errors (see...
Tab.2), a comparison can be made with the value $d_0 = 3.30 \text{ Å}$ quoted for bulk Nb crystals. The samples have thus the same lattice parameter within the experimental uncertainties ($\pm 0.006 \text{ Å}$).

![Diffraction data for sample 4*](image)

**Fig. 4** Diffraction data for sample 4*

Other conclusions can be drawn from an analysis of the relative intensities of the diffraction peaks from the (110), (211) orientations. For a polycrystalline sample the ratio of the intensities can be calculated using standard crystallography packages (including temperature factor corrections), yielding the value $I_{211}/I_{110} = 0.305$. The same ratio has been estimated from the experimental data (see Tab.2). From these results it is readily seen that the films have a tendency to grow along a preferred orientation, in this case the (110). The effect is particularly evident in samples 3 and 4*, where the intensity from the (211) orientation is depressed by a factor of 30 compared to the predicted intensity from a polycrystal.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depos. rate [Å/sec]</th>
<th>$d_0$ [Å]</th>
<th>$I_{211}/I_{110}$</th>
<th>Thickness [μm]</th>
<th>RRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.4</td>
<td>3.312</td>
<td>$9.2 \times 10^{-2}$</td>
<td>1.6</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>4.4</td>
<td>3.314</td>
<td>$9.7 \times 10^{-3}$</td>
<td>1.6</td>
<td>10.5</td>
</tr>
<tr>
<td>3</td>
<td>6.1</td>
<td>3.314</td>
<td></td>
<td>2.2</td>
<td>12.5</td>
</tr>
<tr>
<td>4°</td>
<td>8.7</td>
<td>3.316</td>
<td>$1.1 \times 10^{-2}$</td>
<td>2.6</td>
<td>16</td>
</tr>
</tbody>
</table>

**Table 2** Results on samples measurements

An analysis of RRR shows that the values increase with the deposition rate and with the thickness; for sample 4° a lower deposition pressure works together producing a further increase.

**Conclusions**

We need more statistics, but preliminary results on RRR measurements show that this new magnetron sputtering configuration is competitive with the CERN one [8].

In the near future we plan to optimize the magnetic field in order to further improve the discharge confinement.

Surface resistance measurements are also foreseen to obtain a more complete diagnostic picture of film quality.

**References.**


PROGRESS UPDATE ON THE DEVELOPMENT OF THE $^3$He LINAC FOR PET ISOTOPE PRODUCTION

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J. Link, K. Krohn, of the University of Washington, and J. Bida of the Biomedical Research Foundation of Northwest Louisiana

Abstract

In 1995, Fermilab and SAIC formed a collaboration with partners from the University of Washington (UW) and the Biomedical Research Foundation of Northwest Louisiana (BRF) to explore an innovative approach to the production of radioisotopes. The accelerator system that is being developed accelerates $^3$He to 10.5 MeV and then delivers this beam to the target to produce the short lived radioisotopes of interest to the PET community ($^{18}$F, $^{15}$O, $^{13}$N, $^{11}$C). Research is being conducted to investigate the contribution that this promising approach can make to clinical and research PET.

The accelerator system has several very interesting aspects. These innovations include multiple RFQ accelerators configured in series, a gas stripper jet to doubly charge the low energy (1 MeV) $^3$He beam, and an isochronous matching section to manipulate the transverse and maintain the longitudinal profile of the beam (without the use of an RF buncher) in the charge doubler transition section between RFQ’s. This paper updates the progress of the $^3$He RFQ accelerator, the current status of the design, and some of the interesting ongoing research.

Introduction

The idea of using $^3$He for the production of radioisotopes for PET is not new. Development work on this concept was conducted by SAIC and the University of Washington in the early 1990’s. When the original program was being formulated, the PET environment in which it could make a contribution was significantly different than it is today. The original development was based on the belief that $^{18}$F labeled compounds would be favored by the PET community. Also important was a global shortage of $^{18}$O which made the standard approach of producing $^{18}$F using $^3$H$^{18}$O expensive and potentially unpredictable.

Since that time things within the PET community have changed significantly. There is no longer a significant shortage of $^3$H$^{18}$O. Also, FDA policy has changed regarding regulation of PET radiopharmaceuticals (Federal Register, February 27, 1995). The new policy no longer gives an advantage to $^{18}$F labeled compounds. This means that $^{11}$C agents are no more trouble than $^{18}$F. Carbon opens up a much larger array of molecules to label. Furthermore, recent developments in radiochemistry for preparing the important precursor, $^{11}$CH$_4$, avoid the use of liquid solvents and LiAlH$_4$ which are very air and moisture sensitive, and make the precursor directly in the gas phase and at substantially higher specific activity. This leads to a smaller yield (mCi) requirement of $^{11}$CO$_2$. But, to take full advantage of this new technology, higher specific activity is necessary (i.e. new PET machines must be good producers of $^{11}$C as well as $^{18}$F). In these several ways the environment in which $^3$He RFQ technology can make a significant and meaningful contribution to the advance of PET has changed.

While there have been interesting developments of several new low energy accelerators over the last 2-3 years - the Cyclone 3D (IBA), the TR13 (EBCO), PETtrace (GE), the tandem cascade from SRI or the new deep valley machines (CTI Siemens) - all of these machines use essentially the same nuclear reactions and target chemistry. The RFQ using $^3$He, on the other hand, is a different approach and thus holds significant potential and research opportunities for advancing the state of the art in PET isotope generation.

System Description

Before the radiochemistry and targetry for $^3$He could be investigated, an accelerator was needed that would supply a beam with the desired characteristics and parameters. The accelerator that had been developed by SAIC and the University of Washington in the early 1990’s was a good starting point but needed to be upgraded to provide a more powerful tool for researching $^3$He in light of current information. Analysis and a series of discussions resulted in the baselining of new operating parameters as indicated in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Accelerator Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
</tr>
<tr>
<td>Existing Sys</td>
</tr>
<tr>
<td>New Sys.</td>
</tr>
</tbody>
</table>

Since the radiochemistry and targetry associated with pulsed high intensity $^3$He beams was to a large extent unknown, it was decided that the system being developed needed to follow a conservative approach, i.e. it needed to be flexible and powerful enough to accommodate a wide range of targetry options. In particular it needed to be able to produce large quantities of $^{11}$C since this isotope is likely to be used increasingly in PET. Table 2 indicates the beam required as a

<table>
<thead>
<tr>
<th>Table 2: $^3$He Current Required for PET RFQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radionuclide</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>$^{18}$F</td>
</tr>
<tr>
<td>$^{11}$C (low SA)</td>
</tr>
<tr>
<td>$^{11}$C (high SA)</td>
</tr>
<tr>
<td>$^{13}$N</td>
</tr>
<tr>
<td>$^{15}$O (low SA)</td>
</tr>
<tr>
<td>$^{15}$O (high SA)</td>
</tr>
</tbody>
</table>

* 1 MeV energy loss in target window
** 1.5 MeV energy loss in target window

*Operated by the Universities Research Association under contract with the U. S. Department of Energy.
function of the final energy for the target quantities of the various PET isotopes. The requirements of Table 2 led to the accelerator current and energy requirements stated in Table 1. With this baseline information from our radiochemistry collaborators at UW and BRF, the existing 8 MeV $^3$He accelerator was redesigned to meet the new requirements. The results of this redesign are shown in Figure 1. This layout makes the most efficient use of the existing equipment while solving some of the more challenging technical problems. Some interesting aspects of this accelerator system are:

**Ion Source**

Since one can achieve a much more efficient acceleration (length and power) with a doubly charged beam, a very attractive approach would be to make use of a doubly charged ion source. Unfortunately, nature works against this goal. With the second electron being bound with an energy of about 54.4 eV, common ion sources do not produce sufficient quantities of the doubly charged ion (15 mA required). As an alternative, the singly charged beam can be accelerated to an energy where it can be efficiently stripped (1 MeV). It is this approach that has been taken.

**Radio Frequency Quadrupole**

The accelerator that had been developed under the earlier program had been designed for a final energy of 8 MeV. In order to achieve the higher energy requirements of the new system, it was decided that the most direct approach would be to add a third RFQ (manufactured by SAIC) to the high energy section to go from 8 MeV to the final energy of 10.5 MeV. This resulted in three RFQ’s operating in series. The RFQ cavities are not resonantly coupled. Each cavity must be synchronized to and resonant at the same frequency. To accomplish this the resonant frequency of each cavity is controlled through adjustment of the temperature of the cavity cooling water. No mechanical tuners are used. Tests on this tuning system at full (2.5%) duty factor have been successful.

**Status**

The development of this system has taken place in two phases. A 1 MeV test stand was assembled from the accelerator components of the old system. Using this test stand, a number of the more difficult aspects of the system were addressed. Among the things that were studied are: low energy and medium energy beam characterization, ion source operation with He, charge doubler stripping efficiency, and charge doubler gas containment. The results of these tests have been incorporated into the design of the new components. Some of the information gained in the 1 MeV tests are summarized below.

**Ion Source**

He$^+$ ions are obtained from a fairly standard duoplasmatron ion source. The source operates at 360 Hz with a pulse length of 70 μs. It requires a gas consumption of 2-4 std cm$^3$/min (~1 liter / day of operation). Since $^3$He is relatively expensive all attempts are made to minimize loss by reducing the source button (aperture) and pressure. Also the source is started and operated on $^4$He except when $^3$He is necessary. Because of the heavier ion and high duty factor, filament shielding is critical to prevent overheating and fast erosion. The filament is enclosed in a cylindrical shield with a sufficient opening to extract electrons while minimizing backstreaming ions. Several weeks of reliable and stable operation have been obtained. A 25 mA beam is extracted at 20 kV from an ~1 cm plasma cup through a 0.8 cm grounded extraction electrode with an electron suppression electrode. Slightly after extraction the ~90% normalized beam emittance was measured to be 0.5 - 0.7 π mm mrad. One magnetic solenoid is used to focus the 20 keV beam into the RFQ. At the entrance of the RFQ, 0.7 m beyond the source, 75% of the beam is within ~0.5 π mm mrad emittance (normalized)$^2$.

**Measured Emittance of the 1 MeV beam**

After the Prestripper RFQ, at 1 MeV, the rms emittance has been measured to be 0.2 mm mrad (or ~34 π mm mrad unnormalized for 90% of the beam)$^2$. This was measured with 5.5 - 7 mA at 1 MeV from the RFQ. Better matching and understanding of the RFQ transmission is needed. A maximum beam of 11 - 13 mA has been observed from the RFQ and appears to have similar characteristics. This was achieved with a larger solenoid in the 20 keV transport line.

Figure 1. Layout of the BRF PET Accelerator.

**Charge Doubler**

At an energy of 1 MeV and a current of 400 μA$_{avg}$ (20 mA$_{peak}$), carbon foil strippers could not survive the high power density. Both gas cells and gas jet strippers have been investigated. A jet stripper has been developed and tested with very promising results.

**Medium Energy Beam Transport (MEBT)**

The most difficult aspect of this accelerator system is the matching element between the prestripper and the post stripper RFQ’s. This transition section needs to accomplish several things. It must provide sufficient space to accommodate the gas stripper (gas containment) while maintaining the longitudinal bunching of the beam and transversely matching the beam into the second RFQ. To overcome experimental realities, tunable components are desired. The longitudinal phase space of the beam must be maintained in order to eliminate the buncher/shaper section from the second RFQ (which at this beam energy would add about 1.5 m to the length of the second RFQ). Previous attempts to utilize an RF buncher to contain the beam longitudinally had been unsuccessful due to the very tight space constraints and the large number of free electrons (due to the proximity of the charge doubler). Based on this, it was decided to build an isochronous beam transport system that maintains the longitudinal and manipulates the transverse phase space of the beam.
Charge Doubler tests

A prototype stripper cell based on a pulsed gas jet was built to determine efficiency and gas flow in a realistic geometry. A mechanical injector (Nissan fuel injector) provided gas pulses to a converging-diverging nozzle. A directed gas jet of line density approximately 3.6x10^10 cm^-2 was created at the nozzle. It passed across the beam and was directed into a vacuum pump. The flow rate of the gas jet was sufficient to prevent excessive heating of the gas by the beam, and the injected gas was pumped out between beam pulses.

A magnetic spectrometer that bends the 1-MeV He^+ and He^{++} beam ions into Faraday collectors at bend angles of 11.5° and 23.6° respectively, was used to test operation of the gas jet. Stripping efficiency was determined by measuring the relative distribution of beam current on the two collectors. Stripping efficiency for several gases is shown in Figure 2 as a function of back pressure on the injector.

![Figure 2 Performance of gas-jet stripper on He^+ beam](image)

The best performance was obtained with argon gas, which reached 80% stripping efficiency at a pressure of 25 psia. Pressure measured at the RFQ was 2.8x10^4 Torr for this operating point, at a repetition rate of 60 Hz. We expect to be able to operate at no less than 70% stripping efficiency at the design rate of 360 Hz by increasing pumping capacity. An operational version of the stripper cell is now in fabrication.

Medium Energy Beam Optics

As part of the design effort for the new MEBT (Figure 3), a number of options were investigated. It was recognized that folding the machine would accomplish the goal of keeping the length of the system manageable and could also do the longitudinal dynamics. Designs were investigated that included 180 degree bends, two 90 degree bends, three 60 degree bends, four 45 degree bends, and 30-60-60-30 degree combinations. In each case where multiple dipole designs were tried, quadrupoles were placed between the dipoles and varied in strength and position. Various internal gradients and edge angles were also tried. While it is possible to make a 180 degree bend which has the proper transition energy, it has not yet been possible to have a 180 degree bend design which is isochronous. For this and other reasons it was decided to use 2 x 270 degree bending MEBT which could be made isochronous.

![Figure 3 MEBT Mechanical Layout](image)

The beam optics of the MEBT are shown in figure 4. The major magnets for this transport system have been fabricated and are being tested. The installation and commissioning of the transport system is scheduled to take place over the next two months.

![Figure 4 MEBT Optics](image)

**Schedule**

The modifications to the accelerator system are scheduled to be completed and tested in late 1996. Once completed, the accelerator will be run at Fermilab for 6 to 8 weeks in order to test shielding and do some initial targetry development. Following this run, the machine will be disassembled and shipped to the Biomedical Research Foundation. The accelerator system has been built in a modular fashion in order to facilitate moving. We anticipate that the move and commissioning will take about 8 weeks, after which the in-depth targetry and radiochemistry research will begin.

**Reference**

OPERATING PERFORMANCES AND CURRENT STATUS OF THE LASER INJECTOR COMPLEX FACILITY (LIC)

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Abstract

Paper is dedicated to description of the operating performances and current status of the Laser Injector Complex Facility (LIC). This linac was constructed for investigation of physics of the high-brightness electron beam forming and acceleration. The linac consists of a multipurpose RF gun and a novel acceleration structure. LIC can be operated with microsecond (thermionic emission) and nanosecond (laser stimulated emission) duration of current pulse and energy of electrons 13-20 MeV. In thermionic regime we have obtained electron beam duration 0.5-1 μs, beam current about 1 A and normalized rms emittance about 20 π mm mrad. The results of experimental measurements of beam performances are given.

- the feasibility of acceleration of beams with high charge in the stored energy mode at moderate values of RF-power input (P = 20 MW);
- reduction of amplitudes of TEM waves which are exited by high-intensity electron beam and lead to emittance enhancement or even to shortening of pulse length (BBU instability);
- the feasibility of intense electron beam acceleration with small radial dimensions with the minimum number, or even absence, of external focusing elements.

Introduction

LIC, (Linear Injector Complex), facility was developed and constructed in view of forming and acceleration of high-brightness electron beams. This R&D was to be followed by beam research in the following ares:
- ultra-short wave generation;
- wake-field generation in plasmas and other systems;
- relativistic electron beam focusing in plasmas;
- testing of the diagnostic equipment developed within the framework of the VLEPP program.

The electron energy at the accelerator output was to be 15 to 20 MeV which is sufficient to carry out the above programs. One of the major factors taken into account during development of the facility was limitation of the RF-power (20 - 25 MW) obtainable using the available klystron K12-12. LIC accelerator complex was commissioned during 2 years (1991 - 1992). In 1994, the facility was shut down in order to reconstruct the injector and assemble experimental devices in the area of plasma physics. The work was renewed in 1995.

Its basic components are an RF-gun [2,3], the accelerating section, beam steering and its focusing elements, beam diagnostics, cooling water system and control elements. The RF system includes a klystron with the maximum power operation up to 25 MW, a set of waveguides, controllable phase shifter and attenuator.

Having in view the multipurposeness of the facility under development, we brought out the following major criteria which were taken into account while choosing the necessary type of the accelerating structure:

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>4π/3 (2π/3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>2.31</td>
</tr>
<tr>
<td>Disk hole diameter, 2a (cm)</td>
<td>5</td>
</tr>
<tr>
<td>Disk thickness, t (cm)</td>
<td>5</td>
</tr>
<tr>
<td>Periodic length, D (cm)</td>
<td>7.145</td>
</tr>
<tr>
<td>Attenuation, α (1/cm)</td>
<td>2.44 x 10⁻³</td>
</tr>
<tr>
<td>Group velocity</td>
<td>0.01c</td>
</tr>
<tr>
<td>Frequency, f (MHz)</td>
<td>2797</td>
</tr>
<tr>
<td>Shunt impedance (for fundamental space harmonic amplitude/for synchronous space harmonic amplitude), (Megohms/m)</td>
<td>31.3/11.3</td>
</tr>
</tbody>
</table>

The most attractive was the accelerating structure STRAM-90 (the abbreviation standing for STRucture Accelerating Modified) developed at NSC KIPT which has been designed to accelerate intense short-pulsed electron beams in the stored energy mode at moderate values of RF power input values (P = 15 - 20 MW) [4,5]. This structure represents a disk-loaded waveguide with the period being two times higher than that in the disk-loaded waveguide with 2π/3 mode. Particle acceleration in such structure is made by the first spatial mode of the electromagnetic wave propagating in the opposite direction to the electron beam. Beside increasing the charge value, which can be accelerated in the stored energy mode, the STRAM-type structure has the RF-focusing owing to the presence of a large non-synchronous spatial mode [6,7].

The period increase also leads to a considerable reduction in the TEM-wave generation, since the particles are synchronous with higher spatial modes of these oscillations. However, employment of such a structure in the linac under development was hampered by two factors. The first one being in the fact that due to a small shunt impedance at the first spatial mode there was the necessity to make use of the traveling wave resonant ring in order to increase the
acceleration gradient. The second one was the structure losing its advantages during transition to the single-bunch acceleration mode [4]. We have developed a new version STRAM-91, producing acceleration at the first spatial mode, but having both an increased value of the accelerating field and a low level of higher mode amplitudes irradiated by particles [4]. This was achieved by making use of unusually thick disks with large values of the coupling hole.

Major parameters of this section, developed and fabricated at NSC KIPT, are given in Table 1. The dispersion characteristics measured at a six-cavity assembly are given in Fig.1.

![Dispersion characteristics of STRAM-91](image)

**Fig.1. Dispersion characteristics of STRAM-91**

The beam characteristics measurement system consists of two pulsed beam current monitors, a magnetic particle energy analyzer, a unit of movable slot collimators, a Al₂O₃ screen with a TV camera and a multi-sectional Faraday cap. Beam emittance measurements at the linac exit are performed by the three gradient technique. A quadruple lens is used for this purpose together with the particle spatial distribution monitor, placed at a distance of 2 m from the lens, and consisting of a set of moving slots 0.3 mm wide. In order to make estimations of the transverse dimensions a Al₂O₃ screen with TV-camera as well as a sectional Faraday cap consisting of several coaxial ones are employed.

**Calculation Results**

At all stages of the accelerator development calculations were performed both analytically and as computer simulations. In this way, during development of the acceleration section its geometrical dimensions were calculated, as well as basic RF-characteristics for operation at 4ε/3 mode. Besides, the calculations were done of the particle dynamics in the sections allowing to evaluate the degree of RF- focusing and peculiarities of wake-field generation.

During designing of the gun, in order to optimize its resonators and determine the beam characteristics a set of calculations and simulations (the SUPERFISH and PARMELA codes were used) was performed. In a more detail, the calculation results are given in [3]. From the calculations it follows that the gun can be used successfully both in photo- and thermionic emission modes.

In order to study the particle dynamics in the accelerator using the numeric simulations within the PARMELA code, a model of the entire accelerator was constructed including the RF gun, beam-forming elements and the accelerator section. At first stage we began to study the thermoemission regime with long pulse duration. Preliminary results show that despite of the high injection energy (Wₑ=1 MeV) there is a strong phase movement of the particles at the initial part of acceleration process. We connect this fact with the smallness of accelerating field amplitude at the entries of our section. Under such conditions a strong phase movement can take place at sufficiently high energy of the injected electrons. Under optimum conditions the length of bunches can be strongly reduced (from 50° at the exit of the RF-gun to 4°- 7°- at the exit of the accelerating structure).

Very interesting are the results of radial motion. As it have been mentioned in previous papers [5,6], in the accelerating structure under consideration there is RF- focusing and at the accelerator exit we should have converging electron beam. Besides, we modeled various accelerator operation modes and beam relationship vs. different parameters in order to compare them with experimental results.

**Experimental Results**

Experimental studies in the operation mode of forming and acceleration of single picosecond pulses require utilization of very complicated and costly laser system. Over and above, studies on wake-field generation in plasmas in 1995 called for beams of microsecond duration. In this connection, research into accelerator characteristics during the initial stage was done at a microsecond beam current pulse. With this in mind, the gun had been outfitted with a thermionic emission cathode 5 mm in diameter [2]. The RF-tuning provided for the equal field strength in the first and second cavities which is optimum in case of the thermionic emission cathode at field strength inside the cavity of 25 to 30 MV/m.

In stable accelerator operation regimes (pulse repetition rate ≤6.25 PPS, current pulse duration 2 μs, RF-power input ~1.8 MW) the typical current pulse amplitude at the exit was 1.5 - 2.0 A. With an optimum phasing of the acceleration section the output pulsed current was 1- 1.1 A making the capture rate near 70% which is in accordance with the calculated data. Experimentally shown is the possibility of current pulse reduction at the linac exit from 2 to 0.25 μs by way of decreasing of RF-power input or increasing of cathode heating. This is accompanied by particle energy decrease at the gun exit due to beam loading, and only the most energetic electrons become involved in the acceleration process.

In the experiments was observed a ramp in pulse current of RF-gun and a drop of field strength in the cavities on account of the electron back bombardment of the cathode surface. This phenomena was studied during the experiments. It was found that at a pulse repetition rate exceeding 6.25 PPS the overall average cathode surface temperature
went up above 90° C which called for a decrease of the heating, leading under certain RF-power input conditions to an unstable gun operation.

An analysis of the particle energetic distribution at the linac exit showed that at a pulsed current ~1 A and pulse duration 1.4 μs the energy spectrum possesses an additional maximum in the high-energy region. The shape of the energy spectrum is determined by particle energy coherent losses (beam current loading). In this way, at \( f = 1.05 \text{ A} \) the mean energy was 13.5 MeV, the width of the integral energy spectrum 7% (Fig.2-1), while the width of particle spectrum distribution, as they were injected into the section after ~1 μs from the beginning of the pulse, did not exceed 3% (Fig.2-2).

For the same accelerator operation regime a three gradients method was used to measure beam emittance. From this measurements it follows that in the vertical plane the integral (during the entire pulse) normalized emittance was 26 π-mm-mrad. During emittance measurements in the vicinity of the temporal point corresponding to the current maximum (~1 μs after the beginning of the pulse) this value did not exceed 16 π-mm-mrad.

Experimental results show that at the accelerator exit we have converging electron beam.

As there is a dependence of beam dimensions on the beam injection phase into the accelerating section (Fig.3), we can make a conclusion that this phenomena is determined RF-focusing.

During the tests after upgrading the beam characteristics were also studied in the photo-emission operation mode. At the first stage, BaNi cathode was used as a photocathode at such a temperature that practically excluded operation in the thermionic emission mode. During cathode irradiation at the wavelength 355 nm the gun produced pulsed current 2 - 2.5 A, with the pulse width 6 - 7 ns. At the accelerator output the pulsed current value was 1.3 - 1.6 A. Beam current measurements were done relative to cathode temperature and field strength in the gun cavity.

At present, an experimental research on wake-field excitation in plasmas of various density is carried out at the accelerator. Having this in view, an experimental device was assembled at the accelerator exit, including a coaxial plasma gun (plasma density being 10^9 - 10^10 cm^-3) and a diagnostic set for plasmas and the wake-field. During the assembly, the problem was solved of in-vacuum separation between the accelerator part of facility and its plasma-relation portion. Taking into account the fact that the beam has small dimensions, an extended collimator was placed at the accelerator exit (4 cm long, 4 mm in diameter), as well as auxiliary vacuum pump. Such a set up allowed to maintain the necessary vacuum condition in accelerator during plasma gun operation. Particle losses in the collimator do not exceed 10%.

Conclusions

Thus, NSC KIPT has built and put into operation a multipurpose accelerator facility for R&D purposes. Our simulations and experimental data allow to state that combination of an RF gun with the accelerating section operating at the 1-st spatial harmonic makes it possible to create injector accelerators with a high beam brightness. The subsequent research on particle dynamics in the accelerator should be continued in the direction of studies on the radial dynamics and clearing out the conditions to provide at the linac exit for intense beam production with the minimum emittance. Over above viewing to employ LIC as an FEL driver, we are planing to increase the current pulse duration to 8 - 10 μs.

Acknowledgments

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References

DEVELOPMENT OF INHOMOGENEOUS DISK-LOADED ACCELERATING WAVEGUIDES AND RF-COUPLING

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Abstract

A description of different types of the accelerating structures that have been studied and constructed in NSC KIPT for electron linacs during last years is given in this paper. The accelerating structures consist of the inhomogeneous disk-loaded waveguides and input and output couplers. The disc-loaded waveguides operate at \( f = 2797 \) MHz in \( 2\pi/3 \) mode and have different laws of variation of the disk apertures. Before brazing cups were tuned with using special method. This method is discussed in this paper.

Introduction

During development and tuning of linac accelerating sections, based on homogeneous disk-loaded waveguides, widely used are various cavity stacks, shorted at each end or at only one (plunger method) (see, for example, [1]). In case of homogeneous structures, the possibility of their employment for E-modes is based on the fact that the infinite periodic waveguide there exists for E-modes an infinite number of symmetry planes whose replacement with metal planes does not affect the field structure. For such short-circuiting, despite the fact that only the finite number of cavities are involved in the cavity stack, the characteristics of the both traveling waves (into which the standing wave of the stack can be expanded) are completely identical to those of the wave propagating through infinite (or matched at the ends) waveguide.

A more complicated is the case of inhomogeneous disk-loaded waveguides for which the periodicity condition is violated and, strictly speaking, the grounds disappear not only for utilization of cavity stacks, but for existence of traveling waves which are synchronous with charged particles. If the disk-loaded waveguide parameters vary slowly along the waveguide, then, the amplitudes of reflected waves are small, and in the system there is a traveling wave with slow-varying parameters. Tuning of such waveguides, using cavity sets, is performed with a low systematic error which is proportional to the inhomogeneity value. As far as the possibility of using for acceleration (generation, amplification) purposes disk-loaded waveguides with highly variable parameters, in each specific case, there is necessity to analyze the types and structures of waveguide fields and, then, develop techniques for tuning the components of this slow-wave structure. In general case, there are no stringent laws which could guarantee one or another property of the inhomogeneous structure, as different from homogeneous ones.

One more requirement imposed on the cavity stacks is the possibility of a consecutive tuning (i.e., a selection the geometrical dimensions one way or another) of waveguide cells. In case of cavity stacks, which model the homogeneous disk-loaded waveguides, this requirement is fulfilled automatically: when one has tuned K cells he can tune (K+1)-cell. In case of inhomogeneous structures, such condition becomes realizable depending upon the degree of coupling between different resonators that form the disk-loaded waveguide.

The calculations performed by us on the base of a new disk-loaded waveguide model (coupled cavity chain) [2] indicate that for waveguides with the period \( D \geq \lambda /3 \), where \( \lambda \) is the free-space wavelength, the "remote" coupling influences weakly on the phase-shift per cell. For \( \varphi = 2 \pi /3 \), taking into account the "cross-cavity coupling" ((i,i-1), (i,i+1), (i-1,i+1), i - is the cavity number) at \( a / \lambda < 0.14 \) (a - is the coupling hole radius), one can expect to achieve an accuracy of forming a phase-shift per cell of the order of \( \Delta \varphi \leq 0.05^\circ \). If one restricts oneself only "paired coupling" ((i,i), (i,i+1)), then, the accuracy of phase-shift per cell is getting worse - \( \Delta \varphi \leq 0.5^\circ \). Development of the techniques of disk-loaded waveguide cell tuning that should allow to make feasible the cross-cavity coupling is a difficult task, since during tuning of the i-th resonator one has to take into account, somehow, the effect from the (i+1)-th resonator which has not yet been tuned.

This paper presents the results of our research on the technique of cell-tuning in a strongly inhomogeneous disk-loaded waveguides which realizes paired coupling.

Underlying Theory

From the paper [2] it follows that an infinite chain of cylindrical cavities of the length \( d \) and the radii \( b_1 \), coupled through co-axial cylindrical holes with the radii \( a_i \) in the cavity dividing walls with the thickness \( t \) (inhomogeneous disk-loaded waveguide with the period \( D = d + t \) at \( D > \lambda /3 \) can be, with a definite accuracy, described by a set of coupled equations

\[
[\alpha_n^+(1 + \alpha_n^{-1} + \alpha_n^{-1}) - \omega^2] u_n = \omega^2(\beta_{n,n+1} u_{n+1} + \beta_{n,n-1} u_{n-1})
\]

(1)

where \( u_n \) - are the amplitudes of \( E_{\text{om}} \)-modes in the n-th cavity, \( \omega_n \) - is the n-th cavity eigen frequency, \( \sqrt{\alpha_n^{\text{om}}} \), \( \sqrt{\beta_n^{\text{om}}} \) are the relative n-th cavity eigen frequency shift due to coupling with (n+1) and (n-1) cavities, \( \beta_{n,n+1} \), \( \beta_{n,n-1} \) - are the coupling coefficients. If \( \alpha_n^{\text{om}} \) and \( \beta_n^{\text{om}} \) are determined by geometrical dimensions of only the n-th and (n+1)-th...
cavities, as well as by the coupling hole radius $a_\nu$ ($\alpha^{(n)}_\nu$, $\beta_{\nu_{n-1}}$) are determined by geometrical dimensions of the $n$-th, (n-1)-th cavities and the hole radius $a_{n-1}$, then we shall say that the cavity coupling is paired. If these coefficients depend on geometrical dimensions of three cavities (n-th, (n+1)-th and (n-1)-th), as well as two coupling hole radii $a_\nu$, $a_{n-1}$, then such coupling we shall call "cross-cavity coupling".

Let's find the conditions, when the set (1) at $\omega = \omega_0$, ($\omega_0$ is the operating frequency) has the solution of such form $u_{n,0} = u_{n,0} \exp(i\phi)$, where $u_{n,0}$ is the real value. From (1) it follows that in order to achieve this, the following conditions is to be fulfilled $\beta_{n_{n-1}} u_{n_{n-1},0} = \beta_{n_{n-1},0} u_{n_{n-1},0}$. For the n-th cavity (1) will take on the form

$$[\omega^2_n (1 + \alpha^{(n)}_n + \alpha^{(n)}_{n-1}) - \omega_0^2] u_{n,0} = 2 \omega^2_n \beta_{n_{n-1}} u_{n_{n-1},0} \cos(\phi),$$

and for the (n-1)-th cavity

$$[\omega^2_{n-1} (1 + \alpha^{(n)}_{n-1} + \alpha^{(n)}_{n-2}) - \omega_0^2] u_{n_{n-1},0} = 2 \omega^2_{n-1} \beta_{n_{n-2}} u_{n_{n-2},0} \cos(\phi).$$

From (2) and (3) it follows that, if $\alpha^{(n)}_n$ is independent from the parameters of the (n+1)-th cavity, $\alpha^{(n)}_{n-1}$ - from the parameters of the (n-2)-th cavity and $\beta_{n_{n-1}}, \beta_{n_{n-2}}$ depend only upon the parameters of the n-th and (n-1)-th cavities, then, two equations (2) and (3) become closed and determine fully the relation of geometrical dimensions of the n-th and (n-1)-th cavity. In this case, having tuned the (n-1)-th cavity, one can find the conditions which must satisfy the geometrical dimensions of the n-th cavity, and, consequently, allow to consecutively tune all waveguides cavities. It can be shown that at the paired coupling $\beta_{n_{n-1}} = \beta_{n_{n-1},0}$ and these coefficients are determined by the geometrical dimensions of the n-th and (n-1)-th cavities, only. Things are more complicated with the dependence of coefficients $\alpha^{(n)}_n$ on the parameters of the (n+1)-th cavity and $\alpha^{(n)}_{n-1}$ on the parameters of the (n-2)-th cavity. Even under the assumption of paired coupling such dependence exists. However, our calculations shown that this dependence is considerably weaker than the dependence on the parameters of the n-th ((n-1)-th) cavity, and can be neglected, as a result.

Cavity stacks for tuning inhomogeneous waveguides with $\varphi = 2 \pi / 3$

From the equations (2) and (3) it follows that in order to achieve the traveling wave mode in an inhomogeneous disk-loaded waveguides with the mode type $\varphi = 2 \pi / 3$ it is necessary that the parameters of the (n-1)-th and the n-th cavities be connected via the relationship

$$[\omega^2_{n_{n-1}} (1 + \alpha^{(n)}_{n-1} + \alpha^{(n)}_{n-2}) - \omega_0^2] [\omega^2_n (1 + \alpha^{(n)}_n + \alpha^{(n)}_{n-1}) - \omega_0^2] = 0$$

$$\alpha^{(n)}_n \alpha^{(n)}_{n-1} \beta_{n_{n-1},0}.$$  

(4)

Suppose we have placed the n-th and (n-1)-th cavity into some sort of a cavity stack. It can be shown that the conditions (4) is fulfilled in the case, when in the cavities A and B (see Fig.1), adjoining the cells under consideration, the amplitudes of $F_{q,n}$ modes equal to zero. For cavity stacks, shorted at both ends, this condition can be accomplished by coupling the cavities A and B to terminal cavities, resonance-tuned at the frequency $\omega = \omega_0$, with taking into account the frequency shift due to the hole effect. Such cavity stacks have already been used for tuning separate parts of quasi-constant impedance sections for LIL accelerator [3]. However, there the cells were tuned not consecutively, i.e. beginning from the entrance (or exit), but in different stacks being then simply joined one-to-one.

The above results indicate that it is possible to use a consecutive tuning of all cells for disk-loaded waveguides with an arbitrary law of the coupling hole radius variation. With that, at the operating frequency $\omega = \omega_0$, the traveling wave mode with the phase shift on the order of $2 \pi / 3$ with a certain accuracy is guaranteed in a waveguide. However, a quite natural question arises about the characteristics of such traveling wave, since the inhomogeneity in a disk-loaded waveguides is created with the purpose of optimizing its characteristics. Let's consider, for instance, a quasi-constant impedance section. Such a waveguide is supposed to consist of several homogeneous ($a_n = const$) segments with different radii of the coupling holes and transition sells which provide the matching of these segments. Our analysis indicates that fulfillment of such a requirement is realizable only under a certain law (unknown a priori) of hole radius variation. If one use the disks in the transition sells with some law of the hole radius variation (for instance, the linear one) and consecutive tune all cavities following the above technique, he can obtain a waveguide which will operate in a traveling mode at $\omega = \omega_0$, but its segments which are homogeneous relatively the hole radius will not be homogeneous relatively the waveguide inside diameter. Thus, under application of the above technique to the consecutive cell tuning in the case of the linear law of hole radius variation in the transition sells, the waveguide inside diameter will be periodically change within the second segment, i.e. the second segment of the section will be bi-periodic. For the subsequent "homogeneous" segments the law of the waveguide inside diameter variation will be more complicated. In the case of the linear law of hole radius variation in the transition sells two homogeneous segments cannot be matched together without violation of the condition $\varphi = 2 \pi / 3$. and the precise matching is impossible and from the transition there occur certain reflection with a small phase jump. What is more expedient for the accelerating section: the traveling wave mode with cavity frequency variation along the length of the structure, and, consequently, with the acceleration amplitude variation causing a certain decrease in the energy gain or a
joining of segments with a small phase jump and reflection that, also, leads to a certain decrease in the energy gain? There is no unambiguous answer to this question. In each case one will have to analyze the energy gain (or other characteristics) with taking into account the above factors. Our calculations indicate, for instance, that in the case of a structure with two homogeneous segments and for the linear law of hole radius variation in the transition sells more preferable would be the situation with the periodic cavity frequency variation in the second segment from the standpoint of energy gain.

Consecutive tuning feasibility is determined by stability of the technique, as well. The numerical analysis indicates that small errors in the tuning of individual cells should not lead to the exponential growth of subsequent deviations, i.e. the technique must be stable.

Inhomogeneous accelerating sections

The National Science Center "Kharkov Institute of Physics&Technology" (NSC KIPT) has created a technological base for building accelerating structures on the base of disk-loaded waveguides. The basic elements of a disk-loaded waveguides is asymmetric cell ( disk and cup). The high-precision copper cups and disks are made on diamond tool lathers. Prior to brazing, the cups are tuned using different cavity stacks. Brazing a segment of cups and irises, segments and couplers are made in a vacuum RF-furnace at 779°C using the KIPT technology.

We have developed and manufactured four short inhomogeneous accelerating sections with $\beta_{m0}=1$ and $\varphi=2\pi/3$, three of which (S1, S2, S3) have quasi-constant law of coupling hole radius variation with a linear decrease of radii in transition cells, while in the fourth one (S4) the coupling hole radii decrease linearly from entrance to exit. Calculated characteristics of the first three sections are given in Table 1.

Prior to brazing the first section cells were tuned using the method completely coinciding with the one presented in [3]. Cavities in the second, third and fourth sections were consecutively tuned in the cavity stack using the above described method. While doing so, as compare with [3], the number of auxiliary cells was reduced to the minimum - we used only four auxiliary cells (see Fig.1). Cells A and B were composite ones (A=A_{0},A_{m}, B=B_{0},B_{m}) and during tuning process cells A_{0} and B_{0} were uncharged while the radii of cells A_{m} and B_{m} were changed according to a certain law. For sections S2 and S3 the radii of cells A_{m} and B_{m} were changed after tuning the transition cells, for section S4 - they were consecutively tuned together with the main cells. After brazing the sections cells were tuned by way of a small external deformation of the cups until the needed phase shift was achieved ($\delta \varphi=4\pi/3$) during the shortening plunging movement. Since such a tuning cleaned away all the errors of the first tuning (before brazing) we did not see the difference in the characteristics between sections S1, S2 and S3.

| Table 1 |
| Calculated characteristics of the S1, S2, S3 sections |
|-----------------|-----------------|
| Frequency, MHz  | I=0.0 A         | I=1.2 A |
| 2797.2          | 2797.2          |
| Input Power, MW | 13              | 13     |
| Energy Gain, MeV| 17.8            | 9.5    |
| Beam Power, MW  | 11.4            |        |
| Gradient, MeV/m | 14.3            | 7.6    |
| Section Length, m| 1.227           | 1.227  |
| Filling Time, \mu sec | 0.31           | 0.31   |
| Field Attenuation, Nep/sec. | 0.24        | 4.2    |
| Output Power, MW | 8               | 0.03   |
| Number of Homogeneous Segments (Iris Diameters, mm) | 4 (25.441, 23.630, 21.821, 19.620) |

During measurements of the after-brazing phase shifts it was found that the operating frequency of all sections was 150 to 200 kHz lower than the calculated one. It can be explained as errors of used cavity stack. Indeed, the above stacks are just for paired cavity coupling. According to the results of our calculations [2] the negligence of the "remote" coupling can produce errors during tuning about $\Delta \varphi \approx 0.5^\circ$ which agrees in value and sign with the obtained deviation of the operating frequency.

The section S1 was installed on KUT accelerator [4]. The results of beam characteristics measurements agreed with simulations.

Thus, our R&D has shown that the feasibility is there to tune (with a certain error) of disk-loaded waveguides with arbitrary law of hole radius variation. In order to achieve the necessary characteristics the choice of such law must be made with taking into account both the properties of inhomogeneous waveguides as the feasibility of tuning such waveguides. In view of all the above-said, a procedure should be worked out to optimize the structures considered. At present, based on the approach [2] we have begun to investigate this problem.

Acknowledgments

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References

OPTIMIZATION OF ION SOURCE EXTRACTION AND TRANSPORT WITH SYMBOLIC MANIPULATION PROGRAMS: ELECTROSTATIC LENSES FORMULAS

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Abstract
The partly built line of the ECR ion source Alice, mainly based on electrostatic elements, needs several optimizations for different ion beam (A/q ranges from 2 to 9). Numerical codes easy to maintain and fast to execute were in demand. Beam optics codes are usually implemented as a kind of object oriented programs followed by a purposely written high level interpreter. This level was here replaced by general programs, combining symbolic and numerical capability, which therefore support different programming styles and a much finer physical description. Highly efficient linear tracking of electrostatic elements was obtained combining piecewise analytical solutions for quadratic and linear elements; some basic formulas and a sample result for Alice line are shown. Extension of elements to nonlinear case is given here, with detail for the anode lens.

Introduction
The beam transport system of the ECR [1] ion source Alice is mainly constituted by electrostatic elements (extractor, three einzel lens and the accelerating column), with one magnetic dipole for charge selection (Fig. 1). Due to the relative importance of fringing fields, our need for a flexible and easily adaptable matrix tracking code was apparent; nonlinear effects were also considered a second goal. We wrote some application programs, executed interactively by Mathematica [2]. Usual formulas for sources, drifts, thin lens and dipoles were easily implemented, as well as graphic capabilities. This paper describes the nontrivial approximations and equations that we used in simulating round electrostatic elements in some detail.

Paraxial analysis of einzel lens was indeed possible, by decomposing the lens in seven regions (or elements), where the axial field $E_z$ is assumed either constant (linear elements) or linearly increasing (quadratic elements) [3]. Use of more than three regions allows a closer fit to actual fields. A noteworthy nonlinear approximation (nonlinear means applicable to nonparaxial rays), namely the Piecewise Quadratic Approximation (PQA) is first introduced and briefly discussed; matching between linear and quadratic elements is extended off-axis, allowing region boundaries to make a $\arctan \sqrt{2}$ angle with $z$ axis and introducing fictitious charges on element boundaries. We apply this general concept to anode lens effect.

We follow SI units in the code (generally) and use nonrelativistic mechanics, as suitable for ion sources. Since orbits do not depend on mass and charge in electrostatic fields, in section 2 and 3 we set unit mass and charge $e = m = 1$ for brevity.

Figure 1: Beam line from platform (scale is approximated; transverse dimension exaggerated).

Einzel Lens Paraxial Model
Let $E$ be the total particle energy, a constant of motion, valid for every element of our beamline. First, we review the quadratic element. Consider a vacuum region where the electrostatic potential $\phi(r, z)$ is exactly:

$$\phi(r, z) = A + Bz + C\left(\frac{1}{2}r^2 - \frac{1}{2}z^2\right)$$ (1)

Hamiltonian separates as $H = H_x + H_r$, with $H_r = (2p_r^2 + Cz^2)/4$, whose value $H^e$ is a constant of motion; also the value of $H_z$ is the constant of motion $H^e = E - H^e$. Solving motion equations and eliminating $i$ in favour of $z$ we write the motion from $z_1$ to $z_2$ as

$$\begin{pmatrix} r \\ r \end{pmatrix} = \begin{pmatrix} \cos \psi & \sqrt{2/C} \sin \psi \\ -\sqrt{2/C} \sin \psi & \cos \psi \end{pmatrix} \begin{pmatrix} r \\ p_r \end{pmatrix} \bigg|_{z_1}^{z_2}$$ (2)

$$\psi(x_1, z_1) = \frac{1}{\sqrt{2}} \text{Arsh} \left( \frac{Cz - B}{\sqrt{2H_z C - 2AC - B^2}} \right)$$ (3)

with $2H_z = 2E - p_r^2(z_1) - Cz^2(z_1)/2$. From these nonlinear formulas a linear approximation in $(r, p_r)$ is obtained by putting $H^e = E$ in eq. (3). In case $C < 0$ analytic continuation is taken. Case $C = 0$ is the linear element.

The potential of einzel lens $\Phi(r, z)$ can be fitted by elements like eq. (1) on intervals of $z$ axis $r = 0$; interval borders $z_n$ are called breaking points here. In present code, we find convenient to use the well-known approximation for symmetrical einzel lenses [3]:

$$\Phi(0, z) = \frac{V_2}{2\omega(z_n - z_0)} \log \frac{\chi[\omega(z + z_0)]\chi[\omega(z - z_0)]}{\chi[\omega(z + z_0)]\chi[\omega(z - z_0)]}$$ (4)

with $\omega = 1.318/R$ where $R$ is the radius of electrodes and $z = z_0, z = z_0$ their faces; in perspective, also the potential
\( \Phi(0, z) \) numerically computed (by POISSON) and adequately interpolated can be fitted by the same elements.

Elements are easily counted by plotting (see Fig. 2a) the second derivative \( \Phi_{zz} \) and associating a \( C > 0 \) element to some maximum (region III) and a \( C < 0 \) element to some minimum (region I) or low plateau. Between these elements, a \( C = 0 \) element (region II) will certainly improve matching. At \( z = 0 \) we can include a \( C = B = 0 \) element (region 0) or not, depending on lens dimension \( z_a \). In these regions, potential elements on axis are better written:

\[
\begin{align*}
\phi &= a & 0 < z < z_0 \\
\phi &= a + \frac{1}{3}b(z - z_0)^2 & z_0 < z < z_1 \\
\phi &= c + d(z - z_0) & z_1 < z < z_2 \\
\phi &= \frac{1}{3}e(z - z_3)^2 & z_2 < z < z_3
\end{align*}
\]

and \( \phi = 0 \) for \( z > z_3 \). Imposing continuity of \( \phi(0, z) \) and \( \phi_z(0, z) \) everywhere, we get \( c = a - \frac{1}{3}d(z_1 - z_0) \), \( e = d(z_2 - z_3) \) and \( z_3 = -2(a/d) + z_0 + z_1 + z_2 \).

![Figure 2: a) Breaking point determination from potential derivatives on z axis; b) Regions at a breaking point.](image)

We choose \( a = \Phi(0, 0) \) to exactly reproduce the field at lens middle. The remaining parameter \( z_0, z_1, z_2 \) (breaking points) and \( d \) can be determined by fitting \( \phi \) to the actual potential \( \Phi \), that is by minimizing the norm

\[
\sum_{x(t)} w_0(\phi - \Phi)^2 + w_1(\phi_x - \Phi_x)^2 + w_2(\phi_{zz} - \Phi_{zz})^2
\]

where \( z^{(s)} = j(L/N) \) and \( L \) is long enough (\( L = z_b + 3R \) suffices). Considering also the second derivative is essential for sound results of the fit, even if weights \( w_0, w_1 \) and \( w_2 \) may be varied; we choose \( w_n = R^n \). Note that \( z_0 \leq 0 \) is our criterion to drop region 0, which case leaves five intervals in total instead of seven.

In the paraxial approximation we can take region boundaries as \( z = z_n \) planes, and extend potential off-axis according to (1). Indeed, at any \( z_n \), \( \phi_{xz} \) is discontinuous, so that a \( r^2 \) discontinuity in potential arise; this term may be neglected in paraxial approximation.

### Piecewise Quadratic Approximation

To apply the quadratic elements in nonparaxial case, imagine to have matched the potential \( \phi \) and field \( E_z \) on axis at breaking point \( z_n \) between two element intervals; to fix ideas, let \( z_n = 0 \). The two elements are \( \phi_1 = A + Bz + C_1(r^2/2 - z^2/4) \) and \( \phi_{11} = A + Bz + C_{11}(r^2/2 - z^2/4) \), with \( A \) and \( B \) equal because of matching for \( r = 0 \). Requiring potential continuity \( \phi_1 = \phi_{11} \) implies

\[
r = \sqrt{2(z - z_n)} \quad \text{or} \quad r = \sqrt{2(z_n - z)}
\]

These two lines (in fact cones) are the element boundaries and separate three regions; in region III we may have another element as eq. (1) with a different \( C_{11} \) if desired.

Matching \( \phi_z \) off-axis is not possible. Discontinuity of \( E_z \) is equivalent to a charge (say positive), which implies a balancing charge (negative) to be located at lines (7). More quantitatively, \( \Phi_1 \) be the true potential (\( E_z \) the true field), \( \phi \) our collection of elements (so that \( E = -\nabla \phi \) is a part of the electric field) and \( \Phi_c = \Phi - \phi \) the correction (localized near eq. (7) lines) that restores matching between elements. From Laplace eq. \( \Delta \Phi_1 = 0 \) we indeed get:

\[
\Delta \Phi_c = \text{div} E
\]

From eq. (7), boundaries associated to different \( z_n \) may intersect at \( r = \sqrt{(z_n - z_{n+1}/2} \), which determines the maximum radius of validity of our element decomposition.

Non paraxial analysis is more easily applied to the remarkable case of the anode lens [4], a hole of radius \( R \) in a conducting metal sheet (at \( \Phi_0 = 0 \)) separating a semispace \( z < 0 \) with field \( E_z = E_1 \equiv E_z - E_d \) for \( z \rightarrow -\infty \) from a semispace \( z > 0 \) with field \( E_z = E_2 \equiv E_z + E_d \) for \( z \rightarrow +\infty \). Our field elements are explicitly

\[
\begin{align*}
\phi_T &= -E_dz + E_dz \quad \text{for} \quad r - \sqrt{2z} - R_p > 0 > z \\
\phi_V &= -E_dz - E_dz \quad \text{for} \quad r + \sqrt{2z} - R_p > 0 < z \\
\phi_U &= -E_dz + (E_d/Z_p)(1/4r^2 - 1/2z^2 - 1/2Z_p^2)
\end{align*}
\]

elsewhere, with \( Z_p = R_p/\sqrt{2} \). Here \( R_p \) is a parameter; breaking points are at \( \pm Z_p \). Choosing \( R_p = 4\sqrt{2}/\pi \) gives the exact values for \( \phi_U(0, 0) \), similarly to einzel lens [4].

From (9) we can compute the fictitious charge of (8):

\[
\Delta \Phi_c = \frac{3E_d^2r^2}{28/2^{1/2}} \left[ \delta(z - Z_p + (r/\sqrt{2})) + \delta(z + Z_p - (r/\sqrt{2})) \right]
\]

The effect of \( \Phi_c \) on particle motion can be approximately described by a (small) transverse kick \( K \) when passing boundaries; for example crossing \( T-U \) boundary gives

\[
K_r = \frac{E_d^2}{2\sqrt{2}Z_p} \left[ 1 + 2^{-5/2}\alpha_i - 0.75\alpha_i^2 + O(\alpha_i^3) \right]
\]

where \( \alpha_i, \gamma_i \) are \( r, z \) at the crossing; \( \gamma_i \) at this time; \( \alpha_i \) at \( p_r/p_z \) at this time. Component \( K_r \) is such to maintain energy unchanged. This kick does not contribute to linear focusing, but to aberrations.

We can now formulate a fast tracking for the anode lens. For convenience we project initial and final states on \( z = 0 \). The initial motion:

\[
r(z) = r_0 + p_0[\sqrt{f + 2(E_z - E_d)z} - \sqrt{f}]/(E_z - E_d)
\]
with \( f = 2E - p_0^2 \) is therefore parameterized by \((r_0, p_0)\), which would be the values of \((r, p)\) at \(z = 0\), if our particle would propagate in a constant field \(E_z = E_2\) up to there. From (12) and boundary eq. \( r - \sqrt{2z} = Z_p\), crossing values \(r_1, z_1\) can be easily determined. After crossing we have \(p_z = p_0 + K_r\) with the kick (11). Motion follows eq. (2) up to crossing with \(U\)-\(V\) boundary, at \(z = z_o\), \(z_o\) is determined by

\[
z_o = Z_p - \sqrt{\frac{r_1}{\sqrt{2}}} \cos\psi(z_o, z_1) + \frac{p_z}{\sqrt{2}} \sin\psi(z_o, z_1)
\]

(13)

which can be solved iteratively. A good starting value for \(\psi\) is

\[
\psi(Z_p, -Z_p) = \frac{1}{\sqrt{2}} \left[ \text{Arsh} \left( \frac{E_4 + E_3}{\sqrt{g + E_4^2 - E_3^2}} \right) - \text{Arsh} \left( \frac{E_4 - E_3}{\sqrt{g + E_4^2 - E_3^2}} \right) \right]
\]

(14)

g = 2H^2_c E_4/Z_p . Final value of \(p_z\) is \(p_z(z_f) = p_0 + K_r\), where the second kick is given by eq. (11), with \(r_1\) replaced by \(r_o\) (and similar replacement for \(z_1, p_1, \alpha_1\)).

**Remarks on Programming**

As a general remark, programs become more involved with their size; in our opinion, no recipe can guarantee order and clarity (and absence of error). It is then natural to break a program into several parts, mainly a “physics part” [5], where formulae as (1)-(14) are coded as plainly as possible, and an “interpreter”, ultimately relating with numbers and graphics; for example, as COSY and FOXY (interpreting COSY to Fortran [5]). Our try in this direction is the use of an external interpreter, at present Mathematica [2]; advantages of this approach are more evident at the beginning (as now), when the physics code is small enough to make errors unlikely; and reformulation is possible.

A Mathematica applicative program (code in brief) consists of definition of transformation of symbols, with possibility of delaying or conditioning their execution: almost any kind of programming style is possible. It is probable that object programming, implemented by “SetUpDelayed” [2], will be a fairly good recipe to order information about the several treated objects: dipoles, regions of einzel lenses or of accelerating tubes, drifts. At present, a traditional style was used: an element is a list, including the element name, kind of approximation used, and parameters. For example, \{dipole,fringe,R,\phi,\alpha,\beta,n,D,I_2(in),I_2(out)\} represents H.Engel’s model of dipole [4]. Symbols “matrix2” and “matrix3” represent actions on \((x, p_x)\) phase-space and \((x, p_x, \theta)\) space respectively. An einzel lens is converted into a sequence of seven lists. A beamline is a list of lists, on which a traditional loop distributes the action of “matrix3”. Operations on lists may be more concisely done with in-built symbols “Thread” and “Map”, in an advanced style. Graphics rendering was very flexible and satisfying. We plan to merge fitting of elements to einzel into some post-processor of Poisson equation numerical solvers.

**Simulation Results**

Let \((V_2, V_3, V_4)\) be the voltages of the three einzel lenses, \(V_1\) be the source voltage and \(-V_p\) be the linac voltage, referenced to platform. Fig. 3a) was computed for a beam of He\(^{2+}\), setting \(V_1 = 9\) kV, (i.e. \(E = eV_1 = 18\) keV), \(V_2 = 3.45\) kV for the first einzels and optimizing \((V_3, V_4, V_p) = (7, 5.65, 67)\) kV; a \(\delta V_1 = 10\) V perturbation was added. Simulation for Ar\(^{14+}\) and U\(^{28+}\) beams proved even better transport, provided that latter voltages (and intermediate waists) are changed: \((V_3, V_4, V_p) = (0, 0, 99.6)\) kV and \((0, 6.3, 314)\) kV respectively. Fig 3b) shows that also aberration can be reproduced by PQA, in fairly good agreement with Runge-Kutta computations.

**References**

The New Superconducting Positive Ion Injector for the Legnaro ALPI Booster.

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Abstract

Following the demand of very heavy ion beams at the Laboratori Nazionali di Legnaro a new injector for ALPI is foreseen. At present ALPI is fed by a 16 MV XTU Tandem providing, routinely, beams up to masses of the order of 90 amu. In order to upgrade the possibilities of the complex and accelerate masses up to 200 amu the novel injector has been designed. The new machine consists of an ECR source on a high voltage platform, capable of 350 kV, followed by two superconducting RFQ resonators operating at 80 MHz and boosting the beam energy up to about 570 keV/amu. Downstream the RFQ’s eight Quarter Wave Resonators similar to the ALPI bulk niobium cavities are foreseen, to reach a proper ALPI injection energy of about 950 keV/amu. This paper describes the project.

Introduction

The new positive ion injector for the Legnaro heavy ion facility PIAVE (Positive Ion Accelerator for Very-low Energy) will increase the capability of the complex in delivering very heavy ion beams to the experiments. The user request, after more than a decade of operation of the XTU tandem, is to have very heavy ion beams with intensities of few particle-nA onto the target. The new machine will allow the simultaneous operation of the two main accelerators operating at Legnaro, the XTU tandem and the post accelerator ALPI, that are forced to work in alternative, at present, being the tandem the only injector for ALPI [1,2,3]. Figure 1 shows the PIAVE technical layout from the ion source to the injection in ALPI.

The beam is formed in the ECR source Alice [4] which is located on a high voltage platform and accelerated by the 350 kV applied voltage. As shown in figure 1 the HV platform is placed 4 m higher than the ALPI vault floor on a concrete support. This solution, dictated by the dimension of the platform and the required distances from the wall, calls for a transport line which displaces the beam by about 5 m in the vertical direction and about 2 m in the horizontal one [5].

The transport line contains the double-drift double-frequency bunching system operating at 40–80 MHz for the proper injection into the RFQ.

The first accelerating section of PIAVE which consists of two superconducting RFQ cavities housed in the same cryostat (see fig. 1). The output energy of the RFQ section has been optimized with respect of the acceleration efficiency of the structure. Following the RFQ’s there are eight accelerating Quarter Wave cavities of the same type of the bulk niobium low-beta section of ALPI[6], with some minor modifications in order to decrease the beta_min value from 0.055 to 0.05. The QWR’s are housed in two cryostats and in between there is a quadrupole doublet for transverse focusing.

Downstream the accelerating sections of PIAVE there is the transport and matching line to ALPI which includes two room temperature bunchers (in fig. 1. only one of them is shown being the second one hidden in the chosen view).

The choice of using superconducting structure has been driven by the fact that ALPI is capable of running in CW mode, being itself a superconducting machine. This follows the traditional use of electrostatic machines in nuclear physics and fulfill the request of the high efficiency multi-array γ-spectroscopy detectors which need a beam intensity of some pA with 100% duty cycle.

Fig. 1. The PIAVE layout
**Table 1**

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<tr>
<th>Source and LEBT</th>
<th>ECR</th>
<th>14 GHz</th>
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<tbody>
<tr>
<td>Mass to charge ratio</td>
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<td>Platform voltage*</td>
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<td>Energy</td>
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<td>Beam emittance</td>
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<td>Bunching system</td>
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<td>ΔW</td>
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**RFQ Accelerator**

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<td>Output Energy</td>
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<td>Output emittance</td>
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**SRFQ Parameters**

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<tr>
<td>Synchronous Phase φₛ</td>
<td>-40+18-8 deg</td>
</tr>
<tr>
<td>Tank diameter</td>
<td>46 cm</td>
</tr>
<tr>
<td>Max. surface B field*</td>
<td>280 G</td>
</tr>
<tr>
<td>Shunt impedance Rsh/Q</td>
<td>22.7 Ωm</td>
</tr>
<tr>
<td>Quality factor Q</td>
<td>768</td>
</tr>
<tr>
<td>Power dissipation (4K)*</td>
<td>≤7 W</td>
</tr>
</tbody>
</table>

**QWR Section**

<table>
<thead>
<tr>
<th>Number of resonators</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output energy*</td>
<td>948 keV/u (β=.045)</td>
</tr>
<tr>
<td>Radio Frequency</td>
<td>80 MHz</td>
</tr>
<tr>
<td>Optimum β</td>
<td>0.05</td>
</tr>
<tr>
<td>Accelerating Field</td>
<td>3 MV/m</td>
</tr>
<tr>
<td>Shunt impedance Rsh/Q</td>
<td>3.2 kΩ/m</td>
</tr>
<tr>
<td>Quality factor Q</td>
<td>10⁶</td>
</tr>
<tr>
<td>Power per cavity (4K)</td>
<td>≤7 W</td>
</tr>
<tr>
<td>Synchronous Phase ηₚ</td>
<td>20 deg</td>
</tr>
</tbody>
</table>

**Beam Dynamics**

The new injector has to provide the very heavy ion beam for ALPI replacing the tandem, which means that the beam quality of the machine has to compete with the very good transverse emittance of an electrostatic machine. Moreover, the longitudinal structure of the beam has to be acceptable for the injection into ALPI. These requests have to be combined with the optimization of the acceleration efficiency due to the very high costs of the superconducting structure and ancillary.

The main features of this design are the bunching of the beam outside the RFQ, the optimization of the acceleration efficiency with proper choice of voltages and apertures and the minimization of the output longitudinal emittance, that determines the modulation law[3,5,7].

The ion velocity for the transition between the RFQ structure and the QWR has been chosen balancing the acceleration efficiency of the two structures. Indeed at higher beam energy the rf stored energy in the RFQ becomes prohibitive, at lower beam energy the transit time factor in the two gaps QWR's is too low.

The result of the design study is summarized in table 1.

**The Superconducting Structures**

The project foresees two different resonators for the RFQ section for a total structure length of ~ 2.5 m, housed in a single cryostat mainly to reduce the unavoidable drift space between the cavities. We are forced to split the RFQ into two resonators otherwise the rf energy stored in the cavities would make the phase lock with a reasonable rf power amplifier impossible [3].

The first of the two cavities to be built is the second RFQ, named SRFQ2, because it is the most critical one concerning the rf electronics demands. The drawing of the cavity is shown in figure 2.

![Fig. 2. The SRFQ2 resonator](image)

The SRFQ's are made of e-h welded niobium sheets. The choice of this construction technology is advised by the tightness of the time schedule of the project, but a parallel research experiment on the feasibility of this kind of structure in OFHC copper with a sputtered niobium film is in progress.
From the mechanical point of view, effort has been put in the calculation and modification of the eigenfrequencies of the mechanical vibrations of the cavities to minimize the effect on the rf operation [3, 8]. The stiffening ribs and the bars push the mechanical resonant frequency to ~150 Hz, whereas the frequency without any stiffening but with the already optimized shape of the supports is ~50 Hz; this is more convenient considering the environment mechanical noise.

The SRFQ resonators will work in a self-excited loop mode and one needs a rf amplifier power of at least 500 W [3, 9] in order to have a dynamic range of ±10 Hz, considering the quite high stored energy. This high rf power needed for the feed back control loop puts both rf and thermal constraints on the rf feed lines and on the cryostat.

The slow tuner range is of ±100 kHz, through elastic deformation of the two end plates by ±2.5 mm. A tuning system to compensate the ±50 mbar pressure variation of the liquid helium bath is under investigation.

As mentioned above, the second part of the accelerator is made of eight superconducting QW resonators operating at 80 MHz similar to the low energy section cavities of ALPI [6]. The only modification we foresee is the variation of the $\beta_{pec}$ through modification of the beam port geometry. This minor change will not require a new study of the structure, that has been constructed and successfully tested.

**Infrastructures**

The most demanding ancillary system of the whole project is the liquid helium production and distribution system. PIAVE requires a cooling power of 130 W at 4.5 K and 600 W at 80 K and it is connected with the ALPI cryogenic complex. To avoid the overloading of the 80 K circuit the use of a separated liquid nitrogen refrigeration system is foreseen.

Another important constraint on the cryogenic system is the quietness concerning the mechanical noise because of the sensitivity of the SRFQ cavities to the vibrations. Different solutions are now under investigation ranging from an inexpensive system made of a dewar for the phase separation of the liquid helium to the use of superfluid helium.

All the other accelerator systems are an upgraded replica of the well proven ALPI systems [2].

The main novelty, concerning the beam diagnostics, is the design and construction of a beam emittance measuring box essential for the tuning of the transfer lines.

**Status of the Project**

PIAVE has been approved as a “Special Project” by the executive committee of INFN in its meeting of July 1996. It is a three years project with a cost of ~7.7 Billion Lit.

The feasibility studies of the project are going on since the middle of 1995 and in March 1996, before presenting officially the project to the INFN, an international committee reviewed the design in all aspects, giving scientific approval.

The SRFQ cavities are in a prototyping stage and the internal parts of the stainless steel full scale model of SRFQ have been e-b welded. The model is meant to check all the construction details of the cavities and to construct the proper mechanical jigs because the construction of the niobium cavity will immediately follow.

![Fig. 3. The test cryostat and the SRFQ2 cavity](image-url)

A test cryostat, able to house both the different SRFQ cavities, is under construction. The main feature of the design is the use of titanium for the liquid helium reservoir to avoid the stresses due to the different thermal contraction between the cavity, made of niobium, and the reservoir which contains it in a helium bath (see fig. 3.).

**References**

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A NEW MATCHER TYPE BETWEEN RFQ AND IH-DTL FOR THE GSI HIGH CURRENT HEAVY ION PRESTRIPPER LINAC

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Abstract

The adaptation of a RFQ beam to the typical requirements at the entrance of a drift tube linac is rather difficult at high intensities and high A/q values. The high focusing power needed for such a matcher can be provided by a conventional array with rather large quadrupoles and rebuncher cavities only. Many problems arising from such a design can be avoided by using an element which is focusing in transverse and longitudinal direction at the same time, that is a short RFQ ("Super Lens") with 10 cells typically and a larger aperture as compared to the main RFQ. A xy-steerer and a short quadrupole doublet with small aperture were added to gain flexibility with regard to beam mismatch and misalignment corrections. This new concept is realised for the GSI 15 mA U²⁺ injector, which is under construction.

Beam dynamics calculations are presented and compared with results for a conventional solution consisting of a rebuncher and a quadrupole triplet.

Introduction

At present a new UNILAC prestripper LINAC is under construction in order to fill the Heavy Ion Synchrotron SIS up to the space charge limit [1],[2].

The new LINAC consists of a RFQ cavity up to 120 keV/u and a IH-DTL section up to 1.4 MeV/u.

So far, for the beam matching from a RFQ into an IH-DTL the conventional array consisting of the elements quadrupole triplet (doublet) - rebuncher cavity - quadrupole doublet was used [3] [4]. These accelerators however were zero current designs with A/q values below 9.5.

For the new GSI High Current Injector with A/q ≤ 65 the use of similar matching designs would lead to considerable difficulties: very powerful and long conventional quadrupole lenses with big apertures are necessary, as well as a powerful rebunching cavity. According to the separation of longitudinal and transverse focusing within such a system, it is rather sensitive with respect to beam intensity fluctuations.

These problems led to the idea of using a short adapter RFQ ("Super Lens") focusing in all three dimensions and located directly in front of the first IH-DTL [5]. A short, small aperture quadrupole doublet placed behind the main RFQ adds the needed flexibility to that system.

Parameters of the Matching Section Components

The main parameters of the matching section are summarized in Table 1. The geometric arrangement is shown in Fig. 1. Between accelerator RFQ output and adapter RFQ input a distance of about 560 mm is taken by a xy-steerer, a quadrupole doublet, a vacuum valve and a diagnostic box. Along that distance the beam radius is increased to around 5 mm. A 'Super Lens' minimum aperture radius of a = 6.8 mm (compared to a = 4.1 mm at the main RFQ output) was chosen, which allows to get the needed emittance shapes at the entrance of the IH-DTL. The adapter RFQ is designed for $\phi_{r} = -90^\circ$ in order to get maximum longitudinal focusing power and to reduce the vane-vane voltage. This leads to a rather simple structure with 11 identical cells.

<table>
<thead>
<tr>
<th>Characteristic Matching Section Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length / m</td>
</tr>
<tr>
<td>Magnetic Quadrupole Doublet</td>
</tr>
<tr>
<td>Effective Length / mm</td>
</tr>
<tr>
<td>Effective Gradient / T/m</td>
</tr>
<tr>
<td>Aperture Diameter / mm</td>
</tr>
<tr>
<td>Adapter - RFQ</td>
</tr>
<tr>
<td>Cell Number</td>
</tr>
<tr>
<td>Electrode Length / mm</td>
</tr>
<tr>
<td>Frequency / MHz</td>
</tr>
<tr>
<td>Peak Vane Voltage / kV</td>
</tr>
<tr>
<td>Min. Aperture Radius / mm</td>
</tr>
<tr>
<td>Modulation Factor</td>
</tr>
<tr>
<td>Synchr. rf Phase / deg</td>
</tr>
</tbody>
</table>

Fig. 1 Schematic of the Matching Section Components
Beam Dynamics Code Extensions

For beam dynamics calculations along the IH-DTL the LORASR code has been developed during several years. It is particularly well adapted to the beam dynamics concept of 'Combined Zero Degree Synchronous Particle Sections' [6]. With the standard routines drift tube accelerating sections as well as quadrupole lens sections can be calculated. A space charge routine is included. For the new matcher, the LORASR code had to be extended in order to calculate the matcher and the IH-DTL in one step. The aim was to have an additional tool for investigating short RFQ sections.

From a data set containing the maximum vane-vane voltage \( V \), the longitudinally effective voltage \( AV\pi/4 \), the cell number, the minimum aperture \( a \) and the synchronous phase for each cell, the code calculates the cell lengths \( \beta\lambda/2 \) and modulation factors \( m \) and simulates the RFQ fields based on the 2-term-potential description from ref. [7].

At \( \phi_0 = -90 \), the entrance and exit regions of the adapter RFQ are very sensitive with respect to fringe field disturbances, because the electrodes are on maximum potential at bunch passage. For that reason fringe field calculations are included, based on the analytical potential expansion as proposed in ref. [8]. Unfortunately it was not very well suited in the present case with matching in and out sections relatively short compared to the cell lengths and high modulation factors, so careful fitting of boundary conditions was necessary. To get rid of the disturbing higher order potential expansion modes along the real geometric distance from electrode end to the resonator end wall, the calculated space was extended by 80% beyond the end wall. This led to a remaining potential on the end wall of 5% of the max. electrode potential, the equipotential surface fitting rather well to the end wall geometry.

The main result on fringe field calculations was that beam quality deteriorations are kept small if the matching in and out region is short. Therefore it was decided to have a distance of 7 mm only between electrode ends and end walls.

Beam Dynamics Calculations

Calculations were performed with 4 different beam intensities of 0, 5, 10 and 16.5 emA respectively and with corresponding input particle distributions as derived from the main RFQ calculations. A optimum parameter set for each intensity was defined [9]. Additionally, the sensitivity of a given parameter set with respect to beam intensity changes was investigated.

In routine operation, the new LINAC will have to assure good beam quality at the full range of intensities and should be independent of beam intensity fluctuations.

Fig. 2 and 3 illustrate the calculation results for the entire matching section at 16.5 emA. The main characteristics are: the transverse beam envelope is rather smooth; the longitudinal focusing into the IH-DTL is done in a controlled way and is stable against moderate shifts of rf operation parameters at the RFQ and at the 'Super Lens'. The complete array is also resistant to the different beam parameter requirements described above.

Emittance growth is essentially due to space charge effects, because at low beam current values it is negligible.

Fig. 2. Transverse and longitudinal 100 % beam envelopes.

Fig. 3. Matcher Output Emittance Plots (16.5mA ; A/q=65).
Comparison with a Conventional Matching Array

In early design studies the possibility of using a conventional matching section was checked. The beam dynamics calculations result for a 16.5 emA beam with \( A/q = 65 \) is shown in Fig. 4 and 5. The corresponding parameters of the components are summarised in Table 2.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Parameters of the Conventional Matching Array Components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magnetic Quadrupole Triplet</td>
</tr>
<tr>
<td>Total Length / m</td>
<td>1.3</td>
</tr>
<tr>
<td>Effective Length / mm</td>
<td>230 ; 320 ; 190</td>
</tr>
<tr>
<td>Effective Gradient / T/m</td>
<td>65 ; 63 ; 65</td>
</tr>
<tr>
<td>Aperture Diameter / mm</td>
<td>36 ; 36 ; 36</td>
</tr>
<tr>
<td>Rebuncher Cavity</td>
<td></td>
</tr>
<tr>
<td>Gap Number</td>
<td>2</td>
</tr>
<tr>
<td>Total Length / mm</td>
<td>( \equiv 200 )</td>
</tr>
<tr>
<td>Peak Gap Voltage / kV</td>
<td>240</td>
</tr>
</tbody>
</table>

As the design presented in Fig. 4 has some disadvantages which will be mentioned below, it was decided early not to investigate this alternative further on, so that detailed calculations for different beam currents are missing. However from the experience with the 16.5 emA optimisation the design is expected to be much more sensitive to beam current and rf level variation.

From Fig. 4 it can be seen that before transverse focusing first becomes evident, a big beam radius of around 10 mm in one space is already reached, which makes refocusing by a long and powerful quadrupole triplet necessary. Placing the triplet in front of the rebuncher would have made the beam focusing into the IH-DTL even more complicated.

On the other hand, placing the rebuncher in front makes the longitudinal focusing difficult and sensitive to beam intensity fluctuations (Fig.5). One can see that a compact beam with small phase extension cannot be properly focused into the DTL. In fact it had to be enlarged in phase space at the main RFQ output, which needed additional matching out gymnastics at the main RFQ.

The emittance growth values for the investigated case were comparable to those of the new matcher.

![Figure 4](image.png)

**Fig. 4.** Transverse 100 % beam envelopes for the rebuncher cavity - quadrupole triplet configuration.

![Figure 5](image.png)

**Fig. 5.** Longitudinal 100 % beam envelopes for the rebuncher cavity - quadrupole triplet configuration.

Acknowledgments

Many thanks to all members of IAP - University Frankfurt engaged in this project - especially to A. Schempp - for the close collaboration in finding out the optimum beam parameters at the matcher input, and to J.Klabunde for the discussions on this subject.

References

SPACE CHARGE DOMINATED BEAM TRANSPORT IN THE 1.4 MeV/u-UNILAC-STRIPPER SECTION

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Abstract

The intensity upgrading program for the GSI accelerator facility comprises major modifications of the UNILAC for its operation as a high current injector into the heavy-ion synchrotron SIS. This paper focuses on space charge effects arising in the stripper section at 1.4 MeV/u between a new 36 MHz preaccelerator (under construction) and the existing Alvarez structures.

In this section the charge states of incoming ions, having a mass-to-charge ratio of A/q ≤ 65, are increased by stripping in a nitrogen jet to allow further acceleration at A/q ≤ 8.5. The anticipated high current beam of e.g. 4 pmA uranium will experience considerable space charge forces, most severely after the charge state jump in the stripper (from 4+ to an average charge state of 28+ for uranium).

The associated emittance growth has been studied for the present transport section, it was found to depend strongly on the underlying particle density distribution. The amount of 'useful' beam remaining within given emittance limits will be discussed.

Introduction

The goal to fill the SIS up to the space charge limit requires beam intensities of up to 15 emA ($^{238}$U$^{24+}$) in the UNILAC prestripper section. [1] The necessary replacement of the present Wideröe accelerator by a high current RFQ and two IH-type cavities will be realized in 1998. The beam transport at 1.4 MeV/u and matching from the exit of the IH-tank to the gas stripper, charge state separation after stripping and matching to the existing Alvarez poststripper linac, all under space charge conditions, have been studied.

<table>
<thead>
<tr>
<th>Table 1: Parameters of stripper section for uranium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
</tr>
<tr>
<td>238</td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Energy (MeV/u)</td>
</tr>
<tr>
<td>Bunch frequency</td>
</tr>
<tr>
<td>Phase width</td>
</tr>
<tr>
<td>Energy spread</td>
</tr>
<tr>
<td>Horizontal emittance</td>
</tr>
<tr>
<td>Vertical emittance</td>
</tr>
<tr>
<td>Relative space charge force (d)</td>
</tr>
</tbody>
</table>

(a) Present result of particle dynamics calculations in RFQ and IH
(b) Chosen for low emittance growth
(c) Upper limit, defined by the acceptance of SIS
(d) For identical bunch dimensions

As the present length of the stripper section may be maintained in the future, the study has to resolve if the existing installation, modified as shown in Fig. 1, is capable of high current operation. Emphasis is given to the study of emittance growth as the SIS poses limits; the acceptance of the poststripper Alvarez section is uncritical. Table 1 summarizes the beam parameters at the IH exit, at the gas stripper and at the entrance of the Alvarez structure.

UNILAC stripper section as studied for high current beam transport

Fig. 1. Optical elements and beam diagnostic devices in the stripper section between IH exit and the Alvarez accelerator, including the gas stripper ST and the charge analysing system of four dipoles D30.

The mechanical layout of the stripper section is shown in Fig. 1. Two quadrupole doublets and a six gap rebuncher (operating frequency 108 MHz) are provided to match the beam to the gas stripper. The charge separator is composed of four 30° bending magnets, charge separation is required between the second and third dipole at maximum dispersion. Transverse and longitudinal matching to the poststripper linac is done with a quadrupole doublet, a triplet and two 36 MHz rebunching cavities.

Matching to the gas stripper

Due to the beam current jump in the stripper (e.g. 12 mA to 105 mA) the downstream section up to the charge analysis is heavily space charge loaded (see Table 1). By iterative
calculations reasonable beam properties at the gas stripper were found, which allow the beam passage through a 9 mm aperture, minimize emittance growth and account a larger growth value to the vertical plane as allowed by the SIS acceptances (Table 1). As a consequence a bunch width of \( \pm 25^\circ \) (36 MHz) at the stripper is demanded and beam waists are to be located before resp. after the stripper in the vertical resp. horizontal plane.

Fig. 2. Transverse matching to the gas stripper, calculated with the code MIRKO. [2] Notations see Fig. 1.

Fig. 3. Long. matching to the gas stripper, calculated for a KV-distribution with PARMT.

Fig. 4. Transverse KV- and longitudinal homogenous phase space distribution at the stripper position corresponding to the input beam parameters of Table 1.

The envelope matching to the gas stripper including space charge forces is shown in Fig. 2. The required bunch length is obtained by transforming the beam to an energy spread of \( \pm 1.7\% \) in the six gap structure with gap voltages of 0.6 MV. Quadrupole strength up to 12 T are required due to the magnetic rigidity of the beam of 10 Tm.

Emittance growth in this section is below 10 % for all planes and different particle distributions. A KV distribution remains virtually undistorted (Fig. 4).

**Charge separation and matching to the poststripper linac**

In the section from the stripper to the entrance of the Alvarez accelerator the electrical beam current is reduced by the charge state separation (from 105 mA \(^{238}\text{U}\) of average charge state 28 to 12.5 mA \(^{238}\text{U}_{28}\)). An exact modeling of the space charge effect in the separation process, not yet possible with existing tools, was approximated by a current jump before the second dipole magnet. The transverse and longitudinal beam envelopes are given in Fig. 5 and Fig. 6.

Fig. 5. Transverse beam dynamics between the stripper and the entrance of the poststripper linac (notations as in Fig. 1).

Fig. 6. Longitudinal beam dynamics between the stripper and the entrance of the poststripper linac.

Growth of energy spread by space charge forces after the stripper is obvious in the plot of the particle dynamics calculation. The bunches are required to limit the initially large phase width growth and to produce short bunches at the Alvarez entrance.

**Emittance growth effects**

The charge separator is an achromatic system and the stripper gas jet density of 4\( \mu \)g/cm\(^2\) is too low to induce significant energy or angular straggling. Therefore the emittance growth is dominated by space charge forces.
As an example the horizontal rms-emittance growth along the beamline is shown in Fig. 7, calculated with a KV-distribution and a more peaked distribution (homogenous in a six dimensional hyperellipsoid folded with a Gaussian and cut at 3σ) on the basis of particle-particle interaction. The apparent emittance growth by dispersion is compensated behind the magnet system, leaving the current and distribution dependent space charge effect. For low intensities the net emittance growth is zero.

![Graph showing rms-emittance growth after stripping for three different distributions calculated by PARMT.](image)

Fig. 7  The rms-emittance growth after stripping for three different distributions calculated by PARMT.

Starting with different particle distributions, which all hold 90% of the intensity in emittance areas as given in Table 1, the rms emittance values at the end of the stripper section have been calculated for the three phase planes.

Fig. 8 is a summary of the results. Type 2 is a homogenous distribution in a six dimensional hyperellipsoid. The distributions 12 to 42 have increasingly intensified cores, which result in increasing emittance growths by up to a factor of 2 compared to the homogenous distribution.

![Graph showing rms-emittance for different input particle distributions.](image)

Fig. 8  Rms-emittance for different input particle distributions.

In such a "peaked" distribution the electric field rises more steeply near the center than at the edge; this deviation from linearity causes "ears" of the distribution (Fig. 9), which increase the emittance areas.

![Graph showing results of multiparticle calculations for three different input distributions.](image)

Fig. 9  Results of multiparticle calculations for three different input distributions.

More relevant for the injection into the SIS than the rms emittances is the intensity fraction remaining within the acceptances of the SIS listed in Table 1. Table 2 shows the fraction of beam intensities matching the requirements in the three phase space planes. For the not unrealistic distributions of type 42 the more prominent peaking of the particle density leads to less acceptability; however the loss of useful intensity is less than might be expected from the rms-emittance growth.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>KV</th>
<th>Type 2</th>
<th>Type 42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>0.92</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Vertical</td>
<td>0.82</td>
<td>0.78</td>
<td>0.62</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>1.00</td>
<td>1.00</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Table 2  Fraction of beam intensities corresponding to the design emittances (see Table 1)

### Conclusion

With respect to emittance growth a rather homogenous particle density in the bunch is favourable. Aside from attempting to achieve flatter distributions from the IH-accelerator the activities concerning emittance growth will also cover a rigorous shortening of the very-high-current section, an increase of transverse beam size at the stripper position, analysis and optimization of the charge separation process and beam neutralisation in drift spaces.

### References

1. U. Ratzinger, The new GSI Injector linac for high current heavy ion beams, these proceedings.
HIGH-INTENSITY LOW ENERGY BEAM TRANSPORT DESIGN STUDIES FOR THE NEW INJECTOR LINAC OF THE UNILAC

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Abstract

GSI will replace the Wideröe prestripper linac by an RFQ and IH-type accelerator presently under construction. The new prestripper linac should deliver beam intensities to fill up the heavy ion synchrotron SIS to the space charge limits for all ions. In case of uranium the new injector has to deliver 15 emA U¹⁺. One of the two existing ion-source terminals has already been rebuilt for installation of the high current sources of CHORDIS- and MEVVA-type. Therefore, investigations of high-current beam transport have been made in the existing LEBT. For that, additional beam diagnostic elements have been installed: beam transformers, emittance measurement devices, residual gas ion spectrometer. The measured beam properties, e.g. transverse emittance, degree of space charge compensation, support the design of the future LEBT. According to the various requirements two layouts of the new LEBT have been studied so far.

Introduction

To improve the high-current performance of the UNILAC for injection in the SIS the Wideröe prestripper accelerator will be replaced by an RFQ and an IH-type accelerator [1]. This requires also a redesign of the LEBT from the ion source to the RFQ entrance. For that, the following basic requirements on the beam dynamics have to be considered: High transmission for the high-current beam, preservation of the brilliance along the beam line, isotope separation even for the heaviest elements, achromatic image and slope at the end of LEBT, transverse phase matching to the RFQ, and insensitivity to space charge and energy fluctuations of the beam.

The study of the future LEBT profits greatly from beam investigations at the present beam transport system. Measurements of beam transmissions, transverse emittances, degree of space charge compensation, comparison of beam simulations with experimental data, etc. support the LEBT design considerably.

In the first part measurements on high-intensity beams will be reported. Afterwards different layouts of a new LEBT will be discussed.

Measurements on High-Intensity Beams

The existing injection beam line between the high current ion source and the switching magnet has been equipped with additional beam diagnostic instruments as shown in Fig. 1. The beam transmission has been measured by Faraday cups and calibrated beam transformers. The transverse emittances have been measured by slit-collector systems.

These measurements give information about the brilliance of the beam. Emittance growth along the beam line can be detected. Also profile measurements at different positions will support the evaluation of the beam simulation model.

Fig. 1. Present low energy beam transport line.

Space charge potential and build-up time of beam neutralization can be measured by a new residual gas ion spectrometer. Description of this system and first measurements will be reported in a separate contribution of these proceedings [2].

In Table 1 some representative results of emittance measurements are given for different ion species delivered from the high-current sources CHORDIS and MEVVA, the beam energy was 11.7 keV/u. The beam transfer from DB2 to DB4 (see Fig. 1) was simulated with the ellipse transformation code MIRKO and the Monte Carlo code PARMT.

<table>
<thead>
<tr>
<th>Ion species/ current (mA)</th>
<th>Source type</th>
<th>Locus</th>
<th>$\varepsilon_x$ (95%)</th>
<th>$\varepsilon_y$ (95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}$Ne⁺/16</td>
<td>CHORDIS</td>
<td>DB 2</td>
<td>56</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DB 4</td>
<td>56</td>
<td>57</td>
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Figure 2 shows results of beam dynamics calculations at different current levels. Measured emittances and computed
phase space ellipses at zero current coincide each other. Therefore, a high degree of space charge compensation can be stated. This result was also confirmed by beam width measurements behind the bending magnet where a very small horizontal beam size was adjusted at the mass separator slits. Figure 3 illustrates the big increase of beam width if the beam simulation includes space charge forces. The measured beam width agrees very well with the zero-current simulation.

Fig. 2. Transverse emittances at DB4 calculated for different effective currents.

Fig. 3. Computed beam width at the spectrometer slits.

The comparison of emittance areas listed in Table 1 indicates that there is no evident growth between the diagnostic stations DB2 and DB4. This result is in full agreement with PARMT simulations (at I = 0), higher order effects are included.

Properties of the Existing LEBT

The existing LEBT as shown in Fig. 1 has been studied for the use of high-intensity beam transport for the new injector. To match the beam to the RFQ acceptance it has to be partly rebuilt. Figure 4 shows the transverse beam envelope matched by four quadrupole magnets to the RFQ acceptance. The envelope is based on an emittance of 138 $\pi$-mm-mrad in both planes, corresponding to the RFQ acceptance.

The high current sources deliver beam pulses of 1–2 ms length and a repetition rate $\leq$ 5 Hz for the heavy ion synchrotron. The PIG sources serve the low energy experimental area with a second beam of up to 6 ms length and a repetition rate of 50 Hz. For future time sharing operation laminated magnets are planned.

Fig. 4. Transverse beam envelope calculations for the existing mass spectrometer and a matching quadruplet in front of the RFQ.

The layout of the complete LEBT including also the PIG source beam line is presented in Fig. 5.

Fig. 5. Mechanical layout of the studied LEBT, a shortened version of the existing LEBT.

The 77.5° spectrometer magnet performs a mass resolution $m/\Delta m = 220$. This allows the isotope separation of all elements which is necessary for many experiments and reduces the space charge forces in the following transport and accelerator sections.

This LEBT is achromatic only in the way that particles of different energies coincide in a focus at the RFQ entrance but unfortunately with different angles. This is shown in Fig. 6.

Emittance measurements directly behind the variable high voltage gap (DB1 in Fig. 1) turned out that the emittance areas are in the range of 70–90 $\pi$-mm-mrad at the new energy of 2.2 keV/u and have constant orientation. The acceptance of the LEBT and the RFQ of 138 $\pi$-mm-mrad allows therefore a certain emittance growth due to momentum spread or space charge of the beam. Investigations carried out with PARMT prove a possible momentum spread $\Delta p/p \leq 5 \times 10^{-4}$ which is higher than the specified stability of the high voltage power supplies. Space charge forces at a current of 0.5 mA would
cause an emittance growth of about 70%, which would fill the RFQ acceptance completely.

![Image](image_url)

Fig. 6. Horizontal envelope for a beam with a momentum deviation of $\Delta p/p = 0.001$.

**Study of an Achromatic LEBT**

A new LEBT design was studied which should be doubly achromatic to prevent beam loss due to instabilities of the extraction and preacceleration voltage of the order of $10^{-3}$ due to current fluctuations. Furthermore, it should be capable to transport space charge dominated beam.

The envelopes of the new transport system are presented in Fig. 7. A magnetic quadrupole triplet adapts the beam onto the achromatic deflector consisting of two 45° sector field dipole magnets with an intermediate quadrupole singlet. The dipole edges are vertically focusing. Two quadrupole triplets match the transverse emittances to the RFQ acceptance.

![Image](image_url)

Fig. 7. Beam envelope in a double achromatic system for a space charge force of 4 mA and dispersion trajectory for an energy deviation of 14%.

Q: magnetic quadrupoles, D: dipole magnets.

Mass separation was given up to the benefit of an effective space charge increase to 4 mA, equivalent to a compensation degree of 75%.

Multi-particle calculations for this LEBT were done with the PARMT code considering higher order effects. At an effective beam current of 4 mA a transmission of 100% is obtained with an emittance growths of 35% for the horizontal and respectively 31% for the vertical plane. So only 80% of the RFQ acceptance of 138 $\pi$ mm-mrad is occupied by the calculated phase space distribution.

Investigations of the sensitivity for energy fluctuations show an effective emittance growth caused by chromatic aberrations of the magnetic quadrupoles.

![Image](image_url)

Fig. 8. RFQ acceptance (dotted) and beam emittances for three energy deviations: 0, + 2.8%, - 2.8%.

Figure 8 shows the transversal beam emittances for an energy spread of ± 2.8%. This value is by far higher than assumptions of the order of $10^{-3}$ for high-intensity beams. Fast intensity fluctuations which partly convert into energy spread are therefore not critical.

Also fluctuations within a macropulse of ± 14% of the effective space charge current of 4 mA do not exceed the RFQ acceptance for fixed quadrupole settings.

**Conclusion**

The existing LEBT modified for high-current injection performs high mass resolution, is compact, and enables a low cost modification for high-current operation. The sensitivity for dispersion limits the energy spread to ± $10^{-3}$. The space charge sensitivity needs a space charge compensation degree ≥ 90%.

The alternative LEBT design is doubly achromatic, and therefore insensitive to energy spread or fluctuation up to ± 2.8%. Current fluctuations of ± 14% will be accepted by the LEBT and the RFQ. Even at a space charge compensation of only 75% complete transmission can be reached.

The low momentum resolution of this LEBT design allows only the separation of charge states. Further studies are going on to achieve the high mass resolution additionally.

**References**


Design and Wakefield Performance of the New SLC Collimators

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Abstract

The very small transverse beam sizes of the flat SLC bunches are 100–170 µm in the horizontal and 30–50 µm in the vertical near the end of the SLAC linac. Unexpectedly large transverse wakefield kicks were observed from the collimators in this region during 1995. Upon inspection, it was found that the 20 µm gold plating had melted and formed a line of spherules along the beam path. To refurbish the collimators, an improved design was required. The challenging task was to find a surface material with better conductivity than the titanium core to reduce resistive wakefields. The material must also be able to sustain the mechanical stress and heating from beam losses without damage. Vanadium was first chosen for ease of coating, but later TiN was used because it is more chemically inert. Recent beam tests measured expected values for geometric wakefield kicks, but the resistive wall wakefield kicks were four times larger than calculated.

1 Introduction

To suppress background in the detector, collimators are used at the end of the SLC linac. The surface of these collimators were inspected in 1995 and the gold coating on the titanium jaws was found to be severely damaged. A dark 1 mm wide stripe along the beam path was visible, which consisted of gold flakes and spherules of ≈250 µm diameter (Fig. 1). They were responsible for a 25–50 times larger than expected wakefield kick [1]. A new durable surface material for the coating was necessary with high conductivity to reduce resistive wakefields.

Fig. 1: Damaged collimator surface (stripe width ≈1 mm). The beam enters at the left, creating gold flakes and spherules.

2 Coating Material for Collimators

The core material for the collimator jaws is a titanium alloy Ti-6Al-4V, which best survives beam impact. The coating material requires a higher conductivity (Table 1, [2]).

2.1 Background Issues

The surface material chosen initially was gold to give the particles scattered out of the core material additional dE/dx loss. This was a compromise between the desire to reduce background to the detector as well as resistive wakefields contributions and the known hazards of higher single bunch temperature spikes and resulting thermal shock waves. Since the linac collimators are 1.5 km from the interaction point and additional downstream clean up collimation exists, the high Z surface requirement has now been eliminated.

2.2 Survivability

With respect to survivability of the surface coating, no material is an obvious choice. But since the resistivity of Ti-6Al-4V is about 70 times larger than gold (the resistive

<table>
<thead>
<tr>
<th>Material</th>
<th>Z</th>
<th>X/ρ (cm)</th>
<th>T_{melt} (°C)</th>
<th>R (μΩ-cm)</th>
<th>E (10^4 psi)</th>
<th>α (10^4 °C^-1)</th>
<th>Eα (psi °C^-1)</th>
<th>Eα/σ_{UT} 10^3 °C^-1</th>
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<td>2930</td>
<td>22</td>
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<td>8.0</td>
<td>7.4</td>
<td></td>
<td></td>
<td>0.21</td>
</tr>
</tbody>
</table>

* Work supported by DOE, contract DE-AC03-76SF00515.
wakefield kick would be $\sqrt{70}$ times larger), a material with less sensitivity (up to 10 times of gold) was needed. Nickel, vanadium, and TiN fall into that range. Nickel is somewhat ferromagnetic at the high frequencies of the short bunch, it is difficult to coat and its figure of merit ($E\sigma/c\sigma_{\text{crit}}$) is marginal, but it has the best resistivity (7 $\mu\Omega\cdot$ cm). Vanadium has a larger resistivity but sputters more easily onto Ti. Some collimator jaws were coated with vanadium, which is fine for dry air or vacuum. Unfortunately, it chemically reacts with water and presents handling problems. The final choice was TiN, a golden looking coating (e.g. on drill bits) with a resistivity of 22 $\mu\Omega\cdot$ cm. Not all of the material properties are understood (blank in Tab. 1), but a test with an electron arc welding torch showed good survivability for TiN. The hard coating might allow the phonon shock wave to penetrate to the Ti, while at a gold-Ti boundary it would be reflected [3].

3 Collimator Wakefields

The close proximity of the jaws to the beam (0.8-1.2 mm gap) will lead to wakefields. The following discusses different types due to their origin: geometric, resistive, and "granularity" wakefields with their linear and quadratic effects.

3.1 Geometric wakefield

The peak dipole component of the geometric wakefield for a round collimator (flat: $\pi/8$ larger) is [4]

$$\Delta y = \frac{4\pi N r_e}{\Phi^{1/2}}$$

which is 2 $\mu$rad for $N = 5 \times 10^{10}$ particles, a bunch length $\sigma_z = 1.25$ mm, energy factor $\gamma = 90000$, classical electron radius $r_e$, and a beam offset $y$ equal to the pipe radius $a$. This has to be compared to a beam size $\sigma_y = 50$ $\mu$m, and an angular divergence $\sigma'_y = 1.0$ $\mu$rad for an emittance $\mathcal{E}_y = 0.45 \times 10^{-5}$ m-rad and a betatron function value $\beta = 50$ m. These beam parameters are assumed throughout the paper. The effect of the kick is illustrated in Fig. 2.

By rounding the edges ($r = 9$ mm) the geometric wakefield component of the tapered collimator ($R = 10$ m) is reduced by a factor of 2. This then gives an expected maximum dipole kick for our flat jaws of $\Delta y = 1.3$ $\mu$rad. A $3\sigma'_y$ kick gives an emittance growth of about 30% and 5$\sigma'_y$ about 60%.

The higher order component of the geometric wakefield was calculated with MAFIA [4] and the result divided by 2 for the rounded edges. This simulation agrees well with a round collimator scaling estimate for $y'$

$$\sum_{m=1}^{\infty} \frac{m^2}{m^2 r^2} = \frac{\ln(1-r^2)}{r^2}$$

where $y'_2$ is the offset of a second (test) particle within the centered bunch. For a half-gap of $a = 0.5$ mm and a $\Delta y = 1.3$ $\mu$rad this results in a differential quadrupole kick over the bunch with a maximum which is about 20% of a typical magnetic quadrupole strength at the end of the linac. This effect is somewhat reduced since the x and y collimator jaws are close together and have usually similar gaps ($5\sigma'_y = 800$ $\mu$m, $10\sigma'_y = 500$ $\mu$m), and therefore cancel each other.

3.2 Resistive wakefield

The resistive dipole wakefield kick due to parallel resistive plates of length $L$ is [6]

$$\Delta y = \frac{\pi r_e N L}{4k^2 \gamma (\sigma_{\text{crit}})} f(s/\sigma_z)^{1/2}$$

with a maximum kick of 0.95 $\mu$rad ($a = 0.5$ mm, $f = 1$, and a conductivity $\sigma = 4.1 \times 10^{17}$ s$^{-1}$ for TiN.
To get the higher order components, the term $y/a$ has to be replaced by the following (with $r = y/a$):

$$\frac{1}{\pi} \frac{\pi r + \sin \pi r}{1 + \cos \pi r}.$$

3.3 “Granularity” wakefield

The wakefield due to the spherules was roughly estimated to be [7]:

$$\Delta y = \frac{r e N L}{4 \sqrt{\pi a^2 \gamma \sigma_z}} g \left( \frac{y}{a} \right)$$

where 25% of the surface is covered with spherules and $g$ is the granularity (or corn size). Comparison to the resistive wakefield yields:

$$g = \frac{\pi^{3/2}}{\sqrt{\sigma}} \frac{c \sigma}{\sigma_z}.$$  

For $g = 250 \mu m$ the resultant kick is about 50 times the resistivity kick from gold. This explained the large wakefields of the damaged parts.

4 Experimental Results

The collimators were set to a specific gap size $2a$, and moved across the beam. The beam position monitor signals up- and down-stream were recorded to measure the kick, the beam loss and the incoming offset (Fig. 4).

The expected and measured kicks for $a = 0.5 \, \text{mm}$ are summarized in Table 2. The average kick over the beam from the form factor $f$ is 0.71 (geometric) and 0.78 (resistive). The 40% bigger kick for the geometric part might be due to the uncertainty of the rounded edges. But the factor of 4 difference in the resistive part is so far unexplained.

![Fig. 5: Slope of the linear part of the wakefield kick versus $1/a$. The fit (solid) shows a kick about a factor of 4 higher than expected for the resistive wakefield.](image)

Table 2

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Wakefield kicks in $\mu$rad.</th>
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<tbody>
<tr>
<td>Geometric</td>
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<tr>
<td>Au</td>
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<tr>
<td>V</td>
<td>0.74</td>
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<td>Au, damaged</td>
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</table>

5 Summary

The new collimators with TiN (and V) coatings have survived beam impacts. The wakefield kicks were reduced by a factor of four. The measured resistive wall wakefield kick is a factor of 3-4 larger than expected.

References

Long-Range Wakefields and Split-Tune Lattice at the SLC


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Abstract

At the SLC, a train consisting of one positron bunch followed by two electron bunches is accelerated in the linac, each separated by about 60 ns. Long-range transverse wakefields from the leading bunch were found to cause up to a factor of three increase in beam jitter for the trailing bunches. Incoming jitter is efficiently damped by BNS damping, but excitations in the middle of the linac from sources such as long-range wakefields can grow in amplitude. To measure the wake function, the time difference between the positron and electron bunches was changed, determining the frequency and strength of the dominant mode contributing to the dipole wakefield. By splitting the horizontal and vertical phase advance, or 'tune', of the magnetic lattice, it was possible to decrease the resonant excitation from these wakefields and thereby reduce the jitter of the electron beam by a factor of two.

1 Introduction

Long-range wakefields cause beam break up in multi-bunch beams [1]. The NLC design has adopted the use of damped and detuned structures to overcome these difficulties [2]. In the SLC the problem is less severe since the e⁺ and e⁻ bunches can be individually steered due to their different beta-functions. However positron jitter translates via transverse wakefield kicks into electron jitter, and a positron orbit change (arising e.g. from orbit oscillations for emittance reduction [3]) will also change the electron orbit. The magnitude of these effects were measured by kicking the positron beam in the ring-to-linac beamline (RTL) and measuring the orbits for both beams in the linac. Observations and experiments are discussed, which led to a cure for the jitter.

2 Operational Observations

Several indirect observations indicated that the dominant beam jitter in the vertical plane for electrons was due to long-range transverse wakefields from the positrons. Large electron y jitter, amplified along the linac about 6 times more than expected from the short-range wakefields [4], e⁺/e⁻ jitter correlation, xy y jitter correlation, and the fact that the electron jitter was reduced by a factor of two if the positrons were not present, all were noted. While beam loading changes with positron intensity was a possible explanation, the long-range transverse wakefield hypothesis was confirmed in the following experiments:

a) kick the positrons in the RTL to induce a large oscillation in the linac, measure the electron orbit shift,

b) change the positron-electron bunch separation and look for changes in the amplitude response.

3 Oscillation Experiments

Figure 1 (a) shows an example in which the positron bunch is kicked in the RTL. A large excitation of the electron bunch in the linac results (b). For a 1 mm oscillation with 3.3·10¹⁰ particles in the positron bunch, the amplitude is 250 μm in electron x, and 500 μm in electron y. The positron oscillation is seen to dephase to 100 μm at the end of the linac.

Fig. 1: (a) A positron oscillation in the SLC linac kicks the electrons via long range transverse wakefields, (b) for the design lattice, and (c) the new split-tune lattice (compare Section 6).

Orbits were also measured for different e⁺ and e⁻ bunch spacings, necessarily adjusted in steps corresponding to −2, −1, 0, and +1 S-band buckets, or 0.35 ns intervals. The electron oscillations are locally 90° out of phase with respect to the positron oscillations, as expected if they are driven by the latter. Their amplitude varies in sign and magnitude with the positron bucket. Figure 2 shows the measured signed amplitude vs. bunch spacing fit to a single mode (see Section 5), which is thus determined to have a frequency of 4141.7 MHz and amplitude of 350 μm for a 1 mm oscillation with 3.3·10¹⁰ positrons. Shifting the frequency to 4144.5 MHz (dashed curve) would zero the wakefield at the operation separation of 59.0 ns. Early in the history of SLAC [2], cells 3, 4, and 5 following the input couplers in selected accelerator sections were 'dimpled' to raise the modes by either

* Visiting scientist from KEK.
* Work supported by DOE, contract DE-AC03-76SF00515.
2 or 4 MHz. Therefore implementing such a frequency shift appears to be feasible.

![Graph showing measured wakefield kick vs time for different positron buckets.](image1)

Fig. 2: The average kick in amplitude and sign is plotted versus the time for the different positron buckets. The solid curve has a frequency \( f = 4142 \) MHz while \( f = 4144.5 \) MHz for the dashed curve.

### 4 Static Bucket Changes

In addition to communicating jitter from the leading positron bunch to the following electron bunch, the long-range wakefield will be excited to the extent that the average steered positron trajectory is offset in the accelerator structures. This 'static' long-range wakefield effect is manifested when the distance between the positron and electron bunches is changed. Figure 3 shows the measured trajectory shift due to a shift in the positron-electron separation by one S-band bucket. The positron orbit shift reflects beam jitter and position monitor noise, while the electron shift is clearly an oscillation driven by the static positron wakefield. Its 150 \( \mu \text{m} \) peak amplitude is large compared to the 20 \( \mu \text{m} \) expected from a single 12 m long structure offset by 1 mm.

![Graph showing difference orbit in the electron beam by moving the leading positron bunch by one bucket.](image2)

Fig. 3: Difference orbit in the electron beam by moving the leading positron bunch by one bucket.

Static long-range wakefield effects are not very important for the SLC operation, since they can be steered out. The measurements of the static \( e' \) deflections due to bucket changes however, contain information about the offsets between the positron trajectory and the accelerating structure, including structure misalignments. Preliminary studies aimed at isolating structure misalignments from bucket shift data have demonstrated the need for further work before the technique can be applied to practical alignment problems.

### 5 Theoretical Estimates

Figure 4 shows the dipole wakefield for the SLAC linac structure, calculated using a two-band circuit model [5]. Although the lowest dipole mode has the strongest kick factor of the structure by at least a factor of two, there are about 50 modes of similar strength that span 4140 MHz to 4320 MHz. These modes rapidly decohere for increasing bunch separation up to 10 ns, after which they partially recohere, exhibiting various beating patterns.

![Graph showing theoretical calculation of the transverse wakefield vs time for the lowest dipole modes of the SLAC structure.](image3)

Fig. 4: Theoretical calculation of the transverse wakefield vs time for the lowest dipole modes of the SLAC structure.

In the neighborhood of 59 ns, where the SLC normally runs, a single frequency with an amplitude \( W_\perp = 0.13 \) V/pC/mm/m dominates. This is relatively weak compared to the short-range wakefield which peaks at \( W_\perp = 5 \) V/pC/mm/m, and averages \( W_\perp = 0.9 \) V/pC/mm/m over a 1 mm (rms) bunch. In addition, non-cylindrically symmetric external loading gives a damping factor \( w_\perp \) different in \( x \) and \( y \). For our regime \( w_\perp = 0.85 \) and \( w_\perp = 0.45 \), since the input couplers are oriented horizontally. A 1 mm oscillation extending over 500 m of a bunch with \( 3.5 \times 10^9 \) particles induces an oscillation with a peak transverse momentum \( eV_\perp = 1/2 W_\perp (500 \text{ mm-m}) (3.6 \text{ nC}) w_\perp = 155 \text{ keV/c} \). For a 8 GeV beam this corresponds to an angle of ~20 \( \mu \text{rad} \), and for \( \beta = 20 \text{ m} \) a peak position offset \( \Delta y = 400 \mu \text{m} \), in agreement with measurements (Fig. 2).

### 6 Split-Tune Lattice

In a simple FODO lattice, the long-range wakefield produced by coherent betatron oscillations in a leading positron
bunch will resonantly drive betatron oscillations in a trailing bunch. Despite their opposite electric charges, both bunches see the same magnetic lattice (offset by one quadrupole), and hence have identical free betatron frequencies. The resonance is easily alleviated, however, by using a less symmetrical 'split-tune' lattice in which 'focusing' and de-focusing magnets are given different absolute strengths. The betatron phase advance in the x and y planes for a particular charge differ, and are interchanged for the opposite charge.

A phase advance difference $\Delta(\Delta\psi)$ between the two bunches accumulated over some length of the linac will inhibit the growth in the trailing bunch's oscillation amplitude by $\sqrt{2(1 - \cos[\Delta(\Delta\psi)][1/\Delta(\Delta\psi)])}$ relative to perfect resonance. Thus $\Delta(\Delta\psi) = 218^\circ$ is required for a factor of 2 reduction, $262^\circ$ for a factor of 3, and $885^\circ$ for a factor of 7.8. The corresponding F-D magnet fractional strength difference to produce a unit (small) phase advance split, $1/2 \cos((\Delta\psi + \Delta\psi_{cell})/4)$ for thin quadrupoles, is typically $0.617%$ per cell (for an average $90^\circ$/cell lattice).

A split-tune lattice was implemented in the first half of the SLC linac—more precisely in Sectors 2 through 16, comprising 79 FODO cells. 31 cells (sector 2, 3, and 4) had had nominal $90^\circ$/cell phase advance in both planes, and the remaining 48 had had $76^\circ$/cell. The new lattice has 31 cells with average $\Delta\psi_x \equiv 95^\circ$, and $\Delta\psi_y \equiv 91^\circ$, and 48 cells with $\Delta\psi_x \equiv 81^\circ$, and $\Delta\psi_y \equiv 69^\circ$, all as seen by electrons. Thus the absolute accumulated phase advance difference between electrons and positrons, in both planes, is $680^\circ$.

The choice of 'sign' for the split, i.e., the fact that the positron y plane phase advance is the larger, was made on the basis of its implications for intra-bunch (short-range) wakefield effects. An essential component in the control of the latter in the SLC is BNS damping [6], in which a systematic energy variation along the bunch, in conjunction with phase advance chromaticity, inhibits the resonant excitation of oscillations in the tail of the bunch, and partially compensates the short-range wakefield phase shift. Since the vertical jitter sensitivity is the greater, the positron jitter has tended to be worse than the electron, and a reduction in the former leverages a reduction in the latter, the chosen split direction favors positron vertical phase advance chromaticity. The beam envelope (beta-function) is little affected by the asymmetry in 'focusing'.

Figure 1 (c) shows about a factor of 3 less $e^+$ to $e^-$ coupling. This reduced the rms jitter by about 30% in y from 75% to 50% of $\sigma_x$, and 15% in x from 40% to 35% of $\sigma_x$. (see Fig. 5).

![Fig. 5: Jitter reduction after the introduction of the split-tune lattice.](image)

7 Conclusion

The static effect of long-range transverse wakefield kicks from positrons to electrons were measured, but they can be generally tuned out. However a jittery positron beam has caused an even higher electron jitter. The split-tune lattice has helped to reduce that effect below the natural jitter of the electron beam.

References

Higher Order Beam Jitter in the SLC Linac

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Abstract

The pulse-to-pulse behavior of the beams in the SLC linac is dominated by wakefields which can amplify any other sources of jitter. A strong focusing lattice combined with BNS damping controls the amplitude of oscillations which otherwise would grow exponentially. Measurements of oscillation amplitude along the linac show beam motion that is up to six times larger than that expected from injection jitter. A search for possible sources of jitter within the linac uncovered some problems such as structure jitter at 8 to 12 Hz, pump vibrations at 59 Hz and 1 Hz aliasing by the feedback systems. These account for only a small fraction of the observed jitter which is dominantly white noise. No source has yet been fully identified but possible candidates are dark current in the linac structures (not confirmed by experiment) or subtle correlations in injection jitter. An example would be a correlated x-z jitter with no net offset visible on the beam position monitors at injection. Such a correlation would cause jitter growth along the linac as wakefields from the head of the bunch deflect the core and tail of the bunch. Estimates of the magnitude of this effect and some possible sources are discussed in this paper.

1 Introduction

After the sawtooth instability [1] in the damping rings of the Stanford Linear Collider (SLC) was fixed (reduced) by changing the impedance of the vacuum chamber [2], the current in the linac could be raised from about $3 \times 10^{10}$ to $3.5 \times 10^{10}$ particles per bunch in the 1994/95 run. This resulted in an enormous amount of transverse beam jitter of $\Delta y/\sigma_y = 0.6-0.8$. Many correction schemes for measuring the beam properties evolved, but some reduction in $e^{-}$ jitter was achieved by splitting the phase advance to generate a decoherence in the long-range wakefield excitation [3]. The jitter still remained big and besides some distinct frequency lines [4], the jitter is coming from a white noise source which grows by a factor of up to six in the linac [5]. Possible candidates were: (a) dark currents in the structure exciting transverse kicks (this could not be confirmed), and (b) higher order jitter effects. Under this term we understand, that the whole jitter is already fully developed, but hidden at the beginning of the linac. The easiest understanding would be an $x$-$z$ correlation jitter, where the head and tail distribution cancels the jitter in the beginning but it develops an $x$ jitter down the linac due to the wakefield of the offset head particles. Another type of 'hidden' injection jitter is due to bunch length variations, which would change the linac transport properties. In the sections that follow we discuss those two sources of hidden jitter after reviewing the characteristics of the linac jitter growth.

2 Correlated and Uncorrelated Jitter

By launching a betatron oscillation and looking at the amplitude and phase down the linac, one can measure the effective $R_{ij}$ and their determinant. Transverse wakefields and BNS-damping change the behavior compared to the model lattice.

Since the jitter could be partly visible and partly hidden, the complex correlation of $(x, x')$ in the beginning with $(x, x')$ at the end could uncover some of that higher order jitter. But there was still the biggest factor uncovered (see Fig. 1).

Fig. 1: Measured correlated and uncorrelated jitter development in the linac. While the correlated part (dash) shows the expected jitter profile (up and then down), the uncorrelated part (dash-dotted) grows steadily.

3 Definition and Examples of Higher Order Jitter

Under the definition of higher order jitter we would like to understand any jitter, which is fully present, but hidden at the beginning of a system (e.g. linac) and gets only altered, amplified, or uncovered in that system. No other source in that system (linac) should be counted to "higher order jitter", it is only the hidden, incoming jitter.

An example is a jittery $x$-$z$ correlation at the beginning of the linac. Compared to the normal transverse jitter, which puts the whole bunch to an offset $\Delta x \neq 0$, it puts the head and the tail to opposite directions $\Delta x_{\text{head}} = -\Delta x_{\text{tail}}$ so that $\langle \Delta x \rangle = 0$. The development in the linac is shown in Fig. 2.

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Fig. 2: The normalized jitter in the linac is not constant for high current, but can grow or damp depending on the BNS damping setup. A typical SLC behavior is shown at the top (N = 0), while a higher order jitter (N = 1, bottom) is invisible with a normal BPM at the beginning, but then grows to the same amplitude.

The jitter amplitudes at the beginning were chosen so that there is a 60% jitter (Δy/σy) at the end for all cases with a normalized emittance of 3x10⁻⁸ m-rad and 3.5x10⁹ particles per bunch. The necessary initial jitter scales like

\[ \sigma_{0}(x) = 20 \mu m \langle z/\sigma_z \rangle^{0.5/2^{2}}. \]

One source of such a jitter is a bunch length change Δσ in the damping ring, which creates an energy spread change ΔE/E in the bunch length compression systems. If, additionally, η, η' or their higher order terms (T_{166}, U_{166}) are not exactly zero, a higher order transverse offset change is introduced. A linac bunch length change is also visible as higher order jitter [6].

4 'Weak' Sawtooth Instability

Since the 1993 vacuum chamber upgrade of the damping rings, the turbulent microwave instability (called sawtooth instability in the SLC [1]) has changed its character from strong (r andφ-modes couple) to weak (only radial modes couple) [7]. The sawtooth amplitude was reduced and the diagnostic signals went down below the detectable level. Therefore it took about one year till a small correlation of the linac jitter with some sawtooth signal could be found [9]. Since then major work and considerable progress had been made on the signal processing, so that the 180 kHz signal of one bunch can be studied in amplitude and phase (Fig. 3).

Measuring the signal with a gated ADC over a short gate (ns) it is possible to correlate it with BPMs or other devices in the linac. There are two effects which reduce the correlation: 1. The timing must be right; a big correlation at one time setting of the gated ADC gives a negative correlation 2.75 μs later, and none at 1.375 μs.

2. Even the biggest correlation is suppressed due to the bursts; a medium gated ADC value can come from the crest of the 180 kHz signal of the rising or falling part of the burst, or it comes off-crest (+ or −) from the center part of the burst. Signal Splitting and two ADC at 0 and 1.375 μs would give the whole information.

Fig. 3 Eight “sawtooth” bursts happen in about 8 ms. Here three are visible just before extraction (spike). The burst can or cannot happen at extraction time.

5 Measurements

An ensemble of 512 beam pulses at 120 BPMs (about 1/2 of the linac), the bunch length, the sawtooth signal and some other parameters was studied. The correlation factor (mean subtracted)

\[ r = \frac{\langle xy \rangle}{\sqrt{\langle x^2 \rangle} \sqrt{\langle y^2 \rangle}} \]

between the sawtooth ADC signal and y-data from a BPM at the end of the linac was measured to be \( r = 0.64 \), which means that at least \( r^2 = 0.41 \) of the whole jitter power is coming from the sawtooth. This is a much bigger single source than 30 water pumps generating 59 Hz (0.1 of power) and 8-10 Hz due to water turbulence and quad support (0.2 of power).

The correlation development down the linac is shown in Fig. 4. The x component shows a behavior of a higher order jitter, while the y is slowly decreasing. The last part with less jitter is after the collimators.

There was also a correlation of the sawtooth signal with the bunch length which jittered by 10% (Δσ/σ) with \( r = 0.62 \) (39% of power spectrum), see Fig. 5, and only a small correlation with the current jitter \( r = 0.31 \) (10% of power).

By exciting a bunch length oscillation about 1 ms before extraction, the sawtooth amplitude at extraction was much reduced and less frequent. This resulted in a reduction in linac jitter of 30%, which is somewhat more than expected if all the correlation could be reduced:
\[ J_{\text{new}}/J_o = \sqrt{1 - r^2}. \]

This suggests that some of the correlation was reduced, which could be the mentioned amplitude/phase ambiguity of the sawtooth signal or a not perfect timing setup of the gate.

**Acknowledgment**

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**References**


**5 Summary**

Hidden, incoming jitter or “higher order jitter” can have big effects in the linac due to the high currents and wakefields. A source from the damping ring (sawtooth) has been identified to be a good example of such a hidden jitter. It could be substantially reduced.

![Sawtooth - BPM Jitter Correlation](image1)

Fig. 4: Sawtooth to jitter correlation versus z in the linac (x: solid, y: dashed).

![Linac Bunch Length vs DR Bunch Length](image2)

Fig. 5: Linac bunch length jitter versus sawtooth signal.
THE BROWN-SERVRANCKX MATCHING TRANSFORMER FOR SIMULTANEOUS RFQ TO DTL H+ AND H- MATCHING

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Abstract

The issue involved in the simultaneous matching of H+ and H- beams between an RFQ and DTL lies in the fact that both beams experience the same electric-field forces at a given position in the RFQ. Hence, the two beams are focused to the same correlation. However, matching to a DTL requires correlation of the opposite sign. The Brown-Servrancx [1] quarter-wave (λ/4) matching transformer system, which requires four quadrupoles, provides a method to simultaneously match H+ and H- beams between an RFQ and a DTL. The method requires the use of a special RFQ section to obtain the Twiss parameter conditions βx = βy and αx = αy = 0 at the exit of the RFQ [2]. This matching between the RFQ and DTL is described below.

λ/4 Matching Transformer

Figure 1 shows the two-quadrupole-λ/4 matching transformer with an additional quadrupole placed at each end to produce the appropriate Twiss parameters to match to the FODO lattice of the downstream DTL. This 4-quadrupole transport section will transform a beam with Twiss parameters β1 = β3 and α1 = −α3 to a beam having Twiss parameters β2 = β4 and α2 = −α4. The middle two focusing elements plus the three drift lengths comprise the λ/4 - (quarter wave) transport. Quadrupole Q1, placed where βx = βy and αx = −αy, adjusts α while preserving the condition αx = −αy and is used to adjust the beam size at Q2 while the quarter wave transformer preserves the condition βx = βy, and αx = −αy. Quadrupole Q2 is used to obtain the final desired α while again preserving the condition αx = −αy.

Because of the time varying nature of the RFQ, the H+ and H- beams have the relationship αx(H+) = αx(H-), and αy(H+) = αy(H-) at the exit of the RFQ; but, in a dc quadrupole channel, the matched beam satisfies αx(H+) = αx(H-) and αy(H+) = αy(H-). By setting αx = αy = 0, for both H+ and H- at the end of the RFQ, the Brown-Servrancx [1] matching transformer can be used for matching.

Fig. 1. The Brown-Servrancx matching transformer used to match a beam from an RFQ to a DTL.

The quarter-wave transport matrix, Rλ/4, is (the sign of the focal length depends on the charge of the hydrogen ion)

\[
R_{λ/4} = \begin{bmatrix}
1 & \frac{L}{2} & 0 \\
0 & \frac{L}{2} & 0 \\
1 & \frac{L}{2} & 0
\end{bmatrix} \begin{bmatrix}
1 & \frac{L}{f} & 0 \\
0 & \frac{L}{f} & 0 \\
1 & \frac{L}{f} & 0
\end{bmatrix} = \begin{bmatrix}
1 - \frac{L^2}{2f^2} & \frac{L}{f} & 2L - \frac{L^3}{4f^2} \\
\frac{L}{f^2} & 1 - \frac{L^2}{2f^2} & \frac{L}{f}
\end{bmatrix}
\]

which, in terms of the phase advance per period, μ, and the Twiss parameters, is

\[
R_{λ/4} = \begin{bmatrix}
\cos μ + \alpha \sin μ & \beta \sin μ \\
-\gamma \sin μ & \cos μ - \alpha \sin μ
\end{bmatrix}
\]

Equation (2) for the quarter wave transport system is

\[
R_{λ/4} = \begin{bmatrix}
\alpha & \beta \\
-\gamma & \alpha
\end{bmatrix}
\]

where μ = 90°. This condition is achieved in Eq. (1) when

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\[
\left(1 - \frac{f^2}{2L^2}\right) = 0
\]  
(3)

which determines the focal length, \(f\), of the inner two quadrupole lenses given the lens separation, \(L\).

We require a transport matrix that preserves the condition \(\alpha_x = -\alpha_y\). The Twiss parameter map for any matrix \(R\) is

\[
\begin{pmatrix}
\beta_2 \\
\alpha_2 \\
\gamma_2
\end{pmatrix} =
\begin{pmatrix}
R_{11}^2 & (R_{11}R_{12}) & R_{12}^2 \\
(\alpha_{11}R_{12}) & R_{11}R_{22} + R_{12}R_{21} & (-R_{12}R_{22}) \\
(\alpha_{21}R_{22}) & R_{21}R_{22} + R_{22}R_{22} & R_{22}^2
\end{pmatrix}
\begin{pmatrix}
\beta_1 \\
\alpha_1 \\
\gamma_1
\end{pmatrix}
\]  
(4)

The matrix elements in parenthesis change sign in going from the x-plane to the y-plane. The other elements do not change sign. For \(\beta_{x1} = \beta_{y1}\) and \(\alpha_{x1} = -\alpha_{y1}\), then \(\beta_{x2} = \beta_{y2}\) and \(\alpha_{x2} = -\alpha_{y2}\). This is achievable with the quarter-wave transport system because the diagonal matrix elements \(R_{11}\) and \(R_{22}\) change signs between the x- and y-planes while the off-diagonal matrix elements \(R_{12}\) and \(R_{21}\) do not change.

The quadrupole lenses placed at the beginning and end of the quarter-wave transport preserve the condition \(\alpha_x = -\alpha_y\). The transport matrix elements for a single lens,

\[
R = \begin{pmatrix}
1 & 0 \\
\pm f/L & 1
\end{pmatrix}
\]
(5)

when substituted in Eq. (4), gives

\[
\begin{pmatrix}
\beta_2 \\
\alpha_2 \\
\gamma_2
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
\pm f/L & 1 & 0 \\
\pm f^2/L & \mp 2/f & 1
\end{pmatrix}
\begin{pmatrix}
\beta_1 \\
\alpha_1 \\
\gamma_1
\end{pmatrix}
\]  
(6)

When \(\beta_{x1} = \beta_{y1}\) and \(\alpha_{x1} = -\alpha_{y1}\), then \(\beta_{x2} = \beta_{y2}\) and \(\alpha_{x2} = -\alpha_{y2}\).

**Discussion**

The Brown-Servranckx transport system is straightforward to tune. Given a circular beam at the location of quadrupole Q1 in Fig. 1, the focal length of the middle two quadrupoles is adjusted to produce a circular beam at the location of quadrupole Q2 giving a quarter wave transport between Q1 and Q2. Quadrupole Q1 is then adjusted to give the proper beam size at the location of Q2 (giving \(\beta_2\)). Finally, quadrupole Q2 is adjusted so that the beam size is a constant after each FODO cell of the DTL (giving the correct \(\alpha_2\)).

There are limitations to the degree of magnification that can be achieved by this transformer. The Twiss parameter \(\beta_2\) has a minimum value equal to \(R_{12}^2/\beta_1\). For details of this and other useful insights to beam transport, see Ref. 1.

If the transverse focusing per unit length is identical at the output of the RFQ and the input of the DTL, the quarter-wave transport can be eliminated. Also, if in addition to the above condition, \(\alpha_x = \alpha_y = 0\) at the RFQ output, a single magnetic quadrupole can be used to obtain the appropriate matching (\(\alpha_x = -\alpha_y\)) of both \(H^+\) and \(H^-\) beams into the DTL.

**References**


BEAM SELF-EXCITED RF CAVITY DRIVER FOR A DEFLECTOR OR FOCUSING SYSTEM

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Abstract

A bunched beam from an accelerator can excite and power an rf cavity which then drives either a deflecting or focusing (including nonlinear focusing) rf cavity with an amplitude related to beam current. If power, generated when a bunched beam loses energy to an rf field when traversing an electric field that opposes the particle's motion, is used to drive a separate (or the same) cavity to either focus or deflect the beam. The deflected beam can be stopped by an aperture or directed to a different area of a target depending on beam current. The beam-generated rf power can drive a radio-frequency quadrupole that can change the focusing properties of a beam channel as a function of beam current (space-charge-force compensation or modifying the beam distribution on a target). An rf deflector can offset a beam to a downstream sextupole, effectively producing a position-dependent quadrupole field. The combination of rf deflector plus sextupole will produce a beam current dependent quadrupole-focusing force. A static quadrupole magnet plus another rf deflector can place the beam back on the optic axis. This paper describes the concept, derives the appropriate equations for system analysis, and gives examples. A variation on this theme is to use the wake field generated in an rf cavity to cause growth in the beam emittance. The beam current would then be apertured by emittance defining slits.

Deflector System

Figure 1 shows the concept in a system designed to aperture a high current beam. The RF generator and deflector are conceptually shown as two units. The beam deflection angle is proportional to the beam current. This deflection becomes a displacement at the beam collimator. Permanent magnet non-linear focusing magnets can enhance the operation of the RF deflector.

Beam Interaction with an Rf Field

In this section, a differential equation describing the rf field generated in a cavity excited by a bunched beam is derived and solved. This differential equation depends on the energy deposited in the cavity by the beam and the energy lost in the cavity due to resistive wall losses. We consider a TM010 mode single-cell cavity (DTL type) where the electric field is along the beam direction and is concentrated on the axis of the cavity between the drift tube noses.

\[ \Delta U_p = \int e E_g \cos(\omega t + \varphi) dz - Z_g I. \]

where

\[ z = vt, \quad \omega = \frac{2\pi}{\beta \lambda}, \]

\( e \) is the charge on an electron, \( Z_g \) is the gap length, \( E_g \) is the gap voltage, \( \omega \) is \( 2\pi \) times the rf frequency, \( \beta \) is the velocity of the particle with respect to the velocity of light, \( \lambda \) is the free space rf wavelength, \( v \) is the particle's velocity, \( t \) is time, and \( \varphi \) is the rf phase when a particle enters the gap.

Assuming that the change in particle energy in crossing the gap is small compared to the particle's kinetic energy and treating \( v \) as a constant, Eq. (1) is integrated to obtain

\[ \Delta U_p = e E_0 T \beta \lambda \cos \varphi \]

where, \( E_0 \) is an average field strength defined by

\[ E_g Z_g = E_0 \beta \lambda, \]

and \( T \) is a transit time factor. The transit time factor is defined as

*Work supported by the U.S. Department of Energy
\[ T = \sin\left(\frac{\pi Z_k}{\beta \lambda}\right) / \left(\frac{\pi Z_0}{\beta \lambda}\right) . \]  

(5)

Equation (3) gives the energy gain in the rf electric field due to one particle crossing the rf-gap.

**Beam Bunch RF Energy Gain**

The individual charges in a beam bunch enter the rf-cavity at different phases \( \varphi \). The phase distribution of the particles is described by the function \( \rho(\varphi) \). The total charge per beam bunch is

\[ q = \int_{-\pi}^{\pi} \rho(\varphi) d\varphi . \]  

(6)

Let,

\[ \Delta U_B = \frac{\text{average rf field power gain}}{\text{beam bunch}} \]

be the energy deposited in the cavity by a complete beam bunch, and use Eq. (3) to obtain

\[ \Delta U_B = E_0 T \beta \lambda \int_{-\pi}^{\pi} \rho(\varphi) \cos(\varphi) d\varphi . \]  

(7)

The integral in Eq. (7) can be defined in terms of a dimensionless charge-distribution form factor as

\[ F = \frac{1}{q} \int_{-\pi}^{\pi} \rho(\varphi) \cos(\varphi) d\varphi . \]  

(8)

The value of \( F \) is less than 1 (it is equal to 1 for a \( \delta \) function distribution). This form factor is rather insensitive to beam bunch length. For example, assume that \( \rho(\varphi) \) is described by the rectangular distribution

\[ \rho(\varphi) = \begin{cases} 
q/2\varphi_0 & -\varphi_0 < \varphi < \varphi_0 \\
0 & \text{otherwise}
\end{cases} \]  

(9)

where \( \varphi_0 \) is the phase extent of the distribution. Then,

\[ F = \sin(\varphi_0)/\varphi_0 . \]  

(10)

When \( \varphi_0 = 0 \), \( F = 1 \), and when \( \varphi_0 = \pi/2 \) (severe debunching), \( F = 0.64 \). Equations (24) and (25) (derived below) show that the maximum-generated electric field scales as \( F \). We see that the rf-electric field is somewhat insensitive to significant beam debunching.

Let \( U_T \) equal the total rf field energy in the cavity. The rf electric field will scale as the square root of \( U_T \). Combining Eqs. (7) and (8) and defining the constant \( k_1 \) as

\[ k_1 = E_0 / U_T^{1/2} \]

(11)

gives

\[ \Delta U_B = q k_1 T \beta \lambda F U_T^{1/2} . \]  

(12)

The constant \( k_1 \) depends on the electric field distribution in the cavity and is a function of the cavity geometry. We will later assume a model for the electric field distribution that will permit a rough calculation of \( k_1 \).

**Resistive Wall Losses and \( Q \)**

Equation (12) gives the rf field energy gain due to one beam bunch crossing the rf-cavity gap against the rf electric field. There are power losses in the cavity due to the finite resistance of the cavity walls. This power loss can be determined from the \( Q \) of the cavity defined as

\[ Q = \omega U_T / W_L \]  

(13)

where \( W_L \) is the average rf power loss per unit time. The rf energy loss in one rf cycle (time \( \tau = 2\pi/\omega \)) is then

\[ W_L \frac{2\pi}{\omega} = \frac{\omega U_T}{Q} \frac{2\pi}{\omega} . \]  

(14)

**RF Time Dependent Field Equation**

The change in total rf power per time is

\[ \frac{\Delta U_T}{\Delta t} = \frac{\Delta U_T}{2\pi/\omega} - \frac{W_L}{2\pi/\omega} \]

(15)

Using Eqs. (12), and (13) gives

\[ \frac{dU_T}{dt} = \frac{\omega q k_1 T \beta \lambda F}{2\pi} U_T^{1/2} - \frac{\omega}{Q} U_T . \]  

(16)

Equation (15) is easier to solve if \( E_0 \) [from Eq. (11)] is substituted for \( U_T \). Equation (15) becomes

\[ 2 \frac{dE_0}{dt} = \frac{\omega q k_1^2 T \beta \lambda F}{2\pi} - \frac{\omega}{Q} E_0 . \]  

(17)

Assuming that the rf power is zero when \( t = 0 \), Eq. (16) can be integrated to give

\[ E_0 = \frac{q k_1^2 T \beta \lambda F}{2\pi} (1 - e^{-\omega t/2}) . \]  

(18)

The charge per beam bunch, \( q \), can be calculated from the instantaneous average beam current, \( I \), and is

\[ q = 2\pi I / \omega . \]  

(19)

Substituting Eq. (18) into (17) gives

\[ E_0 = E_{0_{\text{max}}} (1 - e^{-\omega t/2}) . \]

(20)
Relationship Between RF Electric Field and RF Power

A crude estimate of $k_1$ can be obtained by assuming that most of the rf electric field is concentrated between the drift-tube noses and is a constant. The maximum stored energy in the electric field can be calculated and related to $U_T$ to give $k_1$. The value of $U_T$ calculated from the electric field is

$$U_T = \frac{e_0}{2} \int E^2 \, dV = \frac{e_0}{2} E_0^2 \pi R_0^2 Z_4.$$  \hspace{1cm} (21)

Solving this equation for $E_0$ and using Eq. (4) gives

$$E_0 = \left( \frac{2Z_4}{\epsilon_0 \pi R_0^2 \beta^2 \lambda^2} \right)^{1/2} U_T^{1/2}.$$  \hspace{1cm} (22)

Comparing Eqs. (11) and (22) gives

$$k_1 = \left( \frac{2Z_4}{\epsilon_0 \pi R_0^2 \beta^2 \lambda^2} \right)^{1/2}.$$  \hspace{1cm} (23)

Equation Summary

Combining Eqs. (4), (11), (13), (20) and (23) give

$$E_{\text{max}} = \frac{2QITFZ_4}{\omega e_0 \pi R_0^2 \beta} = \text{max. average electric field},$$  \hspace{1cm} (24)

$$E_{\text{gmax}} = \frac{2QITF}{\omega e_0 \pi R_0^2} = \text{max. gap electric field},$$  \hspace{1cm} (25)

$$U_{\text{rmax}} = \frac{2Q^2 T^2 F^2 Z_4}{\omega^2 e_0 \pi R_0^2} = \text{max. total rf energy},$$  \hspace{1cm} (26)

and

$$W_{\text{lmax}} = \frac{2Q^2 T^2 F^2 Z_4}{\omega e_0 \pi R_0^2} = \text{max. rf power loss / time}.$$  \hspace{1cm} (27)

Examples

We calculate $E_{\text{gmax}}$ and $W_{\text{lmax}}$ using Eqs. (25) and (27) for a 100 µA beam at 800 MeV. Assume a 10% beam duty factor, then $l = 1.0$ mA. We let $\omega/2\pi = 200$ MHz, $Q=1000$, $\varphi = 1$ deg, $Z_4 = 1.0$ cm, and $R_0 = 1.0$ cm ($e_0 = 10^{-9}/36\pi$).

Equations (25) and (27) give $E_{\text{gmax}} = 5.7 \times 10^5$ V/m (rf-gap voltage) and $W_{\text{lmax}} = 5.7$ watts (maximum power extracted from the beam).

We calculate the beam deflection due to a transverse rf-electric field. From,

$$\frac{dP}{dt} = eE \cos(\omega t),$$  \hspace{1cm} (28)

we obtain

$$\Delta P_{\perp} = \int_e E \cos(\omega t) \, dt = \frac{2eE \sin \varphi_0}{\omega}.$$  \hspace{1cm} (29)

The deflection angle

$$X' = \frac{\Delta P_{\perp}}{P_{\perp}}.$$  \hspace{1cm} (30)

For $E = 0.57$ MV/m, $\varphi_0 = \pi/2$ (complete rf half cycle), 5 rf deflection cavities (each of length $\beta \lambda/2 = 0.68$ m), and an 800 MeV beam, we find that $X' = 10^{-3}$ radians. This will produce a deflection of 1 cm in 10 meters. Given this same geometry, a 10 mA beam will have a deflection angle of $10^{-2}$ radians and will be deflected 10 cm.

There are issues to be addressed if this system is to be used for limiting beam current for personnel safety. These include: sensitivity of the rf cavities to detuning, possible long term degradation in cavity Q due to oxidation of cavity surfaces, determining the envelope of off-nominal linac operational parameters that will cause the beam to sufficiently debunch so that the rf deflection system will no longer work, and rf cavity conditioning.

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BEAM-BUNCHING WITH A LINEAR-RAMP INCLUDING SPACE-CHARGE FORCE EFFECTS CYLINDER MODEL

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Abstract

The voltage-amplitude requirement of a saw-tooth wave-
form buncher is calculated to give a desired degree of bunching for a
given beam current and particle species. This calculation includes the
effect of space-charge forces with and without
adjacent beam buckets. The results are compared to TRACE-
3D calculations which do not include the space-charge effects of
adjacent bunches. It appears that TRACE-3D calculations
underestimate the bunching voltage required. The methodology and
a listing of the spreadsheet that performs the analytical
bunching calculation are included.

Models

The beam consists of a series of uniform-density charge
cylinders, see Fig. 1, that are spaced \( D = \beta \lambda \) apart, with length
\( L = D \varphi /180 \) where \( \varphi \) is half the total bunched-beam phase spread,
\( \beta \) is the average beam velocity divided by the velocity of light
\( c \), and \( \lambda \) is the fundamental-frequency-rf free-space wave
length.

![Diagram of beam bunching calculation](image)

Fig. 1. Geometry for the beam bunching calculation. The motion of
a reference particle at the edge of beam bunch A is determined.
Two different equations of motion which include effects of space-
charge forces from beam bunch A but with and without space-charge
forces from beam bunch B are compared.

Space-charge forces, due to beam buckets adjacent to the
reference particle, are calculated for a reference particle that is on
the beam axis at a cylinder edge. The motion of this reference
particle models the bunching of the entire distribution. The
electrostatic potential for the reference particle is calculated from
which the axial electric field seen by this particle is determined.
The equation of motion for the axial motion of the reference
particle is solved (the on axis reference particle experiences no
transverse forces) which gives the required bunching voltage in
the beam center-of-mass frame of reference. Velocities are added
nonrelativistically to give the buncher voltage in the laboratory
reference frame.

TRACE-3D uses a uniformly filled ellipsoidal model to
estimate the space-charge forces. The equation of motion for an
on-axis reference particle, using the ellipsoidal model, is
integrated and the resulting bunching voltage is compared to
TRACE and the cylinder model.

Derivation - Cylinder Model

Given that \( I \) is the beam current and \( f \) is the bunch
frequency, the charge density of the beam in the cylinder is

\[
\rho = I / ( \pi R_0^2 L f )
\]

(1)

where \( R_0 \) is the beam radius \( (R_0 \) is assumed to remain constant
during the bunching process).

We consider only electrostatic forces in the Lorentz force
equation for the time evolution of the reference particle, ignore
all image-charge forces that could exist due to a beam pipe, and
consider only axial motion. Therefore,

\[
m \frac{dv}{dt} = e E_z .
\]

(2)

where \( m \) is the particle mass, \( e \) is the electron charge, \( E_z \) is the
axial electric field due to space charge, \( t \) is time, and \( v \) is the
velocity of the reference particle in the beam bunch rest frame.

The on-axis axial electric field due to the two bunches can be
obtained from the potential function

\[
\Phi = 1 \int_0^{2\pi} \frac{R_0}{\sqrt{(Z - Z_{ref})^2 + R^2}} d\theta + \int_0^L \frac{\rho}{R_0} \frac{R_0}{\sqrt{(Z - Z_{ref})^2 + R^2}} d\theta.
\]

(3)

where \( \varepsilon_0 \) is the free space permittivity. The first set of integrals
is for bunch B, and the second set for bunch A. Integrating
Eq. (3) for \( \Phi \), taking the derivative with respect to \( Z_{ref} \) (\( Z_{ref} \) is
the Z coordinate of the reference particle), and setting \( Z_{ref} \) equal
to zero to obtain \( E_z \) gives

\[
E_z(\text{bunch A}) = \frac{\rho}{2\varepsilon_0} \left( \sqrt{L^2 + R_0^2} - R_0 - L \right)
\]

(4)

for the electric field seen by the reference particle due to bunch
A, and

\[
E_z(\text{bunch B}) = \frac{\rho}{2\varepsilon_0} \left[ \sqrt{(D - L)^2 + R_0^2} - \sqrt{D^2 + R_0^2} + L \right]
\]

(5)

for the electric field due to bunch B. Adding Eqs. (4) and (5)
gives the total electric field seen by the reference particle

\[
E_{tot} = \frac{\rho}{2\varepsilon_0} \left[ \sqrt{L^2 + R_0^2} - R_0 - \sqrt{D^2 + R_0^2} + \sqrt{(D - L)^2 + R_0^2} \right].
\]

Because the electric field does not depend on velocity,
Eq. (2) can be integrated to give the required reference-particle
energy gain, \( \delta W_{cm} \), due to bunching in the beam rest frame.

---

*Work supported by the U.S. Department of Energy*
The initial velocity $v_0$ for an unbunch beam ($L = D$) gives a final bunch length $L_{\text{min}}$ when $\nu = 0$. The bunch length, $L$, and the beam radius, $R_0$, are normalized to the bunch center separation distance, $D$, by defining $r = R_0/D$ and $s = L/D$. Using Eqs. (1), (4), (5), and (6) in Eq. (7) and integrating gives

$$\delta W_{cm} = \frac{el}{2\pi r^2 fc_0 D} (J_A + J_B)$$

(8)

where

$$J_A = \sqrt{s^2 + r^2} - \sqrt{1 + r^2} + r \ln \left( \frac{r + \sqrt{1 + r^2}}{r + \sqrt{s^2 + r^2}} \right) + 1 - s$$

(9)

and

$$J_B = \left[ \begin{array}{c} s + \sqrt{(1-s)^2 + r^2} \\ \sqrt{1 + r^2} \ln \left( \frac{\sqrt{(1-s)^2 + r^2} + 1 + r^2 - s}{r + \sqrt{1 + r^2}} \right) \\ -\ln \left( \frac{(1-s)^2 + r^2 + s - 1}{r} \right) - r - 1 \end{array} \right]$$

(10)

Velocities, corresponding to the center-of-mass bunching energy-spread and the average beam velocity, are added to give the buncher voltage required in the laboratory reference-frame. The nominal beam-velocity in the laboratory reference frame is $v_0 = \sqrt{2W_0/m}$ where $W_0$ is the nominal beam energy. The velocity of the reference particle in the beam center-of-mass reference frame is $\delta v = \sqrt{2 \delta W_{cm}/m}$. Calculating the reference particle's energy in the laboratory reference frame and subtracting the average beam energy gives the energy gain that the buncher must supply to the reference particle which is

$$\delta W_{\text{lab}} = \delta W_{cm} + \sqrt{4W_0 \delta W_{cm}}$$

(11)

**Derivation - Ellipsoidal Model**

The electric field due to a uniform-charge-density-ellipsoid beam-bunch seen on axis by a reference particle at the edge of a single bunch is [1], [2], [3]

$$E_z = \frac{3IZ_{\text{ref}}}{4\pi c_0 R_0^2 (L/2)} g(p), \quad p = \frac{L/2}{R_0},$$

(12)

and $g(p)$ is a "form factor" which can be approximated by [1]

$$g(p) = \frac{1}{(3p)}.$$

(13)

Substituting Eq. (13) into Eq. (12) and picking the reference particle coordinates to be on axis at the beam edge ($R = 0$, $Z_{\text{ref}} = L/2$) gives for the electric field

$$E_z = \frac{I}{4\pi c_0 R_0 Z_{\text{ref}}}.$$

(14)

Carrying through the same procedure as for the cylinder model gives

$$\delta W_{cm} = \frac{el}{4\pi c_0 r D} \ln \left( \frac{1}{s} \right).$$

(15)

Combining Eqs. (11) and (15) gives the buncher voltage required in the Lab system.

**Examples and Conclusion**

Figure 2 show the spread sheet used to calculate the buncher voltage. The parameters are meant to be self-explanatory. Figure 3 shows a comparison of this model calculation to results obtained from TRACE-3D, which uses an elliptical beam bunch model. The TRACE transport channel, used for the comparisons, consisted of a periodic series of solenoidal magnets with the beam channel focusing strength set to minimize the space-charge tune depression even in the maximum bunching case. For the maximum bunching case, the initial beam size was increased 3% to keep the beam nearly matched (the solenoid magnetic field strength was not varied).

The discrepancy between the TRACE calculation and the spread sheet calculation for the elliptical distribution is due to the approximation used for the form factor in Eq. (13) where this approximation overestimates the space-charge force by as much as 10%. The difference between the cylindrical model and the elliptical model can be understood by comparing the ratio of the electric field calculated in Eqs. (4) and (14). Taking the ratio of these two equations and using Eq. (1) gives

$$\frac{\text{Eq. (4)}}{\text{Eq. (14)}} = 2 \left[ 1 - \frac{R_0}{2L} \right]$$

(16)

Equation (16) gives a value of close to 2 for the ratio corresponding to our examples. This ratio is also the ratio of the center-of-mass energy spread required for bunching. Using Eq. (11) to transform to the Lab frame shows that the buncher voltage required for the cylinder model should be 40% ($\sqrt{2}$) higher than the elliptical model and is consistent with the result shown in Fig. (3). Also, the TRACE beam distribution for $\phi = 180^\circ$ is already bunched with a pseudo-gaussian shape which causes a further underestimate of the buncher voltage required to obtain the final degree of bunching. Figure 3 shows that including adjacent bunches for calculating longitudinal space-charge effects is important only for minimal bunching ($\phi \geq 150^\circ$).
### Bunching Design Spread Sheet

**E. A. Waltinger**

**8/24/95 9:52**

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**BUNCHER VOLTAGE TO GIVE DESIRED FINAL PHASE WITH SPACE-CH.**

- Buncher voltage for two cylinder bunches: V = Wcm + sqrt(4*Wcm)
- Buncher voltage for single cylinder bunch: V = Waing + sqrt(4*Waing)
- Buncher voltage for single ellipsoidal bunch: V = Weellipse + sqrt(4*Weellipse)

**Fig. 2.** Spread sheet to calculate the required buncher voltage to bunch the beam to a desired phase spread. Calculations are done for both a single bunch and for adjacent beam bunches.

**Fig. 3.** Comparison of the cylindrical model calculation to results obtained from TRACE-3D for various degrees of bunching for a fixed beam radius.

**References**


INDUCTION LINEAR ACCELERATORS FOR PHYSICS DIAGNOSTICS

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University of California - Berkeley

Abstract
The short pulse, very high current capabilities of the induction linear accelerator make it a logical candidate for certain applications to diagnosing physical properties. Two examples are fast high density explosive experiments and material science using neutron scattering. Flash x-rays are needed for imaging high density metal compression experiments. The short (50-75ns) pulse-burst capabilities of the induction linac are well suited to this. Because high x-rays doses are necessary to image the experiment and characterize density variations the multi-kiloampere capabilities of induction machines are attractive. Short neutron pulses from proton induced spallation can provide excellent energy and time resolution in material studies using neutron scattering. The induction linac simplifies spallation sources by transporting and accelerating the total beam current necessary (amperes of H\(^+\)) in a single beam with no storage. Concepts for both applications are discussed with emphasis on technical risks and costs.

Introduction
Induction linear accelerators have properties that make them valuable in physics diagnostics applications. These properties are the ability to accelerate very intense beams and the ability to generate discrete short pulses\(^1\). The two applications discussed here are the use of proton beams to generate spallation neutrons for material science, chemistry, and biology and the use of short high current electron pulses for fast time resolved radiography of dense rapidly moving objects. Induction linacs can accelerate any beam current that the transport system is capable of handling provided that the pulser that drives the accelerator cells can supply the required current. This is because induction accelerators do not suffer from the cavity loading effects that occur in RF machines. However, fast rep rate pulse power systems have design problems of their own, such as switch and component lifetime, and cost.

In the application of such machines to a spallation neutron source, the main advantage is that one can accelerate the entire beam current required on the spallation target in a single pass thus eliminating the need for a storage ring. Not using a ring eliminates the need for H\(^+\) ion sources which are a more complex and a lower current density technology than H\(^+\) sources. The absence of a ring also avoids the problems associated with stripper foils and excited neutrals. By extracting the required short pulse directly in the injector one avoids the beam chopping problems of RF machines. Finally, since the physics limit placed on the beam emittance in an induction machine comes from the final focus conditions, the ion temperature of the source is not a limiting factor. The very low emittance required for injection into a ring is small compared to the emittance limit imposed by final focusing in this application.

Radiography of fast moving dense objects needs multiple pulses separated slightly in time and possibly simultaneously from more than one direction to obtain 3D imaging of the object. Such a project is underway at Los Alamos National Laboratory called DARIT\(^\circ\) (Dual Axis Refractive Hydro-Dynamic Test facility). The physics requirements for this application are quite severe: beam current of 4-6KA, beam energy up to 20MeV, focal spot < 1mm, 4 pulse burst with 50-70ns pulse length and 250ns pulse separation. Induction linac cells designed for long pulse applications may be useful for this radiography application.

Spallation Neutron Source
The first point is bunch dynamics in the machine. The simplest approach is to accelerate a bunch as a rigid body relying on acceleration to provide both current amplification and pulse shortening. One can also vary bunch lengths by varying the velocity along the bunch as a means to reduce the length of the machine. Designing for short length can reduce costs, but the limits on acceleration gradient may prevent this. Consider accelerating the head of the bunch according to a Z\(^2\) schedule, where Z is the distance along the machine, and accelerating the tail on a linear schedule. Now assume that the output beam has an energy of 1.25 GeV, a current of 57.5A, a pulse width of 580 ns, and a rep rate of 60 Hz. These conditions correspond to a steady state output power of 2.5 MW, reflecting the initial goal of the NSNS (National Spallation Neutron Source) design team for a machine between 1 and 5MW average power. Also assume a 2MeV proton injector generating 8\(\mu\)s, 4.2 A pulses, parameters achievable with technology developed in the LBNL Heavy Ion Fusion Accelerator Research\(^2\) program. The injection parameters come from imposing the condition that geometric length of the bunch is the same during its entry into the accelerator as during its exit. Inside the accelerator the bunch expands longitudinally before recompressing to its original length. Solving the relativistic equations of motion for the head and the tail with the entry and exit conditions listed above, yields a machine length of 1761m plus the length of the injector which might be 15m. There are two problems with this approach. First, the linear charge density in the bunch is 0.21\(\mu\)coul/m which is very low in terms of the transport limits that can be achieved in quadruple or solenoid magnetic fields. More importantly, the peak accelerating gradient reaches 1.42MeV/m for the head and the linear gradient for the tail is 0.71MeV/m. Figures commonly used for the technologically achievable gradient range from 1MeV/m and to a more realistic 0.5MeV/m.
Assume a more practical acceleration gradient of 0.5 MeV/m and use a higher linear charge density that makes more efficient use of transport capabilities. Making the beam diameter small also reduces the mass of core material for a given number of volt-seconds (pulse voltage times pulse duration) and a given core length. In this case the beam bunch enters the accelerator completely before the acceleration cells are turned on. The entire bunch is then accelerated at the same rate and therefore the bunch length remains constant through the machine. E.P. Lee has developed an envelope equation model to calculate the space charge transport limit for a given quadrupole focusing channel. A similar model describes the quadrupole magnetic field gradient in terms of the linear space charge density, \( \lambda \), the beam maximum radius, \( a \), the normalized emittance, \( \epsilon_N \), and the relativistic constants, \( \beta \) and \( \gamma \):

\[
B' = \frac{650.6 \lambda}{\beta \gamma a^2} \left[ \frac{9859 \pm 3043}{1 \pm (11.24 \gamma a^2 / \epsilon_N)} \right].
\]

(1)

Using this expression one finds that it is feasible to triple the linear charge density to 0.639\( \mu \text{coul/m} \) m. The injection bunch length is reduced from 157m to 52.3m. The resulting higher injector current is not a problem. One can transport this bunch within a maximum radius of 1.5cm in a quad system with pole tip field 777T and bore radius of 4cm. The effects of quad length and the bore size on aberrations present no problem. The resulting accelerator is 2548m long plus the 2MeV injector and produces 200ns pulses at 60Hz with an average power of 2.5MW. The accelerating cells are 250KV each, using Metglas as the core material; there are 4992 of them in the main accelerator and 105 in the bunch entry section just after the injector.

This design was costed using scaling rules and experience from the Heavy Ion Fusion and RTA programs. The result was a total accelerator system cost of $542.7M including all design, assembly, and commissioning labor and overhead. A permanent magnet quadrupole transport system was assumed to minimize core inner radius relative to room temperature or superconducting systems. Dropping the exit energy from 1.25GeV to 1GeV, eliminates 500 of accelerator length at the cost of dropping to 2MW average power but with a financial saving of $85.1M. The exit pulse length remains essentially the same. This cost must be viewed with considerable caution. The design was a first cut point design. Second, it’s a broad, thumb scaling law based on various peoples’ experience, used and the bias was toward conservatism. A more detailed design is needed to achieve reliable costs with computerized cost models. The transport system represents $87M but is based on an unoptimized constant period configuration. Substantial saving could result from better design. The cooling budget is $78.4M and probably could be reduced by better design.

In addition to the cost uncertainties there is technical risk. The issue of getting the 12.5A proton current out of the ion source with suitably low emittance for target focussing is not a problem. However, fast pulse extraction preserving good beam optics from the gas source is. Recent work at LBNL on source beam chopping may provide the solution to this problem but experimental work is needed. Another risk is the lifetime and reliability of the pulse power components. Operation at 60Hz for 24 hrs/day and 80% up time implies 1.5\( \times 10^9 \) pulses per year. Life tests at LBNL using FET switches have reached 2.5\( \times 10^7 \) pulses at 72Hz on a nickel-iron core and 2\( \times 10^8 \) pulses at 100Hz on Metglas both with convective air cooling. The systems were still operational at conclusion. Further experimental work especially on cheaper thyatron switches is needed to reduce risk and to define cooling requirements better. The beam clearances used were based on theoretical models used in the Heavy Ion Fusion program in which beam halo was not a consideration. This problem needs further study to better define the clearance requirements which in turn affect the cost of the magnets and cores. Finally, at short pulse lengths(\(< 0.5 \mu s \)), the power loss in Metglas cores grows quickly. Consideration should be given to ferrite materials which cost more but which would reduce cooling requirements and operational costs.

**Fast X-ray Metallic Objects of Dense Radiography**

Long pulse induction linac technology under development for heavy ion inertial fusion may be suitable for the radiography application. A gated cathode of some type, either electronically or laser switched, could supply a train of pulses to the accelerator. The pulse duration and separation would be governed by the cathode system while the voltage that accelerates the beam would be on throughout the burst. The two most important problems in the linac design are the accelerator cell voltage flatness and the transverse mode impedance of the cell. Other physics issues include especially the interaction between the intense beam and the bremsstrahlung target, corkscrew motion of the focal spot due to beam energy variations, and emittance growth.

An induction linac cell is normally designed to operate with a pulser that is matched to a specific beam load. If the beam is not present while the voltage is on, an overvoltage condition on the acceleration gap and the cell insulator will be created. One way to deal with this problem is the use of a compensation resistor in the pulser circuit. The pulser then sees the core magnetization current, the beam current, the compensation resistor current, and the gap capacitance all in parallel. If one dominates the loading with the compensation resistor the system efficiency will be low but in a testing application like this, efficiency is not important. In this concept one is deliberately creating a beam on-beam off situation and therefore much attention needs to be devoted to this problem. Not only is it a high voltage design problem but also a beam chromaticity issue. If the accelerating voltage is not at its nominal value when a bunch arrives, the change in beam energy will contribute to transverse motion of the focal spot which reduces the geometric resolution of the radiography system.

Another approach is driving a large core, containing sufficient volt-seconds to accommodate the number of beam pulses required, with separate pulzers that are electrically
isolated from each other. There are two ways of isolating the pulser. One is diodes and the other is to use a switch capable of holding off the acceleration gap voltage in the back direction. In the case of diodes the problem is to provide enough back voltage isolation to withstand the full acceleration gap voltage of possibly 250KV. Also the diodes must be capable of handling the full discharge power in the forward direction. It is probably easier to use high voltage switches such as thyatrons or spark gaps. This approach has the disadvantage of requiring multiple pulser which represent extra cost, but the advantages are avoiding the load matching problem and allowing the use of less Metglass by not maintaining voltage during periods when the beam is absent. A third possibility is the use of branch magnetics⁵ to drive the core without resetting between pulses.

The beam breakup (BBU) instability in linear accelerators is driven by coupling between longitudinal beam motion and the excitation of transverse modes in the acceleration cavity. The BBU parameters for the existing DARHT first axis cells have been thoroughly studied. Changing to a new cell design will require detailed computer simulation to understand the precise properties of the new cavities. A code such as AMOS⁷ will have to be modified to include the properties of Metglass for the calculation of the transverse impedances of the new cavities.

In the modeling of BBU the parameter⁶

\[ \omega_0 \frac{Z_\perp}{Q_\perp} \left( Q_\perp \right) \]  (2)

where \( Z_\perp \) is the transverse mode impedance of the dominant transverse mode and \( Q_\perp \) has the value for this mode, is an important quantity in the growth rate for the instability. It is therefore important to consider how this factor will change if one makes small changes in the existing cavity by changing the ferromagnetic material.

Consider a simple cylindrical cavity in which one first has ferrite suitable for 70ns pulses and then replaces it with Metglass for 1μs constant voltage pulses. The total mass and therefore the cost of the core depends on the inside radius, the core length and the required cross section. If a length of the cavity has been chosen by system considerations the, core cross section is determined by \( \Delta B(r_0 - r_1)d = V_p \tau \) where \( V_p \) is the gap voltage, \( \tau \) is the effective pulse length, and \( \Delta B \) is the total flux swing before saturation allowed by the ferromagnetic material. The question is what happens to the quantity \( Z_\perp / Q_\perp \) while the outside radius \( r_0 \) is changed to accommodate the change in material and the change in \( \tau \) while keeping \( d \) and \( r_1 \) fixed. Therefore \( r_0 = (V_p \tau / \Delta Bd) + r_1 \).

A single pill box model⁸ of an induction cell cavity has a transverse mode impedance estimated by

\[ Z_\perp = \frac{-8d}{\omega_0 r_1^2} \text{Im} \left( P_1(\omega_0) \right) \]  (3)

where \( P_1(\omega_0) \) is a function determined by \( d \), \( r_1 \), and the ratio of assumed wall impedance at the outside radius \( r_0 \) to the impedance of free space. If one only increases or decreases the cavity radius then

\[ \omega_0 \left( \frac{Z_\perp}{Q_\perp} \right) Q_\perp = \frac{8d}{r_1} \]  (4)

For a given current, machine length, number of cells, beam noise spectrum, acceleration gap, and pipe radius the BBU growth rate should not change. This is because it is not the cavity in which the ferromagnetic material for the cell is contained that determines the \( Z_\perp \) of interest but rather the cavity that contains the acceleration gap. This gap will probably not have a simple cylindrical shape and transverse mode damping structures will be included in the cavity.

The resonant frequency of a radial cavity transverse mode is

\[ \omega_{1n_0} = \frac{c x_n}{r_0} \]  (5)

where \( x_n \) is a constant dependent on the mode number. If the change in radius causes the resonance of the relevant mode to coincide with a portion of the beam noise spectrum that is relatively high, the BBU growth will be more severe.

Acknowledgments

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References

All-Electrostatic Split LEBT Test Results*

John W. Staples, Matthew D. Hoff and Chun Fai Chan
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Berkeley, California 94720, USA

Abstract

An all-electrostatic LEBT for an RFQ has been assembled and tested with beam. The LEBT includes two quasi-einzel lenses, allowing a wider range of Twiss parameters to be accommodated, and the lenses are split into quadrants, allowing electrical steering of the beam. Moreover, mechanical steering by moving the entire LEBT with a special low-friction vacuum joint was also demonstrated. The LEBT was tested with unanalyzed protons from an RF-driven bucket source by measuring the beam directly and by measuring the transmission through a subsequent RFQ as a function of LEBT electrode parameters. Agreement between calculated LEBT beam characteristics and actual measured values is excellent. This LEBT offers fully unneutralized beam transport with steering and two-knob control of exit Twiss parameters, and can be applied to negative hydrogen as well as proton beams.

Introduction

An advanced, all-electrostatic LEBT has been built and successfully tested. This new design[1] offers several advantages over previous LEBT designs, particularly for injection into RFQ accelerators.

The strongly convergent beam required at the RFQ entrance, transport, which may be unstable in the presence of any intensity modulation noise from the ion source, and the lack of sufficient steering or matching capability often results in betatron function mismatch at the RFQ entrance.

The all-electrostatic LEBT designed and built by the Ion Beam Technology (IBT) group at LBNL eliminates the neutralization problem and offers several other advantages. This new design incorporates two electrostatic lenses that allow a wide range of matching conditions (Twiss parameters) to be established, insuring betatron function match to an RFQ accelerator. The design has exceptionally low aberrations, offers beam steering, in both angle and displacement, and is physically compact.

Figure 1 shows the layout of the LEBT inside the re-entrant support insulator. The ion source resides in the cylindrical cavity on the left. The total acceleration potential is 40 keV, with 59 kV across the first (extraction) gap. The two thick electrodes comprise the variable-voltage einzel lenses.

Beam steering is incorporated by splitting both einzel lenses into four quadrants and applying a balanced deflection voltage across opposing quadrant pairs. Up to ±7 mrad deflection is attainable from each of the two lens electrodes with 1 kV across opposing quadrants. In addition, the entire source and LEBT assembly can be moved transversely during operation in both planes by up to ±4 mm with 40 micron reproducibility. This combination of electronic and mechanical steering guarantees optimum steering of the beam into the RFQ.

Figure 2 shows the beam envelope from the ion source to the RFQ match point and Figure 3 the r-ᵦ phase space predicted by the WOLF ion source code (ref in [1]). The smallest lens aperture radius is 0.5 cm at the final electrodes on the right, the last one representing the beginning of the RFQ vane and the immediately preceding one the exit aperture of the LEBT itself.

Test Procedure

The LEBT performance was first measured with an Allison-

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type emittance scanner[2] substituted for the RFQ with the first analyzer slit located 20 cm downstream of the RFQ match point. The pulsed 30 mA beam current was measured with a toroidal current transformer at the exit of the LEBT. The nominal voltages for the electrodes, referred to ground, are listed in Table 1.

| Ion Source Body | 40 kV   |
| Extraction Electrode | -16 kV |
| First Focus Electrode | 35 kV (nominal) |
| Intermediate Electrode | 16 kV   |
| Second Focus Electrode | 36 kV (nominal) |
| Ground End | 0 kV    |

Table 1. Electrode Voltages

The first and second focus electrodes were varied over a matrix of 33 to 37 and 33 to 38 kV, respectively, in 1 kV steps, and the Twiss parameters $\alpha$, $\beta$ and $\varepsilon$ were measured. These were compared to the values predicted by the WOLF calculation for several representative values of the focus electrode voltages, the data showing good agreement between the predictions and the measurements. Figure 4 shows a typical emittance plot, with the ellipse representing the shape of the RFQ acceptance (but at a smaller emittance to emphasize the congruence of the ellipses).

At a total current of 30 mA, measured with the toroidal current transformer, the following emittances and Twiss parameters were measured. In this case, the electrode voltages were set to the nominal values indicated above, and the measured emittance back-projected a distance $d_{back}$, assuming ballistic transport, to a point 20 cm upstream of the plane of measurement, corresponding to the original WOLF calculation.

<table>
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<th>$\alpha$</th>
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Table 2. Measured and Calculated (WOLF) Twiss Parameters

and to the match point of the RFQ. Table 2 lists measurements done on separate days, showing the excellent consistency of the measured values, and the results of the WOLF calculation. Also listed are measured values back projected 19.5 cm, which give better agreement to the WOLF calculation, indicating a mere 0.5 cm discrepancy of the longitudinal position of the RFQ match point between the measured and calculated values for nominal focusing electrode potentials.

**Electrical Steering**

Angular beam steering is accomplished at the two focusing electrodes, split into quadrants, by applying a balanced transverse field at those points. Each pair of opposing quadrants of each of the two focusing electrodes can be operated at a voltage offset from the mean by as much as ±500 volts, or 1000 volts across an opposing pair. The angular deviation of the beam was determined by the emittance scanner, along with any variation in the Twiss parameters, including the beam emittance.

Figure 5 (next page) shows the variation in exiting beam angle, and the variation of the Twiss parameters and emittance when the voltage across an opposing pair of quadrant segments in the second focusing electrode is varied from -1000 to +1000 volts. The angular deviation is quite linear with voltage and the Twiss parameters and beam emittance are only slightly affected at large steering angles.

**Coupling to an RFQ**

In the second phase of the experiment, the LEBT was coupled to an 800 keV, 400 MHz RFQ[3] manufactured six years ago at LBNL designed with an injection energy of 40 keV and 50 mA beam current. The LEBT was designed to match the Twiss parameters of the RFQ with a generous margin of adjustability by varying the potentials of the two focus electrodes.

The transmission of the RFQ was calculated, using PARMTEQ, for a range of input Twiss parameters. The effect of steering, both angular and position on the RFQ transmission was measured, verifying the initial alignment of the system. The optimum transmission occurred with minimum electrical steering and with the initial mechanical alignment position.

The focusing electrode voltages were varied over the same matrix of values for which data were taken with the emittance scanner. The transmission of the RFQ over the range of Twiss parameters available from the LEBT matched very well with the predicted transmission calculated by PARMTEQ for a mismatched input beam. The maximum transmission was experimentally found at almost the exact focusing electrode voltages predicted by WOLF. We can thereby conclude that the actual acceptance of the RFQ is in agreement with the PARMTEQ prediction, and that the measured beam parameters from the LEBT show excellent agreement with the WOLF calculations over a wide range of focusing lens parameters. Further measurement taken after the RFQ was removed from the beam line showed the species distribution from the LEBT was
approximately 64\% H^+, 17\% H_2^+ and 19\% H_3^+. The RFQ accelerates only the H^+ component, and the expected transmission of the RFQ was expected to be only 59\% for the H^+ species, due to a poor choice of geometry of the vane tips. (A $r_1 = 0.75r_0$ constant transverse radius geometry was used. Subsequent simulations with the 8-term PARMTEQ-H[4] showed that this geometry was a poor choice and a $r_1 = 1.0r_0$ geometry would have given much better transmission.) The total current (all species) injected into the RFQ was about 18 mA, which should result in 6.8 mA of accelerated H^+ beam. About 5.5 mA was accelerated, 81\% of the expected value. This small discrepancy has not been resolved to date.

**Chopping Experiment**

Recently, LBNL has joined a team to develop the front end of a proposed pulsed spallation neutron source, which incorporates a 1 GeV linac and a storage ring[5]. The beam circulating in the ring requires a 35\% circumference gap with a dark current of $10^{-3}$ of the rest of the circulating bunch. To establish this very deep gap, choppers will be placed at the ion source, in the LEBT, and a fast, 2.5 nsec chopper at the 2.5 MeV point in the linac. An experiment was prepared for this LEBT to test the feasibility of fast (1 MHz) chopping at the 40 keV level.

In the first phase of the experiment, a high-voltage pulser provided a ±1500 volt pulse, rising in 100 nsec and decaying somewhat more slowly, to opposite quadrants of the second focusing electrode to deflect the beam into a 0.6 cm diameter aperture located at the LEBT exit. With 2.7 kV across the opposite quadrants the beam was fully extinguished with a risetime comparable to the risetime of the pulse generator. Transit time in the LEBT itself limits the rise/fall time of the chop to about 15 nsec, and the 2.5 nsec risetime travelling wave chopper at the 2.5 MeV level will sharpen up the edge of the chop. The slower LEBT and ion source choppers contribute the very low dark current in the middle of the chop, and reduce the heating of the 2.5 nsec chopper beam stop.

**Future Plans**

The operation of this LEBT has been so successful that a minor variant of it will be used in the low-energy part of the injector for a proposed National Spallation Neutron Source[5]. Added to the basic LEBT design shown here will be the beam chopper, a segmented thin Faraday cup that pivots in from the side and a pivot-in one-way vacuum gate valve, both located between the last focusing electrode and the ground end, operated with the last focusing electrode at ground potential.

**Acknowledgments**

The authors thank all those who worked tirelessly on this project, including Rick Gough, Ka-Ngo Leung and his ion source group, Jim Ayers and his electronics technicians, and Bob Aita and his mechanical technicians.

**References**


THE ELECTRON GUN FOR THE DARESBURY SRS LINAC

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Abstract

The electron gun for the Daresbury SRS linac injector has been modified to use the cathode-grid assembly from the Eimac planar triode 8755. The gun now has improved beam characteristics, is more reliable and the cathode assembly is quicker and easier to change. This paper describes the assembly of the electron gun, and then the re-conditioning of the cathode highlighting the vacuum environment. The action of the grid modulation system on the electron beam, which pre-bunches the electron beam, is described, and typical gun characteristics are shown.

Proposed developments to the gun system are discussed.

Introduction

Daresbury Laboratory operates the UK’s national synchrotron light source, the SRS. It is operational for approximately 7000 hours a year, providing synchrotron radiation used by many varied scientific disciplines. The electron storage ring energy is 2 GeV and the beam lifetime is in excess of 30 hours at 200 mA. The storage ring is filled to 250 mA once every 24 hours.

The injection system consists of a 80 kV electron gun feeding a 10 MeV S-band electron linac, the electron beam is accelerated to 600 MeV in a 500 MHz booster synchrotron. The beam is injected into the storage ring at 600 MeV and the energy ramped to 2 GeV. The injection process takes approximately 20 minutes. Consequently the gun injection equipment is operational for less than 1 hour per day.

The electron gun has been modified to use the cathode-grid assembly from the Eimac planar triode 8755 [1]. This gives improved beam characteristics over the previous system, it is more reliable and the cathode assembly is quicker and easier to change. The paper describes the assembly of the electron gun, and the re-conditioning of the cathode, highlighting the vacuum environment. The action of the grid modulation system, which pre-bunches the electron beam, is described, and typical gun characteristics are shown. Proposed developments to the gun system are also discussed.

The Electron Gun - Mechanical Layout

The original electron gun was similar to the design by Willard [2] for the Manchester Christie Hospital Linac. It contained a 1 inch (25.4 mm) spherical oxide cathode with a separate de-mountable grid, which was modulated at 500 MHz. When the cathode failed the cathode - grid assembly was de-mounted, and the cathode sprayed with the usual carbonate mix (barium, calcium and strontium). The carbonates were converted to oxides, and when this was completed activation of the cathode took place. This process took several hours, and satisfactory conversion and activation could never be guaranteed. As this process took place while the gun was attached to the linac, the decomposition products of the carbonates could have harmful effects on the vacuum surfaces of the linac.

The gun has now been modified. Figure 1 shows the mechanical arrangement of the present gun. A miniature ceramic - metal planar triode, Eimac type 8755, has been modified to be used as the cathode grid assembly of the gun. The triode can be used up to frequencies of 3 GHz. The cathode is a conventional oxide coated cathode, but the heater power is only 10 watts, a factor of ten lower than the original.

Figure 1: Mechanical Layout of the Gun

The triode is inserted in the gun assembly which is connected to a temporary heater supply, with the heater voltage set to about 2 V to keep the activated cathode temperature above 150 °C. The triode anode and body ceramic are broken off, and the beam forming electrode attached. The gun assembly is bolted to the linac and the gun evacuated, whilst maintaining the cathode temperature. Haas and Jensen [3] found that by keeping the temperature to 150 °C cathodes are not poisoned when exposed to air as the oxides are converted.
to hydroxides and the hydrate is prevented. The emission capabilities are preserved.

10 times a second. The action of the triode is used to pre-bunch the beam before injection into the linac.

A three quarter wavelength coaxial cavity is connected to the gun, and sits at the gun HT, which is provided by a half sine wave pulse modulator, giving a -80 kV pulse. The heater power supply is at HT potential. There is a 0 to -200 V grid bias supply, and the 500 MHz grid modulation is fed via an 80 kV waveguide isolator.

Figure 2: Plot of Gun Vacuum during Cathode Activation

When the vacuum pressure is better than $10^7$ torr, the heater voltage is gradually increased, keeping the vacuum pressure below $10^5$ torr. Figure 2 shows the typical vacuum pressure variation during this re-activation process, and Figure 3 the residual gas analysis at the same time. Note that the water peak increases initially, but that it is the methane peak that determines the overall pressure.

Figure 3: RGA during Cathode Activation

The installation and re-activation process is simple and quick, taking only 4 or so hours. The cathode life is typically two years, but recently improved vacuum conditions have extended that time.

The Electron Gun - Electrical Layout

Figure 4 shows the electrical layout of the gun system. The gun has to produce a 400 nS 80 keV bunch of electrons
Gun Characteristics

A current transformer type monitor with a bandwidth of 500 MHz, but followed by a 10 MHz filter monitors the gun current, Io. Typical gun characteristics are shown in figures 5a, the gun current as a function of gun HT for various values of grid RF modulation -dc grid bias set to -100 V, and 5b, gun current at a fixed HT at -80 kV as a function of DC grid bias for various values of grid RF modulation. These characteristics should be compared with the triode characteristics in the Eimac data sheet [1]. The differences in the slopes in figure 5b is because the output voltage of the Io monitor is proportional to average current, and the conduction angle is smaller the greater the RF amplitude.

Pre-bunching

The SRS linac does not have a pre-buncher cavity, but pre-bunching is achieved by the DC and RF biasing of the gun grid. The linac accelerating voltage is a 4 mS, 4 MW pulse at 3 GHz. The voltage is phased locked to the 500 MHz gun grid modulation. As can be seen from figure 6, by accurate phasing of either of the grid modulation or the accelerating voltage and a large grid DC offset short current micro-pulses can be injected into the linac. The more negative the DC bias the shorter the current pulse.

Figure 6: Linac Pre-Bunching

Future Developments

For a small but significant period, the SRS operates in single bunch mode, where only one of the 160 RF buckets in the storage ring is filled with electrons. At present this is achieved with a chopper system operating on the 10 MeV beam in the flight path between the linac and the booster synchrotron. Recently investigation has started on using the gun grid modulation system to produce the single bunch and other bunch patterns [4].

The grid modulation equipment will sit at the HT potential, whilst triggering and clock pulses will be fed via optical fibre.

Summary

The electron gun for the SRS linac injector uses the already activated cathode-grid assembly of an Eimac 8755 planar triode. The installation is simple and quick, and the cathode life is relatively long.

The measured gun characteristics are as expected and follow the original triode characteristics.

The action of the RF and DC biasing of the gun grid perform some pre-bunching for the linac.

In the future the grid modulation system will provide single bunches and any required bunch pattern.

Acknowledgements

I would like to thank Mr. Brian Taylor for the original idea of using a planar triode as the grid-cathode assembly for the SRS linac electron gun.

References

Ion Source Development and Operation at GSI

P. Spädtke, J. Bossler, H. Emig, K.D. Leible, M. Khaouli, C. Mühle, S. Schennach, H. Schulte, K. Tischert
GSI Darmstadt

At GSI different ion beams are delivered to the UNILAC, the synchrotron SIS or to the storage ring ESR. For that purpose three different injectors are in use for the UNILAC, equipped with different ion sources. The standard injector with a Penning ion source and the high current injector (with CHORDIS or MEVVA ion source) supply the Wideröe accelerator (pre-stripper section of UNILAC) with an injection energy of 11.7 keV/u. The newly built high charge state injector HLI is equipped with an ECR ion source (CAPRICE). The injection energy for the succeeding RFQ and IH accelerator is 2.5 keV/u. Both beams are further accelerated in the Alvarez accelerator (post-stripper section of UNILAC) with an injection energy of 1.4 MeV/u. For ion source tests and developments additional test benches are available. The specific advantages of each injector, recent improvements and specific operating modes are described.

1 STANDARD INJECTOR

The regular injector is equipped with a Penning ion source (fig. 1). This source is operated in a pulsed mode, typically 50 Hz with pulse length from 2 to 6 ms. Extraction voltage is between 10 and 15 kV. For SIS-operation such a high repetition rate is not necessary, and the extracted ion current within the pulse can be increased by reducing the duty cycle allowing higher peak discharge power.

Typical ion currents measured in front of the Wideröe are listed in Tab. 1. The absolute acceptance of the analyzing and transport system is about 100 mrad.

Table 1: Ion currents from the PIG source. Different operation modes are not distinguished.

<table>
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<th>Element</th>
<th>eµA</th>
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We hope to increase the available intensities, especially in the low repetition mode for SIS, by further development of the PIG ion source. These investigations and developments will be carried out at the newly built PIG test bench in close collaboration with the JINR in Dubna. The following modifications are planned:

- A pulsed gas feeding system should decrease the base pressure within the source and the beam line. The optimum case would be to have enough atoms to ignite the source and to decrease the pressure during the pulse to shift the charge state distribution to higher charges.

- A higher peak discharge power should yield an increased plasma density. Together with higher extraction voltages and an improvement of the extraction system higher ion currents should be achievable.

- Different cathode materials will be tested in order to improve the life time of the source.

- A splitted anode with an additional electric field perpendicular to the magnetic field will be tested to improve the extraction efficiency[1].

![Figure 1: GSI Penning ion source.](image)

2 HIGH CURRENT INJECTOR

To increase the available ion currents for the synchrotron the Wideröe pre-stripper section will be replaced by a RFQ/IH accelerator in the near future [2].
The injection energy will be reduced from 11.7 keV/u to 2.2 keV/u. This implies the use of lower charge states from the ion source (design ion U⁺⁺, el. current 15 mA). The total extracted current from the ion source will be in the range of 100 mA. To minimize beam transport problems at low energies, there is no charge or mass separation on the high voltage platform. To preserve the beam quality during post-acceleration, the acceleration column is equipped with a movable single gap and a screening electrode[3]. The present 320 kV high voltage power supply limits the current to 40 mA. It will be replaced by a new one with a maximum voltage of 150 kV and maximum load current of 150 mA in 1997.

Like the PIG source, the CHORDIS (shown in fig. 2) is regularly operated in a pulsed mode up to 50 Hz and pulse length from 0.5 to 5 ms. Extraction voltage is between 20 and 40 kV.

Typical ion currents from the CHORDIS for D and Ne are given in table 2. The currents are measured at the same location as for the PIG source.

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<td>0.5</td>
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Table 2: Ion currents from the CHORDIS.

For high current investigations at the UNILAC and SIS we use the Ne-beam delivered by the CHORDIS. The molecular deuterium beam has been used instead of the atomic one for two reasons:

- The operation regime for the atomic beam is not favorable (very low rf and magnetic field level).
- Passing the gas stripper behind the Wideröe at 1.4 MeV/u the electrical current is increased by a factor of 3 by braking up the molecule and ionizing the atoms. Thus we have had a higher particle current at the experiment.

For all beams from metallic elements we are using the MEVVA ion source [4]. Our version of that source type (see fig. 3) is operated in a pulsed mode with a repetition frequency of up to 5 Hz and pulse length from 0.5 to 2 ms [5][6]. Extraction voltage is between 20 and 40 kV. The same extraction system as for the CHORDIS is used.

Typical ion currents for the MEVVA ion source are listed in table 3.

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<td>²⁴Mg⁺²⁺</td>
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<tr>
<td>⁴⁰Ti⁺</td>
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<td>⁴⁰Ti⁺²⁺</td>
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<tr>
<td>⁵⁸Ni⁺</td>
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<td>⁵⁸Ni⁺²⁺</td>
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</table>

Table 3: Ion currents from the MEVVA.

The Mg⁺ beam has been measured at the UNILAC injector, whereas all other data have been taken at the high current test bench (analyzed current after 5 m beam transport).

For the Ti-beam the maximum of the charge state distribution is at the required charge state, for other elements special measures are necessary to get the maximum current in the desired charge state. Higher charge states can be achieved by applying a high magnetic field close to the cathode region. To decrease the charge state (1+ desired for the Mg-beam) additional gas is fed into the discharge chamber. This is shown in fig. 4.

The development of the MEVVA ion source is made in close collaboration between TASUR in Tomsk, LBL in Berkeley and GSI. After achieving the desired currents, the main activity is now to decrease the noise level on the beam as well as the pulse-to-pulse reproducibility.
very similar to that for normal gases with the supplementary condition that a minimum microwave power of around 200 W should be applied to the source to avoid condensation of the material in the front part of the feeding system.

Table 4: Ion currents from the ECR ion source. Enriched isotopes are marked by an asterisk.

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The main activity for that source is to develop different techniques to create ions from solid materials [7]. Tests at the ECR test bench revealed that for Se (vapor pressure $10^{-3}$ mbar at $\approx$ 200°C) the regularly used oven did not yield stable operating conditions, even with some modifications to minimize the influence of the discharge on the sample temperature. For such high vapor pressure materials we built a new low temperature evaporator (fig. 6) in which the sample is placed outside the source and the vapor is guided to the standard quartz gas feeding system through a long heated quartz capillary. Thus the source operation is

Comparison between test bench and injector beam line is not satisfactory. Therefore we are building an injector test bench, which will allow to transfer results to injector operation.

4 REFERENCES

FEASIBILITY OF SHORT WAVELENGTH, SHORT PULSE LASER ION SOURCE FOR THE LHC INJECTOR

J. Wołowski¹, P. Parys¹, E. Woryna¹, J. Krása², L. Láska², K. Mašek², K. Rohlena²

Abstract

Results of experimental investigations of characteristics of ion streams generated from laser plasma after focusing the laser beam either with an aspheric lens or with a parabolic mirror (allowing an observation of the ion emission in the direction of the target normal) are presented. The photodissociation iodine laser PERUN operating with \( \lambda = 1.315\mu m \) and delivering energy up to 50J was exploited in the experiment. In this contribution we restricted ourselves to the results of ion emission measurements from Ta−, Pb− and Bi− plasma.

Introduction

Present studies of the emission of ions from the laser produced plasmas are mainly motivated by a growing interest in the physics of heavy ion accelerators. In the application of the laser plasma as a source of multiply charged heavy ions high current densities are required. From this viewpoint, as numerous experiments show, the laser plasma sources seem to be very promising. In comparison with the electron cyclotron resonance ion sources, which are employed for heavy ion injectors at present, higher current densities of highly charged ions are expected. Thus the charge state of ions, the ion velocity (or the ion energy) and the ion current density were the basic parameters of interest. However, it is evident that whilst the ECR sources are nowadays highly developed as far as their reliability and simplicity of operation is concerned, the laser sources still face major technological and even scientific problems.

PERUN Experiment and Results

Ion emission experiments were mainly performed with the photodissociation iodine laser system PERUN [1]. Ion collectors (IC), a cylindrical electrostatic energy analyzer (IEA) and a Thomson mass spectrometer (TS) were applied to monitoring the emission of the ions [2]. The ion species, their energy, abundance and/or velocity distribution were explored in dependence on the laser power density, focus setting with respect to the target surface and the changing the angle of observation. The collectors are based purely on the time-of-flight effect, the spectrometers combine time-of-flight with the action of electric or magnetic field on the ions. The collectors first separate the electron component and then they measure the ion current. The outcome is, however, influenced by the secondary emission, which is adding to the net current. Since the secondary emission coefficient, which is specific for any cathode material, may be energy and charge dependent, it introduces a certain degree of uncertainty in the results. This is the main source of error in the absolute estimates of the ion number. In the following it was assumed that for each ion charge unit impinging on the collector cathode one extra secondary electron is struck out.

The analyser devices use either an electric field alone to separate the ion species as in the IEA or the combined electric and magnetic field in the TS. The geometry of IEA is that of a cylindrical capacitor segment, where the radial electrostatic field separates the ions entering through a slit. The sensor is a vacuum windowless electron multiplier. An IEA requires a repetitive laser operation (typically 20 shots) to determine the charge energy spectrum.

Figure 1: IC signals and IEA record of Bi.

TS renders the whole spectrum in a single shot, but the resolution power for highly charged species is poor. The output picture formed either on an ion sensitive foil or a multichannel plate is composed of a set of parabolas, each corresponding to a single value of \( e/m \). Whereas for light elements like contaminants in the vacuum of the target chamber the parabolas are quite distinct,
the higher charges usually coalesce. In practice it is thus imperative to use an IEA to get a quantitative answer. However, if the recordings of the TA are processed numerically, in particular, a grid of precalculated parabolas is overlaid with the output the identification of ion groups is fast and convincing. Both the devices are difficult to calibrate absolutely, but placing a coaxial IC in the path of flight of an IEA makes an absolute calibration possible. Examples of ion collector signals and electrostatic analyzer spectra for Bi is shown in Fig. 1. Two groups of ions (fast and thermal) are clearly discernable on the charge-integrated and time-resolved signal from an ion collector, which was located in a far expansion zone. The spectra in Fig. 1 clearly prove the existence of ions with charge states about 50+. We registered fully stripped Al, or nearly stripped Co and Ni, and ions with charge state higher than 48+ of heavy elements: Ta, W, Pt, Au, Pb and Bi. In principal, the mass-to-charge ratios, energies and abundance of the emitted ions can be determined from the spectra. The ions are not only generated, but also accelerated. The maximum energy of the ions increases with the laser pulse density. In our experiments with high-Z targets the highly ionized ions with energies up to several MeV were registered. Keeping in mind a two group electron model [3] the fast ion expansion velocity can be interpreted as a sound speed with the hot electron temperature.

Estimates of the ion current density and the number of ions with a given charge state produced during a single laser shot were performed by processing of the IC signal with the use of the data from IEA spectra. The total maximum ion current density attained 12mA/cm² with lense and ~ 22mA/cm² 94cm from a Ta target (recalculated value according to *r²* law) using the parabolic mirror. An evaluation of the experimental data pointed out that about 30% of the ions of their total amount are in a high charge states (from 35+ to 45+). When recalculated to the number of the particles our measurements give thus at least 10⁸ of ions in a single charge state within a single pulse lasting about 1μs. The maximum values are observed in the direction of the normal to the target, as it follows from the measurements with the parabolic mirror. To obtain the entire ion energy distribution for a single value of the laser energy a series of measurements changing the analyzer voltage was made. As the measurements are fairly laborious and time consuming they were performed only for Ta—ions, see [3].

Exploiting the theoretical considerations in [4-8] a dependence of the average charge state of ions on electron temperature was constructed, which is shown in Fig. 2. It is seen that an average charge state of Ta-ions 45 is attainable at an electron temperature of about 1.0 - 1.5 keV, while at the same temperature the average charge state of Au- and Bi-ions is 51 and 55, respectively. This corresponds to the electronic structure of the heavy ions, which unlike the neutral atoms tend to form a closed electron shell with 28 electron left (Ni-like ions). For a further ionization a fairly high potential barrier would have to be overcome. In this sense it is easier to achieve a higher ionization degree starting from heavier elements.

The generation of the ions in the laser plasma, as far as their charge states and numbers are concerned, is very sensitive to the position of the laser focus with respect to the target surface. The results of our studies of the effect of focus setting on the ion emission is summarized in Fig. 3. There is a position of the target lying behind the true focus (aim in front of the target surface), which is most favourable not only for generation of the highly ionized particles but also for attaining a maximum yield of the ions. Then it is most likely that the laser shots aimed repeatedly in the same point on the target surface deteriorate both the amount and the average charge state of the emitted ions. It was found that after the 3rd laser shot the plasma parameters are so changed that the energetic highly charged ions are missing and the total ion emission is much weaker.

**Discussion and Conclusions**

It is interesting to compare the requirements of an ideal LHC injection at CERN with the performance of the short pulsed lasers as potential ion source drivers. Since these lasers appear to be more costly and less practical then the CO₂ these drawbacks must be balanced by specific advantages offered by them. A principle advantage might well be skipping of the first stripper in the Linac line. Also the number of ions and the timing of their arrival should be such, as to allow for a single turn booster operation and possibly to avoid the use of LEAR (which would, however, be the purpose of any laser source). The requirements of CERN are summarized as follows:

For the lead ions experiment an ideal source should yield

\[
Pb45^+ \quad 3.6mA \quad 6μs \quad (= 3 \times 10^9 \text{ ions}) \quad 17.3keV/μ\text{u} \\
Pb54^+ \quad 4.3mA \quad 6μs \quad (= 3 \times 10^9 \text{ ions}) \quad 20.8keV/μ\text{u}
\]

In deriving these numbers it was assumed that the extraction voltage is set to 80kV and no stripper. This compares with the numbers obtained e.g. with the iodine laser using a Ta target

\[
Ta42^+ \quad 22.8mAcm⁻² \quad 1μs \quad (= 10^8 \text{ ions}) \quad 12.7keV/μ\text{u}
\]
the Czech Republic and of the Czech Ministry of Education grant KONTAKT ES008(1996).

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Figure 3: Dependence of the ion current and of the mean charge on the focus setting

In the last line the second number is the current density in the collector current maximum of the fast ion group (about 30% of the total) obtained with the mirror focus measured in reality by a coaxial IC 174 cm from the target, but transformed using a quadratic law to a distance of 94 cm (to make it compatible with the lens focusing). The fast group involves about 10 ion species and the pulse is short. Although the estimate of 10^8 ions available for the extraction is fairly conservative, it is difficult to see, how especially the pulse timing could be extended to the required 6 μs tempering just at the laser. Looking at the charge-energy spectra a natural spreading of the pulse by the time-of-flight would dictate an intolerably long flying path.

A certain improvement might be expected resorting still to shorter wavelength laser. Then there is a less acceleration and the energy spectrum is narrower. Equally a larger focus, while keeping the power density constant, might supply more ions, but at the cost of a disproportionate increase in the pulse energy, since not only the focus area grows, but also the pulse should be prolonged, see [1]. But it is unlikely that the timing of the pulse might be reconciled with the LHC injection demands without a major change in the subsequent acceleration regime.

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ION EMISSION FROM HIGH-Z LASER PLASMAS


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Abstract

The results of systematic studies of ion emission from plasmas generated in the focus of laser beams of short wavelengths, short pulse lasers (Nd:glass, 1 ns, 1060 nm; iodine, 0.5 ns, 1st harm.- 1315 nm 2nd harm.- 675 nm, 3rd harm.- 483 nm) are presented. The corpuscular diagnostics were based on (i) Thomson parabola spectrometer to display a general view of the ion spectra, (ii) cylindrical electrostatic ion energy analyzer to determine the detailed charge-energy ion spectra (iii) ion collectors to estimate the current density of the ion fluxes far from the focus. The ion current densities about 1 m from the focus are typically mA/cm². Fairly high charge state (>50+) and simultaneously energetic (>8 MeV) ions were registered. The results are interpreted either in term of a two-temperature model of the expanding plasma or by an ion emission from a dual focal spot including a hot primary focus and a colder peripheral zone.

Introduction

An expanding laser plasma is an efficient source of highly charged ions [1]. It is formed by focusing a nanosecond laser beam on a target. In the plasma corona an intense collisional ionization is going on. If the plasma is left to expand the phenomenon of charge freezing sets in. Due to the fast expansion the plasma is diluted before the recombination eradicates all the highly ionized ion species. Hence, at least part of the ions has a chance to conserve the charge state acquired in the hot plasma core and carry it at a considerable distance away from the focus. There, the ions can then be either registered by various sensors of particle diagnostics, such as ion collectors and ion analyzers (Thomson or electrostatic), or after a separation of electrons they can be transformed in an ion beam and introduced in a beam line of an accelerating system. In the following we shall concentrate, in particular, on the subnanosecond pulse laser in the near infrared region.

Laser drivers

The photodissociation iodine laser PERUN [2] in the Institute of Physics of AS CR in Prague is operating at the wavelength 1.315 μm, producing pulses of ~ 50 J, which are roughly 350-500 ps long and can be focused in a spot size (lens optics) of 80 μm. The average power density attainable on the target is thus ~ 10¹² W/cm². Frequency conversion by DKDP crystals to 2ω and 3ω is available with about 50% efficiency. The target chamber was fitted either with an aspherical f/2 (f = 20 cm) lens or alternatively, with a mirror (f = 28.5 cm) having a 12 mm hole in the centre to allow access to the part of the plasma expanding directly against the laser beam. The mirror focal spot is somewhat larger (~ 100 μm) than with the lens focus.

The Nd:glass laser in the Institute of Plasma Physics and Laser Microfusion in Warsaw gives at maximum 15 J at 1.06 μm in 1 ns pulses. The spot size with lens optics is about 100 μm with a power density on the target < 6 x 10¹⁰ W/cm². Besides the aspherical focusing lens a combination of a lens with an ellipsoidal mirror with a central hole was used. The CO₂ Lumenics TEA 601 laser [3] gives 50 J in a 50 - 70 ns pulse. The power density on the target is ~ 2 x 10¹² W/cm². Focusing is with a parabolic mirror f = 30 cm with a hole of 30 mm.

The CO₂ TIR-1 system at Troitsk [4] delivers about 100 J in either 25 ns or 2.5 ns pulses. The focusing system using a parabolic mirror f = 60 cm with a hole of 25 mm achieves the power density on the target either ~ 4 x 10¹⁵ W/cm² or ~ 6 x 10¹⁴ W/cm².

At this stage of development the potential performance of laser ion source is synonymous with the results of particle diagnostics of the expanding laser plasma. None of the near infrared lasers used has an adjacent LEBT line or an RFQ to assess directly the quality of the preaccelerated ion beam. Nevertheless, the charge-energy spectra of the expanding laser plasma allow for qualified estimates of at least some properties of the ion beam derived from such a plasma.

Results

The collector signal usually indicates several ion groups, which are separated by the time-of-flight effect. The highest charge is carried by the fastest group, to which the following table relates. It presents the results obtained with the first
harmonics of the iodine PERUN system for various elements. The geometry of the measurements was either a coaxial one using a mirror (M) or the measurements were off the axis using a lens (L) focus.

Table 1 was compiled by uniting the data of IC measurements in two different distances from the focus. In the case of lens focus the IC collector was 94 cm from the focus, with the mirror the distance of a coaxial IC was 174 cm. The current densities are the peak values of the fast ion signal, recalculated in each case to the shorter distance of 94 cm using a quadratic law. The values for the mirror case are thus estimated fairly conservatively, [5].

Table 1

<table>
<thead>
<tr>
<th>Elem.</th>
<th>$&lt;z_{\text{tot}}&gt;$</th>
<th>$&lt;E_{\text{fast}}&gt;$ [keV/u]</th>
<th>$j[\text{mAcm}^{-2}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co (M)</td>
<td>22 (25)</td>
<td>32.7</td>
<td>14.2</td>
</tr>
<tr>
<td>Ni (M)</td>
<td>20 (26)</td>
<td>15.7</td>
<td>18.5</td>
</tr>
<tr>
<td>Cu (L)</td>
<td>(25)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ta (L)</td>
<td>(55)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tm (L)</td>
<td>42 (48)</td>
<td>12.7</td>
<td>12.8</td>
</tr>
<tr>
<td>W (M)</td>
<td>45 (49)</td>
<td>10.9</td>
<td>22.8</td>
</tr>
<tr>
<td>Pt (M)</td>
<td>45 (50)</td>
<td>15.9</td>
<td>12.8</td>
</tr>
<tr>
<td>Au (M)</td>
<td>38 (49)</td>
<td>15.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Pb (M)</td>
<td>40 (51)</td>
<td>15.9</td>
<td>8.5</td>
</tr>
<tr>
<td>Bi (M)</td>
<td>40 (51)</td>
<td>12.9</td>
<td>10.0</td>
</tr>
</tbody>
</table>

It would seem that the sharper focus for the lens case yields higher maximum charge numbers (values in parentheses second column) and that the higher currents are emitted from the larger mirror foci. In reality, the dependence of the ion current as well as of the maximum charge number on the power density and on the size of the focal spot are not trivial and are different in character. It is more likely that the differences between the mirror and lens geometry are given by the directional characteristics of the ion emission. When defocusing the dependence of the current has a sharp peak for the maximum power density, whilst the maximum charge number changes just slowly. This has implications, for instance, for the quality of the target surface, in particular, when placing several shots in the same spot and a crater is formed, [6].

The results are to be understood in the following way: the plasma is formed by a short intense pulse, in its hot core the electron temperature is exceeding 1 keV and the system is essentially in a thermal equilibrium. The highly charged ions are born in the core by an intense collisional ionization. During the expansion stage the electron temperature is falling fast, because also the laser power in the case of the short pulse goes down quickly. Not even the recombination heating can maintain the temperature on a steady level. The temperature is decreasing when the ions are still passing through a comparatively dense region. Owing to the temperature drop, the recombination sets in. The high charge states will thus be destroyed before the system is (due to the fast expansion) out of the thermodynamic equilibrium and the high charge states have been “frozen in”. Especially vulnerable are the high $z$ ions. This scenario applies to the thermal ion group, which follows the fast group and is carrying charge states, which are generally lower.

The existence of the fast group is pointing to an accelerated expansion mechanism. Such a mechanism is triggered by a group of superthermal (hot) electrons which originate from a non-dissipative laser energy deposition in the plasma. A part of the primary laser energy is transformed in electrostatic plasma waves, which accelerate the plasma electrons by the mechanism of inverted Landau damping. The resulting hot electron population is guiding the fast plasma expansion contributing thus to a survival of highly charged species.

From what has been said it is clear that an ideal laser driver should provide both the fast plasma ionization to attain as high charge state as possible and also a fast expansion to conserve the charge once formed in the core by suppressing the recombination during the expansion stage. These two requirements are difficult to meet at once. The ionization rate is mainly controlled by the electron density in the vicinity of the critical surface in the plasma, i.e. the density surface where the electron plasma frequency equals the laser frequency, $\omega_L = \omega_{ce}$:

$$n_{ce} = \omega_e^2 \frac{m}{4\pi e^2}$$

(1)

beyond which the laser radiation cannot penetrate ( $n_{ce}$ is the critical electron number density, $e$ is the elementary charge and $m$ is the electron mass). Another factor determining the maximum attainable ionization degree is the time available for the ionization process. It is either equal to the characteristic hydrodynamic build-up time $\tau_{hyd, p}$ of the plasma plume, which is also the residence time of an ion inside the hot plasma core

$$\tau_{hyd, p} = R_{spot} / C_s , \quad C_s = \sqrt{<z> (n_n + n_z) / M (n_n / T_n + n_z / T_z)} ,$$

(2)

or to the laser pulse time, $\tau_L$, which one happens to be shorter ( $n_n$, $n_z$, $n_n = n_n + n_z$ , and $T_n, T_z$ are the number densities and temperatures of thermal and hot electron population, $R_{spot}$ is the focal radius, $M$ is the ion mass, $C_s$ is the ion acoustic velocity and $<z>$ is the mean charge).

For a well tuned laser the hydrodynamic time should thus be shorter or equal to the laser pulse duration,

$$\tau_{hyd, p} \leq \tau_L$$

(3)

to use the ionization process to a full advantage [7].

Conclusion - comparison of various lasers

In the previous sections mainly the performance of the iodine laser was being assessed, in the following we shall use the same criteria for the other types of laser driver. Since the frequency conversion changes the wavelength, the iodine
laser with a beam converted to higher harmonics (2\(\omega\) and 3\(\omega\)) will be considered as separate cases.

CO\(_2\) drivers: The CO\(_2\) lasers are an obvious choice for their high repetition rate and commercial availability. They also have usually a long pulse, meeting thus the criterion (3). However, owing to a long wavelengths (10.6 \(\mu\)m) the critical density (1) is too low and the ionization is slow. The highest attainable ionization degree is thus lower than that of the short wavelength lasers. Moreover, the focusability of the beam is usually bad, which reduces the power density on the target. Also, the pulse tends to have a fairly long "ramp", containing a non-negligible portion of the total energy, which induces low temperature phenomena on the target like digging an outsized crater and a splutter of the target material.

Nd:glass laser performance is not, in principle, different from that of iodine, it has a slightly longer pulse, which is a favourable feature, the energy is less controllable. A repetitive action is more difficult to implement, because of a heat build-up in the glass, but a future diode pumping might solve the problem.

Converted iodine 2\(\omega\), 3\(\omega\) is giving about the same results as 1\(\omega\), but with less acceleration. Clearly, the fast expansion phase is missing, the hot electrons are absent. This means that in the hot plasma core, which is considerably more dense than in the case of 1\(\omega\), see (1), much higher charge states are formed, which only partially recombine during the expansion. A second maximum of very slow ions, which sometimes appears on the collector signal, is likely caused by an emission from a peripheral part of the focus, which is heated by an intense x-ray radiation of the primary plasma. A direct experimental prove of the existence of very highly ionized species in the focal spot created by the blue 3\(\omega\) beam is, unfortunately, still missing, though the calculations seem to point in this direction.

An extrapolation towards still shorter wavelength points out that the use of excimer lasers (such as KrF) in the ultraviolet range should be given a serious thought. These lasers are technically related to CO\(_2\), are easy to operate in a repetitive regime and the deposition of laser energy in the plasma is very high. There are however difficulties with controlling the pulse shape, especially in the nanosecond range, but at least in a single pulse regime the ways of circumventing them are known.

A repetitive action is neither easy to implement in the case of iodine lasers. Though the sealed-off systems are known to operate with the frequency nearly 1 Hz at about 70 J of energy [8], the operation is in the free running regime and the pulse is thus far from being in the nanosecond range. There should be, in principle, no difficulties in changing the generation regime to obtain a subnanosecond pulse with the same rep rate, but this would mean to sacrifice a part of the energy. A serious obstacle is also the cost of such a would-be instrument, which might lie anywhere between 300 and 1000 k\$ (US).

Acknowledgements

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SMOOTH ION ENERGY TUNING IN LINEAR ACCELERATOR

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Abstract

This paper presents the results of experimental research of energy variable proton linac, which consists of independently driven one-gap accelerating cavities. Cavity design proposed by authors seems to be optimal for high values of energy gain and beam current. A multichannel accelerating structure allows to accelerate several ion beams. Beam focusing is accomplished by means of electrostatic quadrupoles with variable potential, which is chosen from the viewpoint of maximum beam transit factor for each operation mode, determined by output energy. The other energy variable accelerating structures with operating frequency changing are also under consideration.

The modern stage of accelerator engineering development in Russia is characterized by a peculiar combination of the requirements to expansion function opportunities radiation installations and their efficiency increase with decrease of material inputs on their creation and exploitation. In the ion accelerators area to number of such problems it is possible to relate creation of complexes, capable to receive beams with any by given energy from a zero up to maximum and ensuring thus transfer to ions reasonably large (up to several tens percent) part of RF energy from a generator.

This problem not decided so far due to problems of practical realization. The last were connected mainly to absence of the constructive decisions enabling to supply high energy gain in a meter range (i.e. ions accelerators range), that is significant longitudinal sizes of resonators at a limited potential gradient, stipulated with breakdown significance on a small accelerating gap.

The accelerator block diagram of which is indicated on fig. 1. By the authors was offered as the main accelerating element of installation to use a polaxial resonator (PR). Ones formed from a known cylindrical resonator with wide aperture drift tube by its installation on the end face of a disk with a diameter close to size of a resonator cylindrical wall. On fig. 1 are entered following reviews: 1 - ions injector, 2 - PR, 3 - RF feed system specifying generator, 4 - phase shifters, 5 - RF amplifiers, 6 - electrodes of a electrostatic focusing system, 7 - magnetic analyzer, 8, 9 - ions beam collectors, 10 - variable resistance of a power supply system of the electrodes 6, 11 - beam slot-hole collimating system. Given scheme has basic character and does not exclude an opportunity of phase adjustment in a most specifying generator, or directly in accelerating cascades. As well as variant of discrete phase change at the expense of replacement wave cable with fixed electric length. The length determine the phases difference on the generator 3 output and each particular resonator.

![Fig. 1. The accelerator block diagram.](image)

The schematic drawing of a structure in two projections is shown on fig. 2. On a drawing are indicated: 1 - resonator cylindrical wall, forming a vacuum chamber, 2, 3 - resonator face wall, 4 - drift tube, 5 - disk, 6 - drift tube face cover, 7 - dielectric electrodes 8 holders of electrostatic focusing system, 9 - electrodes 8 potentials input, 10 - loop of a RF capacity level measurer, 11 - power input from a generator, 12 - pump system vacuum collector, 13 - frequency adjustment element, 14 - drift aperture. The drift tube cover 6 and disk 5 are replaceable, that permits by a way on selection of these elements with the various sizes to adjust resonant frequency of resonators in small limits, that it is convenient on stage of accelerator start. The focusing system electrodes fix on a plate with a opportunity them tuning on mandrils. The diametrical sizes of a drift tube internal cavity admit accommodation of a focusing system for several channels located on circles by some centimeters diameter. Accelerating structure pump carried out through cylindrical collectors, connected to nonoil pumps. Ones provided vacuum in a structure better then 3·10^-6 Torr. Tuning is executed with help of the laser beam and mandrils.

Diameter of a circumference channels centers circle in spent experiments makes 6 sm. The resonator loaded quality equals ~700, coupling factor ~2, own quality ~2000. Arriving to the resonator power was defined as differences by the dropping and reflected waves power. The shunt resistance significance was determined by the power spectrum comparison of a simulating electron beam (instead of ions were injected electrons with energy ~40 keV). Dependence based on the accelerated electrons energy maximum and appropriate entered power level in view of the previous changes allowed to estimate shunt resistance significance. Within the measurements accuracy limits of 10% it has made 80 kOm.

The proton acceleration in an energy adjustment mode for the account of appropriate resonators phasing was executed after preliminary selection of transportation optimum conditions in a electrostatic quadruple lenses system. Thus in each of quadruples one electrodes pair of
opposite transportation channel was ground and second was under positive or negative potential.

Fig. 2. The accelerator structure schematic drawing.

At the power level in one resonator 40 kW the energy gain in it reached up to 56 keV. On fig. 3, 4 experimental dependencies of a current in magnet winds (power spectra analogue) are submitted. Ones removed for various RF fields phases significance in first and third resonators (in second - the RF power was not entered). As well as for a various RF power level at its division equally on the general accelerator cascade output by means of phase shifter bridge scheme. As it is visible from these drawings given regime of proton output energy smooth adjustment is realized in complete volume.

Fig. 3. The dependencies of proton current from the current in magnet winds for various RF fields phases significance (P/2=17 kW).

Fig. 4. The dependencies of proton current from the current in magnet winds for various RF power levels (φ=40°).

The realization simultaneous phase and peak regulation provides the task opportunity of any change law of
RF fields accelerating harmonic phase speed along system length. That it is necessary for particles acceleration in the high energy fields. It means that the accelerators on all energy (up to relative) can be executed on the basis of identical single gap resonators optimized under the form and sizes from a point of view of power walls losses minimization, that is efficiency increase. Besides fall away necessity of transition to higher frequencies. That is increase a ions capture factor at the expense of losses absence on transition sites. As well as simplifies RF system as a whole. Besides a new functional opportunity of acceleration in the same acceleration complex of a various type ions is opened.

In particular, in a considered structure it is possible deuterons acceleration. For transition to heavier ions can be recommended PR with several disks installed on drift tube and external wall.

Use of a double gap resonators sequence in the kind quarter wave vibrator with drift tube is represented reasonably effective also. Thus the each resonator frequency is determined by a situation relocatable short piston in the vibrator basis. The ions flight time between backlashes can be adjusted in potential of electrode, located in each tube.
Beam Loading Effects in LINACS with Resonant Loaded RF-Power Upgrade System.

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Abstract

The RF power upgrade systems with microwave energy compression are used for accelerating wave power increase [1-3]. The energy compression systems (ECS) with a resonant loading present the certain interest for practical use because of their specific properties [4]. They are capable to increase an accelerating wave power up to 50...100 times (up to 20 dB) and keeps this wave in accelerating structure for a longer time then conventional ECS. The resonant load is an essential part of the system and renders influence significantly on its parameters. The system consists of two connected resonators, one of which is using as a storing element and the second — as a load. Load may be a standing or a traveling wave resonator (TWR) formed by accelerating structure. Beam loading effects would change the properties of RF field in the load resonator. ECS characteristics and the accelerated beam parameters are discussed.

Introduction

The main principle of the system with resonant loading operation is based on using connected resonators [4]. Wave emitted from storing cavities (SC) pass through TWR (see Fig. 1) and becomes incident wave for SC. The resultant wave amplitude at the accelerator structure is equal sum amplitudes of those waves. This process continues while all energy primarily stored in SC passes by turns to TWR. So it causes significant field increase at accelerating structure.

Schematic drawing of the ECS with resonant load is submitted on Fig. 1. Accelerating structure input and output connect through switched coupler and SC and form the TWR. The switched coupler transfers the system operation mode from storing energy to its use. During the energy storing period (state A) the coupler connects generator output to storing cavities and the acceleration structure output — to an absorbing load. To use the stored energy (state B) the coupler is switched in such way that the acceleration structure output becomes connected to storing cavities, forming TWR.

At state A (see Fig. 2) energy storage occurs in SC. The wave, reflected from storing resonators, passes through a TWR and arrives in a load. When the energy storing process ends the coupler transformed in state B. The wave coming to SC is a wave leaving from accelerating structure. A wave phase shift in a TWR is chosen so that the wave coming on SC has the same phase as the wave emitted from it. Amplitude of a wave circulating in TWR ring will grow so long as all accumulated in SC energy will not pass completely in TWR. After this the return swapping of energy from TWR to SC will begin. The qualitative graph of the circulating in TWR wave average amplitude variations is shown on Fig. 2.

![Fig. 2. The RF wave average amplitude variations in a system with a resonant load ($E_0$ - generator wave amplitude; $E_w$ - wave in TWR ring; $I$ - beam current).](image)

Theory

Traveling wave resonator is forming at the end of storage period (at moment $t_0$) by the switched coupler. RF generator is connected with an absorbing load and accelerating section output — with storing cavities. The wave, emitted from the SR, is added to a wave circling in the TWR. In this case the amplitude of a summarized wave at the
acceleration structure entrance during the energy use period is described by a following expression [4]:

\[
E_w(t) = \begin{cases} 
(\frac{-2\beta}{1+\beta} - (1-e^{-t/\tau}) + 1)E_0, & \text{for } 0 \leq t < t_0 \\
\sum_{n=0}^{N} E_w(t_n), & \text{for } t \geq t_0 
\end{cases}
\tag{1}
\]

where:

\[
E_w(t_n) = \frac{-2\beta}{1+\beta} E_0(1-e^{-t_0/\tau}) e^{-nT} = \frac{-2\beta}{1+\beta} \cdot \frac{t-t_0-nT}{\tau} F(-n,1,A)
\]

\[
F(-n,1,A) = \sum_{k=0}^{n} \frac{C_k^n}{k!} (-1)^k A^k = A^{\frac{t-t_0-nT}{1+\beta}}
\]

\[N = \frac{(t-t_0)/T}{T} \cdot \text{number of wave revolutions in TWR, } T \cdot \text{time duration of one turn-over of a wave in a TWR.}\]

For function \(F(-n,1,A)\) evaluation one can use formula:

\[
F(-n,1,A) = \frac{2n+1-x}{n+1} - F(-n,1,x) - \frac{n}{n+1} F(-(n-1),1,x)
\]

where \(F(0,1,A) = 1\) and \(F(-1,1,A) = 1-A\).

The expression (1) describes microwave amplitude at accelerating section without current loading. Coupling factor \(\beta\) depends on the storing energy duration period \(t_0\).

In case, when the current loading appears essential, it is necessary to take into account changes of wave amplitude falling on cavities. Using principle of independence of fields, it is possible to consider that two waves exist: one wave is connected with RF energy in SC, second — will be formed by electron beam. The expression for field amplitude of the beam radiation wave at any point of accelerating section with coordinate \(z\), has a kind:

\[
E_b(t) = \begin{cases} 
-IR(1-e^{-az}) + \sum_{n=0}^{N} E_{bn}(t-t_1 - \frac{z}{v}) e^{-az}, & \text{for } t > t_1 + T \\
-IR(1-e^{-azv}), & \text{for } t \leq t_1 \leq T 
\end{cases}
\tag{2}
\]

Where designations are used:

\[
E_{bn}(t) = \frac{2\beta}{1+\beta} E_i e^{-(n-1)a\tau} e^{-t_{nT}/\tau} \sum_{i=0}^{n-1} \frac{2\beta}{1+\beta} (1-\frac{2\beta}{1+\beta})^i \times
\]

\[
x F(-(n-1),1,\frac{2\beta}{1+\beta} \cdot \frac{1-nT}{\tau}) + (1-\frac{2\beta}{1+\beta})^n E_i e^{-(n-1)a\tau}
\]

\[E_j = -IR(1-e^{-aj}), I \cdot \text{beam current, } R \cdot \text{shunt impedance of accelerating section, } v \cdot \text{group velocity of accelerated wave, } t_1 \cdot \text{beam injection moment, } I \cdot \text{accelerator structure length.}\]

The resulting amplitude of a high-frequency wave at accelerating section input is determined by addition of two waves \(E_w(t)\) and \(E_b(t)\):

\[
E(t) = E_w(t) + E_b(t)
\tag{3}
\]

Analytical expression of beam energy is enough difficult problem. For this reason the determination of beam energy of linear accelerator was carried out in numerical kind by using formula:

\[
W_b(t) = \int_0^1 \left( E_w(t-t_0 - \frac{z}{v}) + E_b(t-t_1 - \frac{z}{v}) \right) e^{-az} dz
\tag{4}
\]

ESC with resonant loading give increased amplitude RF wave on extent several turn-overs of a wave on TWR. So it can receive much longer pulses of an accelerated beam in comparison with other type compression systems. For example, we have obtained RF pulses with 15...17 dB multiplication factor and about 0.5 \(\mu s\) pulse duration for accelerating section filling time about 24...40 ns [4]. The electric field is considerably changed in time at accelerating section at one turn-over period. However, it does not result in increase of beam energy spectrum. It is possible to assume, that stored in traveling wave resonator energy is almost in accelerating section. So the beam energy is close to constant during one turn-over period.

**Calculation results**

Calculation was made for following parameters of ESC and accelerating section: power of the generator output \(P_0 = 10\) MW, \(Q\)-factor \(Q_w = 90-10^3\), shunt impedance of accelerating section \(R = 40\) M\(\Omega\)m/m, \(t_0 = 2.5\) \(\mu s\), power decrease per unit of acceleration section \(\alpha = 0.04\) and 0.08 m\(^{-1}\), accelerator section feeling time \(T = 40\) and 60 ns.

To achieve maximum beam energy it is need choice coupling factor \(\beta\) for an energy storage period \(t_0\). Dependences of maximum value \(E_w/E_0\) and optimum coupling factor \(\beta\) are shown on Fig. 3.

![Fig. 3. Dependence of maximum averaged wave amplitude at an accelerating structure entrance \(E_w/E_0\) and coupling factor \(\beta\) on an energy storage period \(t_0\) \((T=40\) ns\)](image)

The accelerator beam energy \(W_b\) (normalized to \(W_0\) - accelerator energy without any ECS) depend upon time \(t\) as shown at Fig. 4. Width electron energy spectrum remains practically constant \((\Delta W_{pe}/\Delta W_0)\) for current values from 0 up to 1.5...2 A. At given current pulse of beam duration \(t_0\) the influence of a beam loading has an effect on average energy of particles. The maximum beam energy with minimum spectrum width can be achieved by appropriate choice of an
injection moment $t_1$. Spectrum width less then 3...5% can be obtained for current pulse about $t_0 \leq 2.3T$ for pulse current values up to 2 A.

![Graph showing the dependence of beam energy $W/W_0$ at output accelerating structure from time $t - t_0$ ($T=60$ ns).](image)

**Fig. 4.** Dependence of beam energy $W/W_0$ at output accelerating structure from time $t - t_0$ ($T=60$ ns).

The typical beam energy dependence from accelerating structure length $l$ at output TWR accelerating section is shown in Fig. 5.

![Graph showing the dependence of maximum accelerator energy from accelerating structure length $l$ ($T=40$ ns).](image)

**Fig. 5.** Dependence of maximum accelerator energy from accelerating structure length $l$ ($T=40$ ns).

The normalized energy $W/W_0$ of accelerated beam grows with reduction of length accelerating section (filling time of accelerating section is proportional to its length). Absolute value of beam energy appears higher for longer sections. Therefore to achieve higher energy long accelerating of section should be apply.

**References**


RF-FIELD GENERATION IN WIDE FREQUENCY RANGE BY ELECTRON BEAM

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Abstract

A simple device for generating powerful RF oscillations in the frequency range of 100-250 MHz is considered. The two-gaps cavity is based on the quarter-wavelength coaxial line loaded by drift tubes. Frequency tuning is accomplished by using the movable shorting plunger. A permanent electron beam being modulated at the first gap return the energy at the second one. The additional tube with the permanent decelerating potential, introduced into the main drift tube, allows to decrease the drift tube length and keep the excitation conditions in frequency tuning. Both autogeneration and amplification modes are under consideration. RF-parameters of the cavity and experimental results are described.

At present there is a number of scientific and applied problems, for the decision of which it is necessary to have RF generator with power up to hundreds kW with smooth adjustment of frequency in a wide range. At the same time, made and used the powerful lamp generating devices are allowed rebuilding up to by several percents. As far as the frequency change in wider range requires agreed rebuilding of several resonant contours of amplification cascades. Conventional klystron and magnetron devices not allowed significant rebuilding owing to specific character of a volumetric resonators design. Generating devices on TWT base can not supply required exit power value.

To ensure a condition of beam resonance interaction with RF structure in a wide range of wave length it is possible by changing system period or electron speed. However, it is practically impossible to change RF structure space charge by virtue of the constructive reasons. On the other hand, it is required a relative electron beam with energy ~100 keV for high-power reception. The speed of one makes size ~0.5c. The speed reduction, for example, in two times would result in this case in injection beam essential loss. Other the discussed scheme defect is a large RF system period length: at the electron energy 100 keV and wave length 2 m the period will make 1 m. That will cause to excessive general accelerator length growth and efficiency fall. Besides the injection energy change can ensure synchronism maintenance at frequency rebuilding only on an initial structure site.

That to minimize installation dimensions and to ensure electron beam resonant interaction with a resonator in wide range of wave length scheme with electrical adjustment of a structure effective length is offered. This scheme is based on system with drift tubes. Inside ones are coaxial located additional isolated tubes, those are under electrons slowing down (or accelerating) constant potential. Thus the electrons speed inside tubes can vary depending on value and sign of potential. It enables to support synchronism at frequency rebuilding and constant injection energy.

As the first section of a generating device based on these principles is developed double-gap buncher resonator with drift tubes. One capable to work as in a mode of self-excitation (that is independent generation) and as a buncher with independent excitation. In the self-excitation mode the electron beam receives modulation on energy in a first backlash, is grouped in drift tube and gives back energy (brake) in the second backlash. Distance between backlashes centers is 200 mm. Thus on frequency 150 MHz electrons with relative speed β=0.5 past first backlash in optimum group phase (φφ=−π/2 in cosine readout) and fall in the second backlash in a phase φφ=−π/2+π, that is close to the slowing down half-wave top. With frequency increasing the significance φφ is increased and for preservation of self-excitation optimum conditions it is necessary to submit breaking potential on internal tube or to reduce injection energy. Self-excitation conditions on high frequencies are possible also at multiple flight corners. For example, 5π/4.

The developed resonator design is schematic submitted on fig. 1. Resonator contain vacuum jactet

![Diagram](image)

Fig.1. The resonator design scheme.
with face flange 2 and vacuum volume 3. In one's place is own rebuilding resonator. It consists of a cylindrical screen 4 with face cover 5 and internal coaxial guide 6. On guide is fixed drift tube 7. In a resonator is present a mobile shorting piston 8 with sliding silvering contacts 9. The piston can be moved through coaxial at the help of the rod 10. For restriction of moving and azimuth turn prevent is stipulated restrictive pin 11, which moved in cylindrical RF screen longitudinal split. The design provides a piston moving without vacuum infringement through a traffic input device. Bush 12 is placed in a framework 13 and upsets by a rubber lining 14, the effort on which is created at the help of a device 15. The smooth surface of the rod permits to move the piston and save vacuum in systems at a level $10^{-5}$-$10^{-6}$ Torr. The cylindrical screen 4 RF contact with jact 1 is provided by special copper ring compression 16, which is established in stipulated slot and key between a jact and screen at screw 17 protracting. Thus, drift tube should be fixed in the resonator by the tightening ring 18 only after screws 17 protracting.

In drift tube 7 on isolator 19 coaxial fixed potential tube 20, on which constant voltage feeds. The copper guide is used for transmit voltage. High-voltage copper guide 21 placed in rigid ceramic tube. Ones, in turn, place in isolation tube. Isolation tube is fixed in internal coaxial at the help of bush 23 and exit bush 24. Further high-voltage guide is removed from vacuum chamber through isolator 25.

The made installation is represented reasonably simple and at the same time reliable for study powerful RF oscillations in a wide wave lengths range.

Maximum rebuilding range of resonator own frequency makes 117-235 MHz and is limited from below by coaxial line length. The top limit is connected to a significant drift tube length, which at close to it a shorting piston situation represents large part of a quarter wave line. Own resonator quality is weak drops with frequency decrease from 1300 up to 800. It is connected with two circumstances:

1. It is necessary to reduce magnetic field screening of pulsing focusing tube. So coil drift is executed from stainless steel and have become in comparison with copper coaxial much more resistance. At a piston approach to tube relatively more part of currents flow on tube, that results in quality decrease.

2. At high frequency the resistance of mobile contacts grows.

Separate problem is choice of connection factor with a making path value. By use of a resonator as a buncher with independent excitation optimum is the critical connection. If the resonator works in a selfexcitation mode, the choice is not obvious. On the one hand, at small connection conditions of selfexcitation are facilitated at small beam currents. From the other hand, connection should increase for effective generated power transfer to a load. Hence, for ground choice of a connection factor value in a selfexcitation mode and system power efficiency optimization it is necessary to carry out detailed numerical accounts and subsequent experimental research.

Other problem of a broadband generator is its coordination with a path in all frequencies range. In considered construction individual connection unit in a kind of a loop is used. Loop is located near to internal coaxial line guide in the field of junction with drift tube. On first stage the resonator was investigated in a independent excitation mode on frequency 148,72 MHz. Thus close to critical ($\approx 1,2$) connection value was supplied. The rebuilding in the low frequencies area results in connection reduction. In the area of higher frequencies connection, opposite, grows. It is stipulated as by shorting piston reactive impedance change, as its situation relatively shorting piston. Here in after, for preservation of coordination conditions, probably, expediently to use capacitor connection, as far as in this case the effect of reactivity change at frequency rebuilding can be compensated (completely or partially) by connection unit situation displacement relatively shorting.

The RF generator model research was conducted on a experimental stand, the block diagram of which is submitted on fig. 2. Stand contains following main elements:

![Fig. 2. The experimental stand block diagram.](image)

electron injector 1, electromagnetic lens 2, compressor coils 3, focusing solenoid 4, double-gaps buncher 5, electrons collector 6, external RF path 7 and load 8. The lens 2 and coils 3 formed a site cross compression of an electron beam in adiabatic increasing longitudinal magnetic field. The field value changes from significance 0.005 $\Omega$ on injector cathode up to 0.2 $\Omega$ on compressor output. The beam diameter decreases from 30 mm up to 8 mm. The compression site length is equal ~1 m. The resonator placed inside the solenoid 4. One creates on the installation axis close to a similar magnetic field by size up to 0.25 $\Omega$. The lens 2 feed scheme is operated in a continuous mode, but the coils 3 and solenoid 4 - in pulsing.

The described system of the electron beam formation permits to receive pulsing electrons beams with energy up to 100 keV and current up to 20 A at a pulses duration ~100 $\mu$s.

As far as for maintenance of the best electrons beam grouping it is desirable to have more electrons slowing down in potential tube, its potential should be approximate to injection potential up to value, determined by optimum current flow conditions. For experiments at a initial stage a settlement ratio of high-resistance divider shoulders resistance equals 0.85 was chosen. At high-voltage system tests on a idle running (without electron beam) the measured relation of potentials on tube $U_i$ and injector $U_i$ has appeared close to this significance. At the same time, at experiments with beam for the account of current load and hit electrons part on tube redistribution of potentials occurred. Therefore the significance $U_i/U_i$ was increased and actually has
appeared close to 0.95. The generation was observed at injection voltage exceeding by 12 kW.

Experimental electron current oscillograms on collector is shown on fig.3. The form of the flat top of a electrons current pulse is close to sine with period ~10 ns.

![Fig.3. The electron current oscillograms on the collector.](image)

The resonator excitation process is largely defined by the electrons beam geometrical characteristics, as far as the generation takes place only in a in comparison narrow range of electron injector magnetic field B value change. That is exists optimum significance A in relation to electrons energy. We shall note, that at the increase U_i the optimum significance B also grows.

The RF oscillations occurrence in a resonator is accompanied by signal arising on detector in external RF path and eroding of the electron current pulse flat top on the collector (a dotted line on fig. 3, a continuous line shows the pulse form at generation absence). Availability of electron beam RF modulation in the sine form signal is well visible on oscillogram (fig.3). The modulation period within the limits of measurements error well coincides significance 0.67 ns, appropriate resonator working frequency equal to 148.72 MHz (the modulation frequency coincides resonator self-excitation frequency).

Dependences of constant I_b and of the first harmonic amplitude variable I_1 of a making electrons current signal on a collector from the value U_i are shown on fig.4.

![Fig.4. The dependences of I_b and I_1 from U_i.](image)

Both signal are increased with the growth U_i. The relation I_1/I_b dependence from the significance U_i is submitted on fig.5. In accordance with the increase U_i the share of the first harmonic grows, reaches a maximum, and then decreases up to some significance, about constantly.

RF amplitude signal U dependence in external RF path from U_i is shown on fig.6. Availability of optimum significance U_i at which maximum U is reached is visible. It is connected as appear with selfexcitation optimum phase conditions (grooped electron beam falls in the second backlash in close to a break phase). At the same time the pulse duration T RF signal continuously grows at the increase U_i (fig.7).

![Fig.6. The dependence of U from U_i in external RF path.](image)

![Fig.7. The dependence of T from U_i.](image)

At a following stage resonator serviceability check was conducted at other significance of its own resonance frequency. For this purpose by shorting piston 8 moving (fig.1) the working frequency was biased in the lower frequencies area (piston was moved closer to input voltage unit on ~800 mm). The experiments results have appeared similar above described. The resonator selfexcitation frequency was measured with the help of a spectrum analyzer and has appeared equal 132 MHz.

Thus, is experimentally proven, that creation of waves lengths meter range generator with smooth frequency rebuilding in a wide range (in some times) is possible at enough large efficiency. For the entered power level increase and the maximum efficiency mode realization expediently work making on manufacturing and start of the RF structure second series. One can be based on the same principle of action, as described above.
RECENT STATUS OF FCI :
PIC SIMULATION OF COUPLED-CAVITY STRUCTURE

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Abstract

New version of FCI(Field Charge Interaction)-code simulates beam dynamics of an electron beam running in a coupled-cavity structure, such as a multi-cell output structure in a klystron amplifier, a coupled cavity TWT amplifier, a bunching structure in an electron injector and also an rf-gun with multi-cell accelerating cavity. The particle-in-cell simulation takes into account the space charge field, the beam loading effect and energy exchange with an external circuit in a self-consistent manner.

Introduction

FCI-code is 2+1/2 dimensional particle-in-cell simulation code developed by the author in 1989 [1], which has been used to analyze the beam dynamics in the klystron. FCI-code has contributed to develop many high-power klystrons at KEK and in industries [2]. The FCI is a name of a code group, which includes a cavity-field calculation routine, a magnetic-field routine, a main routine of beam simulation, and post-processors. Recent version is equipped with MOVIE-PLAYER to show an animation of beam profile.

In this paper, new version of FCI is described, which simulates beam dynamics in a multi-cell coupled-cavity structure. It can be applied to several electron beam devices such as
(1) Klystron with multi-cell output cavity.
(2) Electron Injector ( sub-harmonic, pre-buncher, buncher ).
(3) TWT amplifier.
(4) RF-gun ( single-cell or multi-cell ).

Modeling of RF-Field in Multi-Cell Structure

In FCI-code, the RF-field in a coupled-cavity structure is represented by a superposition of eigenmodes in each cell ( here we call this as "cell-mode"). For example, the traveling wave in a disk-loaded structure is represented by a superposition of cell-modes, whose field intensity (cell-voltage) oscillates at the rf-frequency, but their phases are differ from cell-to-cell, resulting in a traveling wave as a group motion.

The electro-magnetic interaction between cells, which is so called "the coupling", is taken into account in a coupled-cavity circuit-model (see the next section).

The electric field of the cell-mode is represented by

\[ E_z(r,z,t) = E_{z0}(r,z) \cdot \cos(\omega t + \phi) \]

where \( E_{z0}(r,z) \) is the electric field pattern at the maximum phase. In vacuum electron beam devices the dominant mode (TM01-mode) in a cylindrical cavity is usually used, whose electric field is uniform around the axis. Therefore, an azimuthal dependence was dropped in eq.(1). We define the cell-voltage by the line integral on the "frozen electric field" along the axis as follows.

\[ V_{CF} = \int E_{z0}(r = 0,z) \cdot dz \]

The subscript CF denotes "Cell-voltage on Frozen electric field". The shunt-impedance is given by

\[ (R/Q)_{CF} = \frac{V_{CF}^2}{20W} \]

This definition does not include the transit-time factor. Note that this definition is different from the accelerator definition used in theory of the high energy accelerators, which includes the transit-time factor. The relation between them is

\[ (R/Q)_{CF} = (R/Q)_{acc} / 2T^2 \]

where \( T \) is the transit time factor for a particle of speed of the light.

An electron beam running in the coupled-cavity structure interacts with cell-mode in each cell independently. The field excitation is taken into account into the equivalent circuit as an induced current given by

\[ I_{ind} = \frac{\int f_k \cdot E_{z0}(r,z) \cdot dr}{V_{CF}} \]

Modeling of Coupled Cavity Structure

Figure 1 shows an equivalent circuit model for a multi-cell coupled-cavity structure. The circuit equation for the \( n \)-th cell is given by

\[ \frac{dV_n}{dt} + (1 - \delta_n) \frac{V_n}{Q_n} + (1 - 2\delta_n) V_n \]

\[ = \frac{1}{2} (1 - 2\delta_n) \left( k_{n-1,n} V_{n-1} + k_{n,n+1} V_{n+1} \right) + I_{ind} \]

where

\[ V_n = dV_n / d\theta = dV_n / \omega d\theta \]

\[ V_n = dV_n / d\theta^2 = dV_n / \omega^2 d\theta^2 \]

\[ k_{n-1,n}, k_{n,n+1} : \text{coupling constant.} \]

\[ \delta_n = (\omega - \omega_n) / \omega_n : \text{detuning of cell from the rf-frequency.} \]

\[ \omega_n : \text{resonance frequency of} \ n\text{-th cell.} \]

\[ V_n : \text{cell voltage (peak) normalized by} \]

\[ V_n = V_{CF,n} / (\omega_n (R/Q)_{CF,n})^{1/2} \]

\[ I_{ind} : \text{beam induced current normalized by} \]

\[ I_{ind} = (R/Q)_{CF,n} / \omega_n^{1/2} I_{ind} \]

Above normalization makes the stored energy in a simple form:

\[ (W_{EM}) = W_{EM}^{max} = \frac{1}{2} C_n V_n^2 = \frac{1}{2} V_n^2 \]

Here we introduce "the quasi-steady state approximation".

Since in most applications, the time variation of the cell voltage and current is much slower than the sinusoidal oscillation at the rf-frequency, we can separate the time
variation into two parts: a slow change in voltage and phase and a fast sinusoidal oscillation at rf-frequency as follows.
\[
\vec{V}(t) = \vec{V}(t) \cdot \exp(j\omega t), \quad \vec{V}(t) = (\vec{V} + \dot{\vec{V}}) \cdot \exp(j\omega t)
\]
(7)
Using eq.(7) into eq.(6), we have the quasi-steady state circuit equation.
\[
\vec{V}_n = (2j + \frac{1}{Q_n})\vec{V}_n + \frac{J}{Q_n} - 2\delta_j \vec{V}_n
\]
\[
= \frac{1}{2} \left( k_{n-1,n} \vec{V}_{n-1} + k_{n,n+1} \vec{V}_{n+1} \right) + \bar{I}_n + j\bar{I}_{ind}
\]
(8)
In FCI-code, eq.(8) is solved by the finite difference method in time sequence.

Fig. 1. Equivalent circuit model for a coupled cavity structure.

**Particle-In-Cell Simulation**

In FCI-code, an electron beam is simulated by a flow of macro-particles of ring shape (2D, circular symmetry). The space charge field is calculated by solving the wave equations of the scalar and the vector potentials by the finite difference method. The particle motion is determined by integrating the relativistic equation of motion in 2+1/2 dimension: \((r, \dot{r}, \dot{z}, \dot{\theta})\), which takes into account the space charge field, the self-magnetic field, the external focusing magnetic-field and the rf fields in cavities. The details are described in references [1] and [2].

**Traveling Wave Output Structure**

As an example, a traveling wave output structure was simulated by FCI. A structure was designed as shown in Fig. 2 and attached to the 5045-tube[4] in place of the single-cell output cavity of original design. The coupling constant and the loaded-Q were determined as follows. The steady state circuit-equation of the coupled cavity is given by[3]
\[
\left[ j \omega - \omega_0 \omega_n - \frac{1}{Q_n} \right] = j \frac{\omega_n}{2} \left( k_{n-1,n} \vec{V}_{n-1} + k_{n,n+1} \vec{V}_{n+1} \right) + \bar{I}_{ind}
\]
(9)
We use a traveling \(\pi/2\)-mode, which requests resonance frequencies of all cells being tuned to the rf-frequency: \(\omega_0 = \omega_2 = \omega_3 = \omega\). Applying eq.(9) to all cells and neglecting the cavity loss (1/\(Q_n \rightarrow 0\)), we have
\[
\begin{bmatrix}
0 & jk_3/2 & 0 & \vec{V}_1 \\
jk_3/2 & 0 & jk_{23}/2 & \vec{V}_2 \\
jk_{23}/2 & jk_{33}/2 & 0 & \vec{V}_3 \\
1/Q_{33} & \bar{I}_{ind1} & \bar{I}_{ind2} & 0
\end{bmatrix}
\]
(10)
To smoothly extract the kinetic energy from the beam, we assume the same energy loss in each cell. Since we want to establish a traveling \(\pi/2\)-mode running with beam, the cell-to-cell distance was chosen at \(\lambda/4\) wavelength on the beam, additionally the cell-voltage must be \(V_2 = -jV_1, \ V_3 = -V_3\).
Applying this relation into eq.(10), we get the optimum condition of the coupling constant and the loaded-Q as follows.
\[
k_{12} = 2[(R/Q)_1(R/Q)_2]^{1/2} \frac{\bar{I}_{ind1}}{|V_1|}
\]
(11a)
\[
k_{23} = 2[(R/Q)_2(R/Q)_3]^{1/2} \frac{\bar{I}_{ind2}}{|V_3|} + k_{12}
\]
(11b)
\[
\frac{1}{Q_3} = \frac{2}{(R/Q)_3} \frac{\bar{V}_{ind}}{|V_3|} + k_{23}
\]
(11c)
We design the beam deceleration voltage close to the beam voltage of 350 kV. By taking into account the transit-time factor (-0.7), the required total cell-voltage becomes 500 kV. Thus, \(|V_2| = |V_3| = |V_3| = 163 kV\). On the other hand, the modulation rf-current on a beam is normally as high as 1.5 times of DC-current. It is 600 A in the present case. By considering the transit-time factor and de-bunching effect, we assume the beam induced current as 350, 300, 250 A in the 1st, 2nd and 3rd cell, respectively. From eq. (11), we have the optimum coupling constants as listed in Table-1. Once, we execute a beam simulation, we get precise values of the beam induced currents, then we can refine the coupling constant using eq.(11), and execute the beam-simulation again. In actual design works, we need a few cycles of this iteration process to reach an optimum solution.

The cell-mode and shunt impedance were calculated by the DENKAI-code[5]. Figure 3 shows the electric field plots of the 1st, 2nd and the 3rd cell. In calculating each mode, the neighboring cavity was detuned by terminating the cavity wall by the "magnetic short". The cavity radius was determined to tune the resonance frequency at 2856.0 MHz.

Fig. 2. Klystron output structure using traveling \(\pi/2\)-mode.

The simulation results are summarized in Table-1. At 150 W of the input power, simulation predicted the output power of 69.2 MW, and the power efficiency of 48.5 %. The simulated voltages are about 10 % higher than the expected one. This is due to a difference between the simulated beam induced-current to the assumed one. The maximum surface electric was reduced to 13.7 MV/m, which is 51 % of the field in the original single-cell cavity design.

Figure 4 shows a snap shot of the beam. The top is the beam profile on \((z,t)\) plane. Since in a traveling wave structure the aperture can be designed much wider than a single cell cavity, we can keep a large clearance for a beam to the cavity wall. Additionally, the beam deceleration is smooth and the radial kick by the cavity field is much less, resulting
in a smooth profile in beam shape after the output structure. This is an important feature of the traveling-wave output-structure to eliminate collision of electrons in beam hollows on the cavity surface, and avoid accompanied rf-break-down in the output gap. The middle plot is the kinetic energy profile and bottom is the instantaneous beam current, where deceleration and de-bunching of beam in the output structure are clearly shown. The MOVIE-PLAYER shows animation of this plot on BIM-PC machine.

![Diagram](image)

Fig. 3 Cell-modes in the 1st, 2nd and 3rd cell.

Discussions

In this paper, the rf-field in a multi-cell couple-cavity was approximated by the superposition of cell-modes, and whose voltages were calculated by the equivalent circuit model. In case of a small coupling, the energy transfer per one cycle along cell-to-cell is much smaller than the stored energy in one cell, therefore this approximation works very well. However, in a case of a large coupling, such as in a klystron output structure, we has to pay attention on errors in the approximation. In order to verify accuracy of the simulation, we are continuing studies, such as comparison of cell-mode model to standing wave modes in coupled cavity without beam, or direct finite-difference modeling of coupled-cavity structure with beam. The code is also under testing on several existing cases, such as X-band klystron having multi-cell output cavity, and an electron injector with traveling-wave buncher.

<table>
<thead>
<tr>
<th>Cavity parameter</th>
<th>$f_0$</th>
<th>$(R/Q)_{CF}$</th>
<th>QL</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>2856.0</td>
<td>39.4</td>
<td>2000</td>
</tr>
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<table>
<thead>
<tr>
<th>Beam Parameter</th>
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<tr>
<td>Beam Voltage</td>
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<td>Beam Current</td>
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<td>Drive Power</td>
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<table>
<thead>
<tr>
<th>Simulation Results</th>
<th>$V_c$ (kV)</th>
<th>$I_c$ (A)</th>
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<tr>
<td>No.1</td>
<td>177.6</td>
<td>345.2</td>
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<tr>
<td>No.2</td>
<td>187.2</td>
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<tr>
<td>No.3</td>
<td>170.9</td>
<td>167.8</td>
</tr>
<tr>
<td>Surface Electric Field</td>
<td>13.7 MV/m</td>
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</tr>
<tr>
<td>Output Power</td>
<td>69.2 MW</td>
<td></td>
</tr>
<tr>
<td>Power Efficiency</td>
<td>48.5 %</td>
<td></td>
</tr>
</tbody>
</table>

References


C-BAND MAIN LINAC RF SYSTEM FOR e⁺e⁻ LINEAR COLLIDER
OF 0.5 TO 1.0 TeV C.M. ENERGY

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Abstract

A hardware R&D for the C-band (5712 MHz) rf system for a linear collider started in 1996 at KEK. An accelerating gradient of 32 MV/m (including beam loading) will be generated by 50 MW C-band klystrons in combination with an rf-compression system. The klystron and its power supply can be fabricated by conventional technology. The straightness tolerance for the accelerating structures is 30 μm, which is also achievable with conventional fabrication processes. No critical new technology is required in a C-band system. Therefore, a reliable system can be constructed at low cost with a minimum of R&D studies. The first high-power test is scheduled for 1997.

Introduction

The e⁺e⁻ linear collider is a large-scale machine. In the main linacs for two beams, we use more than 8000 accelerating structures, 4000 klystrons and pulse modulators. Therefore, the system must meet the following demands:

(1) High reliability

To provide beams with reasonable availability, the system must be highly reliable; that is, the fault rate must be negligibly small and the lifetime of the key devices must be sufficiently long. To achieve this, we eliminate any critical parameter or excessive stress in the hardware components.

(2) Simple

For the same reason as (1), the system must be simple. This will also help to lower the construction cost and to make hardware maintenance easier.

(3) Lower construction cost

We should try to reduce the construction cost while not sacrificing the system performance and reliability.

(4) Reasonable power efficiency

We assume that the maximum limit on the whole wall-plug power in a site is 200 MW. To meet this requirement, the rf system must efficiently accelerate the beam. However, since an actual rf system needs auxiliary power in addition to the wall-plug power to generate rf, we must optimize the total system, not just the acceleration hardware.

(5) Easy to operate

The machine operation should be easy. In the actual machine operation, the system must have flexibility to accelerate various patterns of the beam current. The tuning procedure must also be simple and easy.

The above list provides a guide-line and boundary conditions to our design work. Among the system parameters, the choice of the drive rf frequency plays the most important role concerning the system performance as well as the hardware details. We proposed the C-band frequency as being the best choice to meet all of the demands listed above [1-4].

Overall Parameters

The overall parameters are listed in Table-I for 500-GeV and 1-TeV C.M. energy linear colliders. In the 500-GeV case, an accelerating gradient of 31.7 MV/m is generated by a 50-MW klystron in combination with rf pulse compression; thus, an active length of 7.3 + 7.3 km is sufficient to reach 500 GeV C.M. energy. A luminosity of 6.6 × 10³³ cm⁻²/sec can be obtained using a 150 MW wall-plug power. The details are described in ref.[3].

| Table-I |
|-------------|------|------|
| CM Energy   | TeV  | 0.5  | 1.0  |
| Number of electrons per bunch | x10¹⁰ | 1.1  | 1.4  |
| Number of bunches per pulse   |      | 72   |      |
| Bunch separation              | nsec | 2.8  |      |
| Repetition frequency           | Hz   | 100  | 50   |
| Bunch length                   | mm   | 0.2  |      |
| RF frequency                   | GHz  | 5.712|      |
| Peak input power at cavity     | MW   | 83.0 | 165  |
| Nominal accelerating gradient  | MV/m | 40.0 | 56.0 |
| Effective accelerating gradient| MV/m | 31.7 | 46.4 |
| Wall-plug power for RF (2 linacs) | MW  | 150  | 133  |
| Accelerating Structure         |      |      |      |
| Number of structures per beam  | km   | 4080 | 5748 |
| Total length of cavities per beam |      | 7.3  | 10.3 |
| Structure Type                 | CG with choke-mode |      |      |
| Unit length of structure       | m    | 1.80 |      |
| Iris radius/wavelength         |      | 0.13 - 0.17 |      |
| Shunt-impedance                | MΩ/m | 59.2 - 47.0 |      |
| Pulse-compressor               |      |      |      |
| Compression Scheme             | multi-cell coupled cavity | |      |
| Pulse compression ratio        |      | 5    |      |
| Pulse compression efficiency   | %    | 70   |      |
| Klystron                       |      |      |      |
| Klystron peak power            | MW   | 50.3 | 98.6 |
| Efficiency                     | %    | 45   | 70   |
| Number of klystrons per beam   |      | 2040 | 2874 |
| RF pulse length                | μsec | 2.5  |      |
| Modulator                      |      |      |      |
| Number of modulators per beam  |      | 2040 | 2874 |
| Power efficiency from AC to pulse | %  | 75   |      |
| Beam Dynamics                  |      |      |      |
| Injection energy               | GeV  | 20   |      |
| Phase delay of rf-crest        | deg  | 14.5 | 10.0 |
| Structure straightness tolerance| μm | 30   |      |
| Final focus                    |      |      |      |
| Spot size at IP (horizontal)   | nm   | 318  | 318  |
| (vertical)                     | nm   | 4.3  | 3.0  |
| Crossing angle (crab crossing) | mrad | 8.0  | 8.0  |
| Luminosity                     | x10¹³ | 6.6  | 7.0  |
**System Description**

Figure 1 shows a schematic diagram of one unit in the main linac rf-system. Two 50 MW klystrons are driven by two high-voltage pulse modulators independently, followed by a 3dB hybrid power combiner and pulse compressor to generate 350 MW peak power, which drives four accelerating structures. The pulse-compression action is performed by rotating the phase of the input rf-signal in opposite directions in each klystron. By combining two powers at 3-dB hybrid, the phase modulation (PM) is converted to the amplitude modulation (AM) of the ramp-waveform, which compensates the beam loading effect in the accelerating structure. The energy-storage cavity consists of three coupled cavities using a low loss TE01n mode.

We use a standard rectangular waveguide: EIA187 (47.55 mm x 22.15 mm, 3.95-5.85 GHz), whose attenuation constant is 0.03 dB/m (5% loss/m).

Figure 2 shows the key points concerning the C-band, which make the system simple and reliable.

**Klystron Power Supply & Pulse Transformer**

The filling time of the accelerating structure scales as

$$t_f = \frac{2Q}{\omega} \propto \omega^{-3/2}.$$

At the C-band, it becomes 280 nsec. Including the pulse-length of the beam and a compression factor of five in the rf-compression system, the rf-pulse at the klystron becomes 2.5 μsec. Including the rise- and fall-times, the pulse-length of the high-voltage applied to the electron-gun of the klystron becomes 3 μsec or longer, which is quite suitable to the conventional power-supply consisting of a Pulse Forming Network (PFN) and a step-up pulse-transformer. This type of power supply has been used in many linear accelerators, owing to its high reliability and good efficiency.

To charge high voltage into the PFN capacitors, we use an inverter power supply. Such a high-voltage power supply has been widely used to drive pulsed lasers for a long time. Modern technology for power-semiconductor devices (such as IGBT) has improved the power efficiency by better than 90%. Using this power supply, we can simplify our modulator design, making it modular according to the required functions: the inverter power supply (DC block), the PFN module (pulse forming block), and the pulse-transformer tank (matching block to a klystron). With this approach, it becomes easier to reduce the cost, improve the reliability and ease maintenance. In the case of a failure, we simply replace any broken block with a new one and send the old one to a factory for repair.

**RF Pulse Compressor**

We use a three-cell coupled-cavity pulse-compressor instead of a delay-line type pulse-compressor. The cavity is compact, having a length of 1 m, and its diameter is 160 mm. Therefore, it will be easier to fabricate at lower cost. A computer-simulation code was made to simulate the time response of the coupled-cavity system, which has shown a maximum efficiency as high as 70%. The details are reported in ref. [5].

**Accelerating Structure**

We use a choke-mode cavity structure[6], in which all of the higher-order modes are heavily damped. Therefore, the multi-bunch wakefield and any associated instability will not harm the beam emittance. The only concern is the single-bunch emittance dilution due to the short-range wake-field, which is a strong function of the iris aperture. We use relatively large iris-aperture: average <2a> = 16 mm. As a result, the straightness tolerance for one structure becomes 30 μm or larger. This is a controllable level in conventional fabrication techniques of the disk-loaded structure. To eliminate any stress and make the structure straighter, a low temperature brazing technique will be adopted[7].

To align the structure with beam, we use an RF-BPM attached to the structure. This type of RF-BPM was tested using the FFTB beam line at SLAC in December 1995[9]. It demonstrated a very high resolution of 44 nm for a single bunch. Three RF-BPM were assembled in one block, and the misalignment between them was measured with electron beam. It was only 3 μm. This is a quite promising result for a structure-alignment procedure.

The dark-current problem due to field-emission under the high accelerating gradient has been studied using computer simulations[10]. From which, no serious contributions to the background in the detector at IP is expected at C-band frequency.

**Hardware R&D Program**

In January, 1996, the hardware R&D has been started at KEK. In 1997-1998, we will construct one unit of rf-system. Since we use one klystron, the input rf will be directly amplitude modulated to demonstrate the flat-top output from the compressor. The first klystron tube will be available in 1997.

**References**

[4] T. Shintake, et al., "C-band RF Main Linac System for e⁺e⁻ Linear Colliders at 500 GeV to 1 TeV C.M. energy", Proc. 5th European Particle Accelerator Conference (EPAC96), Sitges
MAIN LINAC RF-SYSTEM

C-band LINEAR COLLIDER

By T. Shintake (KEK)

Fig. 1 One unit of the C-band RF system.

What makes the C-band system simple & reliable. C-band JLC

Fig. 2 What makes the C-band system simple and reliable. The key points in the C-band rf-system.
PERFORMANCE OF THE RF-SOURCE FOR THE KEKB LINAC

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Abstract

The KEKB project, which requires an energy upgrade of the KEK linac from 2.5 GeV to 8.0 GeV, started in 1994, and has been progressing. About fifty 50-MW high-power klystrons (including equivalent 40-MW tubes) have been produced and tested. Twenty-eight of them have already been installed in the klystron gallery. We also obtained more than 60-MW rf peak power with a reasonable efficiency from this 50-MW tube. The klystron assemblies, including the magnets and pulse transformers, have been operated with no problems. In order to operate the SLEDs, we have also developed a sub-booster klystron, a driver klystron which produces more than 60-kW peak power for 8 high-power klystrons. Two of them have been successfully operated in the klystron gallery. We have started SLED operation at 2 sectors (sectors #4 and #5) and are accumulating data concerning the SLED and accelerated beams. We now describe this performance of the rf-source for the KEKB linac.

Introduction

An upgrade of the PF linac in order to increase the acceleration energy from 2.5 to 8 GeV, by using a combination of 59 klystrons having an average output power of 41 MW (max. 46 MW) and SLAC-type rf compressors (SLED) is now in progress[1]. We have achieved progress concerning the sub-booster klystron, the driver klystron, and feeding to 8 high-power klystrons, since it is necessary to change the driving scheme (shown in Fig. 1) in order to use the SLED operation with proper timing. In this modification, more than 40 kW of output power is required from the sub-booster klystron by taking account of the transmission losses. We had manufactured 5 tubes, including a prototype; 2 tubes have already been set in the gallery in order to test the SLED operation. Installation of the high-power tubes is proceeding on schedule. Twenty-eight tubes have already installed to the gallery, and 12 tubes are being operated under the SLED mode. Those tubes are operated during an injection to the PF ring and AR (Accumulating ring) for the SOR experiment users. Some of the high-power tubes are being operated at 335 kV to 350 kV, and have succeeded in outputting more than 60 MW. They are expected to be used at the unit just after the positron target position, where high-gradient acceleration is desirable.

Sub-booster Klystron Development

For the KEKB energy upgrade project, new 50-MW klystrons have been developed. In order to feed a drive power to these 8 high-power tubes, which are operated with SLED cavities, a 60-kW sub-booster klystron (SBK) is required. Since there are no commercial tubes which satisfy our specifications, this tube has been designed at KEK, and manufactured under the collaboration of KEK and MHI (Mitsubishi Heavy Industry Co.).[2]. The specifications for the sub-booster klystron are the collaboration of KEK and MHI (Mitsubishi Heavy Industry Co.).[2]. The specifications for the sub-booster klystron are given in the table 1.

We have been using two 10-kW tubes of Thomson CSF (TH2436) in parallel in each sector, as shown in Fig. 1a[3]. The different points between the old TH2436 tube and the new SBK-tube are as follows: (1) Electromagnet focusing has been adopted instead of permanent magnet focusing. (2) The tuning frequencies for the each klystron cavity are fixed, since our purpose of this tube is limited. The new tube has 6 cavities, while the old tube has 4. These modifications enable us to obtain a high gain. (3) The new tube has an integrated pump. (4) Water cooling is adopted in order to stabilize the operation performance. (5) The input power feeder is set vertically to make the inside bore diameter of the magnet small. (7) The output waveguide is a coaxial 39D-type waveguide and the output waveguide flange type is BFX-39D, which is popular in Japan (old type is EIA-39D standard.) (8) An Ir-coated dispenser cathode of 1 inch diameter is adopted instead of the oxide cathode based on a life consideration. (6) Our tube configuration is partly based on the design of the SLAC sub-booster klystron, especially concerning item (5). [4]

The basic design of the tube is fulfilled in KEK and some manufacturing processes: for instance, as the cathode processing, baking-and-evacuation of the tube and pinching off
Table 1. Specification of SBK

<table>
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<tr>
<th>Item</th>
<th>Unit</th>
<th>Specification</th>
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</thead>
<tbody>
<tr>
<td>Peak pulse voltage</td>
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</tr>
<tr>
<td>Peak pulse current</td>
<td>A</td>
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</tr>
<tr>
<td>Microperp</td>
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<tr>
<td>Pulse width (rf)</td>
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<tr>
<td>Pulse width (beam)</td>
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<td>&gt;6.0</td>
</tr>
<tr>
<td>Repetition</td>
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<tr>
<td>Peak RF power</td>
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<td>&gt;60</td>
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<td>Average RF power</td>
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<tr>
<td>Efficiency</td>
<td>%</td>
<td>&gt;30</td>
</tr>
<tr>
<td>Gain</td>
<td>dB</td>
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</tr>
<tr>
<td>Input power</td>
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<td>120</td>
</tr>
<tr>
<td>Total length</td>
<td>mm</td>
<td>about 690</td>
</tr>
<tr>
<td>Electric gun</td>
<td></td>
<td>B1 Cathode</td>
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<tr>
<td>Focusing magnet</td>
<td></td>
<td>Electromagnet</td>
</tr>
<tr>
<td>Cooling</td>
<td></td>
<td>Water cooling</td>
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<tr>
<td>Ion Pump</td>
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<td>Output Waveguide</td>
<td></td>
<td>39D Coaxial Waveguide</td>
</tr>
<tr>
<td>Output Flange</td>
<td></td>
<td>BFX-39D standard</td>
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</table>

We have already purchased 50 tubes, including both types. Performance tests of 27 tubes have been finished and the tubes have been installed in the klystron gallery. During the first stage of tube development, some instabilities and arcing problems were observed in the Toshiba 50-MW tubes, which were completely solved by changing the cathode processing of the manufacturing process. Another type of instability and poor gain problems were observed in the MELCO tubes. These were solved by changing the structures inside the tube so as to prevent any distortion of the cavity during the manufacturing process.

60-MW test using the 50-MW klystron

Performances at an applied voltage higher than 310 kV have been of interest since the FCI[8] calculation predicted an output power of 70 MW at the 350-kV beam voltage. This test has been attempted using a prototype tube (PV3050#2) as a tentative low-duty test; a 64-MW output power was observed with an efficiency of about 42%; the performance has strongly depended on the magnetic-field distribution near the output-cavity region, as predicted by FCI. Furthermore, the E3730 tube produced a 60-MW output power at 331 kV beam voltage and rf pulse width of 2 μs with an efficiency of 47% at a factory test. These output power level are highest when using single output windows. We have been planning that this tube operation mode will be used at the #2-1 unit, which is located just after the positron-conversion target, since high-gradient acceleration is required.

Status of High Power Klystron

Test and Installation in the Gallery

As previously reported[5, 6], we have been developing 2 types of high-power klystrons for this project: one is an improved type of an old 30-MW tube by enlarging the high-voltage ceramic-seal; the other is an improved one by using a larger cathode and larger high-voltage seal. PV3030A3 (MELCO; Mitsubishi Electric Company) and E3728 (Toshiba) are the former types of tubes and PV3050 (MELCO) and E3730 (Toshiba) are the latter types. Both types have abilities to produce more than 50 MW of output power at 310-kV applied voltage. The focusing electromagnet has compatibility between these two types with only a slight change at the gun region of the tube.

An output power of 50 MW and an efficiency of 45-46% were achieved on the average in the 50-MW tubes. The saturation point is located at 250-300 W at the input power on an average (a gain of around 53 dB is achieved). The typical performances of the 50-MW tubes are shown in Figs. 2 and 3. Our tubes have a single window and cooling structures are set on the upper and lower waveguides of the windows. The window material of our tube is high-density pure alumina of 99.7% (HA997; NGK) and has a very low tanδ value[7]. The evaluation after running in the gallery is satisfactory.

![Fig. 2. Input-output power characteristics predicted by the FCI and those of two 50-MW tube performances.](image-url)

Design and Status of the Socket Assembly

The final design of the pulse transformer is such that the step-up ratio has been changed to be 1 : 13.56; there are 7 primary turns and 95 secondary turns. This is an bifiller auto-winding type; a core reset bias is applied. More detail descriptions are given in reference [6]. We have newly
developed corrugated high-voltage insulators made from epoxy material to support the klystron heater transformer, which is at a high-voltage potential. The heater transformer has been redesigned, and the final thickness is half that of the old one. Owing to these design changes, we can continue using the same oil tanks and same configurations, including the waveguide ports. A feeder section inside of the tank comprises a knife-switch-type connector made by Multi-contact Co., which enables it to be easily disconnected. The capacitive divider, used as a voltage monitor, has been replaced from the Pearson-Inc. type to the Stangenes-Inc. type for higher voltage applications of up to 350 kV. Two small-size current transformers are set in a tank circuit instead of the old home-made one; one is used for the current monitor and the other for a dedicated application of an interlock signal. So far, we have experienced no troubles up to around 320 kV in full duty and 350 kV under in lower duty. For the 350-kV application it is necessary to use a pulse-transformer with a step-up ratio of 1:15; this approach is being prepared.

Forty-nine electromagnets have been manufactured up to FY95, including 2 types of magnets. Both types can be easily changed from one type to another by replacing the iron skirts and coil part. Thirty-two pulse-transformer assemblies have been modified from the old type to a new type by rewinding the pulse-transformer windings and adding pulse-circuits components. Since machine operation has been continued during the construction periods, the reformation schedule for the pulse transformer is the most tightest part.

![Graph](image)

**Fig. 3.** Output-power characteristics as a function of the applied beam voltage

**SLED Operation in the Gallery**

Up to the FY95, 12 SLEDs have been installed in the gallery, and more 13 SLEDs are being installed during the summer shut-down period of 1996. Two sub-booster klystrons were installed in sectors #4 and #5; complete mode operation of the SLED has been carried out. In these sectors, conditioning of the upgraded high-power units is proceeding, and such processing data as discharging and the time dependence of the processing etc. have been analyzed. The averaged energy gain and energy-multiplication factor of the developed units in operation is 163 MeV/unit and 1.93, respectively[9].

The performances of the two sub-booster klystrons have so far been satisfactory. However, the tube efficiency is around the 30%, and the optimum focusing-magnetic field is quite different from the design field. It was found that a weak parasite oscillation exists under some conditions. It might be necessary to check the magnetic field, especially near to the cathode region. So far an output power of about 60 kW is sufficient for each high-power klystron to work at the saturation point, while 10 kW from the previous TH2436 tube was short for saturation-point operation for some poor-gain tubes. It is not clear that the some unstable operation of the SBK affects the SLED's operation or not.

A long processing time was necessary for some special unit up to the specified value. The main task for us will be to investigate what kind of the causes prevent full processing. This summer we will install another 2 sub-booster klystrons in the sectors #2 and #3, and we will also start operating in the SLED's mode there.

**Conclusion**

We are progressing satisfactorily regarding high-power klystron testing and installation in the klystron gallery. Purchasing the tubes and focusing electromagnets is on schedule. The final design of the pulse-transformer assembly has been fixed, and also continues to be modified. The sub-booster klystrons, which are inevitable for our SLED's operation, are being developed and evaluated in the klystron gallery. Since FY95, the useful processing data have been accumulated by the SLED's operation of the sectors #5 and #4. These kinds of studies will be continued after this summer shut-down; roughly half of the construction will be completed.

**References**

[4] Private communication
DES Y LINAC-III U P G R A D E S T U D Y

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Abstract

In the frame of the HERA luminosity upgrade program, the present performance of the HERA preinjectors has been studied in detail. Upgrading the proton linac (Linac III) energy from 50 MeV to 160 MeV is one possibility currently under discussion to obtain higher luminosity. Taking into account the limited space between the existing setup and the injection beam line to the DESY III, DESY’s proton synchrotron, an upgrade study of an 810 MHz linac has been carried out. The results are summarized in this paper and some aspects are discussed leading to the solution presented here.

Introduction

The present transport channel from Linac III to the synchrotron is long enough in order to use the straight beam line downstream of the last tank of the Drift Tube Linac (DTL) for installation of additional accelerating structures in order to upgrade the energy of the H⁻ linac. According to our study a frequency of 810.24 MHz should be used for the upgraded part. Using four times the frequency of the 50 MeV Alvarez linac allows to obtain a high accelerating gradient which accelerates the H⁻ beam up to 160 MeV over a distance of approximately 33 m. A higher injection energy could be a remedy against beam emittance blow-up in the DESY Synchrotron and finally would allow beams with higher brightness in HERA.

Using existing diagnostic equipment in the Linac, both the longitudinal and transverse emittances have been reconstructed by measuring the momentum spread and beam profiles [1,2,3]. In order to estimate the full emittance an elliptical symmetry for lines with constant density in phase space has been assumed. The final values of the measured emittances, which have been used for the design of the upgraded linac part as well as the main beam characteristics of the LINAC III are presented in the Table 1.

2 General Design

In the energy range to be considered which in this case is greater than 50 MeV no efficient accelerating structures other than DTL’s existed so far. However recent studies carried out mainly at Los Alamos Laboratories resulted in the development of accelerating structures for intermediate energies of light ions between 20 to 100 MeV [4]. The structure is a combination of the Coupled Cell Structure (CCS) and DTL - CCDTL. Careful studies of the beam dynamics show that even for the 50 MeV beam with the characteristics listed in Table 1, an operating frequency for a CCDTL four times higher as compared to the Linac III frequency is appropriate. The use of a 810 MHz structure allows to achieve a high accelerating gain. In addition 810 MHz klystrons are available (e.g. supplied by LITTON) as well as with small modiﬁcations as compared to the 805 MHz klystrons which have been developed for the Fermilab linac upgrad [5]. Also the modulator system could be very similar to the Fermilab design [5] except for the average power which is 30 times smaller.

Table 1: Linac III beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate, Hz</td>
<td>1</td>
</tr>
<tr>
<td>Pulse length, μs</td>
<td>30</td>
</tr>
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<td>20</td>
</tr>
<tr>
<td>Energy, MeV</td>
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</tr>
<tr>
<td>Emittance:</td>
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</tr>
<tr>
<td>Long. (α, φ, A/W)</td>
<td></td>
</tr>
<tr>
<td>α</td>
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<tr>
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<tr>
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</tr>
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<td>η₀</td>
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</tr>
<tr>
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<td>9.68</td>
</tr>
<tr>
<td>Horizontal/Vertical</td>
<td></td>
</tr>
<tr>
<td>α₁</td>
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</tr>
<tr>
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<tr>
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<td>-100%</td>
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<tr>
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<td>1.81</td>
</tr>
<tr>
<td>-100%</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Providing a high accelerating gradient and the use of the fourth harmonic on the other hand results in some disadvantages which must be taken into account:

a) Smaller longitudinal acceptance with respect to the Linac III DTL;

b) High accelerating gradient causes a coupling of longitudinal and transverse motion which produce transverse emittance growth.

Both transverse and longitudinal motions of the particles require a transition region (TR) at the output of the present DTL. Using a 12 MW klystron the upgraded part of Linac must be divided into three parts. Each part is powered by a separate klystron. With one CCDTL part an energy gain of approximately 40 MeV can be achieved while the other two parts are based on a more conventional CCS. Considering in addition proper beam focusing results in 10 accelerating sections with constant phase velocity and 9 coupling bridges in the CCDTL part and 6 accelerating sections and 5 bridges in each CCS part. The quadrupole lenses are placed between the sections as well as the cavities to provide a FODO lattice. The design of the CCS has been made, taking into account that each accelerating section consists of 16 cells each.

Special attention has been given to the distance between the sections. It is obvious that this length must be as small as possible from the requirements determined by the
longitudinal beam motion. In practice this distance is chosen according to the design of the focusing lenses which are installed in between, as well as steering magnets and beam instrumentation required at these places. For linacs operating today which are based on the CCS, this space is an odd multiple of $3\beta/2$ and the shortest length of $3\beta/2$ has been realized for example in the upgraded Fermilab linac. In the energy range between 50 to 100 MeV this value is not sufficient to fit the equipment mentioned before and we decided to choose the inter-section distance in the CCDTL cavity equal to $2\beta$, while for the CCL this distance is $3\beta/2$. Rectangular coupling bridges operating in a $TE_{11n}$ mode are planned for coupling of accelerating sections in each part. This type of bridge has been successfully applied in the main part of INR linac [6]. The $TE_{11n}$ bridge avoids mode mixing, provide the space needed for equipment and can provide either $\pi$ or $2\pi$ phase shift between accelerating sections.

The Accelerating structure

The well known Side Coupled Structure (SCS) could be a good solution for the Linac Upgrade. However relatively large number of cells in the CCL sections (96) require strong coupling (> 5-7 %), which is more than typically used for the SCS. The use of a SCS in the CCDTL would result in even smaller coupling (-1%). On the other hand the Disk and Washer (DAW) structure can be used for this purpose. Nevertheless, for a comparatively short linac (272 accelerating gaps in total), the development and production cost for DAW structure is higher as compared to the CCSs. In addition a DAWDTL has not been studied in detail and preliminary studies show that more interfering modes exist. Methods to remove parasitic modes from the vicinity of the operating mode, which have been developed for standard DAW structures, are not evidently effective in DAWDTL and need more detailed analysis.

An On-axis Coupled Structure (OCS) was chosen in order to provide a larger coupling constant. In addition this structure is comparatively simple from the mechanical point of view and with the low repetition rate (heat load of the structure is only 60 W/m) it is not necessary to use internal cooling of the accelerating cells. A sketch of the OCS and OCSDTL is shown in Figure 1 and 2.

An OCS has been used already in many electron machines. For the upgrade we have studied and optimized the On-axis Coupled Structure for cells, which are used in the velocity range of $0.3<\beta<0.52$, with the 2D/3D MAFIA code [7].

A few key points have been taken into account:

- To reduce possible sparking rate during transients in the coupling cells the ratio of $E_{c,\text{max}} / \sqrt{W_c}$ has been limited. Here $E_{c,\text{max}}$ is a maximal electric field on the surface for the coupling mode for given value of the energy $W_c$ stored in a coupling cell.

- The coupling slots have been investigated and optimised. The axial length of the slot has been varied to achieve a coupling constant of 15% for OCS sections and 10% for OCSDTL sections. The calculated values of $Z\nu_T^2$, taking some degradation into account and $E_0T$ for the finally chosen option of the OCSDTL and OCS are plotted in Figure 3.

Beam Dynamics

The accelerating structure geometry has been modeled using functions of the effective accelerating gradient $E_0T$, effective shunt resistance $Z\nu_T$ with respect to the relative beam velocity $b$, as being obtained from the MAFIA calculations. A general parameter list of the upgraded Linac is given in the Table 2.

Due to the different periodicity of the focusing structure in section 1 (16-bl) and section 2 (19-bl), matching of the transverse beam dimensions is necessary between these two sections. This is provided using four quadrupole lenses at the end of the cavity 1.
The main component of the transition region (TR) is a buncher cavity followed by a drift space in order to reduce the phase spread of the 202.56 MHz bunches from $\pm 13^\circ$ to $\pm 4^\circ$ as required for the matching conditions at the entrance of the upgraded linac. The TR contains four quadrupoles to match the transverse phase space parameters.

In Figure 4 the beam envelopes (x-plane = solid line, y-plane = dashed line), the relative energy spread DW/W and the phase spread D$p$ of 90% of the particles are presented along the longitudinal coordinate for the upgraded part of the linac. The simulation has been performed for all 100% particles including a beam halo. The beam losses are less than 0.04%. An rms-emittance growth of 22% in the transverse phase planes due to the rf defocusing has been calculated.

Several sources of accelerator imperfections and their effect on beam dynamics have been studied. The conventional random deviation of linac parameters from the design values produce a transverse rms-emittance growth of 20% and a longitudinal rms emittance growth of 3% with a probability of 90%. Two other sources of accelerating field distortions in a long CCS cavity are:

a) a natural drop of the rf power along the cavity containing a large number of coupled cells;
b) transient beam loading and compensation schemes. The first effect is negligible due to the high cell coupling. The latter slightly increases the momentum spread of a 20 mA beam for a very short part of the beam pulse.

![Fig. 4. Beam envelopes (90% of particles) along the linac.](image)

### References

A THREE DIMENSIONAL BUNCH SHAPE MONITOR FOR THE CERN PROTON LINAC

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Division FS, CERN, CH-1211, Geneva 23

Abstract

The development, performance and test of the Three Dimensional Bunch Shape Monitor (3D-BSM) are presented. The principle of operation is based on the analysis of secondary electrons produced by a primary beam on a 0.1 mm tungsten wire to which a potential of -10 kV is applied. The horizontal particle distribution is provided by moving the wire across the primary beam. A horizontal slit located outside the primary beam area is moved vertically in order to analyse the secondary electron density distribution in the vertical direction. The longitudinal profile is measured as in the bunch length detector developed at INR earlier. The 3D-BSM has been installed and commissioned at the CERN proton linac.

Introduction

The distribution of charge in the real beam of linear accelerators is described by a three dimensional distribution function \( I(x, y, z) \) or \( I(x, y, \phi) \). Conventional beam instrumentation devices provide projections of this function for just one of the co-ordinate axes or planes. Thus, widely used wire scanners and harps provide a one co-ordinate function. To measure the longitudinal distribution, bunch shape monitors are used [1-3]. There is also the method and device to measure two dimensional distribution in the transverse plane [4] as well as the proposal to obtain a two dimensional distribution with a combination of the longitudinal and one of the transverse planes [5].

The first idea to measure a real three dimensional distribution is described in [6]. This idea has been revised and implemented in the Three Dimensional Bunch Shape Monitor (3D-BSM) developed and built at INR for the CERN proton linac.

General Configuration and the Design

The general configuration of the 3D-BSM is presented in fig. 1. The beam under study crosses the target (1) (tungsten wire 0.1 mm diameter) and knocks out low energy secondary electrons. A HV negative potential (-10 kV) is applied to the target. Owing to the high strength of electric field near the target, the electrons move practically horizontally and their vertical co-ordinates at the plane of the horizontal slit (2) correspond to a short vertical section of the target wire determined by the position of the slit. If the target has a horizontal co-ordinate \( X_o \) and the slit a the vertical co-ordinate \( Y_o \), then the intensity of the electron current downstream of the slit is proportional to the intensity of the primary beam at the point \((X_o, Y_o)\) of the transverse plane and its temporal structure reproduces that of the proton beam. The temporal structure of the electron beam downstream of the slit is coherently transformed into a spatial one through transverse rf modulation in the deflector (3) combined with the electrostatic lens as in the conventional bunch shape monitor. This spatial distribution is measured with the 30 channel electron collector (4). For a fixed position of the target and the slit, the signal from one channel of the collector is proportional to the intensity of the protons having the corresponding transverse and longitudinal co-ordinates. The signals from all the channels represent the longitudinal distribution of protons with the transverse co-ordinates \((X_o, Y_o)\). By measuring the longitudinal distribution for different locations of the collimator one can get a two dimensional distribution \( I(X_o, y, \phi) \). A three dimensional function can be obtained if a horizontal movement of the target is added. If however, the target were displaced without the collimator and slit following it, the temporal structure and intensity of the electrons would change. To avoid these effects the target is surrounded by an electrostatic screen (5) which moves with the target. Since now the electrostatic field pattern in the target - collimator area remains constant, the temporal structure of the electrons is not modified. Similarly, the intensity of the electrons passing through the slit does not change. Variation of the drift distance from the slit to the

Fig. 1 General configuration of the 3D-BSM
deflector entrance results in a systematic phase error which has however, been taken into account knowing the well-defined velocity of the electrons. When the position of the target, along with the screen changes with respect to the deflector-lens, the size of the focused beam at the collector varies but the variation of phase resolution is negligible.

When the target and the electrostatic screen are moved, the collimator plate also moves, sliding along the guide (6). Vertical movement of the collimator is provided by the vertical displacement of the guide.

There are strict requirements for the vertical uniformity of the accelerating electric field in the target region and for the focusing field in the deflector-lens. Non-uniformity of the accelerating field leads to vertical displacement of the electron beam from the working area of the collector when the collimator is moved, thus resulting in loss of information. Non-uniformity of the focusing field is the main reason why the phase resolution is dependent on the collimator position. To avoid the first effect, the correcting elements (7) are installed on the target holders. The second effect is corrected with the help of the elements (8) installed on the plates of the deflector-lens. Use of these elements helped obtain a vertical operating range of ±10 mm. There are also requirements for the uniformity of the rf deflecting field but in our case this problem was negligible.

The assembly drawing of the detector is presented in fig. 2. The 3D-BSM includes the following main units: body of a sandwich type consisting of collector, insulating and bias plates. The latter are used to limit the influence of secondary emission electrons from the collector plates.

The signals are amplified by fixed gain (30 mV/nA) preamplifiers followed by amplifiers with remotely controlled gains. The overall gain can be changed from 3 mV/nA to 1500 mV/nA in 10 steps. For normal operation of Linac-2 (peak current 130-140 mA) the gains of 50-100 mV/nA were used. A calibration mode with a 10 nA input signal has been incorporated. The response time of the amplifier chain is 2-3 μs and the rms noise level is about 0.5 pA/√Hz.

The 3D-BSM has an independent control system using an IBM PC and one VME crate. Special electronic modules (HV, rf, interface, stepper motor drivers) are housed in two additional CAMAC crates. Using five 8 channel STR755 digitizers gives the possibility of sampling all of the signals with 250 ns steps, thus providing information on the behaviour of the distribution in time and allowing a four dimensional function \( I(x, y, \phi, t) \) rather than the three dimensional distribution to be obtained.

The software includes three programs. The first one is used for signal observation, detector parameter adjustment and detector tuning. The measurements and the initial data processing are made with the help of the second program whilst the third gives visual presentations of the results.

Total measuring time depends on the number of points in the transverse plane. For example 20 points along the vertical and 20 points along the horizontal axis require 420 pulses of the accelerator = 504 sec. plus about 1 minute for setting up and 5 minutes for data processing.

Parameters of the 3D-BSM

To find the vertical resolution, a simulation of electron dynamics from the target to the collimator was made. The vertical size of the electron beam emitted from a fixed point on the target was calculated to be about 0.5 mm at the slit, therefore this is the best vertical resolution that can be obtained, however, a 1 mm slit was chosen rather than risk an inadequate signal intensity.

A value of phase resolution of less than 1° of rf phase can be achieved. However, to fully cover the 60° rf phase of the linac bunches with the 30 channel collector, the power in the deflector was decreased from 15 W to 1.5 W thus reducing the resolution from 1° to 3°.

The detector has the following main parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>Horizontal resolution</td>
<td>&lt;0.1 mm</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>1 mm</td>
</tr>
<tr>
<td>Phase resolution</td>
<td>&lt;1°</td>
</tr>
<tr>
<td>Horizontal range of measurements</td>
<td>±10 mm</td>
</tr>
<tr>
<td>Vertical range of measurements</td>
<td>±10 mm</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>202.56 MHz</td>
</tr>
<tr>
<td>RF power consumption</td>
<td>1.5-15 W</td>
</tr>
<tr>
<td>Signal response</td>
<td>2-3 μsec</td>
</tr>
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</table>

Fig. 2 Assembly drawing of the 3D-BSM
Detector Commissioning

Laboratory commissioning included testing of the hardware and tuning electron optics using thermal electrons produced by heating the target. Selection of the shape and size of the correcting elements has also been made from observation of thermal electrons. The spiral shape of the correcting elements (8) was chosen to minimise their influence on the resonant frequency.

After installation of the detector in the beam line, it was tuned with secondary electrons; the values of the focusing voltage \( V_{foc} \), the steering voltage \( \Delta V \) and the rf voltage \( U_m \) (fig. 1) were optimised and the correspondence of the channel number to phase was determined. To find the latter, the dependencies of the channel output signals vs deflecting field phase for slow phase variations (from pulse to pulse) are measured. The functions obtained represent the same bunch shape but are shifted along the phase co-ordinate. This shift gives the function of channel to phase correspondence for given values \( \Delta V \) and \( U_m \).

The very first measurements proved the efficacy of the detector. However we encountered the following unexpected phenomenon. In a range of target positions from -9 mm to -3 mm the signals from all the channels increased abnormally. These signals appeared for beam currents above 50 mA, they increased with time, and after 50 \( \mu \)sec considerably exceeded the signals obtained with normal beam current. Analysis of the observations enabled the following assumption to be made about the nature of the unexpected signals. On passing through the detector, the beam induces electromagnetic fields and moving the target unit with its electrostatic screen and collimator plate changes the resonant frequencies of the system. For the target positions mentioned above, resonant conditions are satisfied for high harmonics (presumed >1 GHz) of the bunch frequency. Electromagnetic fields penetrate into the deflector through its openings and initiate oscillations on the correcting elements (8) (fig. 1), initially made as spirals, and thereby cause a multipactor discharge in equipotential space between the turns. Owing to the HV focusing potential applied to the spirals, the space between the turns is equipotential and the electrons produced in the discharge are accelerated by the electrostatic field; a fraction of them reaches the collector producing the unexpected signals. This mechanism explains all the observed experimental effects.

The following improvements were made to avoid the unexpected signals: the spiral elements were replaced by plates, screening of the deflector cavity was improved and additional screening of the space between the collimator and the deflector exit was made. After the improvements the unexpected signals totally disappeared.

It was anticipated from the design calculations that the 3D-BSM target could overheat if the product of the beam current and its duration exceeded a certain value. Experimental testing of the thermal stability of the wire showed that neither thermal emission nor target destruction occurs for the maximum beam intensity during normal operation: current 140 mA and pulse duration 145 \( \mu \)sec.

Up to now we have no final conclusion about the influence of the beam fields on the detector operation and its parameters. Whilst increasing the target potential should decrease these effects, measurements with different target potentials have shown no change in the transverse parameters for target potentials of -7.5 kV and -10 kV.

The main results of the first experiments are presented in [7].

Conclusion

A fundamentally new beam instrumentation device for the CERN 50 MeV proton linac has been developed, built and successfully commissioned. The 3D-BSM enables proton density distribution to be measured in real time in three dimensional co-ordinate space and, moreover, shows its variation along the beam pulse. Commissioning and first measurements have confirmed the validity of the principal idea and the correct choice of elements for the realisation of this detector. The complexity of the detector and its application in an area of very intense proton beams resulted in some problems during its initial operation. Most of these seem to be solved successfully. A full understanding of the device's potential and limitations will, however, require machine development studies dedicated to the characterisation of the device itself. So far no degradation of quality has been observed in the PS-Booster beam when the 3D-BSM is being used.

References

STUDY OF BEAM PARAMETERS OF THE CERN PROTON LINAC USING A THREE DIMENSIONAL BUNCH SHAPE MONITOR

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Abstract

A Three Dimensional Bunch Shape Monitor (3D-BSM) has been developed for the CERN Proton Linac 2. A new area for beam studies at high intensities has been opened by this detector. Bunch density distributions in all three dimensions and their variations along the beam pulse can be obtained. Changing field gradients in linac quadrupoles, emittance variation along the bunch has been calculated. Measurements of beam halos become possible thanks to the large dynamic range of the device. Beam parameters at various linac settings have been measured and analysed.

Introduction

The new detector [1] allows the measurement of the three dimensional density distribution $I(x,y,z)$ of a bunch and its evolution along the beam pulse. For example, using this distribution the first and second moments and the beam profiles in each direction $(x,y,z)$ have been obtained. The CERN Linac 2 is a high intensity accelerator consisting of an RFQ and three Alvarez tanks producing 140 mA of protons at 50 MeV [2]. As proven during the detector commissioning, the 100 $\mu$m tungsten wire can operate safely with pulse lengths up to 145 $\mu$s. The insertion of the target in the beam does not disturb injection into the downstream booster synchrotron. Therefore the 3D-BSM can be used as a non-destructive beam diagnostic tool during linac operation.

Bunch Shape Measurements of the 50 MeV Beam

In Fig.1 the evolution of the longitudinal profile along the beam pulse is presented. The analysis of the figure as well as of the evolution of other beam parameters along the bunch shows that beam-loading is well compensated in Linac 2. There is no variation either of the bunch centre or the bunch shape along the entire pulse length. It has been demonstrated that the bunch shape changes along the pulse if beam-loading is not sufficiently compensated. This can be seen in Fig. 2 where the RF field in tank 3 has been increased by 4% while keeping the maximum power to the tank constant.

![Fig. 1. Bunch shape evolution along the beam pulse for nominal settings. Linac RF frequency is 202.56 MHz.](image1)

![Fig. 2. Bunch shape evolution along beam pulse in case of insufficient beam loading compensation in tank 3.](image2)

When changing the phase of tank 3 in a 60° range, the bunch length varies between 13° and 30° (1 rms values) and the phase of the bunch centre (with respect to the phase of the reference line) varies by 130° (see Fig. 3). Deviation of the bunch centre phase is due to two main reasons: the energy change and the coherent oscillations in the longitudinal phase space.
Study of Transverse Emittance Variation along the Bunch

From the measured data, the transverse rms size of the proton beam has been calculated for "slices" (in phase) through the bunch. The rms beam widths have been measured for three magnetic field gradient settings in upstream quadrupoles inside tank 3. Using these data the (rms) emittance as a function of phase along the bunch has been calculated (see Fig. 5). Due to limited time for all experiments, only the measurements enabling the derivation of horizontal emittance have been made. These studies were restricted to the central part of the bunch, where the signal level ensures a good precision. However, the beam transverse behaviour can also be studied in the bunch tails using a higher dynamic gain of the signal amplifiers of the 3D-BSM. There is a significant variation of the rms beam size with phase.

The iterative use of TRACE and TRANPAR [4] allowed the derivation of horizontal transverse emittance taking into account space charge and acceleration in the last three gaps (between the quadrupoles used for the experiment) for different "slices" along the bunch (see Fig. 5 and 6). The use of the TRANPAR code alone to reconstruct emittances showed that neglecting space charge in this calculation process can induce an error of up to 50% on emittances.

The bunch shapes have been measured for various rf field levels in the first and third tanks and different beam currents. All the measurements showed a strong dependence of the density distribution of the bunch on the parameters of the linac.
The horizontal rms emittance averaged over the whole bunch and the whole pulse (0 to 75 µs) is 2.5 mm.mrad, which is consistent with the theoretical value from PARMIL (2.4 mm.mrad).

**Measurement of the Transverse Density Distribution.**

The 3D-BSM has a wide dynamic range: the signal gain can be varied by a factor 300. It can be used for the measurement of transverse cross-sections of the beam (see Fig. 7), including halo because these measurements do not require rf voltage on the deflector of the 3D_BSM [1].

![Graph showing beam cross-section](image)

**Fig. 7.** Beam cross-section. This graph shows log(j) where j is the proton current density in µA/mm². The total current is 150 mA. The maximum current density is 3.95 mA/mm². The borders between shades represent 1000, 100 and 10 µA/mm². They contain respectively 69.0, 96.9 and 99.7% of the beam.

**Bunch Distribution in φ-x Plane**

The bunch length depends on the horizontal position (see Fig. 8a). The bunch length has a maximum for a horizontal position different from the mean. This effect could be due to the influence of the field created by the space charge of the proton bunch on the trajectory of the secondary electrons ejected from the tungsten wire[1]. However, it is still unclear why this effect is smaller for shorter bunches, when the proton density is higher (see Fig. 8b). Therefore, it could be a real feature of the proton beam due to a misalignment of quadrupoles in the linac. It is possible to simulate such an asymmetry by arbitrarily misaligning quadrupoles in tank 1 with DYNAC [5], but large alignment errors are required. More theoretical and experimental work is required to explain this effect. For instance, the 3D-BSM will be studied by a computer model including the influence of the space charge of the bunch on secondary electrons.

![Graph showing bunch distribution](image)

**Fig. 8.** Beam density distribution in φ-x plane for long (a) and short (b) bunch.

**Conclusion**

The study proved the effectiveness of the 3D-BSM in monitoring both transverse and longitudinal beam parameters. It has demonstrated that the bunch density distribution is very sensitive to the working parameters of Linac 2. The 3D-BSM will be an essential tool in future high intensity studies at currents greater than 180mA at the exit of the linac.

**References**

THE STATUS OF DESY H⁻ - SOURCES

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Abstract
Two different types of H⁻ sources are operated at DESY, a magnetron source and an rf- driven volume source. H⁻ sources for HERA have to run for long uninterrupted periods with a low duty factor and a high reliability. Several necessary improvements are under construction for our rf- driven volume source. The status of both our magnetron and our volume source will be discussed and the first LINAC III experiment with the rf-driven volume source will be presented.

Introduction
The H source is a component of LINAC III, the injector for DESY III. The H⁻ ions are converted to protons using a thin stripping foil. Multiturn injection then allows particle accumulation in the synchrotron, as described in Ref. [1].

At present an 18 kV magnetron source [2] is operated as the H⁻ source for LINAC III, with the matching of the source to the 750 kHz RFQ (Radio Frequency Quadrupole) done by a LEBT (Low Energy Beam Transport) consisting of two solenoids. A magnetron source has to be operated with cesium in order to reduce the work function for electrons. The availability of the source is limited by the delay due to cesium [3]. A cesium free source became even more desirable for use on LINAC III when a glow discharge was seen in the four vane RFQ and multipactoring occurred in the first section of the Alvarez tank of LINAC III. Although it was not possible to detect cesium in the RFQ or the Alvarez tank nevertheless measurements showed traces of cesium leaving the source [3]. A volume source can be operated without cesium. It has a lower emittance, but if uncesiated it produces a lower output current than a magnetron source.

Status of the magnetron source
The DESY magnetron has been operating since 1985. It is based on the design of FNAL [2] and was modified according to the DESY requirements [3]. Since 1993 the magnetron has been operated from one HERA maintenance period to the next for 152, 301 and 291 days without breaking the vacuum. There were only minutes of interruption due to failures of the electronics. Figure 1 shows the run periods since 1993. Until now the source has run in 1996 for 171 days.

![Figure 1: Uninterrupted operation period of the magnetron vacuum unit.](image)

Table 1: Data of the magnetron H⁻ source.

<table>
<thead>
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<tr>
<td>H⁻ beam current</td>
<td>60 mA</td>
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<tr>
<td>emittance</td>
<td>π mm mrad</td>
</tr>
<tr>
<td>εₓ rms norm (εₓ 90% norm) (35mA beam)</td>
<td>0.28(0.15)</td>
</tr>
<tr>
<td>εᵧ rms norm (εᵧ 90% norm) (35mA beam)</td>
<td>0.25(0.81)</td>
</tr>
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<td></td>
</tr>
</tbody>
</table>

The emittance in the vertical plane, is reduced due to aperture limitations of the magnet gap. A beam of up to 100 mA can be produced.

Status of the rf - driven volume source
The rf - driven volume source was originally built by AccSys [12] using plans from LBL [4]. The source was redesigned by DESY in order to gain a better reliability, higher currents and a beam energy of 35 keV.
A DESY designed piezo valve is now used which has successfully operated in the DESY magnetron source for many years. As the pulser of the piezo valve has to be rack mounted we had to build a new high voltage deck (see Fig. 2). The filament was replaced by a flash light which is directly mounted to the source bucket. It has a UV window Ref. [5]. The source is connected to a computer control system which delivers histograms and programmed diagrams of parameter dependencies.

![Image of rf driven volume source at DESY R&D laboratory.](image)

A 2000 l/s vacuum pump and a water cooling system for the multi cusp bucket are necessary.

Figure 2 shows the rf driven volume source at DESY R&D laboratory with the new 35 kV box connected to the bucket. The extraction system is an electrode with a 60 mm wide spectrometer similar to the LBL design [4]. An electron current of about 1A is dumped on a grooved graphite plate. The magnets are encapsulated in vacuum tight steel boxes in order to protect them against hydrogen (see Ref. [6]).

The beam position is corrected with a horizontal and vertical adjustable collar and plasma electrode. The adjustments were measured with a multi faraday cup [6] which was inserted into the beam pipe. The beam current was measured in the 35 mm beam pipe with a current transformer. For several weeks it was possible to run the source above 23 kV with a current of 33 mA. Details are given in [9]. Measurements of the emittance are done after the beam is collimated by a 35 mm Ø beam pipe which is more than 80 mm long.

The emittance was measured with a slit and grid system. Table 2 summarizes the data of this configuration.

**LINAC 3 - DESY 3 test with the rf driven volume source**

During January 1996 the magnetron source of LINAC 3 was replaced by the rf driven volume source. The extraction system shown in Fig. 3 was connected to a LEBT consisting out of two solenoids.

![Diagram of rf driven volume source with a wide spectrometer and an adjustable collar electrode.](diagram)

At the beginning the source delivered a 18 keV, 20 mA H⁻ current and about 39% of the beam was measured behind the RFQ. Emittance measurements were made in the HEBT (High Energy Beam Transport) line. Table 3 summarizes the measurements with the magnetron and the volume source done at LINAC 3 [7].

There is almost no beam loss between tank 1 and tank 3 of the Alvarez.

At DESY 3 after accumulation and acceleration to 7.5 GeV/c a proton current of 60–70 mA was measured [8].

**Future source plans**

The rf driven volume source of DESY has delivered a H⁻ beam of 15–33 mA for more than a year.

---

**Table 2: Data of the rf H⁻ source with a spectrometer.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy</td>
<td>18–35 keV</td>
</tr>
<tr>
<td>beam current</td>
<td>16–33 mA</td>
</tr>
<tr>
<td>emittance</td>
<td></td>
</tr>
<tr>
<td>$e_{x, 90%} (e_{x, 90%})$</td>
<td>0.18 (0.81)</td>
</tr>
<tr>
<td>$e_{y, 90%} (e_{y, 90%})$</td>
<td>0.16 (0.72)</td>
</tr>
<tr>
<td>source voltage</td>
<td>−18 to −35 kV</td>
</tr>
<tr>
<td>extraction voltage</td>
<td>0 V</td>
</tr>
<tr>
<td>electron current</td>
<td>0.8–1.8 A</td>
</tr>
<tr>
<td>rf output power</td>
<td>25–45 kW</td>
</tr>
<tr>
<td>pulse width</td>
<td>100 µsec</td>
</tr>
<tr>
<td>repetition rate</td>
<td>1–6 Hz</td>
</tr>
</tbody>
</table>
The long term experience shows that the graphite dump for the electron current deteriorates. It will be replaced by a multi faraday cup which makes it also possible to check the position of the electron beam.

**Table 3: LINAC 3 measurements**

<table>
<thead>
<tr>
<th>magnetron</th>
<th>volume source</th>
<th>current</th>
<th>transmission</th>
<th>current</th>
<th>transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>source</td>
<td>60 mA</td>
<td>16.9 mA</td>
<td>0.33</td>
<td>34 (.39)</td>
<td></td>
</tr>
<tr>
<td>RFQ</td>
<td>20 mA</td>
<td>5.8 mA</td>
<td>0.64</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>alvarez</td>
<td>14 mA</td>
<td>4.4 mA</td>
<td>0.78</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>HE.T</td>
<td>11 mA</td>
<td>4.3 mA</td>
<td>0.68 τ mm mrad</td>
<td>0.43 τ mm mrad</td>
<td></td>
</tr>
<tr>
<td>ε&lt;sub&gt;x,rel&lt;/sub&gt;</td>
<td>.0 .0</td>
<td>.0</td>
<td>.0</td>
<td>.0</td>
<td>.0</td>
</tr>
<tr>
<td>ε&lt;sub&gt;y,rel&lt;/sub&gt;</td>
<td>0.6 τ mm mrad</td>
<td>0.46 τ mm mrad</td>
<td>0.68 τ mm mrad</td>
<td>0.43 τ mm mrad</td>
<td>.0</td>
</tr>
</tbody>
</table>

The reliability of the source depends very much on the quality of the antenna coating. The H<sup>+</sup> current will not only depend on the insulation of the antenna but also on sputtering of antenna insulation to critical parts of the bucket surface. This insulation will limit the recombination of H<sup>+</sup> ions to Hz and the production of excited H<sup>+</sup> on the walls.

Reliable tests were developed which make it possible to check the antenna insulation outside and inside of the source bucket. Before installation a power test in salt water detects even small defects in the coating. After installation in the bucket the antenna insulation can be checked by applying HV during gas pulsing and measuring the antenna current. This makes a change of the driving circuitry necessary. During operation of the source it was checked if critical parts of the antenna are not isolated by measuring the antenna bias voltage.

The transition during sparking damages the antenna significantly. Even with well designed HV circuitry it cannot completely be avoided. It happens mainly at the gap between extractor and plasma electrode.

Successful tests were done with a small insulated plasma electrode. It is situated on the main plasma electrode opposite to the extraction electrode and is directly connected to the HV power supply. If sparking occurs in the gap the current can flow directly to the HV supply.

Besides the insulation and sputter problem of the antenna there is also a limitation due to the different expansion of the coating and the copper material in a source pulsed with 50 kW rf.

These problems can be easily solved by separating insulation and antenna. Al<sub>2</sub>O<sub>3</sub> has similar sputtering coefficients to the Ti O<sub>2</sub> coating presently used.

With new methods [10] extremely smooth surfaces can be produced. The disadvantage is that only simple geometries can be improved. Mafia calculations [11] show that rectangular antennas have similar fields to the present antenna. They can be built out of Al<sub>2</sub>O<sub>3</sub> bends and straight pipes with a copper pipe inside.

A flat circular antenna behind a Al<sub>2</sub>O<sub>3</sub> window has a different field but would be mechanically less complicated. Both antenna types are under production.

**Conclusion**

The magnetron source was successfully adapted to the HERA environment. Further test and development of the volume source is necessary to improve its reliability and performance.

**Acknowledgment**

The author is grateful for the contribution of the following colleagues at DESY: N. Holtkamp, I. Hansen, H. Sahling and R. Subke.

I wish to thank the technical groups at DESY for their support, the students T. Butschkat (FHH) and O. Krücken (FHW), T. Warner (FHW) for their programming and J. Maidment of DESY for helpful suggestions to wording of the report. The support of the source groups ofLBL, FNAL and BNL is gratefully acknowledged.

**References**

SPACE-CHARGE NEUTRALIZATION EXPERIMENT
WITH A LOW-ENERGY PROTON BEAM

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Abstract

The mechanism of space-charge neutralization of a low-energy proton beam is investigated both experimentally and theoretically. In the experiment, the transverse profile of a 500 keV proton beam delivered by a duoplasmatron source is accurately measured at the end of a 3 m long drift space. Profile measurements are performed by using a scintillating screen and an intensified CCD camera. Measurement results done with different beam intensities (between 0.5 and 15 mA) and various residual-gas pressures are described. They show that, at high beam current an increase of the gas pressure results in a reduction of the beam spot, which indicates an increase of the value of the neutralization coefficient. On the other hand, the behavior is the opposite at low beam current: the beam size increases with the gas pressure. An interpretation of these experimental results is proposed.

Introduction

Beam losses result from the existence of a diffuse halo which can extend far away from the dense beam core. Halo formation originates from different processes including space-charge effects [1] and Coulomb scattering on the residual gas [2]. In the first process, mismatch and misalignment in the transport of an intense beam in a long periodic channel, as well in a linac, are believed to be important sources of halo. To check these predictions, an experimental program has been initiated, aiming at the investigation of halo formation and development in the transport of an intense low-energy proton beam through a periodic focusing FODO channel [3]. Accurate measurements of beam emittance and brightness performed at the channel entrance indicate that the initial beam conditions are suitable for further halo development through the FODO channel [4].

The low-energy proton beam may however be partially neutralized in the residual gas of the transport channel, which would increase the tune depression and mismatch to the beam to the FODO channel. Interpretation of the halo measurements would then be questionable.

Therefore, an experimental study of the space charge neutralization has been undertaken to provide compensation coefficients at various beam intensities for a low-energy proton beam. This study will be also useful for the design and simulation of the low energy part of a high-intensity linac such as the one studied for the TRISPAL project [5].

Experimental procedure

Space-charge neutralization measurements have been performed in the matching section between the proton source Amalthée and the FODO channel of our halo experimental set-up at Saclay.

Measurement method

The basic idea for measuring the space-charge neutralization rate is the following:

- A proton beam propagates freely in a residual gas toward a screen. We first measure its transverse size while the only force acting on it is the space-charge force.
- A pepper-pot is then placed on the beam path at the beginning of the drift space. The beamlets passing through the pepper-pot holes do not feel the full-beam space-charge force. The envelope of the beamlet spots corresponds to the full-beam transverse profile without space-charge effect. The pepper-pot can be replaced by a single-hole moved across the beam; a technique which yields more accurate beam profile measurement.
- The neutralization rate is recovered from a simulation which gives an equivalent beam current adjusted to reach the measured beam size.

Experimental set-up

The measurements are performed with a pulsed (500 μs, 1 Hz) proton beam at 500 keV with up to 50 mA peak current, delivered by the Amalthée duoplasmatron source. In the experiment (see Fig. 1), the beam is collimated by a φ10 mm diaphragm (D) located at the source exit. It propagates through a drift space toward a scintillating screen (S) 2.8 m downstream. The pepper-pot (PP) and single-hole (SH) plates are located very close to the diaphragm. The SH plate with a 0.2×0.2 mm² sampling hole is moved in the horizontal direction across the beam by a stepping motor (0.2 mm step). Both beam-profile and beamlet-spot images are observed with an intensified CCD camera.

Fast responses of both light intensifier and scintillator (a P46 phosphor (Y, (Al,Ga), O₃; Ce) crystal powder deposited on a stainless-steel plate) allow to take beam-profile images during a 5 μs snapshot anywhere within the beam pulse. This good time resolution is very useful for analyzing the temporal evolution of the neutralization rate in the pulse.

Residual gas pressure and composition can be adjusted by modifying pumping conditions and injecting nitrogen gas at a given flow in the vacuum chamber.
Fig. 1: Schematic layout of the experimental set-up for space-charge neutralization measurement.

\[ \text{Beam-size increase} = k(L, P) = \frac{\phi_{L, P}}{\phi_0} \]

Measurement results

- In a first run, measurements were taken using the PP plate with a beam current of \( \approx 10 \text{ mA} \) behind the diaphragm D. Fig. 2 shows the beam profiles with and without the PP plate in the beam path.

Analysis of the experimental results shows that the "PP-in" beam size is systematically smaller than the "PP-out" beam size, whatever residual gas pressure (up to \( 5.10^5 \text{ hPa} \)) and sampling instant in the pulse. This behavior indicates clearly that the proton beam is not totally space-charge compensated.

Nevertheless, these measurements are not entirely conclusive since the "PP-in" beam size is determined with up to 40% uncertainty due to large spacing of the PP holes.

![Beam transverse-profile images](image)

- During a second run, the SH plate is used to accurately measure both beam size (\( \phi_0 \)) without space-charge and beam transverse emittance at the diaphragm location. Beam profiles (with and without SH plate) and emittances were measured for 8 beam currents ranging from 0.8 to 15.0 mA and four sets of residual gases and pressures, \( P_1 \) (2 \( 10^4 \) hPa \( \text{H}_2 \)), \( P_2 \) (1.2 \( 10^5 \) hPa \( \text{H}_2 \)), \( P_3 \) (1.2 \( 10^4 \) hPa \( \text{H}_2+2.6 \times 10^5 \) hPa \( \text{N}_2 \)) and \( P_4 \) (1.2 \( 10^5 \) hPa \( \text{H}_2+5.8 \times 10^4 \) hPa \( \text{N}_2 \)). Pressures given here are mean values on the drift space. All measurements were done 350 \( \mu \text{s} \) after the pulse start.

For each measurement, data processing consists in determining the beam-size growth \( k \) defined as the ratio of beam diameters with and without space-charge effect:

\[ k(I, P) = \frac{\phi_{L, P}}{\phi_0} \]

where \( I \) is the beam current, \( P \) the residual gas pressure, \( \phi_0 \) the beam diameter on the screen without space charge and \( \phi_{L, P} \) the beam diameter with space charge.

Analysis of the data shows that below 6 mA the beam size increases with the gas pressure, remains almost constant around 6 mA, and decreases at higher currents. This behavior is illustrated in Fig. 3 where the curves for the two extreme pressure sets \( P_1 \) and \( P_4 \) are displayed. This indicates that at high-current the beam is more space-charge compensated in a high-pressure gas, as mentioned above. On the contrary, a low-current beam seems to be "undercompensated" when the pressure is high.

Fig. 3: Beam-size growth \( k \) as a function of beam current, for the pressure sets \( P_1 \) and \( P_4 \).

![Graph showing beam-size growth](image)

The rate of beam size growth with residual gas pressure is defined by:

\[ \nu(I) = \frac{\text{d}k(I, P)}{\text{d}P} \]

with \( I \) the beam current, \( P \) the residual gas pressure and \( \nu \) is an average over the pressures.

The parameter \( \nu \) has only a qualitative meaning since a precise determination of both gas pressure and composition along the drift is not possible. Nevertheless, Fig. 4 shows a clear variation of this parameter with the beam current. A negative value of \( \nu \) indicates that space-charge compensation increases with the pressure, since a positive \( \nu \) indicates that the beam spread is larger than the one expected from the space-charge effect.

![Graph showing variation of beam size growth](image)

Fig. 4: Variation of the rate of beam size growth with residual gas pressure versus the beam current.

For each beam current, emittance measurements are processed to yield the beam-particle distribution in the phase
space at the diaphragm position. The space-charge neutralization coefficient is determined as follows. Starting from the particle distribution for a given current \( I_0 \), the transport to the scintillating screen is simulated taking into account the space-charge effect. For each pressure set, the space-charge force is adjusted through an "equivalent" beam current \( I_{eq} \) to give a beam size equal to the measured one. The mean space-charge neutralization coefficient \( \tau \) is set by:
\[
\tau = \left( I_0 - I_{eq} \right) / I_0 .
\]

For the low hydrogen pressure (P1), \( \tau \) is always equal to 0. For the high pressure (P4), the mean neutralization coefficient range from -20% for \( I=3.3 \) mA to 20% for \( I=15 \) mA.

**Theoretical basis - Interpretation of the results**

There are 3 species in the plasma created by ionization of the residual gas: beam particles (p'), ions (I'), and electrons (e'), the last two being created by the ionization process. Neutral species (gas) are not taken into account because they have a negligible influence on the dynamics.

The ions are created at very low kinetic energy, while the electrons initial kinetic energy can be larger than 10 eV. Ions and electrons move under the action of a potential well \( \Delta V \) generated by themselves, the beam and the vacuum chamber. Furthermore, the electrons, much lighter than the ions, undergo collisions inducing dispersion in their kinetic energy.

The combination of ionization and transverse transport of the charged particles leads to an equilibrium where the potential is \( \Delta V > 0 \). If the initial beam potential \( \Delta V_b \) (without neutralization) is larger than \( \Delta V \) (high current), the expulsion of the ions is enhanced and the electrons are trapped. This decreases the potential down to the equilibrium. If the initial potential \( \Delta V_b \) is smaller than \( \Delta V \) (low current), the reverse occurs. This means that

i) the equilibrium is stable,

ii) one observes partial neutralization [6] at high current, and the inverse effect ("undercompensation") at low current. Note that in the case of a negative beam, one can have \( \Delta V_b < 0 \) and \( \Delta V > 0 \), which leads to an overcompensation [7].

An interpretation of our experimental results can be the following: for a high beam current (>6 mA), the initial uncompensated potential well \( \Delta V_b \) is deeper than the stable equilibrium \( \Delta V_e \), then the potential decreases and the beam becomes partially compensated. For low beam current, \( \Delta V_b \) could be less than \( \Delta V_e \), leading to an increase of the potential, the beam is "undercompensated".

**Conclusion**

A positive potential well \( \Delta V \), should exist at the steady state. Its shape and depth depends on the beam properties (shape, energy and current), the gas composition (differential cross section and ion mass) and the vacuum chamber size. This well would drive the beam dynamics in compensation conditions. This well should be the right parameter to study in order to understand the compensation phenomenon.

A new experiment, not presented here, has been undertaken with H2 residual gas only. It shows the same behavior as with the Nitrogen gas, but with a lower beam current edge (1.5 mA rather than 6mA for Nitrogen). This can certainly be explained by the fact that the H2+ mass is lower than the N2+ one.

The proton beam used for the FODO experiment is not space-charge compensated at low pressure (< 2.10^4 hPa) allowing a good control of the tune depression in the FODO channel.

**References**

THE SACLA HYDROGEN PROTON AND DEUTERON ECR SOURCE

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Abstract

High-current accelerators are studied for several years at CEA-Saclay for applications such as waste transmutation, tritium production or material irradiation. For these projects, the ion source is a key component because its performances determine the accelerator design. A CW Proton and Deuteron ECR Source has been constructed and is now under test. The aim is to reach a 100mA beam current at 95 keV with a rms normalized emittance better than 0.2 π-mm.mm.mrad and a very high reliability. In this paper, the source, the low energy beam transport and the beam diagnostics are described. First measurements of the source parameters and beam performances are presented.

Introduction

The development of a new ECR source for proton and deuteron beam production is part of a considerably larger activity presently ongoing at CEA in the field of high intensity linear accelerators. This source is the first stage of the IPHI demonstration project. This accelerator will consist of an ECR source, a RFQ and a DTL up to 10 MeV. The production of high flux neutron beams for spallation reactions (TRISPAL), the international IFMIF program and nuclear waste treatment are main applications of this project.

It has been decided to develop a new source with the following requirements: 100 mA proton, 140 mA deuteron, 100 keV, 0.2 π-mm.mm.mrad rms normalized emittance and a 90% proton or deuteron fraction. The ECR source principle has been chosen for simplicity and reliability reasons as demonstrated by the Chalk River National Laboratory and the Los Alamos National Laboratory. Moreover, this kind of source shows no intrinsic lifetime limitations.

The CEA-SACLAY Source

Experiences from several teams [1],[2],[3],[4],[5], have been used to design a High-Intensity Light-Ion Source (SILHI - Fig. 1).

The cylindrical plasma chamber is 100 mm length and 90 mm diameter. Both ends of this chamber are covered with boron nitride discs (2 mm thick). The proton beam is extracted through a 10 mm diameter aperture in the plasma electrode.

The magnetic field is produced by four coils independently tuned and positioned. These coils are magnetically shielded to reduce the total power dissipation under 8 kW. This design has been calculated with the 3-D code Opera-3D [6].

Figure 1: Picture of the SILHI source and first part of the LEBT.

The RF signal is produced by a 2.45 GHz, 1.2 kW magnetron source, and is fed into the source via standard rectangular waveguides (WR284, WR340). A three section ridged waveguide transition is placed at the plasma chamber entrance to enhance the axial RF field.

In order to be protected from backstreamed electrons, the RF quartz window is placed behind a water cooled bent section, in a high magnetic field area.

Figure 2: Schematic of the SILHI source extraction region. (A) plasma chamber, (B) plasma electrode, (C) intermediate electrode, (D) ground electrodes, (E) electron trap electrode and (F) DC Toroid.
The above components, including ancillaries, are grouped together on a 100 kV platform. The source is connected to the LEBT (Low Energy Beam Transport) via a 300 mm long HV column. An adjustable intermediate electrode is placed in the acceleration gap of the extraction system. The total system comprises five electrodes (figure 2). This design, optimized with the multi-particles code “Axcel”[7], minimizes the distortions in the phase-space distribution [8].

The actual LEBT is a one solenoid transport line. Simulations have been done with a 77% H+, 15% H2 and 8% H3+ mix. The 1800 Gauss magnetic field focuses the H+ beam on the Emittance Measurement Unit (EMU) which is not yet installed.

Diagnostics

A set of different diagnostics is placed along the 2 m long LEBT in order to characterize the extracted beam (fig. 3).

Figure 3: Source and LEBT assembly.

Current measurements.

A Bergoz DC toroid is located very close to the extraction system, around the last ground electrode (fig. 2). The bandwidth response ranges from DC to 4.2 kHz.

A copper beam stopper is designed to bear a 0.8 kW.cm\(^{-2}\) power density and 10 kW total power. It closes temporarily the LEBT 1.5 m behind the plasma electrode. This device is used both as Faraday cup and as calorimeter. In the future it will be replaced by an insertable beam stopper.

For noise measurement an AC toroid will be inserted 2 m after the extraction aperture. Up to now, the noise ratio is measured on the Faraday cup.

Position and profile monitors

Two CCD cameras allow x and y profile measurements at the end of the accelerator column (60 cm after the extraction electrode) with a 0.15 mm resolution and a 10×10 cm field. The sensitivity is 0.25 lux with a f/1.2 lens. FWHM, beam position and beam divergence are available from these camera images (fig. 4).

Close to the solenoid exit, a four sector ring gives a rough beam off-axis information and collects part of the contaminant species.

Figure 4: Video profile. Notice enlargement due to light parasitic reflection on back flange.

Emittance Measurement Unit

In the near future, the EMU will be installed at 2.3 m from the source. It is composed of a sampler (0.2 mm square aperture) made in a water cooled beam stopper and a multiwire profile monitor 0.5 m forward. The pitch in the center of this profiler is 350 µm. This unit will be moved across the beam by 2 stepping motors. Close to the sampler, a permanent magnet Wien filter will remove the contaminants (H2+, ...) in order to measure the proton only emittance.

Species measurements

The beam proton fraction will be analyzed at the HV column exit by using the sampler and Wien filter which are parts of the EMU. The selected species current will be measured on the insertable Faraday cup.

A Residual Gas Analyzer will help in the water adjunction process which should enhance the proton production.

Temperature measurements

Two thermocouples measure the temperature increase of the two grounded electrodes. These diagnostics are important to minimize the beam losses on the first electrodes during the extraction tuning.

First results

The first plasma was obtained on July, 23. Only two weeks after, on August 7, a 46 mA total beam current at 70 kV was extracted. Table 1 shows the actual source parameters. The extracted current is measured by the DC toroid.

Figure 5 represents the regions where the magnetic field module is between 850 G and 900 G inside the four coils set. Calculation has been achieved with Opera-2d from Vector Fields. The light line delimits the plasma chamber (0 ≤ z ≤ 100 mm, and R ≤ 45 mm). It shows that the 875 G region is near the microwave injection area (z = 100 mm).
Table 1: Summary of the SILHI source requirements and present status.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Req.</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [keV]</td>
<td>95</td>
<td>70</td>
</tr>
<tr>
<td>Intermediate Elec. [kV]</td>
<td>65</td>
<td>47</td>
</tr>
<tr>
<td>Extracted Current [mA] (DC toroid)</td>
<td>111</td>
<td>46</td>
</tr>
<tr>
<td>RF forward power [W]</td>
<td>1200</td>
<td>295</td>
</tr>
<tr>
<td>Duty factor [%]</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>H2 Gas flow (sccm)</td>
<td>&lt;10</td>
<td>2.7</td>
</tr>
<tr>
<td>Proton fraction [%]</td>
<td>90</td>
<td>to do</td>
</tr>
<tr>
<td>Beam noise [%]</td>
<td>±1</td>
<td>&lt;1 (@25mA)</td>
</tr>
<tr>
<td>LEBT exit rms norm. emit.</td>
<td>0.2</td>
<td>to do</td>
</tr>
</tbody>
</table>

![Figure 5](image.jpg)  
**Figure 5:** Magnetic field calculation for the 46 mA extracted beam. The ECR area is located near the microwave injection.

During other experiments with total beam current of 25 mA (on DC toroid), the beam stopper calorimetric and electrical measurements give around 75% of beam transmission through the LEBT. This result gives a rough value of the proton fraction. The noise level has been measured on the Faraday cup with the same beam.

A complete mapping of the total extracted beam current as a function of B1 and B2 solenoids currents has been proceeded. These two coils define the magnetic field inside the plasma chamber. Thus the ECR zone can be moved everywhere inside the chamber. Figure 6 shows that two sets of coil currents give a maximum of extracted intensity.

Similar calculations to those shown on figure 5 indicates that the two intensity peaks on figure 6 coincide to the ECR zone located at both plasma chamber extremities. The left one corresponds to the microwave injection area and the right one to the plasma electrode region. An equivalent result has been achieved without boron nitride liners. The 46 mA total beam has been obtained with the ECR zone near the RF injection. The existence of the two peaks has been already observed by the CRNL team [2]. Moreover, two maximum of the extracted beam as a function of the magnetic field are observed at LANL [9].

![Figure 6](image.jpg)  
**Figure 6:** Extracted beam total current on DC toroid versus axial magnetic field.

**Remarks**

The first results look promising. Nevertheless, beam losses and electrons emitted from the grounded electrode in a sufficiently important number induce a too high electrodes temperature increase. New parts are under study and will greatly improve the power dissipation. The conditioning was not an issue, only few sparkdowns have been observed, even at nominal first or second gap voltage. No glow discharge has been noticed. But sparkdown results in frequent damages to controllers and power supplies located on the HV platform. Surge protections and new shieldings will be installed.

**Acknowledgments**

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**References**

INTENSE ION BEAM TRANSPORT AND SPACE CHARGE REDISTRIBUTION

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Abstract

The main laws that govern the charge redistribution in space charge dominated (SCD) beam during its transport through a periodical channel with solenoidal focusing are considered. Physical mechanisms of halo production and establishment of uniform distribution inside core for matched and mismatched beams are described. The computer codes KERN-HALO generated for redistribution process of charge density and kinetic and potential energies visual representation are described.

We have a clear knowledge of matched (or ideal) beam only in case when space charge does not change a frequency of transverse oscillations. The matched (or ideal) beam is a one which transverse behavior is repeated (or has a smooth change) from one period to the next.

The question "What a matched beam imply?" is arisen when the above definition is extended on the case when space charges essential for transverse oscillation frequency. We can denote that ideal beam has well-known K-V distribution and this distribution must be used for focusing field calculation and for a choice of bore radius. But real beam distributions differ from K-V one and its redistribution during beam transport leads to beam size and emittance growths. It means that such ideal beam definition results in a serious error of bore radius.

The SCD-beam investigations in channel with different initial beam transverse distributions were made by authors in order to answer on the above question. A simple model must be chosen for better understanding of process of SCD-beam redistribution. It can be a continuous cylindrical beam transporting in longitudinal magnetic field. In this case a Coulomb force calculation is very much simplified. Within the context of this model there are only a few characteristics for understanding the cause and effect of halo formation. Only distributions with beam density growth (or keeping constant) from the origin to outlying area were considered as initial ones [1].

Under above considerations beam motion is described by following equations

\[
\begin{align*}
\dot{x} &= \frac{eB(z)}{m_0c\beta^2} \gamma + \frac{2I}{I_0(\beta^2)^{1/2}} \frac{Q(Z)}{r^2} \cdot \dot{x}, \\
\dot{y} &= -\frac{eB(z)}{m_0c\beta^2} \gamma + \frac{2I}{I_0(\beta^2)^{1/2}} \frac{Q(Z)}{r^2} \cdot \dot{y},
\end{align*}
\]

where \(e, m_0\) are charge and rest mass of ion, \(\beta\) is a ratio of ion to light velocities, \(\gamma = (1 - \beta^2)^{-1/2}\), \(B(z)\) is magnetic field induction, \(I\) is beam current, \(I_0 = 3.13 \cdot 10^7\) A is Alfven current for proton, \(Q(r)\) is charge fraction inside circle with \(r\) as radius (\(Q(\infty) = 1\)), \(r^2 = x^2 + y^2\).

The equations of motion have a unitless form after transition to unitless variables \(z = L\tau, x = A\tilde{x}, y = A\tilde{y}\), where \(L\) is focusing period length, \(A = (eL/(\beta\gamma)^2)\), \(\epsilon\) is beam emittance

\[
\begin{align*}
\tilde{x}'' - 2\lambda \tilde{y}' - \alpha \frac{Q(r)}{r^2} \tilde{x} &= 0, \\
\tilde{y}'' + 2\lambda \tilde{x}' - \alpha \frac{Q(r)}{r^2} \tilde{y} &= 0,
\end{align*}
\]

\[
\Lambda = \frac{eB(z)L}{2m_0c\beta^2}, \quad \alpha = \frac{2IL}{I_0\epsilon(\beta\gamma)^2}
\]

This set of equation can be considered as base for further considerations. The magnitude of \(B(z)\) is constant inside solenoidal lens and equal zero outside of them.

It is evident from general form of equations that there are only two parameters \(\Lambda, \alpha\) which define the SCD-beam transverse form in the case when a structure of focusing period is preset.

Combinations of uniform and Gauss distributions are used as initial ones.

The main regularities of SCD-beam transporting were carried out [1]:

1. High-density core and low-density halo with particle active interchange are established in every case.
2. Most of core particles are "ex-halo" or "coming-halo" ones which income from halo in previous instant of time or will emerge from core in next instant of time.
3. Uniform charge distribution inside core is established in every case.
4. Final steady states with uniform distribution of core charge are states with Coulomb field minimal potential energy. The transition from the SCD-beam initial state into a final steady state is accompanied by particle kinetic energy increasing and emittance growth.
5. A steady state which leaves the core-halo transverse sizes unchanged can be established. Such beam will be nominated as matched one.

The value of a beam radius in point where Coulomb force takes its maximum is identified as "core radius". Generally a procedure of matched beam redistribution has been going on the following manner. At the first stage a redistribution from initial to the steady state with an uniform core distribution take place. The potential energy difference between initial and final states (always positive for considered distribution class) transforms into kinetic energy and is accompanied by an emittance growth. In the steady state only small fraction of particles (about 30%) never escapes the core, other particles (about 70%) can turn up in

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core or in halo. It means that it's absurd to cut off the halo particles because it leads to large particle losses.

The core radius is kept constant during beam redistribution. It means that the core radius can be determined from initial redistribution. The matched focusing field value can be determined from a core radius and a core emittance. In the point of a crossover (an average radial velocity is equal to zero) the core emittance is equal to an straight ellipse area with and \( k \beta \), as semi-axes, where \( \beta \) is rms value of radial velocity and \( k^2 = 3 \) is a square of boundary value to rms one ratio for uniform distribution. As is evident from the foregoing the beam kinetic energy is increasing in the steady state on the difference of potential energies between the initial and final space charge distributions. This difference will be called as "a beam heating up". The unmatched beam investigations offer a clearer view of how the core-halo is formatted as well as further regularities of the process:

7. During the process of charge redistribution in mismatched SCD beam core oscillations are drastically damping.

8. If potential Coulomb energy of input beam is much larger than the same energy of beam steady state, core is automatically matched with channel (there is a damping of core oscillation in continuous magnetic field and in periodical field only one clearly defined harmonic in close agreement with external force harmonic stays in core oscillation spectrum).

9. A factor of \( 3 \) is a sufficient estimate for halo-core radii ratio. It is evident that a halo is formatted from particles which increase their kinetic energies during transverse oscillations. A separate particle motion inside the field of oscillated uniform core was considered in order to study of mechanism of particle energy increasing. A comparison of particle potential energy with its kinetic one before and after oscillated core passing gives a possibility to state that:

10. Energy mechanism for halo production is kinetic energy growth in the case when a halo particle have passed through core concurrently with core ultimately decreasing.

At Fig. 1 the changes of kinetic (curve 1), potential (curve 2) and total (curve 3) energies are indicated versus \( \kappa = r_c/r_{out} \) where \( r_c \) and \( r_{out} \) are the core radius values at the moments of particle entrance into the core and its exit from core correspondingly. It can be seen that potential energy decreasing is much smaller then kinetic energy increasing and total energy is increased with core size decreasing. The duration of particle being outside of the core is increased with increasing of the particle total energy. That is the phase of the core envelope oscillation will be changed in the next core traversal. It means there is a mechanism which desynchronized the oscillations of core envelope and halo particles. It limits a kinetic energy of halo particle and as a result limits a transverse size of the halo.

The important conclusion regarding the choice of focusing channel parameters can be made on the base of performed investigations:

11. The choice of focusing channel parameters must be made from a desired core size and the bore radius choice from a value three times over (a halo size).

References

STUDY OF SPACE CHARGE-DOMINATED BEAM BUNCHING

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Abstract

The main laws that govern gentle bunching of Space Charge-Dominated (SCD) beam are considered. It is shown that SCD-beam bunching depends on two main parameters: the first one determines the bunching quality, another one is measure for bunching process duration. The changes in bunching process depending on this parameters and on low of RF-field amplitude increase are described. The optimal conditions of SCD-beam bunching are discussed. The computer codes ZHALO generated for bunching beam characteristic visual representation are described.

An adiabatic bunching section must be presented at a high-current ion linac for beam loss prevention. The problem is to choose an optimal length of the section as well as optimal values for synchronous phase and accelerating field amplitude. In order to clear up the main regularities of the bunching process the simplest model was used by analogy with the previous case. In the context of this model the beam without transverse motion and with fixed transverse size is moving inside a channel with bore radius \( R \). Synchronous phase is equal -90 degrees and the beam is bunching without acceleration. During bunching process the uniform beam gets a longitudinal charge density modulation. The distribution of potential can be obtained in the form of an expansion into a series by solving a Poisson equation for the beam with periodical charge density modulation and uniform density in any transverse crossection

\[
U(r,z) = -\sum_{k=0}^{\infty} \rho_k(r) \cdot \cos(\alpha k z)
\]

where \( \alpha = 2\pi / L \), \( L \) is length of modulation period, function \( C(x,y) \) is defined via Bessel cylindrical function \( I \) and \( K \)

\[
C(x,y) = \frac{I_1(y)K_0(x) + K_1(y)I_0(x)}{I_1(y)K_0(x) + K_1(y)I_0(x)} = \frac{y(I_1(y)K_0(x) + K_1(y)I_0(x))}{I_1(y)K_0(x) + K_1(y)I_0(x)}
\]

\( \rho_k(r) \) are coefficients in the Fourier expansion into a series for periodical function

\[
\rho(r,z) = \sum_{k=0}^{\infty} \rho_k(r) \cdot \cos(\alpha k z)
\]

The equation for Coulomb field intensity has a form

\[
E_z = -\frac{\partial U}{\partial z} = -\frac{2I}{\epsilon_0 \beta c L} \sum_{k=1}^{\infty} q_k F_k(\alpha k R_a, \alpha k R_b) \cdot \sin(\alpha k z)
\]

where \( q_k \) is harmonic coefficient in the expansion of \( \frac{\partial}{\partial z} \rho(r,z) \). Setting \( x = \alpha k R_a \), \( y = R_b / R_a \) we obtain for the field at the axis of beam

\[
F_k(0, x, \gamma) = F_{k0}(x, \gamma) = \frac{1}{(x)^2} \left( 1 - \frac{C(x, \gamma)}{I_0(x)} \right)
\]

In this case

\[
\lim_{x \to \infty} F_{k0}(x, \gamma) = \frac{1}{4} \left( 1 - \ln(\gamma^2) \right) = D_0
\]

and \( F_{0}(x, \gamma) \) decreases exponentially with \( x \) growth. The general form of \( F_{m}(x, \gamma)/D_0 \) for \( \gamma \) values from 0.1 up to 1 with 0.1 as a step is indicated on Fig.1. We will be called these functions the harmonic factors. It can be seen that any harmonic factor is located between 0 and 1.

![Fig.1a](image_url)

![Fig.1b](image_url)

Using unitless variables

\[
\tau = \Omega z, \quad \Omega^2 = \frac{2\pi c E_m}{L m_0 (\beta c)^2}, \quad \psi = \frac{2\pi (z - z_s)}{L}
\]

and the harmonic factors for Coulomb field defined above the equation for bunching process analysis can be obtained

\[
\frac{d^2 \psi}{d\tau^2} = -H(\tau) \cdot \sin \psi + \frac{2I D_0}{\epsilon_0 c^2 L E_m} \sum_{k=1}^{\infty} q_k F_{k0}(x, \gamma) \cdot \sin(k \psi)
\]

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where function $H(\tau)$ describes the general rule of the first harmonic of accelerating field growth up to maximum value $E_m$.

The general view of the above equation shows that in the context of given $R_y/L$ and $R_y/R_x$ the bunching process depends on the single parameter

$$\alpha = 2ID_0 / (\varepsilon_0 \beta^2 E_m L)$$

By this means the task is reduced to the optimal form of function $H(\tau)$ which allows maximal $\alpha$ for the bunching process without beam losses.

The introduced Coulomb parameter $\alpha$ differs from commonly accepted one. It is evident to factor out the term $1/(\omega R_y/L)$ from the equation for bunching process analysis and join it to $\alpha$. The new approach underlines that the Coulomb field determines by parameter $\alpha$ but relations $R_y/L$ and $R_y/R_x$ shows only geometrical similarity. The Coulomb parameter decreased with an energy growth whereas harmonic factors are increasing. But their growth is limited because the values are between 0 and 1.

The image-based simulation code package ZHALO was generated for investigating space charge-dominated beam bunching. In the context of the bunching model considered here, the Poisson equation is solved with initial conditions that correspond to a mono-energy beam with a uniform phase distribution across the full RF period. The function $H(\tau)$ was taken in the form

$$H(\tau) = E_0/E_m + (1 - E_0/E_m) (\tau/\tau_m)^2$$

where the coordinate $\tau_m$ and beginning level of field $E_0/E_m$ are given.

The following "images" are used as subjects of inquiry: (a) a Coulomb field distribution (on the background of external field sinusoid), (b) the beam charge distribution, (c) a distribution of particle kinetic energies on the background of Coulomb field intensity distribution $U_z(z) = U(0) - U(z)$, (d) the beam phase portrait on the background of the external field separatrix, (e) a phase length of an "equivalent" bunch with uniform density along $z$ and the same rms-size, (f) a Coulomb field harmonic spectrum (plots of the first five harmonics).

To determine $R_y/L$ and $R_y/R_x$ a beam with parameters typical for a high-current CW linac was chosen: $f = 350$ MHz, $R_y = 3$ mm, beam energy $W = 0.1$ MeV, $R_y/R_x = 0.5$. (In the context of the chosen parameters, the value ($\alpha = 1$ corresponds to current 0.4 A if $E_m = 1$ MV/m). When the investigation was made with a growing RF field, $E_0/E_m = 0.2$ was taken.

A visual inspection of a SCD-beam bunching with increasing of $\alpha$ parameter step by step gives us a general view of the process depending on $\alpha$.

It is evident that particles with initial positions near the bunching center achieve this center at an earlier instant of time and form a Coulomb potential barrier for other particles. During the first quarter of the phase oscillation period this barrier is increasing and each next particle meets a bigger opposition then the previous one. It means that during the first quarter of the phase oscillation period a high-density core is formed inside the bunch.

Starting from some value of $\alpha$ the energy needed for a particle to overcome the Coulomb barrier may be comparable with the kinetic energy that the RF field has given to this particle. The typical points of inflection appear in the phase portrait. For this and for all bigger $\alpha$-values the beam can be called a SCD-beam. On further $\alpha$ growth particle energy loss becomes larger as the center is approached. In its turn, the phase oscillation amplitude can be increased owing to added momentum which a particle has assumed in escaping from the core. As it will be shown below at this stage the fraction of particles which escape the phase period rises sharply. We call such particles "lost" ones.

The final stage of $\alpha$ growth leads to the situation where particles are completely decelerated by the core Coulomb field and the particle cannot pass through the core.

Nevertheless, as also indicated below beam bunching can take place in this case as well. To do this, it is necessary to "match" the rate of Coulomb barrier growth with the growth of particle kinetic energy. The "matching" can be made by the choice of $E_0/E_m$ and $\tau_m$ values.

A comparison between beam bunching in a channel where RF amplitude is constant (case A) and in a channel where RF amplitude is build-up (case B) shows that in the first case: (a) deformations of phase portrait start from $a = 0.15$, (b) the kinetic energy becomes comparable with the potential energy for a near to 0.25, (c) for $a > 0.5$ lost particle fraction rises sharply.

It is evident that there are two sources for particle losses caused by longitudinal motion. The first one is vertical narrowing of the stable oscillation zone. As a result of this factor boundary particles go out from this zone. When the RF amplitude is constant this effect is present also in the case of small a although the proportion of lost particles is small. The second loss source is amplification of the longitudinal oscillation for particles which pass the core in the stage when the core density is compacting. By analogy this effect can be named "halo formation". With $\alpha$ increasing halo oscillations are amplified. Starting from some value of $\alpha$ (in the case A $\alpha > 0.5$) swing of the halo particle oscillation exceeds $2\pi$.

Because of a small external RF field in the beginning of the channel with RF amplitude build-up (case B), Coulomb effects become detectable for $\alpha = 0.07$.

Visual analysis shows that in the case B the essential influence of the core starts from a smaller kinetic energy of particles than in case A. In case B the total core charge is smaller. For the same $\alpha$ the added momentum from the core is small and it can not raise the amplitude of particle oscillations by a large margin. Although the Coulomb potential energy exceeds the particle kinetic energies, the bunching process takes place practically without losses up to $\alpha = 1.2$ (for $E_0/E_m = 0.2$ and $\tau_m = 1$). It means that the limit current is doubled as compared to case A. The increasing of $\tau_m$ up to 1.5 increases the $\alpha$ limit up to 1.4 but no more. Particles can not pass the core but the attraction momentum does not let them escape from the stability zone of bunching.

The comparison between constant and build-up RF field allows the statement that in Case B the beam phase rms length
is essentially smaller. This statement is valid for zero current too.

A second trend has emerged from observation of the Coulomb field harmonic spectrum for a "frozen" beam. With increase in \( \alpha \) the first harmonic of the Coulomb field far exceeds the other harmonics. Its amplitude approximates that of the external field. It may be concluded that the SCD-beam automatically makes Coulomb field distribution similar to external field distribution. Such a high-current effect can be considered as a beam "auto-matching" with a channel. Along with this for small \( \alpha \) the higher harmonics are comparable with the first one and local resonance effects can be caused in the beam transverse motion.

Only motion along an accelerator axis was considered in the above investigations. A charge distribution also was generated by axis particles. In practical situations particle transverse oscillations take place. As can be seen from the equations for \( E_{\text{coul}}(r,z) \) and for \( E_{\text{rf}}(r,z) \) Coulomb field intensity is decreasing and external field intensity is increasing with the growth of \( r \). It means that a particle during transverse oscillations experience a larger bunching forces as compared to axis particle.

Previous analysis is based on particles which are moving along longitudinal axis. The charge distribution is generated also by axis particles. In reality particle execute transverse motion. With regarding to increase of \( r \) Coulomb field intensity \( E_{\text{coul}}(r,z) \) is decreasing but RF field intensity \( E_{\text{rf}}(r,z) \) is increasing. Bunching forces are larger for peripheral particles then for axis particles.

The corrections in the considered effects must be applied when longitudinal oscillation frequency depends on radius. It is not so easy to predict final result. On the one hand the Coulomb effects are decreasing because the relation between Coulomb and bunching fields is changed in favor of bunching one. On the other hand transverse non-uniformity leads to: (a) transverse velocity increasing for peripheral particles, (b) core density increasing due to (a), (c) core counteraction increasing for particles near axis.

Model for bunching process used in ZHALO.THEORY does not take into account particle transverse motion. But it can be considered the transverse motion of "radial layers" with the same and constant radius for all particle inside layer. Such model can not give the quantity description of transverse motion but can quality estimate longitudinal oscillation effects owing transverse non-uniformity.

Investigations with the use of ZHALO.THEORY show that all physical relations and effects brought out for particles near axis are valid in general case too. There is small quantitative difference between results in both cases. For the same \( \alpha \) loosed particle number is larger in the "layer case" then in the "axis case". The last fact indicates that the effects from faster charge accumulation inside core by peripheral particles are stronger than effects from average phasing force increasing relative to Coulomb one.

References

ISOTOPE PRODUCTION FOR MEDICAL AND TECHNICAL USE AT MOSCOW MESON FACTORY LINAC

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Abstract

At the moment the Moscow Meson Factory Linac provides an average proton beam current up to 65 µA. The linac consists of a 26° bending magnet and transport channel in order to extract the proton beam with an intermediate energy of 158.6 MeV to a facility for high level radioisotope production. Production of $^{85}$Sr, $^{109}$Cd, $^{22}$Na, $^{68}$Ge and other isotopes for medical and industrial applications is in progress now. The paper describes the isotope production facility including the beam channel, target equipment, beam tuning procedure as well as some methods, results and plans of the isotope production program.

Introduction

A new powerful linear accelerator operates at the Institute for Nuclear Research of the Academy of Sciences of Russia in Troitsk (near Moscow). Though the full proton energy and project intensity of the linac for fundamental science are not achieved yet, there is an intense beam with the energy of 160 MeV or lower that is used for production of isotopes for medical radiodiagnostic and technical applications.

Isotope Production Facility

A new powerful Isotope Production Facility (IPF) and a laboratory was constructed for isotope production. A general layout of the IPF is shown in the Fig. 1. The facility can accept a beam current of about 100 µA which is planned to extend up to 500 µA in future. The IPF comprises a production target, 3×3×3 m³ iron shielding, target holder inside the shielding, water cycling cooling system for the irradiated target, manipulator for target handling and operation with high activity and the beam control system (see Fig. 1). Two 1.5 m long and 14 cm diameter tubes are inserted into the shielding iron cube: one for beam delivery and another for the target delivery into the shielding cube. Due to the space restriction the tubes are located at 26° angle to each other.

The target cell containing three targets is shown in Fig. 2. A graphite collimator comprising four segments is mounted in this tube very near to the beam inlet window and the target. Each graphite segment is equipped with a thermocouple and is fine welded to a water cooled stainless steel radiator. Measurements of the temperature distribution between the collimator segments, cooling water flow and temperature and beam current provide an opportunity to calculate beam losses on the collimator during the bombardment as well as the beam position directly before the target.

![Fig. 1. Layout of the isotope production facility.]

1 : Beam diagnostic systems;  
2 : Iron shielding cube;  
3 : Target sliding into the cube;  
4 : Manipulator for target handling;  
5 : Lead window system;  
6 : Main exit;  
7 : Heat exchanger;  
8 : Buffer vessel of cycling water cooling system;  
9 : Main and reserve pumps;  
10 : Ion exchange filters;  
11 : Storage of used radioactive filters;  
12 : Tambour with hatch for radioisotope product removal;  
13 : Reserve exit.

The target holder (position 2 in Fig. 2) is made of hard graphite (to minimize an activation) and has three pairs of sliding slots which are used to insert and hold the targets. Thereby, three targets with different proton energies can be bombarded simultaneously, or a graphite absorber for the beam energy adjustment can be used. All-metal targets as well as the shells are filled with low melting temperature or water-soluble metals (rubidium, indium, gallium, etc.). The target holder is fixed at the edge of a 2 m stainless steel rod which is remotely moved by a cart on the supporting metal frame towards or away from the shielding cube providing the target insertion or removal.

A number of radionuclides can be produced at the facility (see Table 1). Some of the radionuclides have been successfully produced. First was strontium-82. This radionuclide is used for a new promising method of medical diagnostics - Positron Emission Tomography (PET) - developed in North America and being developed in Europe. The half life period of this isotope is 25 days which allows a
safe domestic as well as global transportation. There are not
so many high intensity accelerators in the world possessing
the relevant proton beam energy to produce strontium-82
besides the INR accelerator.

Fig. 2. Target irradiation chamber.
1: Stainless steel rod;
2: Target holder;
3: Slots with screws for holder moving;
4: Target thermocouple in stainless steel shell;
5: Thin targets;
6: Main rubidium target in stainless steel shell;
7: Four collimator thermocouples;
8: Vacuum window made from stainless steel;
9: Graphite collimator;
10: Stainless steel shell as a radiator of graphite collimator.

INR together with Canadian National Meson Facility TRIUMF has developed a new effective method for
strontium-82 production from thick targets of metallic rubidium. A method of radiochemical isolation of
radiostrontium from metallic rubidium targets is also
developed. The latter allows the use of high intensity proton beams which provide a production of large amounts of
strontium-82. The radiochemical isolation of strontium from
the bombarded rubidium targets is provided by a new facility
for radiochemical treatment - "Cyclotron" Company located at
Obninsk, Russia. The purity of the product in this method
is much better than in ordinary productions from other
company.

Many other isotopes for medical, technical and
scientific use are produced at the INR IPF: sodium-22 from
magnesium or aluminum targets, cadmium-109 from indium
targets and germanium-68 from gallium targets. In near
future we plan to produce also palladium-103 from a silver
target, copper-67 from a zinc target, titanium-44 from a
scandium target, thallium from a lead target, and iodine-123,
122, 121 from a sodium iodide target.

Table 1. List of available radionuclides at INR Isotope Facility

| Radio- 
<table>
<thead>
<tr>
<th>nuclide</th>
<th>$T_{1/2}$</th>
<th>Target</th>
<th>Energy range, MeV</th>
<th>Period of bomb, hours</th>
<th>Activity, Ci</th>
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<tr>
<td>Sr-82</td>
<td>25.3d</td>
<td>Rb</td>
<td>100-41</td>
<td>250</td>
<td>15</td>
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<tr>
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<td>Al</td>
<td>150-35</td>
<td>250</td>
<td>1</td>
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<tr>
<td>Mg</td>
<td></td>
<td></td>
<td>150-35</td>
<td>250</td>
<td>2</td>
</tr>
<tr>
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<td>In</td>
<td>150-60</td>
<td>250</td>
<td>2</td>
</tr>
<tr>
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<td>100</td>
<td>100</td>
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<tr>
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<tr>
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<tr>
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<tr>
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</table>

Beam Delivery to IPF

The high intensity operation of the IPF requires reliable
high intensity beam transport to the target. For the effective
target radiation the typical beam diameter at the target
position is 20 mm (~98% of particles). In order to avoid
particle losses the beam position as well as beam size must be
controlled during the irradiation.

The envelopes of 158.6 MeV beam along the beam line
are shown in Fig. 3. The beam diagnostics at this section
include a wire scanner (WS) and a pair of harps. One of the
harp is installed permanently, directly before the shielding
and beam profiles can be observed on-line during the beam
production for the IPF. In addition the segmented graphite
collimator temperatures are extremely useful for beam quality
control at the target (see Fig. 2). The operational experience
shows that along the beam line there is a local radiation of
the beam pipe due to the beam halo which is mainly determined
by momentum dispersion. Initially the accelerator is tuned
well in order to operate with a beam loss level below 0.3% at
the section between the 100 MeV part to the target area. The
main aspects of the beam tuning have been discussed in ref.
[2]. However long term operation causes a slow drift of
the beam parameters at the target position. Therefore beam
parameters are measured on-line by using WS, harp and
collimator temperatures. Recently to control beam losses,
control in four transverse directions at the critical point along
the beam line neutron detectors have been installed (PM in
Fig.3). During the last few years essential work has been done
to improve the fast protection system in order to avoid beam
spill on equipment.
Fig. 3. Beam transport to IPF.
D : Focusing doublet,
HVS : Horizontal and vertical steering,
BM : Bending magnet,
LM : Beam loss monitors,
PM : Beam position measurement by the help of neutron detectors,
T : Target
H : Harp,
WS : Wire scanner,

Conclusion

The isotope production facility is under operation at INR on the bases of high intensity 158.6 MeV proton beam. During the last two years the possibility of production of $^{85}$Sr and $^{109}$Cd has been successfully demonstrated. A high reliability of the whole procedure of isotope production including beam delivery, target irradiation as well as chemical treatment of the target has been proved.

References

INITIAL OPERATION OF A 100 MW X-BAND GYROKLYSTRON FOR COLLIDER APPLICATIONS

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Abstract

In this paper we present the design details of a first harmonic two-cavity coaxial gyroklystron circuit. The tube utilizes a TE_{011} output cavity and a TE_{011} input cavity which is driven by a 150 kW magnetron at 8.568 GHz and is expected to be at least 40% efficient. We present details of all system aspects, including the test bed modifications, simulated beam properties, and simulated circuit interactions. Cold test results are described and our near-term experimental plans are outlined.

Introduction

At the University of Maryland, we have a comprehensive program to study the suitability of gyroklystrons as drivers for linear collider applications. Previously reported experimental results were achieved on a test bed which produced a small orbit beam with a nominal voltage and current of 450 kV and 200 A, respectively. Published accounts of our effort include an amplified power level of 27 MW at 32% efficiency in a three-cavity first harmonic gyroklystron [1]; 32 MW at 28% efficiency in a two-cavity second harmonic gyroklystron [2]; and 28 MW in a second harmonic coaxial gyroklystron [3]. Large signal gains have typically been in the 25 - 40 dB range.

In this paper we present the design details of a first harmonic two-cavity coaxial gyroklystron which is predicted to produce about 100 MW of output power with an efficiency of nearly 40%. This tube utilizes a fundamental mode TE_{011} input cavity which is driven by a 150 kW magnetron at 8.568 GHz. The tube also has an 8.568 GHz TE_{011} output cavity. We present details of all system aspects, including the test bed modifications required to produce the enhanced beam characteristics, simulated beam properties, and simulated circuit interactions. Cold test results of both cavities are discussed.

In the next section we describe the test bed and in the following section we present the results of our simulations. The cold-test results are described in the fourth section and a description of our future plans is given in the fifth section. The project status is summarized in the final section.

Test Bed Modifications

We have just completed an upgrade of our facility which should enable us to produce amplified microwave powers in excess of 100 MW (see Fig. 1). Our modulator voltage and current have been increased to 500 kV and 800 A, respectively. We have designed, installed, and completed acceptance testing of a single-anode Magnetron Injection Gun (MIG) which is capable of producing a 480 - 720 A rotating electron beam at the nominal beam voltage with an axial velocity spread less than 7%. The simulated space-charge-limited pereveance of 5.5 μp was in good agreement with the measured result.

Fig. 1. The gyroklystron test bed.

The original water-cooled magnets have been used, but a larger power supply for the gun coil was required because of a decrease in the magnetic compression. We reduced our drive frequency from 10 GHz to exactly three times the current SLAC frequency, so a new coaxial magnetron and a modified input waveguide were required. The output waveguide (uppers, beam dump, window, kicker magnet, pumping cross) was totally rebuilt to accommodate the expected larger peak powers. The anechoic chamber was modified to accommodate the new output waveguide and the directional coupler diagnostic was completely redesigned.

Fig. 2. The first harmonic two-cavity tube.

Theoretical circuit performance

A detailed design analysis has been carried out with the aid of our partially self-consistent nonlinear code. The two-cavity first harmonic tube is shown in Fig. 2 and consists of an input cavity and an output cavity separated by a drift sec-
tion. The input cavity is defined by a decrease in the inner conductor radius only and the quality factor is brought down to $Q \approx 50-65$ by loading the cavity with two thin rings of carbonized aluminum-silicate placed at either end of the cavity. The inner radius is 1.05 cm and the length is 2.29 cm. Power is injected through two radial coupling ports which are separated by $180^\circ$ and excited in phase. Our start-oscillation code predicts that the input cavity is completely stable up to a current of 800 A.

The drift section has inner and outer radii of 1.825 cm and 3.325 cm, respectively. The inner conductor is required so that the drift tube is cutoff to the operating mode. The regions adjacent to each cavity are made of copper, but lossy ceramics line the majority of the drift tube to eliminate spurious modes. The total length of the drift region is 9.1 cm. Lossy ceramics are also used in the downtaper between the gun and the input cavity.

The output cavity is defined by changes in both radii and has a length of 1.70 cm. Power is extracted axially into the output waveguide via a coupling aperture. The aperture has the same radii as the drift tube and has a length of 0.9 cm. The diffractive quality factor is about 122. The start-oscillation code also predicts the output cavity to be stable at the nominal current, which is given in the middle column of Table 1 along with the other operating parameters. The efficiency is nearly 40% and the output power is about 95 MW.

The dependence of tube efficiency on axial velocity spread is plotted in Fig. 3 with the solid line. The simulated velocity spread of the electron gun is 6.4% at the nominal current. The curve shows a slow but steady decrease in efficiency with increasing spread and indicates that an efficiency of 37% is still possible if the spread is as high as 10%.

### Table 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1st harmonic</th>
<th>2nd harmonic</th>
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<td>Voltage</td>
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<tr>
<td>Current</td>
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<td>770 A</td>
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<tr>
<td>Velocity ratio</td>
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<td>Input Cavity Q</td>
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<td>50</td>
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<td>Buncher Cavity Q</td>
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<td>389</td>
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<tr>
<td>Output Cavity Q</td>
<td>122</td>
<td>320</td>
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<tr>
<td>Gain</td>
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<td>49 dB</td>
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<tr>
<td>Efficiency</td>
<td>39.4%</td>
<td>41.1%</td>
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<tr>
<td>Output Power</td>
<td>94.6 MW</td>
<td>158.2 MW</td>
</tr>
</tbody>
</table>

### Cold-test results

Considerable progress has been made on the construction and cold testing of the first experimental tube. Preliminary cold-testing yielded the approximate dimensions of the input cavity required to achieve the frequency of 8.568 GHz and a quality factor of 55. They are quite near the theoretical estimates given in the previous section. The lossy ceramic ring dimensions have also been finalized. The vacuum-compatible version of the drive cavity has reached the final stages of its construction. The actual injection slots have yet to be cut, but their final size will be determined soon from a final cold test.

![Fig. 3](image_url)

Efficiency of the first (solid line) and second harmonic (dashed line) tubes vs. velocity spread.

All of the metal hardware for the inner and outer drift tubes has been fabricated. All lossy ceramics have been constructed or procured. Cold-test drift tube attenuation measurements are in progress.

The output cavity has twelve separate metal pieces and has been completely fabricated and cold-tested. The cavity's outer radial wall extends to 3.59 cm while the inner radial wall dips to 1.007 cm. As indicated in Fig. 2, a fairly short taper of the inner conductor radius follows immediately after the diffractive tip to convert the coaxial waveguide to a circular waveguide. Cold testing of the output cavity (and adjacent drift tube region) was performed with a symmetric injection scheme and the resonant frequency and quality factor of the operating $\text{TE}_{011}$ mode were found to be 8.565 GHz and 134, respectively.

The construction of the vacuum jacket is well under way. The stainless steel housing for the microwave circuit has been machined. Custom flanges are required in order to fit the tube into the bore of our existing magnetic field coils. These flanges have all been roughed out and are awaiting the final machining of the gasket grooves and brazing tabs. The final step will be to braze the flanges onto the stainless steel housing.

### Future Plans

Upon completion of the hot tests of the first two-cavity system, we are planning on testing one or two three-cavity configurations. Both tubes have been designed and are in various stages of cold-testing. The first three-cavity circuit is achieved by placing a buncher cavity in the middle of the drift region which has the same dimensions as the input cavity and is inserted primarily to increase the circuit gain. Simulations indicate that the efficiency of the tube is not dramatically dif-
ferent for the two- and three-cavity first harmonic systems, so
the later tube will be tested only if the former tube is found to
be gain-limited. The initial gain estimate listed in Table 1
indicates that this could well be the case.

The second planned tube is a three-cavity system for
which the buncher and output cavities interact with the beam
at the second harmonic of the cyclotron frequency. These
cavities are resonant in the TE\(_{021}\) mode at 17.136 GHz. The
input cavity, however, remains the same as for the first har-
monic circuits. The buncher cavity is defined by abrupt radial
wall transitions on both conductors in a way that minimizes
mode conversion from the TE\(_{02}\) to the TE\(_{01}\). The quality fac-
tor is achieved by placing the drift tube ceramics in the
fringing fields of the cavity. An aluminum mock-up of the
buncher cavity has been constructed and cold-tested. Prelimi-
nary results have indicated that the required quality factor
and frequency can be achieved for this design. A mock-up of
the second harmonic output cavity, which also uses abrupt
transitions and has an axial coupling aperture is currently
under construction.

The nominal design parameters are given in the final
column of Table 1. The optimal current according to the
simulations is 770 A and the estimated peak output power is
over 150 MW. The corresponding gain and efficiency are 49
dB and 41%, respectively. The dependence of efficiency on
velocity spread is shown as the dashed line in Fig. 3. Note
that the efficiency begins to drop off fairly rapidly for spreads
above 7%. However, these simulations are not re-optimized
with respect to magnetic field profile, etc., at each point, and
additional investigations indicate that higher efficiencies can
be achieved if the velocity spread is higher than expected.

The buncher cavity is predicted to be stable at the operat-
ing point but the output cavity is highly overmoded and is
linearly stable only up to a current of 400-450 A for the operat-
ing regime from 4.8 kG to 5.0 kG. The beam can excite
various other modes at higher current levels. In the actual
system, the signal injected in the input cavity modulates the
beam. The length of the drift section is chosen such that the
beam is tightly bunched (in gyro-phase) when it enters the
output cavity. The well-bunched beam at 8.568 GHz leads to
forced excitation of the operating mode (TE\(_{021}\)). The operat-
ing mode grows in amplitude first. Then, in the presence of
the large amplitude operating mode, the gain of the other
modes is suppressed. Nonlinear gain calculations show that
the cavity is stable under the operating conditions given in
Table 1.

We continue to work on improving our simulation capa-
bilities. We have recently started using the commercial
High-Frequency Structure Simulator software package
(HFSS). We have been using it to model the second harmonic
buncher cavity and preliminary results indicate good agree-
ment with experiment. We have also begun to model the drive
cavity in order to optimize the design of the coupling apert-
ures. Preliminary simulations with output cavities which
extract the power radially and are expected to be completely
stable to spurious modes have also met with initial success.

Time-dependent capability has been added to our non-
linear (single-mode) code by researchers from the Naval Re-
search Laboratory and initial results have confirmed the
steady-state code predictions. We hope in the future to add
multi-mode capability to our time dependent code.

Summary

The upgrade of our facility is essentially complete. We
have designs of first and second harmonic tubes that promise
to produce peak powers of 100 MW or more with efficiencies
of at least 40%. The cold-testing of the initial microwave tube
is at an advanced stage and all the results are encouraging.
This September we expect to complete the fabrication and
assembly of all components necessary for the two-cavity first
harmonic system. The first hot test results are expected early
this fall. The second harmonic tube test is expected to begin
early next year.

References

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QUADRUPOLE SLOW-WAVE DELECTOR FOR CHOPPING CHARGED-PARTICLE BEAMS

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Abstract

We introduce a new beam-deflector design for chopping low-energy charged-particle beams, the quadrupole slow-wave deflector (QSWD). This new design integrates the traveling-wave beam deflector, an electrostatic quadrupole, and clearing electrodes into a single compact structure. The four-electrode device performs ion clearing and linear focusing in the quadrupole (or transmit) mode, and also serves as a fast kicker in the deflecting mode. A QSWD operates with a constantly sustained electric field that sweeps off the ions and electrons produced by beam-gas scattering. Thus, a deflector using the QSWD can avoid beam neutralization with subsequent emittance growth due to the beam-plasma interaction. We shall present the theoretical studies and the design considerations of the quadrupole deflector. A conceptual design of the deflector for a proposed Long Pulse Spallation Neutron Source (LPSS) at Los Alamos will be given as an example.

Introduction

A typical chopper for low-energy proton or H\(^+\) beams uses a fast beam-deflector of slow-wave structure to deflect the unwanted beam to a beam stop. The H\(^+\) beam chopper at LAMPF, operating at 750-keV energy is an example[1]. With the advances of the Radio-Frequency-Quadrupole Accelerator (RFQ) and ion source technologies, particles produced in the source can be accepted immediately by an RFQ and accelerated to relatively high energy (2 to 7 MeV) to reduce the phase-space distortion caused by space-charge effects. Thus, beam chopping has to be performed either at a lower energy of some tens of keV between the ion source and RFQ or after the RFQ at an energy of several MeV[2]. An example is found in the LPSS design currently under study at Los Alamos.

Chopping beams at lower energy has the advantages that it is easier to deflect particles and to handle the dumped beam. However, in order to keep the low-energy beam transport (LEBT) distance short to minimize the emittance growth and H\(^+\) stripping, the chopper needs to be close to the source. Problems then arise when high vacuum cannot be achieved in the deflecting region to prevent plasma build up and beam neutralization. Instabilities due to the beam-plasma interaction may occur that limit the beam intensity. Even when the beam can be stably transported, the pulsing field of the deflector can induce strong fluctuations in the plasma and beam neutralization that cause phase-space distortion. An attempt to implement a chopper at 35-keV beam energy at Brookhaven National Laboratory failed for this reason[3]. Our recent computer simulations have evinced this effect[4].

A conceivable solution is to apply a clearing electric field in the deflector region to sweep out the unwanted charged particles. In the following, we shall present a new type of deflector, the quadrupole slow-wave deflector that can be operated with a constantly sustained electric field to minimize the beam neutralization[4]. Although we shall concentrate our discussions on the choppers for proton or H\(^+\) beams, the underlying principle should be applicable to all other kinds of charged-particle beams.

The Idea and The Theoretical Study

The idea of a QSWD is to modify one pair of the poles in an electrostatic quadrupole and to use them as the deflector electrodes. To delineate the operational principle, we assume that an H\(^+\) beam will be deflected vertically and that the electrodes are oriented in the upright direction. Fig. 1 shows the structure of a QSWD, in which the horizontally deflecting electrodes are the same as those in a normal quadrupole and the vertically deflecting electrodes are made of hyperbolically curved parallel plates connected by coaxial cables behind the ground plate to form a helical slow-wave structure.

Fig. 1. An illustration of the QSWD structure.

During operation, a dc voltage \(V\) is constantly applied to the horizontally deflecting electrodes and the vertically deflecting electrodes are connected to pulsed-power sources. When the pulsing voltages are switched to the ground level, the QSWD functions as an electrostatic quadrupole that focuses the beam in the vertical direction. This constant quadrupole electric field also sweeps off the ions and electrons produced by the beam-gas scattering. When the two slow-wave structures are excited separately, with synchronized pulses of voltage \(V\) and \(-V\), a deflecting-field pattern with a high dipole component is established as shown in Fig. 2(b).

Fig. 2. Schematics of the field configurations in a QSWD: (a) quadrupole mode, and (b) deflecting mode.

* Work supported by the Laboratory Directed Research and Development Office of Los Alamos National Laboratory.
A beam passing through the QS WD will be deflected vertically. The beam chopping can be accomplished by inserting a beam stop, e.g., a metal plate, in the downstream beam-line to stop the deflected beam. Note that since the quadrupole component of the deflecting field converges the beam in the vertical direction and diverges it horizontally, the beam is spread out horizontally on the beam-stop, so that cooling can be handled easily.

We now discuss some of the considerations and theoretical analyses for designing a QS WD. We notice that in order to clear the ions and/or electrons in the beam, the quadrupole field has to be greater than the beam field. Also, we find from the deflecting-field pattern of a QS WD that a beam can be deflected and optimally focused in the same direction and at the same time only when the voltage on the slow-wave structure is higher than or equal to that on the horizontal electrode. Combining these conditions, we obtain a requirement for the minimum voltage for the optimal operation of a QS WD: \[ V \geq \frac{a^2}{(2\pi e \varepsilon_b b^2)} \], where \( I \) is the beam current, \( V \) is the deflecting voltage of the slow-wave structure, \( a \) is the distance from the central axis to the pole-tips, \( \varepsilon_b \) is the permittivity of the free space, \( b \) is the average beam radius in the channel, and \( v \) is the particle velocity. As an example, consider a 100–keV, 20-mA proton beam; \( a/b = 2.5 \), we need \( V \geq 510 \) volts.

Since an exact solution of the time dependent electromagnetic field in the slow-wave structure is difficult to obtain, measurement results and operational experience of the planar co-axial plate deflector now in service at LAMPF are used for the purpose of estimation and making approximations in our analysis. The electrodes of the LAMPF planar coaxial plate deflector are one-meter long and have a structure similar to those shown in Fig. 1, except that the electrode plates and the ground plates are planar instead of curved. The efficiency was maximized by making the electrode-plates 7.9-mm wide on a 19.2-mm center-to-center spacing. For a separation of 2.8 cm between the deflector electrodes, the bandwidth of the deflector is about 200 MHz corresponding to a rise time about 5 ns. The deflecting electric field measured on median plane is about 94% of that calculated for a continuous pole-face structure using a static-field approximation. Operational experience indicates that the effect of wave dispersion in the slow-wave structure is unimportant. Hence, except for high-frequency operation, one can use the static field computed for an infinitely long smooth pole-face boundary to approximate the field in a QS WD. The approximate electrostatic field for the deflecting mode of a QS WD has been calculated by using a conformal mapping technique [5]:

\[
E_x(x,y) = \frac{-sgn(x)V}{\sqrt{2a^2}} \left[ \sqrt{2x + x sgn(y)} \cos\psi + y \Lambda \sin\psi \right], \tag{1}
\]

and

\[
E_y(x,y) = \frac{V}{\sqrt{2a^2}} \left[ \sqrt{2y - y \Lambda \sin\psi + y sgn(y)} \cos\psi \right], \tag{2}
\]

where \( \Gamma = \rho - \rho^{-1} \), and \( \Lambda = \rho - \rho^{-1} \),

\[
\rho = \left( \frac{\sin^2 q \cosh^2 q + \sin^2 p \cosh^2 p}{\cos^2 p \cosh^2 q + \sin^2 p \sinh^2 q} \right)^{1/4}
\]

\[
\psi = 0.5 \tan^{-1} \left( \frac{\sin p \cosh q \sinh q}{\cos p} \right) + \frac{\pi}{4},
\]

\[
p = \frac{\pi(x^2 - y^2)}{4a^2}, \quad q = \pi y/(2a^2).
\]

To track the motion of the deflected beam, we have developed an envelope-tracking program that uses a set of semi-empirical envelope equations and a particle simulation code utilizing the electric field given in Eqs. (1) and (2). We observe good agreement between the envelope tracking and the particle simulation for a KV beam.

**A Design Example: Application to the Chopper for LPSS**

In the design of LPSS, an upgrade to the front end of LAMPF linac is planned that utilizes an RFQ to replace the injector, the LEBT line, and the first tank of the linac. Such a reconfiguration, however, requires replacement of the chopping function that provides the appropriately time structured H- beam to the LANSCE accumulator ring. Chopping (removal of 25% of the beam at a 2.8-MHz rate) is currently accomplished by a fast-deflector device in the LEBT. With the new configuration, chopping is best accomplished before injection into the RFQ, at a low energy of 100 keV as opposed to the 750-keV energy of the LEBT. At this low energy, a design using a QS WD chopper described below is probably the best choice to avoid difficulties caused by beam neutralization.

For LPSS, the beam condition at the ion source is a 100-keV 15-mA beam with a normalized rms emittance of 0.02π cm mrad and having an envelope of round cross-section with 0.5-cm radius and a divergence of 65 mrad. We use an 18-cm long solenoid with 0.5-T field placed 20 cm in front of the source to focus the divergent beam into the chopper. In the absence of other fields, the beam can be focused to a waist of 0.5-cm radius about 80 cm downstream of the solenoid. The small waist at this point permits adequate separation of the chopped beam at the chopping aperture for a 70-cm deflector length with reasonable voltages.

The maximum voltage of the FET power amplifier now used to drive the slow-wave chopper at LAMPF is about 1 kV. Assuming the same kind of power supply is used in this design, we choose 0.7 kV as the nominal voltage for the deflector and for the electrostatic quadrupole in the QS WD. The energy variation of beam particles caused by this low voltage should be negligible. At a reasonable pole-tip-to-pole-tip distance (6 to 10 cm), the quadrupole gradient is around 1 MV/m². For an average beam radius around 1.5 cm, the electric field in the structure should be sufficient to sweep off all the ions and electrons created by gas scattering. The degree of neutralization can be adjusted by varying the QS WD voltage; the consequent shift in the beam-waist position can be corrected by adjustment of the upstream solenoid field. Tracking the envelopes of the deflected beam indicates that, at a deflecting voltage of 0.7 kV and with a chopping aperture between 3 and 4 cm, the length of the deflector should be more than 60 cm. Shorter deflectors or larger separations between the electrodes would require higher voltage to operate the deflector. We chose a 3.5-cm aperture and a 70-cm long deflector. The beam stop is placed 9 cm downstream of the deflector to block the deflected beam. This stand-off distance is chosen to make the transport distance short and to protect the electrodes from being contaminated by the spallation products knocked off from the beam stop by the deflected
beam. Simulation results show that a beam stop located at 1 cm above the central axis should be adequate to block almost all the deflected beam and to let almost all the undeflected beam pass through. An example of particle simulation results is given in Fig. 3 for an initially Gaussian-distributed phase space truncated at three standard deviations. The results of a sensitivity study indicate that the performance of the QSWD is not very sensitive with respect to small variations of beam conditions and to the voltage on the electrodes.

![Fig. 3. Simulated beam particle distribution at the beam stop. The upper and the lower distributions correspond to the deflected and the undeflected beams, respectively. Beam particles are assumed to have a Gaussian distribution (truncated at 3-rms) at the entrance to the chopper.](image)

A possible beam transport system from the chopper to the RFQ is shown in a TRACE2D output in Fig. 4. In this design example, three electrostatic quadrupoles and one magnetic solenoid are used for beam matching purpose. The electrostatic quadrupoles are adopted to minimize the beam neutralization in transport line. The magnetic dipole is inserted for the purpose of merging the H+ and the proton beam-lines before the RFQ.

Fig. 4. A design layout showing the beam envelopes and the optical elements from the ion source to the RFQ in the conceptual design for the LPSS chopper.

It should be noted here that, due to the finite mobility of ions in the beam channel, a small amount of neutralization is unavoidable. An accurate estimation is difficult because of the complicated field configuration. A crude estimate shows that for the LPSS parameter range, a vacuum of at least 10^{-3} Torr is needed in the QSWD for the chopper to operate successfully. At this pressure, the beam neutralization is a few percent. Also note that chopping at the end of the QSWD has the advantage of making the LEBT short, but, depending on applications, this may not be the optimum design. Alternatively, one can use focusing devices downstream of the QSWD that amplify the beam deflection.

A similar chopper design with 30-mA beam current and 1-kV QSWD voltage was also studied. In this case, at the entrance of the RFQ, phase-space distortion due to space-charge effect becomes noticeable in the transmitted beam. Operation at higher beam current would require higher voltage on the QSWD, better vacuum, and a shorter matching section before the RFQ. The application of a QSWD can be limited by any of these requirements.

**Summary and Conclusions**

We have suggested a chopper-deflector that also provides electrostatic focusing to the chopper and unchopped beams for chopping low-energy charged-particle beams utilizing a QSWD. A chopper using a QSWD can avoid the possible beam neutralization and the complications due to the beam-plasma interaction. We have calculated the electrostatic field of the QSWD. Computer programs have been developed for designing a QSWD chopper. An example of a conceptual design for LPSS has been also presented. Theoretical studies show that it is feasible to build such a working device.

**Acknowledgments**

The authors would like to thank Dr. R. Ryne for his assistance in implementing the particle-in-cell tracking program, Dr. P. Walstrom for providing the conformal transformation of the electromagnetic fields, and Dr. P. Channell for constructive discussions.

**References**


THE SSRL LINACS FOR INJECTION TO THE STORAGE RING AND RF GUN TESTING

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Abstract

The Stanford Synchrotron Radiation Laboratory (SSRL) operates two linac systems. One has three SLAC type linac sections powered by two klystrons for injection of electrons at 120 MeV into the booster ring, boosting the energy to 2.3 GeV to fill the SPEAR. After the ramping, the SPEAR stores up to 100 mA of the beam at 3.0 GeV. The preinjector consists of a thermionic RF gun, an alpha magnet, and a chopper along with focusing magnets. The other has one 10 foot section powered by the injector klystron for the testing of RF gun with photocathode, which is driven by a separate klystron. This paper describes present systems with their operational parameters, followed by plans for the upgrades and RF gun development efforts at the SSRL.

The SSRL Injector

Up until the Summer of 1995, the SSRL injector system had three XK-5 klystrons. With a new demand on more RF power, one of them was replaced by a Type 5045 klystron. Presently this klystron powers one thermionic RF gun and two linac sections. It also provides, through the waveguide directional couplers, input signals for the other two klystrons. The RF power to the gun is controlled by a waveguide power divider and a waveguide phase shifter. The second output port of that power divider is currently terminated by a dummy load, but it is planned to be connected to the fourth linac following the photocathode RF gun. The third linac as a part of the injection linac system is powered by one klystron. The geometric system layout is shown in Fig. 1 and the overall RF system schematic is shown in Fig. 2.

Figure 1: The layout of the SSRL injector and the gun test stand showing thermionic and photocathode gun (TG, PG), alpha magnet(A), chopper(C), linacs (L1 through L4), and dumps (D1, D2).

Each bunch out of the thermionic gun (TG) has about 70 pC of charge at the energy of up to 2.5 MeV. An alpha magnet compresses the bunch length to about 4 ps so that the bunch occupies 4 degrees of RF phase in the linac, leading to less than 0.5% of energy spread after the linac L3. Since the gun produces bunches for every RF bucket over the period slightly shorter than the macro pulse length of 2 μs, the chopper (C) selects three consecutive bunches and throws out the rest. By this, the beam loading at the linac and the booster synchrotron is minimized and the energy of the injected beam is stable. The alpha magnet also filters out particles with lower momentum as set by the position of the scraper at the magnet. When the beam is not used for injection, it is dumped at D1. The gun emission is monitored by measuring the charge collected there, in addition to the current transformers.

*Work supported in part by Department of Energy Contract DE-AC03-76SF00515 and Office of Basic Energy Sciences, Division of Chemical Sciences.
Both guns (thermionic and photocathode) are standing wave structures that reflect a large portion of the driving RF power at the beginning and at the end of the pulse. For the thermionic gun, this reflection is considered to be tolerable since the forward power is tapped from the klystron K2 at the level 8.6 dB down from the K2 output, and the reflected power reaching K2 is minimal. In the case of the photocathode gun, however, the reflected power as a whole reaches the klystron K1 unless an isolator is employed in between. This reflection may cause instability and, when the gun is driven to a high power level, it can damage the klystron.

The pulse repetition rate of 10 Hz for the klystrons is sufficient for injection and limited by the power supply ratings and radiation shielding considerations. The system clock is derived from the 60 Hz AC line so that every sixth zero crossing of the AC voltage triggers the S-band RF system. Since the first two linac sections are phase matched, the RF phase and amplitude at the third section, powered by a separate klystron, is controlled by the medium power (few hundred watts) attenuator and phase shifter. This enables the manipulation of beam energy and bunch length, and facilitates the measurements of beam parameters.

The specifications of the three klystrons are shown in Table 1. For the purpose of the system reliability and longevity, these klystrons are operated at much lower beam power and below saturation.

### Table 1: Test data for the three klystrons

<table>
<thead>
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<th>Klystrons</th>
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<th>K3</th>
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<td>5045</td>
<td>XK-5</td>
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<tr>
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<td>61.6</td>
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<td>270</td>
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<td>Beam Power (MW)</td>
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<td>139.3</td>
<td>75.9</td>
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<td>1.92</td>
<td>2.00</td>
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<tr>
<td>Efficiency (%)</td>
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<td>44.2</td>
<td>43.9</td>
</tr>
<tr>
<td>Power Gain (dB)</td>
<td>50.3</td>
<td>55.4</td>
<td>51.9</td>
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### Thermionic RF Gun

The characteristics of the present thermionic RF gun has been well explored during its commissioning [1]. It has a demountable dispenser cathode of 6 mm diameter heated to 1000°C. For the purpose of thermal isolation, and to contain the RF fields in the cell, a tungsten spring around the cathode provides an interface to the gun cell. Unlike a photocathode gun where the electron bunch profile is controlled by the laser beam, the electron emission from a thermionic cathode is determined by the temperature distribution, which needs to be regulated in space and time. Also important is the beam loading, where almost every RF bucket is filled and bunches take away the RF energy with them. This leads to lowering of the accelerating gradient. Despite of this, the gradient is still much higher compared to a DC gun so that the emittance of the beam is useful for the applications requiring low emittance such as free-electron laser.

The electron bunches out of the gun have a wide spectrum of energy distribution with the peak intensity near the energy maximum of 2.5MeV. The low energy tail of the distribution makes the bunch length almost one half of the RF period of 350 picosecond. Some portion of the electrons emitted from the cathode is accelerated back to the cathode. This back bombardment can cause increase in total current out of the gun, and thus more beam loading and less energy on a thermal time scale. The electrical power to the cathode heater sometimes needs to be manipulated to achieve a level of beam stability during the injection.

In order for the gun to generate stable bunches on a long term basis, it becomes necessary to stabilize the emission from the cathode. One way of achieving this is to divert the reflected beam away from the cathode by applying a steady state magnetic field perpendicular to the path of the beam. The ensuing deflection of the beam needs to be corrected for by similarly subjecting the beam to the second magnetic field. The underside of this scheme is degradation of the beam emittance. The protection of the cathode from back bombardment by means of magnetic bias is being evaluated for the feasibility and merit.

While the present thermionic gun was designed to produce low emittance beams, the transport system increases the emittance considerably. Reconfiguration of the beam line to best preserve the emittance is not realistic from the injection point of view. Redesigning of the gun is not feasible considering the cost and time it takes. One simple solution is to use a smaller size cathode. The present gun has a 0.250 inch diameter cathode and it is an
industrial standard size. We identified one with 0.125" diameter within the same category. One potential problem associated with the use of this small size cathode is the possible limitation in thermionic emission. With the emitting area just a quarter of the bigger unit, the smaller cathode needs to supply the same current at four times the current density. If we take the work function to be 2.8 eV and the operating temperature at 950°C, it is found that the temperature increase by 60°C is sufficient for the purpose.

**Photocathode RF Gun**

As compared to a thermionic gun, a photocathode gun exhibits many advantages in terms of high current and brightness, flexibility in bunch shaping, and ability to control energy spread. There has been a number of projects around the world to realize a state of art photocathode, with varying degree of success [2]. In an effort to generate electron beams suitable for driving an X-ray FEL, a new design of an S-band photocathode RF gun was made at SLAC [3].

Some important features of the new gun are summarized as follows: (1) extended half cell length for higher gradient, (2) coupling of the RF power to the gun through the full cell, (3) symmetrized half cell, which is powered through the iris, (4) extreme care exercised in the course of machining, (5) use of flat cathode plate, (6) use of Helicoflex® O-ring to make an RF seal as well as a vacuum seal. At the test stand of SSRL, the gun has been subjected to up to 13 MW of RF power where the field gradient at the cathode was estimated at 140 MV/m, and the maximum energy of the dark current at 11 MV. This gun was moved to Brookhaven for characterization of photoelectron beam from the gun.

Two more units are under construction with varying degree of completion. For the unit designated for SSRL, some modification has been incorporated in the way the cathode plate is mounted. This gun, presently under cold test, will be installed at the SSRL test stand after some iteration for tuning and brazing. The emittance of the photoelectron beam is expected to reach 1 πmm – mrad. A clean room to house the drive laser has been constructed adjacent to the linac vault. Final plumbing is currently underway to connect the gun and linac assembly to the klystrons.

As can be seen in Fig. 2, there are two master oscillators associated with this project. One is a 2856 MHz unit generating reference signal for the klystrons that power the thermionic gun and linac sections. The other is derived from the laser oscillator at 119 MHz. In order for the photoelectrons to leave the cathode at a predetermined RF phase, the RF system needs to be phase locked to this laser reference frequency. There are commercial sources available for the frequency multiplier that generates stable signal with an excellent spectral purity (spurious side bands are more than 70 dB below the carrier frequency amplitude).

With the 2856 MHz master oscillator, tuning is done either by changing the operating frequency or by adjusting the temperature of the gun and linac by means of circulating temperature controlled water along the channel. In this case, the selection switch is thrown to the position A. When a photoelectron beam is desired, the position B is selected. Since the laser oscillator is not tunable, the cooling water temperature must be set to bring the system to the resonance.

**Conclusion**

A thermionic RF gun operating at 2856 MHz has been used as a preinjector to the SLAC type linac sections. Some areas of improvement have been identified. A magnetic deflection of the beam at the half cell to mitigate the back bombardment to the cathode is being studied. Present plan calls for a testing of the gun with a smaller size cathode in an effort to still lower the beam emittance.

For the production and characterization of photoelectron beam, components of the system are being readied. They are the RF gun of new design, drive laser, the RF systems for the gun and linac, and some diagnostic apparatus. The new gun is expected to produce electron beams at energy of over 10 MeV out of its 1.6 cell cavities. The RF power requirement is at least 13 MW and may have to be higher for more beam energy. As the gun will be powered by one klystron exclusively, the use of a high power isolator before the gun seems to be compelling. The current milestone indicates that the first photoelectron beam will be available before the end of 1996.

**References**

APT LLRF Control System Functionality and Architecture

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Abstract

The low-level RF (LLRF) control system for the Accelerator Production of Tritium (APT) will perform various functions. Foremost is the feedback control of the accelerating fields within the cavity in order to maintain field stability within \(\pm 1\%\) amplitude and \(1^\circ\) phase. The feedback control system requires a phase-stable RF reference subsystem signal to correctly phase each cavity. Also, instead of a single klystron RF source for individual accelerating cavities, multiple klystrons will drive a string of resonantly coupled cavities, based on input from a single LLRF feedback control system. To achieve maximum source efficiency, we will be employing single fast feedback controls around individual klystrons such that the gain and phase characteristics of each will be “identical.” In addition, the resonance condition of the cavities is monitored and maintained. To quickly respond to RF shutdowns, and hence rapid accelerating cavity cool-down, due to RF fault conditions, drive frequency agility in the main feedback control subsystem will also be incorporated. Top level block diagrams will be presented and described as they will first be developed and demonstrated on the Low Energy Demonstrator Accelerator (LEDA).

Resonance Control

Resonance control of each accelerator cavity is required in order to control the shift of the cavity’s resonant frequency due to RF heating, beam loading, ... During normal operation of room temperature copper structures, resonance control is performed by providing a proper drive signal to structure cooling water valves to optimize match. In the superconducting case, a servo loop will be used to mechanically change the cavity’s shape in response to resonant frequency shifts.

Because large amounts of cooling water will be running through the room temperature accelerating structures to accommodate RF heating, a fast shutdown of the RF will cause the cavity to cool down dramatically and cause a large shift in resonant frequency. Rather than rely on the cooling water system to bring the cavity back on resonance, we intend to employ a frequency agile system which will drive the klystron at the cavity’s resonant frequency and slowly bring that drive frequency in to the nominal beam-required resonant frequency. In this manner we can quickly bring a cavity back on to resonance. This frequency agile function, based on direct digital synthesis, will be utilized only when the cavity is far from nominal resonance, not during normal operation.

Amplifier Regulation

For the room temperature linac, multiple klystrons will be driven by a single LLRF control system as shown in Figure 1.

![Block diagram of feedback control system for multiple klystrons](image)

Figure 1. Block diagram of feedback control system for multiple klystrons (RFQ depicted here).

There is concern that by driving a group of klystrons, the overall LLRF control system will be attempting to compensate all of the klystrons for errors introduced by the “worst” one. Therefore in order to achieve maximum source efficiency, we intend to measure the amplitude and phase across each klystron and maintain a predetermined transfer function by applying local feedback control. This is used to linearize the multiple klystrons driving the single accelerator cavity and to negate phase drifts in those klystrons. Since power supply ripple typically occurs at line harmonics (low frequency), and the field control compensator has high low-frequency gain, we do not need to concern ourselves with the power supply ripple in this amplifier regulation loop. It will be rejected with the field control compensator.

Field Control

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* Work supported by US Department of Energy.
The cavity field control functionality is divided into three separate compensators working in parallel. Each of these compensators has a frequency range over which it is most effective.

<table>
<thead>
<tr>
<th>Precision Digital</th>
<th>Fast Analog</th>
<th>Kalman Filter</th>
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<tr>
<td>DC</td>
<td>1 kHz</td>
<td>100 kHz</td>
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<td></td>
<td>1 MHz</td>
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The Precision Digital compensator provides extremely accurate DC and low-frequency measurements by employing quadrature sampling and digital signal processing (DSP) techniques. Its bandwidth is limited to about 1 kHz by the digital throughput of the ADCs and DSPs. The Fast Analog compensator is implemented in high-bandwidth RF and analog circuitry to maximize the closed-loop bandwidth (limited to approximately 100 kHz by the group delay through the other components of the RF system). Transmission delay of up to 700 ns precludes feedback compensation for more than a couple hundred kilohertz. This type of fast analog electronics is susceptible to DC offsets and drifts and will have its low frequency gain reduced for those frequencies where the Precision Digital compensator is most effective. In order to extend the control bandwidth of the system, we intend to add on an optimal state-variable Kalman Filter. The Kalman Filter uses statistical processing (and perhaps other complicated digital algorithms) to predict and correct the high-frequency errors. The Kalman filter will require a beam current signal, and possibly a cathode voltage, in addition to the RF field and drive signals, to perform its statistical processing and correction. The Precision Digital and Fast Analog compensators will be designed to allow independent or joint operation, while the Kalman Filter will be an add-on to improve performance.

The cavity field control system is based on the I/Q control functionality originally developed for the Ground Test Accelerator. It will consist of a four module VXIbus set: a Clock Module, a RF module, and a DSP module, and a Resonance Module. All RF and IF signals will be transmitted between modules using front-panel coaxial connectors. All of the baseband and digital signals will be transmitted over the VXIbus backplane. The Clock Module receives a 10 MHz reference and produces LO (650 MHz and 300 MHz), IF (50 MHz), and ADC (40 MHz) frequencies needed for downconversion and I/Q sampling. The RF module contains all of the RF electronics for the entire control system. The DSP Module is primarily a digital module that performs two functions: the high-precision I/Q detection and control, and the modern control algorithms that extend the control bandwidth. The Resonance Module performs three basic functions: provides a resonance control signal to the water temperature controller that maintains resonance; provides an open-loop I/Q control signal that can adjust the LLRF output amplitude, phase, and frequency; and performs the calculation for amplitude and phase equalization needed to balance the three klystrons. An overall block diagram of the LLRF control system is given in figure 2.

Fig 2. Block diagram of the LLRF control system.

Samples of the RF field inside the accelerating structure, the drive from the klystrons, and reflected power signals are all fed back to the LLRF control system located near the multiple klystrons it drives. (This "supermodule"/multiple klystron concept is described in [1]). The field, drive, and reflected RF signals are mixed with a local oscillator locked to the master oscillator RF reference in order to produce IF signals (50 MHz) for quadrature and digital sampling. In addition the field IF signals are downconverted a second time to produce baseband I/Q signals. These baseband signals are processed in the following order: (1) Error correction, phase rotation, and scaling of the field I/Q signals is accomplished by a 2-by-2 multiplier. (2) Error signals are provided by subtracting the measured field I/Q signals from the I/Q setpoints. (3) The error signals are applied to the baseband control filter. (4) The baseband I/Q control signals from the DSP module are added to the filter-compensated signals. (5) A 4:2 multiplexer selects either these closed-loop control signals or the open-loop drive signals generated by the Resonance Module as the signals that define the LLRF output. (6) The baseband control signals are split three ways and processed by three 2-by-2 multipliers that provide the phase and amplitude equalization for the three klystrons driving the single accelerator cavity (RFQ). (7) The three resulting baseband I/Q signals are double-upconverted back to the RF frequency.

The precision digital I/Q detection and control is accomplished as follows. The 50 MHz Field IF signal is I/Q sampled at 40 MSPS to provide very accurate I/Q data (no DC offsets, no amplitude imbalance) and data are processed in a pre-processor that performs very high speed digital filtering and decimation required to reduce the data rates down to those appropriate for a general purpose DSP. For a digital loop bandwidth of 1 kHz, data are processed around 10 kSIPS. The filtering rate reduction from 20 MSPS (for 40 MHz I/Q sampling) to 10 kSIPS for the I/Q data provides the compensation (PI, cross-coupling, etc.) needed to produce the digital I/Q control outputs. Analog signals are created from these digital control signals in DACs. The general purpose
DSP also provides the I/Q setpoints that are used both within its own algorithms and by the RF module for baseband analog processing. Therefore, I/Q setpoints are generated by the general purpose DSP, converted to analog signals in DACs, and transmitted to the RF module. The modern control algorithms are accomplished in parallel to this process in the following manner. The same sampled I/Q data are processed in a separate processor that provides the *1 multiplication, and possibly some filtering, but does not reduce the data rates significantly. For this reason the general purpose DSP cannot be used. In order to provide 1 MHz of control bandwidth, data rates around 10 MSPS have to be maintained. Consequently, the Kalman Filter DSP has to be implemented as discrete high speed digital components capable of maintaining the 10 MSPS rates. The Kalman Filter DSP uses the field I/Q data along with sampled beam current data to perform the modern control algorithms that result in digital I/Q control signals that are converted to analog signals in DACs. The two analog control signals are combined and transmitted to the RF module for I/Q modulation. We are considering performing the extra function digitally and use a single DAC to convert the combined signal to analog.

Preliminary LLRF control system design for the superconducting portion of the linac has taken place. The largest difference between the room temperature (RT) and superconducting (SC) portions of the linac from a control system standpoint, is that we provide a drive signal to multiple klystrons for RT, but for SC, we drive a single klystron which puts power into multiple accelerating cavities. For the medium beta section of the superconducting portion of the linac, we anticipate driving three linked cavities within a single cryomodule with a single LLRF control system and one klystron split three ways. (The high beta section will only have two cavities per klystron). Control of the fields in these linked cavities is based on an arithmetic average of the field probes within each of the cavities fed back to the LLRF system. The concern with this system is that should one cavity become dramatically detuned, or loaded relative to its companions, we will be compensating the drive to all in order to really only take care of problems in the one. Hence, we also intend to have individual cavity control to compensate for any individual cavity errors. Individual cavity control will be comprised of a mechanical servo-driven tuner for resonant frequency compensation. The overall LLRF feedback loop will be identical to that of the room temperature structure. Combining the overall loop with individual cavity control should provide us with the ability to control the fields in the cavity well within the required 1°, 1% for the linked cavities, or 3°, 5% individually. See figure 3 for a conceptual block diagram of the superconducting system.

Figure 3. Superconducting conceptual block diagram

Summary

The required functions and their implementations for the LEDA/APT low-level RF control system have been described. Presently we are modeling the various components, and schematics and breadboarding are on-going.

References

THE DEVELOPMENT OF AN ANNULAR-BEAM, HIGH POWER FREE-ELECTRON MASER FOR FUTURE LINEAR COLLIDERS

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Abstract

Work is underway to develop a 17 GHz free electron maser (FEM) for producing a 500 MW output pulse with a phase stability appropriate for linear collider applications. We plan to use a 500 keV, 5 kA, 6-cm-dia annular electron beam to excite a TM_{02} mode Raman FEM amplifier in a corrugated cylindrical waveguide. The annular beam will run close to the interaction device walls to reduce the power density in the fields, and to greatly reduce the kinetic energy loss caused by beam potential depression associated with the space charge which is a significant advantage in comparison with conventional solid beam microwave tubes at the same beam current.

A key advantage of the annular beam is that the reduced plasma wave number can be tuned to achieve phase stability for an arbitrary correlation of interaction strength with beam velocity. It should be noted that this technique for improving phase stability of an FEM is not possible with a solid beam klystron. The annular beam FEM provides the opportunity to extend the output power of sources in the 17 GHz regime by well over an order of magnitude with enhanced phase stability. The design and experimental status are discussed.

Introduction

Future linear colliders require microwave power sources in the 10-30 GHz frequency range with output powers of at least several hundred megawatts. The klystron has historically been the source of choice for accelerator applications. The output power from a klystron though does not scale favorably as one goes to higher power and higher frequency, simply because klystrons operate in the fundamental mode and the power density becomes extremely high. As the frequency increases, a klystron shrinks in volume resulting in a higher energy density and a correspondingly high electric field in the structure. Problems such as rf breakdown and microwave pulse shortening become serious and ultimately limit device performance. For output power levels above several hundred megawatts, new approaches are needed for microwave power generation. One example is a microwave tube based on a large diameter annular electron beam instead of the small diameter solid beam used in a klystron [1]. The large diameter beam has several advantages. More power can be transported in an annular beam because the space charge limiting current in an annular beam is higher than in a solid beam of the same voltage and current. At the same time, the perveance per square in an annular beam can be similar to the perveance in an efficient, solid beam microwave tube. This reasoning leads us to the conclusion that microwave tubes with large diameter annular electron beams may be well suited for the extreme peak power requirements demanded by future linear collider applications.

Free-electron lasers and FEMs have demonstrated high peak power and extraction efficiencies. An FEL or FEM offers the possibility of a way to avoid this fundamental power density limitation by operating in a higher-order mode in a larger microwave electrodynamic structure. In 1992, Conde and Bekefi tested an FEM that produced 61 MW at 33 GHz at 27% efficiency [2]. This tube was driven by a 750 kV, 300 A, 30 ns, solid electron beam. The goal of our work is to extend this work to high power (1/2 GW) at 17 GHz by using an annular electron beam.

FEM Phase Stability

Phase stability has been examined in detail by Carlsten [3] for an axial interaction FEM with an annular beam operating in the exponential growth regime. These results are extensively discussed in the reference and the reader is referred here for a detailed discussion. Accelerator applications require phase stability on the order of 5° of phase, and advanced accelerator applications such as bunch compression [4] and short wavelength FELs require phase stability of 1° or less [5]. Phase noise in an FEM arises from fluctuations in beam voltage and current, magnetic field strength, and other tube parameters. The largest source of phase noise is typically the fluctuation in beam voltage. The electron beam voltage in a microwave tube operating between 1/2 and 1 MV can, with care, be controlled to 1/4%. Measurements and simulations of FEL phase stability range from 20° to 40° of shift per percent of voltage variation [6, 7]. This level of stability is inadequate for advanced accelerator applications. The principle mechanism producing the phase noise is the variation in transit time of the electron beam through the microwave tube due to variations in beam energy. Additionally in an FEL the growing mode's phase velocity depends on beam current, plasma frequency, and the interaction strength between the beam electrons and the RF field.

It can be shown that when an annular beam is used in a Raman regime FEM, a correlation between interaction strength and beam velocity is not needed to find a first-order phase and gain stable operating condition. By introducing the effect of the space charge wave, a detuning can be found in the Raman regime that leads to phase stability for an arbitrary correlation of interaction strength with beam velocity. The gain of the autothphase condition can be kept large by proper manipulation of the plasma reduction factor. This is only possible if the electron beam is annular and close to the beam pipe wall. We plot the derivative of the phase evolution of the RF mode (see Fig. 1) with respect to beam energy in the exponential growth regime versus the normalized space-charge wave number $\beta_0^2$, for the case of $\gamma = 2$, frequency = 13 GHz, and a ripple period of 6 cm. Phase stable operation is achieved with a 5 kA beam current at approximately the predicted space-charge wavenumber.
\[ \gamma = 2, \Delta = \pm 50 \text{ m}^{-1}, C = 0.1 \]

Fig. 1. Sensitivity of phase to beam energy for medium gain and low energy ($\gamma = 2$) as a function of space charge wavenumber.

**Axial FEM Experiment**

The construction of an experiment is underway to demonstrate the concept of an annular beam, Raman regime, axial FEM operating in the TM$_{02}$ mode. An axial free-electron laser interaction between an annular electron beam and a TM$_{0n}$ mode is desirable because the resulting particle orbits are inherently more stable than those in conventional transverse FELs with helical wigglers [8]. The net transverse force on an electron integrated over a wiggle period can be made to vanish by the proper choice of waveguide radius. The axial FEL interaction for a synchronous particle is shown (see Fig. 2).

In this device, an annular beam interacts with the field of a mode in a circular waveguide. The radius of the waveguide is periodically rippled which causes the mode to radially expand and contract as it propagates down the waveguide. The ripple amplitude is only a few percent of the average waveguide radius, allowing the rf mode to conform adiabatically to the change in waveguide radius. The annular beam is located at the radius corresponding to the zero of the axial electric field of the TM$_{02}$ waveguide mode with a radius equal to the mean radius of the rippled waveguide. When an electron is at the position of the smallest waveguide radius, the axial electric field at that location decelerates the electron. As the electron travels to the region of larger radius, the rf phase slips by the electron. When the electron is at the position of maximum waveguide radius, 1/2 of the rf wavelength has slipped by resulting in a sign change of the mode’s fields. At the same time the electron has switched from one side of the null in axial electric field to the other side, resulting in another sign change. The net result is that the electric field is still opposing the electron motion. This interaction is equivalent to the interaction of a transverse-coupling FEL except that the RF field is wiggled, instead of the electrons, to achieve synchronism. One should note that this is a fast-wave interaction, not a slow wave one. A dispersion curve is plotted for a generic waveguide with small periodic ripples (see Fig. 3.).

Fig. 2. Axial electric field orientations for a synchronous particle when the particle reaches the centers of the ripples in $r$-$z$ geometry.

As the ripple amplitude goes to zero, the forbidden zone disappears and the dispersion curve reverts to that of an unperturbed waveguide. A slow wave interaction would occur at point “A” where the phase velocity is below the velocity of light. In our experiment, we are operating at point "B" because the RF wavelength is much shorter that the waveguide ripple period.

A particle-in-cell simulation of the FEM using the code ISIS was done. A coaxial geometry, associated with an early design, is shown in Fig. 4.

Fig. 3. Generic dispersion relation for a periodic waveguide with small perturbations.

The RF power propagates in the TM$_{02}$ mode and is driven at 17.1 GHz. The inner conductor wall is at the axial null of the TM$_{02}$ electric field. There are 71/2 ripples with a length of 12 cm each, and the beam is confined with a 0.5 T axial

Fig. 4. Particle-in-cell simulation of coaxial geometry showing electron beam with strong axial bunching.
magnetic field. There is very clear axial bunching in the 60-
100 cm region along the direction of propagation.

Our FEM configuration is shown in Fig. 5. A 600 kV annular beam is supplied by a stainless steel field-emission cathode. The nominal beam radius is about 2.8 cm with a thickness of 4 mm. The beam drift pipe has a 3.6 cm mean radius. An input section has been designed with 6-fold symmetry on the waveguide feeds. This was done to reduce the number of high order modes that, if generated, will be able to propagate down the overmoded waveguide and cause beam disruption. The input section is followed by the rippled wall structure with about 15 ripple periods. The ripple wavelength is 3.5 cm. Following the electrodynamic structure is a circular waveguide with several directional couplers built in to measure power in the desired TM02 mode. A calorimeter will be located at the end of the tube to absorb all the microwave energy regardless of mode. The comparison between the directional couplers and the calorimeter should give us information on mode purity.

Conclusions

An annular beam, Raman regime, free electron maser can be a viable candidate as the power source for future linear collider applications where extremely high peak powers are required. An annular beam, TM02 device is auto-phase stable because the space charge wave propagation constant can be adjusted for an arbitrary correlation of interaction strength and beam velocity. Such a device is being assembled for high power testing.

Acknowledgments

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References

[3] B. E. Carlsten, "Enhanced phase stability for a raman free-

TRANSVERSE MATCH OF HIGH PEAK-CURRENT BEAM INTO THE LANSCE DTL USING PARMILA

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Abstract

A new algorithm that uses a multiparticle PARMILA-based code to match high peak-current H⁺ beam (~21mA) into the Los Alamos Neutron Science Center (LANSCE) drift-tube-linac (DTL) has been developed. Two single-cell RF bunchers in the low energy beam transport (LEBT) prepare the initially unbunched beam for DTL capture. The transverse distribution at the entrance to the DTL is set with four quadrupoles in the 1.26m between the last transverse emittance measuring station and the DTL entrance. Previous matching algorithms used TRACE and TRACE 3-D to determine these quadrupole strengths. PARMILA simulations show this procedure produces non-zero mismatch and additional emittance growth through the DTL for high current beams. Because of strong space-charge forces and a rapidly forming longitudinal bunch, simple envelope calculations do not model the beam evolution in the LEBT well. A PARMILA model of this region was combined with an iterative search routine to set the LEBT quadrupole strengths to achieve a better transverse match into the DTL. Simulations predict a significant reduction in emittance at the exit of the DTL over the typical TRACE 3-D result.

Introduction

The LANSCE accelerator begins with two Cockroft-Walton (CW) injectors which accelerate H⁺ and H⁺ beam to 750keV. Each beam is transported in a separate LEBT to a common LEBT which transports both beams to the DTL. The DTL operates at 201.25MHz and accelerates the beams from 0.75 to 100MeV. The transition region (TR) transports the beam from the DTL to the side-coupled linac (SCL) which operates at 805MHz and accelerates the beams to 800MeV.

The H⁺ beam is prepared for injection into the DTL with two 201.25MHz single-cell buncher cavities and a series of quadrupole magnets in the LEBT. The two bunchers prepare the initially unbunched beam for DTL capture and the LEBT quadrupoles prepare the beam for injection into the magnetic lattice of the DTL. The last transverse emittance measurement diagnostic, a slit and collector separated by 89.1cm, is located in the LEBT downstream of the second buncher and upstream of the last four quadrupole magnets in the LEBT. To match the beam, the measured emittance is used with a model of the LEBT and DTL to determine the final four quadrupole strengths.

Previous studies have shown that space-charge dominated beams which are RMS mismatched when injected into a linear accelerator undergo emittance growth [1] and halo formation [2]. At LANSCE the 750keV H⁺ beam, with a typical peak current of 21mA and a normalized transverse RMS emittance of ~0.008π-cm-mr, is injected into the 201.25MHz DTL. At this energy, emittance and peak-current the tune depression in the first few periods of the DTL is ~0.5 (π/σc = 26°/49°). Thus, the beam is close to space-charge dominated. Achieving a good match into the DTL can therefore minimize emittance growth resulting from transverse mismatch. Excess emittance growth and halo formation due to mismatch at the front of the DTL can result in the loss of high energy particles in the TR and SCL, which in turn can result in the activation of beam line elements and the accelerator structure.

Figure 1 (a) shows the measured horizontal distribution of beam with 21mA peak current at the last LEBT emittance station and the estimated longitudinal phase space distribution. Figure 1 (b) shows the PARMILA prediction of the horizontal and longitudinal distributions at the exit of the tenth drift tube in the DTL. The longitudinal phase space evolution in this region of the LEBT and the first DTL tank is complex. Through space-charge forces this longitudinal evolution couples to the transverse phase space dynamics and complicates the process of matching the beam into the DTL. The use of an accurate model of this region of the LEBT and DTL is critical in determining the parameters of the matched

![Figure 1](image_url)

**Fig. 1:** (a) The horizontal and longitudinal phase-space distributions at the last emittance measuring station and (b) at the exit of the tenth drift tube for the standard quad and buncher settings. The bottom schematic diagram shows the end of the LEBT and the entrance to the DTL (shaded blocks are quadrupole magnets).
beam and setting the quadrupole strengths to achieve that match.

**Beam Dynamics Models**

Various models have been used in an attempt to determine and achieve matched beam into the DTL. Two-dimensional models such as TRACE and a two-dimensional version of PARMILA have been used. These models can not, however, properly model the rapidly increasing transverse space-charge forces due to longitudinal bunching. TRACE 3-D has also been used with limited success. The longitudinal phase space distribution used with TRACE 3-D must be described by an ellipse. Typically, the ellipse is chosen to have the same RMS parameters as the true longitudinal distribution assuming near longitudinal elliptical symmetry. Since longitudinal elliptical symmetry is not present, this model is not expected to properly represent the complicated longitudinal beam dynamics occurring over the long distances in the LEBT and through the many RF gaps of the DTL. Of the models presently used, the three-dimensional version of PARMILA should be successful because of the accurate calculations of space-charge forces and emittance growth. However, the structure and speed of PARMILA has limited its use to the modeling of existing setups rather than the determination of match parameters and quadrupole strengths.

Figure 2 shows a comparison of the ratios of modeled space-charge forces in TRACE, 2-D PARMILA and TRACE 3-D to the space-charge forces calculated by the three-dimensional version of PARMILA. The ratios of the space-charge forces are calculated for a particle at one RMS distance from the center of the beam. As can be seen from this graph both 2-D PARMILA and TRACE 3-D underestimate the space-charge forces by a factor of two initially and by a factor of five when the longitudinal bunch is well established at the exit of the tenth drift tube. In both cases this discrepancy of space-charge forces is due to inaccurate representation of the initial longitudinal phase-space distribution and its subsequent evolution. The spike in the ratio using the TRACE 3-D model is a result of injecting a mismatched longitudinal ellipse into the DTL. The longitudinal beam envelope oscillates and the phase width for the beam becomes very small soon after entering the DTL.

**Matching Algorithms**

The matching algorithm which is presently being used is a hybrid model combining TRACE and the two dimensional version of PARMILA. In the mid 1970's a two dimensional version of PARMILA was used to determine the Twiss parameters for matched low-current beam at the entrance to the DTL. To incorporate the effect of longitudinal bunching an effective current of four times the measured current was used for the simulations. The Twiss parameters resulting from this study have become known as "magic numbers" and an iterative TRACE routine is used to adjust the LEBT quadrupoles to achieve these "magic numbers" at the DTL entrance.

TRACE 3-D has also been used to determine the Twiss parameters at the entrance to the DTL and to iteratively search for LEBT quadrupole strengths to achieve these matched parameters. For these simulations the RMS quantities of an estimated PARMILA distribution were used to determine the ellipse parameters of the TRACE 3-D longitudinal distribution. This procedure resulted in more emittance growth and halo formation than measured from the matching routine previously developed.

A new matching algorithm based on the PARMILA model of the LEBT and DTL has been developed. This new algorithm combines realistic initial phase-space distributions with the extensively tested three-dimensional space-charge calculations of PARMILA and first order corrections for space-charge neutralization.

To accurately model the beam transport through the LEBT into the DTL a large effort was expended to create realistic initial phase-space distributions. Initial particle distributions in transverse phase-space were created from measured distributions and all simulations began at the measurement position. The longitudinal distribution was estimated by tracking particles from the DC injection into the first buncher, through the second buncher, to the emittance station used to measure the input transverse distributions. The buncher phases and amplitudes used in the simulation had been estimated from previous phase-scan measurements while amplitudes were also checked through power and Q measurements for SUPERFISH simulations. To create the
input particle distribution the estimated longitudinal distribution was randomly combined with the transverse distributions created from the measured phase-space distributions.

Because space-charge forces play a dominant role in the beam dynamics in this region, a measurement was made to estimate neutralization in the LEBT. Both horizontal and vertical phase-space distributions were measured at the last emittance station in the LEBT along with beam profiles obtained 89.1cm downstream of the emittance slit. These measured transverse distributions were combined with the estimated longitudinal distribution and used as the starting distribution in a PARMILA simulation. An iterative PARMILA simulation tracked the initial distribution of particles through this drift region with various effective current values and compared the resulting horizontal and vertical profiles to the measured profiles. The effective current which resulted in the best agreement between PARMILA and the measured profiles was 17mA for a measured peak current of 21mA. This value of effective peak current was used for all subsequent modeling of the beam transport in the LEBT. It was assumed that the beam in the DTL is not neutralized and thus the effective current was set to the measured current of 21mA when in the DTL.

The PARMILA program was converted into a subroutine and combined with a non-linear system solving routine employing the Regula Falsi technique (modeled after the fitting routine used in TRACE 3-D [3]). Various minimization criteria were studied for the minimization routine. Since a mismatched beam results in emittance growth, it was found that the minimization of emittance growth in the first two DTL tanks resulted in a good average match along the DTL. The non-linear system solving routine adjusted the LEBT quadrupole gradients to minimize emittance growth in the first two tanks of the DTL.

The results of the three matching algorithms discussed above were simulated with PARMILA and the results are shown in figure 3. The top graph displays horizontal mismatch (\(M_H\)) as defined by the TRACE 3-D code [3]) versus drift-tube number and the second graph shows normalized horizontal emittance (\(\epsilon_H\)) as a function of drift-tube number in the first two tanks of the DTL. The third and fourth graphs are the mismatch (\(M_V\)) and emittance (\(\epsilon_V\)) versus cell number for the vertical plane, respectively.

Because the beam is small in the horizontal plane and large vertically, the horizontal space-charge forces are large as the beam enters the DTL. It is thus most difficult to achieve a horizontally matched beam distribution. The horizontal emittance is thus reduced more than the vertical emittance when the space-charge forces are properly calculated in the PARMILA matching algorithm.

Conclusions

Two-dimensional models and three-dimensional envelope models of the beam in the LEBT and the entrance to the DTL do not properly account for the changing space-charge forces due to the rapidly bunching beam at LANSCE. Because of this inability to properly represent the longitudinal beam distributions, these models do not lead to a satisfactory match of the beam into the DTL. Matching with these models can result in mismatched beam, emittance growth and halo formation.

PARMILA has been combined with a non-linear system solving routine for matching beam into the LANSCE DTL. This new matching tool more accurately models the changing space-charge forces due to the rapidly changing longitudinal distribution. PARMILA simulations have shown that this new matching technique results in less mismatch in the DTL and lower emittance growth. The results of this new matching algorithm, presented here, will be tested before the end of the 1996 run cycle.

Acknowledgments

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References

BEAM DYNAMICS SIMULATIONS USING A PARALLEL VERSION OF PARMILA

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Abstract
The computer code PARMILA has been the primary tool for the
design of proton and ion linacs in the United States for nearly
three decades. Previously it was sufficient to perform simulations
with of order 10000 particles, but recently the need to per-
form high resolution halo studies for next-generation, high inten-
sity linacs has made it necessary to perform simulations with of
order 100 million particles. With the advent of massively paral-
lel computers such simulations are now within reach. Para-
llel computers already make it possible, for example, to perform
beam dynamics calculations with tens of millions of particles, re-
quiring over 10 GByte of core memory, in just a few hours. Also,
parallel computers are becoming easier to use thanks to the avail-
ability of mature, Fortran-like languages such as Connection Ma-
chine Fortran and High Performance Fortran. We will describe
our experience developing a parallel version of PARMILA and
the performance of the new code.

Introduction
Many countries are now involved in efforts aimed at develop-
ing high power linacs for transmutation of radioactive waste,
disposal of plutonium, production of tritium, and as drivers for
next-generation spallation neutron sources. For these projects,
high-resolution modeling far beyond that which has ever been
performed in the accelerator community will be required to re-
duce cost and technological risk, and to improve accelerator effi-
ciency, performance, and reliability. Such accelerators will have
to operate with extremely low beam loss (0.1-1 nA/m) in order to
prevent unacceptably high levels of radioactivity. High resolu-
tion simulations using on the order of 100 million particles will
be needed to help ensure that this requirement can be met. Such
simulations can only be performed on high performance comput-
ing (HPC) platforms. For example, near term massively parallel
processors and clusters of shared memory processors will have
memories of 100's of GBytes and performance of a few TFLOPs.
Compared with high-end workstations (500 MFLOPs) and high-
end PCs (100 MFLOPs), a 1 TFLOP HPC platform would out-
perform these by factors of 2000 and 10000, respectively.

The computer code PARMILA is the most widely used code
in the United States for the design of proton and ion linacs. We
have developed a parallel version of PARMILA that runs on the
massively parallel CM5 at the Advanced Computing Laboratory
of Los Alamos National Laboratory. This version of the code is
written in CM Fortran. In addition to moving the code to the
CM5, we also replaced the 2D (r, θ) space charge routine of the
serial code with a new 3D (x, y, z) routine. The code will be
used to model the LANSCE linac and linac designs for the Ac-
ccelerator Production of Tritium (APT) project. As an example
of its performance, a 2 million particle simulation of a 1.7 GeV
superconducting linac for APT requires 3 hours on the 512 node
partition of the CM5. Simulations of shorter linacs have been
performed with up to 30 million particles.

Approaches to Parallelization
There are three main parallel programming paradigms:
(1) single-instruction-multiple-data (SIMD), (2) single-
program-multiple-data (SPMD), and (3) multiple-instruc-
tion-multiple-data (MIMD). SIMD is the easiest to use but is the
least flexible; all the processors perform the same operations
synchronously on different data. The SPMD approach is
slightly more flexible; every processor runs the same program,
but the programs may execute differently depending on the data.
Finally, the MIMD approach is the most flexible and powerful,
but it requires the most effort by the programmer to use it; here
every processor can run a different program with different data.

To parallelize PARMILA we adopted the data parallel ap-
proach augmented by the use of utility libraries and scientific
software libraries. This has the advantage that much of the re-
sulting code looks like the original serial version; it can be eas-
ily used and modified by a person with little parallel program-
ming experience. Also, if the serial version changes it is easy
to make corresponding changes in the parallel version. The par-
allel version looks like a Fortran90 code, but in addition all DO
loops over large arrays have been replaced with FORALL loops.
Also, compiler directives appear after array declarations to spec-
ify how data is to be distributed across processors.

Steps in Parallelizing PARMILA
The serial version of PARMILA consists of approximately 5000
lines of Fortran 77 code. To port PARMILA to the CM5 we be-
gan by running the serial version on a workstation for a prob-
lem with zero current. As the parallel code evolved, the results
were checked against the serial results. Eventually all DO loops
over large arrays, such as the particle array, were replaced with
FORALL loops. (FORALL loops are parallel DO loops and rec-
ognized as such by the compiler.) This involved rewriting large
sections of the serial code between DO/ENDO statements, fre-
cently making use of temporary arrays. For much of the code
this task was tedious but straightforward. Slight complications
such as testing for lost particles inside of loops could be easily
dealt with by using masked FORALL statements. A more com-
plicated situation arose when tests inside loops effected the pro-
gram flow. Consider, for example, the serial code used to gener-
ate a 4D waterbag distribution:
do 100 i=1,nptcls <loop over particles>
50 generate 4 random numbers x1,x2,x3,x4>
if(x1**2+x2**2+x3**2+x4**2<.2,gt.1) goto 50
<generate coords/momenta for this particle>
100 continue

This had to be replaced with code of the following form:

100 <generate four LARGE arrays x1,x2,x3,x4>
<mask off if x1**2+x2**2+x3**2+x4**2<.2,gt.1>
<pack good data into final array>
<if final array is not complete, goto 100>
<generate coords/momenta for all particles>

This exemplifies a situation where utility routines (namely PACK) that are not part of CMF or HPF are essential.

Besides rewriting large sections of code associated with DO loops, some other simple tasks were required to port PARMILA. As mentioned above, it is necessary to insert compiler directives in subroutines to specify the layout of parallel arrays. Another task was related to subroutine calls and data reshaping. In CM Fortran, parallel arrays cannot be reshaped through subroutine calls as they can in Fortran 90. Thus, a 2D array coord(i,ntot) cannot be used in call mysub(coord(1)) and treated like a 1D array in subroutine mysub. Also, a 1D array x(ntot) cannot be used in call mysub(x(ntot/2)) and treated as a 1D array of half the original length in the subroutine. Again, these situations are straightforward to deal with, but it can be tedious to find all such occurrences and they can easily go unnoticed until the program crashes or produces garbage.

The major difficulty in porting serial codes to parallel machines using CM Fortran or High Performance Fortran is dealing with those operations that cannot be easily dealt with in the data parallel paradigm. In the case of PARMILA, the difficulty is associated with the space charge calculation. This is discussed in the next section.

**Space Charge Calculation**

PARMILA uses a Particle-In-Cell approach to computing the beam space charge. Charge is deposited on a grid, the fields are calculated on the grid, and the resulting fields are interpolated back to the particles. The steps involving charge deposition and field interpolation are not easily parallelizable. Consider, for example, charge deposition on a two-dimensional grid using area weighting. A serial routine would look like the following:

do 100 n=1,np
i=(x(n)-xmin)/hx
j=(y(n)-ymin)/hy
ab=xmin-x+i*hx
cd=ymin-y+j*hy
rho(i,j)=rho(i,j) + ab*cd
rho(i+1,j)=rho(i+1,j)+cd*(hx-ab)
rho(i,j+1)=rho(i,j+1)+ab*(hy-cd)
rho(i+1,j+1)=rho(i+1,j+1)+(hx-ab)*(hy-cd)
100 rho(i+1,j+1)=rho(i+1,j+1)+(hx-ab)*(hy-cd)

The equivalent parallel routine is the following:

i=(x-xmin)/hx ! i,j,x,y,ab,cd = arrays
j=(y-ymin)/hy
ab=xmin-x+i*hx

cd=ymin-y+j*hy
for all(n=1,np)rho(i(n),j(n))=
# rho(i(n),j(n)) + ab(n)*cd(n)
for all(n=1,np)rho(i(n)+1,j(n))=
# rho(i(n)+1,j(n)) + cd(n)*(hx-ab(n))
for all(n=1,np)rho(i(n),j(n)+1)=
# rho(i(n),j(n)+1) + ab(n)*(hy-cd(n))
for all(n=1,np)rho(i(n)+1,j(n)+1)=
# rho(i(n)+1,j(n)+1) + (hx-ab(n))*(hy-cd(n))

The above parallel routine has poor performance. First, the FORALL statements cause significant interprocessor communication. Second, if the density array rho is uniformly spread across processors, then the routine will not be load balanced. For example, if one deposited a Gaussian charge distribution on the grid, then processors associated with the tail of the distribution would finish accumulating charge sooner than processors associated with the core. Performance can be improved in several ways:

- One can use SEND routines. These are optimized utility routines that send data to processors based on index arrays and perform binary operations on the data (e.g. add, overwrite, min, max).
- One can use SCAN routines (also called Parallel Prefix routines). These are optimized routines that perform binary operations cumulatively on a sequence of array elements. For example, a SCAN-ADD operation on an array (1,2,3,4,5) would result in (1,3,6,10,15).
- One can use MIMD-style routines written with message passing libraries. In this approach the programmer explicitly writes the code that includes logic to determine how to partition the data so that the load is balanced.

The approach based on SEND routines is easy to use but the performance improvement is modest. The approach based on SCAN routines is more difficult to implement, but the performance improvement is much better. This approach, using segmented-scan operations and data ordering, was implemented by Ferrell and Bertschinger in an N-body code for astrophysical simulations [1]. Finally, the MIMD-style approach is the most difficult to implement but yields the best performance improvement. This approach has been used as part of the Numerical Tokamak Project, a DOE-funded High Performance Computing and Communications project [2][3].

Currently, the parallel version of PARMILA uses the method of Ferrell and Bertschinger for charge deposition and field interpolation. The field equations are solved using an FFT-based technique to convolve the charge density on the grid with a Green function defined on the grid. Using standard techniques it is possible to treat a bunch of charge assuming open boundary conditions [4]. We have also implemented a procedure that uses open boundary conditions transversely and periodic boundary conditions longitudinally.

**Performance**

We have used the parallel version of PARMILA to perform linear simulations with 1-30 million particles. For example, a 2 million
particle simulation of a 1.7 GeV superconducting linac for the APT project required 3 hours on the 512 node partition of the CM5. The job used only 2 GBytes, well below the 14.3 GByte maximum for the partition, so much larger jobs are possible.

The success of the parallel approach depends on scalability, i.e., the ability to run larger problems in the same amount of time using more processors, or the ability to run problems of a fixed size in less time using more processors. (Note however that increasing the number of processors while keeping the problem size fixed cannot cause the execution time to decrease indefinitely: If the problem size is too small, the processors will do too little calculation, and the execution time will be dominated by communication.) The parallel version of PARMILA has excellent scalability as shown in Table 1:

<table>
<thead>
<tr>
<th>Proc</th>
<th>CPU (min)</th>
<th>MEM (GB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>128</td>
<td>15.5</td>
<td>1.8</td>
</tr>
<tr>
<td>256</td>
<td>8.1</td>
<td>2.0</td>
</tr>
<tr>
<td>512</td>
<td>4.3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 1: Scaling Results (3.75M particles, 64x64x64 grid)

Conclusions/Future Work
We have developed a parallel version of PARMILA that runs on the CM5 at the Los Alamos Advanced Computing Laboratory. This version of the code is written in CM Fortran. In addition to moving the code to the CM5, we also replaced the 2D \((r, \theta)\) space charge routine of the serial code with a new 3D \((x, y, z)\) routine. Using the present version of the parallel code, simulations with 1-30 million particles are possible depending on the length of the linac being modeled. We plan to move the code to the new Cray T3E at the National Energy Research Scientific Computing Center. We expect a significant improvement in performance through the use of charge deposition and field interpolation routines that use message passing.

Acknowledgements
The author thanks Lawrence Rybarczyk, Frank Merrill, Robert Garnett, and Kenneth Crandall for helpful discussions about the PARMILA code. This research was supported by the U.S. Department of Energy, Office of Energy Research, through the Division of Mathematical, Information, and Computational Sciences, the Division of High Energy and Nuclear Physics, and by the Office of Defense Programs, Accelerator Production of Tritium program. This research was performed in part using the resources located at the Advanced Computing Laboratory of Los Alamos National Laboratory, Los Alamos, NM 87545.

References
MEASUREMENT OF THE BEAM DISTRIBUTION OF 433 MHZ PROTON LINAC IN LONGITUDINAL PHASE SPACE

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Abstract

We measured the longitudinal phase space distribution of the proton beams provided by the 433 MHz linac at ICR, Kyoto University, by means of a new monitor which consists mainly of a thin gold target, a deflector cavity, a position sensitive detector (PSD) and three permanent magnet quadrupole lenses. Protons are scattered by the target are guided into cavity, then focused by the PMQs, deflected by the cavity, then focused by the deflector electrodes, and finally reach the PSD. The position and energy data from the PSD are employed to reconstruct the phase space configuration of the beam before hitting the target. The longitudinal emittance of the ICR linac was measured with the present monitor system under some different operating conditions. The obtained measurement results were used to optimize the RF condition.

Introduction

At the Institute for Chemical Research, Kyoto University, a 433 MHz proton linac has been operated. The linac mainly consists of 50 keV ion source, and low energy beam transport, 2 MeV Radio Frequency Quadrupole (RFQ) linac, Beam Matching Section (BMS), and 7 MeV Drift Tube Linac (DTL)[1]. In order to measure the longitudinal beam emittance of the 7 MeV proton beam, we developed a new beam monitor [2]. The monitor enables us to measure the beam distribution in the longitudinal beam phase space.

The longitudinal beam distribution of the proton linac is obtained by measuring the position and energy of the protons which are scattered at the target and then deflected by an rf field whose frequency is the same as those of RFQ linac and DTL. The figure of the longitudinal emittance monitor is shown in Fig. 1.

The position and energy of a proton measured by Position Sensitive Detector (PSD) depend on the phase and energy when it is scattered at the target. By calculating the orbit of the deflected proton, the coordinates of the proton in the phase space can be obtained. In this way, a beam distribution in the longitudinal phase space is reconstructed from the measured position and energy distribution.

When we accelerate the proton beams, how we control the rf condition is large problem. Then the variations of the longitudinal beam distribution at different rf conditions were measured, in order to examine the effect of the rf condition to the longitudinal beam dynamics.

Measurement

We measured the beam distributions for several rf conditions. In the measurement, we used a gold target of 0.37 mm in width and 100 μg/cm² in thickness. The gold is deposited on a thin carbon backing foil whose thickness is 10 μg/cm². The gap voltage of the deflector is 38 keV estimated from the position variation of the deflected protons when the rf phase of the deflector is changed.

The longitudinal beam matching was controlled by adjusting the rf phases and amplitude of the RFQ, the DTL and a double gapped buncher installed in the BMS.

Some of the results are shown in Fig. 2(a)-(d). The four figures are beam distributions on the PSD. We can find two islands on each figure; the upper island comes from the protons scattered by gold target, and the lower island comes from those scattered by carbon foil. The longitudinal emittances can be estimated from the upper island.
Fig. 2(a)-(d) correspond to following conditions A - D. The condition A is well matched rf condition, and the shape of the upper island is well-regulated. In the condition B, the rf phase of the DTL is different from that of A by 11°. The shape of the upper island becomes a little deformed, and the mean output energy is less than A, and protons out of stability region are more than A. In the condition C, the rf is miss matching, where the rf phase of the DTL is different from that of A by 43°. Many unstable protons are found. In the condition D, the buncher voltage was made zero, and the rf conditions of RFQ and DTL were optimized. The spread of the detected positions is larger than that for other conditions. Because the RFQ output beam was not rebunched, not some amount of protons may go out of acceptance of the DTL.

Fig. 2 Proton distributions on the PSD at different rf conditions. Well-matched condition (a), and the rf phase of the DTL is different from the matched condition by 11° (b) and 43° (c). In (d), the buncher voltage is zero, and RFQ and DTL conditions are optimized.

Analysis

The position-energy distribution of the scattered proton are transformed to longitudinal phase space distribution. From the distributions of the upper proton islands of Fig. 2(a)-(c), the phase space distributions are obtained, as shown in Fig. 3(a)-(c). It is difficult to transform the distribution in Fig. 2(d), because the beam spread is too large. The phase center of distribution are varied, and mean energies of (b) and (c) are lower than (a). We estimated the effective rms emittance, considering the effects of measurement resolutions, by using following formula [3],

$$\epsilon_r = \left[ \left( E^2 \right)_m \left( \phi^2 \right)_m - \left( E \phi \right)_m^2 - \left( E \phi \right) \left( \phi^2 \right)_m - \left( \phi^2 \right)_m^2 \right]^{1/2}$$
where \( s_p \) is resolution of the phase measurement, and \( s_E \) is that of energy measurement. In this measurement \( s_p \) is 4.5 deg, and \( s_E \) is 14 keV. In order to get high phase resolution, we used a narrower target than previous experiment, but this was not so effective. Only the change of setting angle of the target as shown in Fig. 1 might be effective to the phase resolution.

We calculated two kinds of rms emittances. One is calculated from all particles, and the other is calculated from the particles in a window of 50 deg \( \times \) 600 keV. The purpose of the window is to estimate the rms emittance of stable beam. The obtained rms emittances for each distributions are shown in Table 1. The size of rms emittance for condition A and B are almost same, but the emittance (all) for C is 1.4 times as large as that for A.

<table>
<thead>
<tr>
<th>Condition</th>
<th>rms emittance (all particles)</th>
<th>rms emittance (in window)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( 0.87 \pm 0.07 ) mm mrad</td>
<td>( 0.43 \pm 0.06 ) mm mrad</td>
</tr>
<tr>
<td>B</td>
<td>( 0.86 \pm 0.06 ) mm mrad</td>
<td>( 0.42 \pm 0.07 ) mm mrad</td>
</tr>
<tr>
<td>C</td>
<td>( 1.24 \pm 0.06 ) mm mrad</td>
<td>( 0.40 \pm 0.07 ) mm mrad</td>
</tr>
</tbody>
</table>

**Conclusion**

We measured the longitudinal beam distribution at the different rf conditions. The distributions were different by the condition, and we got the optimizing rf condition with this measurement. Then longitudinal rms emittances are obtained for three conditions. At a large mismatched phase, the rms emittance found to be 1.4 times larger than that of matched beam.

**References**


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Fig. 3 Longitudinal Phase space distribution of the beam. (a) is transformed from the upper island of Fig. 2(a), (b) and (c) are also transformed from those of Fig. 2(b) and 2(c), respectively.
PERFORMANCE OF THE 100 MEV INJECTOR LINAC FOR THE ELECTRON STORAGE RING AT KYOTO UNIVERSITY

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Abstract

An electron linear accelerator has been constructed as an injector of a 300 MeV electron storage ring (Kaken Storage Ring, KSR) at Institute for Chemical Research, Kyoto University. The output beam energy of the linac is 100 MeV and the designed beam current is 100 mA at the 1 μsec long pulse mode.

The transverse and longitudinal emittance are measured to evaluate the beam quality for the beam injection into the KSR. They are observed by the profile monitors combined with quadrupole magnets or an RF accelerator. The results are that the normalized transverse emittance is 120 π.mm.mrad. The longitudinal emittance is 15 π.deg.MeV and the energy spread is ±2.2 %.

Introduction

A compact electron storage ring (Kaken Storage Ring, KSR) is now under construction at the Institute for Chemical Research, Kyoto University [1]. The layout of the accelerators is shown in Fig. 1. The KSR has a race track shape and its maximum beam energy is 300 MeV. It will be used as the synchrotron radiation source from the dipole magnet and the insertion device. The critical wave length of the synchrotron radiation is 17 nm. It will be also used for research of the free electron laser.

The construction of the linac had been finished and we succeeded to accelerate the electron beam of 140 mA in October, 1995. The design beam energy is 100 MeV and the pulse width is variable from 10 nsec to 1 μsec. Table 1 shows the main linac parameters. The linac will be also used for the experiments of the coherent X-ray generation by the electron beam. Especially, the parametric X-ray radiation (PXR) experiment has been already started.

Accelerator

The electron gun has the Pierce electrode and the cathode assembly is the Y-796 (Eimac). The maximum extraction voltage is -100 kV. The pre-buncher is a single reentrant cavity. It is designed to bunch the beam within the phase spread of 60 degree. The buncher is a disc-loaded and 3 step constant gradient structure. It has 21 cells and the total length is 777 mm. The designed phase spread is within 3 degrees at the beam current of 100 mA when the input power is 12 MW.

Table 1 Beam parameters and main specifications of the linac.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Electron Beam Energy</td>
<td>100 MeV</td>
</tr>
<tr>
<td>Max. Pulse Width</td>
<td>1 μsec</td>
</tr>
<tr>
<td>Max. Repetition</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Electron Gun</td>
<td></td>
</tr>
<tr>
<td>Cathode Assembly</td>
<td>Y-796 (Eimac)</td>
</tr>
<tr>
<td>Max. Extraction Voltage</td>
<td>-100 kV DC</td>
</tr>
<tr>
<td>Accelerating Structure</td>
<td></td>
</tr>
<tr>
<td>Bore Radius</td>
<td>11.74 - 13.4 mm</td>
</tr>
<tr>
<td>Length</td>
<td>3 m</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>2857 MHz</td>
</tr>
<tr>
<td>Maximum Electric Field</td>
<td>15 MV/m at 20 MW</td>
</tr>
</tbody>
</table>

Figure 1 Layout of the electron accelerator.
There are three main accelerating structures. The main characteristics of the accelerating structure are also listed in table 1. The maximum electric field is 45 MV per an accelerating structure without beam loading at the input power of 20 MW. The doublets of the quadrupole magnets are used as focusing elements between the accelerating structures.

Klystron

There is a klystron for each accelerating structure. The total number of the klystron is 4 including the bunched, pre-buncher system. The klystron is ITT-8568. The maximum output power is 21 MW and the pulse width is 2 μsec. We are going to replace the klystron with Mitsubishi PV3030A2. The present modulators and the focusing coils are reused for the new klystrons so that the replacement cost and time can become minimum. The solenoid is a single electromagnetic coil and generates the magnetic field of 0.9 kGauss on the axis. Figure 2 shows the relation between the cathode voltage and the output power. The output power of 30 MW is available at the cathode voltage of 250 kV. The power efficiency is 48%.

Beam Measurement

The beam emittance and the energy is measured downstream of the linac. Figure 3 shows the schematic view of the beam monitor section. The beam current is measured by the current transformer (CT) with ferrite core. The main components in this section are two profile monitors (PM1, PM2). They consist of screens, CCD cameras and an image memory unit. The image data is analyzed by the computer in the control room. The material of the fluorescence screen is an alumina ceramic in which a little chromium oxide is homogeneously doped (Desmarquest, AF995R). PM1 is used for the measurement of the transverse beam profile and the emittance. PM2 is used for the measurement of the energy spread and the longitudinal emittance.

Transverse Beam Profile and Emittance

The shape of the beam distribution in the transverse phase space is assumed,

\[
\chi^2 + 2\alpha x + \beta x^2 = \varepsilon, \tag{1}
\]

where \(\alpha, \beta, \gamma\) are Twiss parameters and \(\varepsilon\) is the transverse emittance. The Twiss parameters are transformed from QD to PM1 according to the following equation.

\[
\begin{pmatrix}
\alpha' \\
\beta' \\
\gamma'_{PM1}
\end{pmatrix} = 
\frac{1}{m_{21}}
\begin{pmatrix}
m_{11}^2 & -2m_{11}m_{12} & m_{12}^2 \\
-2m_{21}m_{11} & 1-m_{12}m_{21} & -2m_{12}m_{22} \\
m_{21}^2 & -2m_{22}m_{21} & m_{22}^2
\end{pmatrix}
\begin{pmatrix}
\alpha \\
\beta \\
\gamma'_{QD}
\end{pmatrix} \tag{2}
\]

where \(m_{ij}\) are elements of a transfer matrix between QD and PM1.

\[
\begin{pmatrix}
x' \\
x'_{PM1}
\end{pmatrix} = 
\frac{1}{m_{21}}
\begin{pmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{pmatrix}
\begin{pmatrix}
x \\
x_{QD}'
\end{pmatrix} \tag{3}
\]

From the formula (2), the rms beam radius \(\sigma\) at PM1 is obtained.

\[
\sigma_{PM1}^2 = m_{11}^2(\varepsilon\beta) - 2m_{11}m_{12}(\varepsilon\alpha) + m_{12}^2(\varepsilon\gamma)
\]

\[
(\varepsilon\beta) - (\varepsilon\alpha)^2 = \sigma^2 \tag{4}
\]

where the Twiss parameters are values at QD. We measure the beam size by the profile monitor (PM1) with various field gradient of QD and calculate the emittance by the least square fitting.

Figure 4 shows the relation between \(\sigma_{PM1}^2\) and the field gradient of QD. The beam current is 100 mA and the pulse width is 100 nsec. It is the operation mode of the beam injection into the KSR. The unnormalized emittance at QD is 0.57 π.mm.mrad and the normalized value is 120 π.mm.mrad.

![Figure 2](image1.png)

**Figure 2** RF output power and the efficiency of the klystron (PV3030A2). The pulse width is 2 μsec.

![Figure 3](image2.png)

**Figure 3** Schematic view of the beam monitor section downstream of the linac.

Acc3: Third accelerating structure, CT: Current transformer, QD, QF: Quadrupole magnets, PM1, PM2: Profile monitors, AM: Analyzing magnet.
Energy Spread and Longitudinal Emittance

The beam energy spread is measured by the profile monitor (PM2) downstream of the 5 degree analyzing magnet. The rms beam radius $\sigma$ at PM2 is,

$$\langle \sigma_{PM2} \rangle^2 = \left( \frac{x_\beta}{\beta} \right)^2 + \left( \frac{\eta \phi}{\rho} \right)^2$$

(5)

where $\eta$ is the dispersion and is 0.15 m. The first term is due to the transverse emittance and it is calculated from the measured data. The second one due to the energy spread. The correlation is assumed to be negligible between the two terms. The measured beam profile at PM2 is shown in Fig 5. The beam current is 100 mA and the pulse width is 100 nsec. The center beam energy is 109 MeV and the energy spread is $\pm 2.2$ %.

To observe the longitudinal emittance, the phase of the last accelerating structure (Acc3) is set so that the relativistic electron beam go through it with the synchronous phase of zero. The transfer matrix from Acc3 to PM2 is,

$$\begin{pmatrix} \theta \\ E \end{pmatrix}_{PM2} = \begin{pmatrix} 1 & 0 \\ V_{rf} & 1 \end{pmatrix} \begin{pmatrix} \theta \\ E \end{pmatrix}_{Acc3}$$

(6)

where $\theta$ and $E$ are relative phase and energy to the synchronous particle. In this formula, the approximation is used because the synchronous phase is zero.

$$V_{rf} \sin(\theta) = V_{rf} \theta$$

(7)

Similar to the formula (4), the relation of the rms energy spread, longitudinal emittance and Twiss parameters is,

$$\langle E \rangle_{PM2}^2 = m_{12}^2 (\epsilon \beta) - 2m_{22} m_{21} (\epsilon \alpha) + m_{22}^2 (\epsilon \gamma)$$

$$\langle \epsilon \beta \rangle - (\epsilon \alpha \alpha) = \epsilon \beta$$

(8)

The energy spread is measured with various RF voltage ($V_{rf}$) and the longitudinal emittance is calculated by the least square fitting.

Figure 6 shows the relation between the square of rms beam radius at PM1 and the RF voltage of Acc3. The beam current is 100 mA and the pulse width is 100 nsec. The center beam energy is 71 MeV. The longitudinal emittance is 15 $\pi$ deg MeV. The phase spread is $\pm 8.0$ degree.

References


NUMERICAL SIMULATION OF IH ACCELERATORS WITH MAFIA AND RF MODEL MEASUREMENTS*

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S. A. Minaev, MEPI, Moscow, Russia

Abstract

Two IH drift tube cavities will be part of the new pre-stripper LINAC for the beam intensity upgrade of the GSI accelerator facility in Darmstadt (Germany). A major part of the cavity design process consisted of numerical electromagnetic simulations using MAFIA\(^1\). The simulation method as well as the dependence of the field distribution on some key geometries are discussed. Based on these calculations the tanks are under construction and a 1:5.88 scaled RF model was built to compare the results and to determine the exact drift tube geometry. This paper describes the most important steps in the design process and presents results for the simulation and the measurement.

Introduction

The accelerator facility at GSI basically consists of a heavy ion linear accelerator (UNILAC), a heavy ion synchrotron (SIS) and a heavy ion storage ring (ESR). To be able to fill the SIS up to its space charge limit, the first (pre-stripper) part has to be replaced. Two IH drift tube linacs (IH1) and (IH2) will be part of the new UNILAC. They are designed to provide an effective voltage gain of 40.8 MV (IH1) and 42.4 MV (IH2) at a resonance frequency of 36.136 MHz (see also [7], [3]).

numeral field calculations. The eigenmode solver of MAFIA [1] was used to calculate the electromagnetic field distribution and the resonance frequencies of both cavities.

<table>
<thead>
<tr>
<th></th>
<th>IH1</th>
<th>IH2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius [m]</td>
<td>0.915</td>
<td>1.017</td>
</tr>
<tr>
<td>Inner length [m]</td>
<td>8.995</td>
<td>10.175</td>
</tr>
<tr>
<td>Drift tubes</td>
<td>52</td>
<td>45</td>
</tr>
<tr>
<td>Input undercut [m]</td>
<td>0.221</td>
<td>0.400</td>
</tr>
<tr>
<td>Output undercut [m]</td>
<td>0.480</td>
<td>0.520</td>
</tr>
<tr>
<td>Gap quadrupole-girdler</td>
<td>0.390</td>
<td>0.390</td>
</tr>
</tbody>
</table>

Figure 1: Layout of IH1 and IH2 after the optimization with MAFIA.

Unlike earlier designs, the IH-cavities were planned to be cylinders with circular cross sections, in order to provide better mechanical stability against gravitational and vacuum forces. Thus it was no more possible to measure and to tune the cavities during the production. As tuning elements reduce the reliability of such a structure, the parameters for the geometry had to be determined in advance as good as possible. This was performed by

\(^1\)Solution of Maxwell's equations using a Finite Integration Algorithm

* Work supported by GSI, Darmstadt, Germany.

Simulation

Electromagnetic properties of IH-resonators

The most important parameters of an IH-cavity are the frequency of the accelerating mode and the gap voltage distribution. The basic relations for such a cavity operated in the H\(_{111}\)-mode are given in [4].

Figure 2: Voltage distribution for different depths of the undercuts in the girders.

Reference voltage distributions for IH1 and IH2 were derived earlier from LORASR beam dynamics calculations and from experience with respect to high shunt impedance values. They are plotted in figures 7 and 8. There are two very effective principles to tune the gap voltage distribution:
• Variation of the ratio \( g/L \) of drift tube gap to period length. A reduction of the capacity per length induces a reduction of the gap voltage and vice versa [5].

• Undercuts at the girder ends rise the gap voltage in the region of the tank ends (see [6] and figure 2).

In contrast to earlier designs the voluminous quadrupoles will be mounted on the girder. Using such an array, the local capacity rises and tends to detune the structure locally. To compensate the resulting increase of the gap voltage, the lens support was elongated and the distance to the opposite girder was enlarged (see figure 3).

![Figure 3: Optimization of the arrangement around the quadrupole lenses. The distance to the opposite girder was enlarged and the lens support was elongated.](image)

**Table 2: Some data concerning the simulations.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smallest mesh step</td>
<td>3 mm</td>
</tr>
<tr>
<td>Biggest mesh step</td>
<td>30 mm</td>
</tr>
<tr>
<td>Number of mesh points</td>
<td>2-3 million</td>
</tr>
<tr>
<td>CPU-time</td>
<td>36 hours</td>
</tr>
<tr>
<td>Machine</td>
<td>IBM RS-6000 590</td>
</tr>
</tbody>
</table>

To locally optimize the voltage distribution, a detached simulation of shorter sections is possible. Some cross-sections of the cavities exist, on which the magnetic field is perpendicular. The cavities can be split at these points, if magnetic boundary conditions are applied.

The arrangement around the quadrupole lenses was optimized, using such a short section. A comparison of the resonance frequencies of single sections also gives a first impression of the total voltage distribution. Sections with higher frequencies will have lower gap voltages and vice versa.

As a last step, after the voltage distribution was optimized, the exact cavity radius \( r_{cav} \) was determined in order to match the nominal frequency \( f_n \). This can be done with sufficient accuracy, using the simple relation

\[
r_{cav} = \frac{f}{f_n} \cdot r
\]

with \( r \) and \( f \) being the radius and the frequency from the last calculation.

![Figure 5: The 1:5.88 model for cavity IH2 (Photo: A. Zschau, GSI).](image)

**Procedure for the Simulation**

In comparison to the complete IH-cavities, the drift tube geometry represents a rather close-meshed structure. A discretization of the real drift tubes with an acceptable resolution would lead to a tremendously large number of meshpoints.

Thus, the main problem was to find an appropriate approximation for the real drift tube geometry. An octagonal cross-section was chosen, that can be modeled with very few mesh-steps (see figure 4). Detailed simulations had to be performed in order to match the capacities of the real drift tubes and their substitutes. In spite of the rather coarse discretization, about 40 000 meshpoints were necessary to model a slice with one gap, resulting in 3 000 000 meshpoints for IH1 and 2 000 000 for IH2.

![Figure 4: The real drift tube and its substitute. The octagonal cross-section can be discretized with only 3 cells along the radius.](image)

**Measurements**

A 1:5.88 scaled model was built, which allowed to compare the numerical results with measurements. In addition, a conical geometry for the drift tubes facing the quadrupoles was designed and tested, which reduced the peak field strength on axis by \( \approx 30\% \). Compared with the other gaps, the peak field still is at least \( 12\% \) higher.

Furthermore, plungers with combined capacitive and inductive action for tuning the resonance frequency in the range of 0% to \(-0.5\% \) were tested (see figure 6).
Figure 6: The LC-plunger and its effect on the resonance frequency.

Results

A comparison of calculated and measured voltage distribution for IH2 (figure 8) shows a good agreement. Even better and more important is the agreement in the resonance frequency (table 3), as a later tuning is only planned in the range of 0% to −0.5% (see figure 6). Figure 7 shows two different results in comparison with the reference after a first optimization of IH1 due to variation of the undercuts in the girders and the g/L-distribution.

Figure 7: Calculated and reference voltage distributions in cavity IH1.

Figure 8: Calculated, measured and reference voltage distributions in cavity IH2.

Summary

With help of the calculations, the tanks for both cavities could be ordered, even though the exact drift tube distances in tank IH1 had not yet been optimized with respect to the reference voltage distribution. The main parameters to be determined were the tank radii and the dimensions of the undercuts in girders. Measurement and simulation showed a very good agreement.

References


Table 3: Calculated and measured frequencies of the accelerating and higher modes for cavity IH2.

<table>
<thead>
<tr>
<th>Frequency of Modes [MHz]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAFIA</td>
<td>36.275</td>
<td>37.962</td>
<td>42.208</td>
<td>47.570</td>
</tr>
<tr>
<td>Measurement</td>
<td>36.287</td>
<td>37.885</td>
<td>41.868</td>
<td>47.011</td>
</tr>
</tbody>
</table>
SIMULATION OF LINAC OPERATION USING THE TRACKING CODE L

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Abstract

In linear accelerators, misalignments of the machine elements can cause considerable emittance growth due to wake fields, dispersion and other effects. Hence, tight limits are imposed on machine tolerances, design parameters and methods of machine operation. In order to simulate the beam dynamics in linacs, the tracking code L has been developed. Including both single- and multi-bunch effects, the behaviour of the beam in the machine can be simulated and adjustments on parameters of the machine elements up to complete correction techniques and operation procedures can be applied. Utilization of the program is facilitated by a graphical user interface. In this paper we will give an overview over the capabilities of this code and demonstrate its efficiency at attacking the problems associated with large linear accelerators.

Introduction

The tracking code L is embedded in the MAFIA software package. It is equipped with a graphical user interface (GUI), guiding the user through the simulation procedure. Figure 2 e.g. shows the dialogue for a quadrupole creation. L is able to compute single and multibunch behaviour inside the accelerating structure. The single bunch case covers the development of the emittance, energy spread and the optical functions due to the influence of short range wake fields and structure misalignment.

The effects relevant for a multibunch simulation are:
- beam loading
- long range wake fields
- charge fluctuation
- RF fieldkicks from tilted accelerating structures
- RF phase errors
- longitudinal jitter of the bunch position

The power of a new software is best demonstrated discussing an example. We will perform a tracking calculation in the first sector of the S-band linear collider (SBLC). This sector consists of 48 FODO cells. Each of them bears two accelerating structures of 180 cavities (total length 6m), one focusing and one defocusing quadrupole magnet with an focal length of 4.3 meter. Another quadrupole with the double focal length is located at the beginning of the structure establishing $\alpha=0$. Therefore the total length of sector 1 is 600 meter. In our example we will consider single bunch dynamics.

The principal simulation procedure is shown in Figure 1. We will follow this concept during this paper.

Figure 1 The tracking code L is embedded in the MAFIA software system. Flux diagram of the tracking procedure

Creating the elements

In the L-code no field problem on a discretised space is solved, but a sequence of transfer matrices belonging to the elements appearing inside a linear accelerator is defined[1]. Implemented elements are:
- drift spaces
- quadrupoles
- accelerating structures
- elements with arbitrary transfer matrices

To each element a beam position monitor and a dipole magnet can be added. This feature is important for the application of correction techniques. The following insufficiencies can be attached to the elements:
- systematic misalignment and tilts in the transverse directions
- accidental misalignments and tilts by a root-mean-square-value
- sag of a structure element

---

1 Now at the Max-Planck-Institut for Plasma Physics, Kothenhaeger Landstrasse, 17489 Greifswald, Germany
Since no drift spaces appear in our example, we will start our input with the quadrupoles (Figure 2). The parameters required are the physical length and the focal length in meter. Finishing our input we add the new quadrupole to the list of existing quadrupoles.

At every time it is possible to display the parameters of previous structure elements using the show button, change parameters with the replace button or remove an unused element by pressing the delete button.

Figure 2 The dialogue for quadrupole creation. The necessary settings like length and focal length are separated from the optional (dipole or BPM), and the description of tilts and misalignments.

We will continue in our problem description by defining the accelerating structures. The geometrical dimensions were already mentioned in the introduction. Furthermore the quality factor (Q=13500), the frequency (f=2.998 GHz), the loss parameter (k_e=1.11 10^6 V/As) have to be defined. Depending on whether single or multibunch dynamics are to be calculated, the short or the long range wakefields respectively have the main influence on the result of the calculation. We will restrict ourselves to the investigation of the single bunch behaviour. Consequently we need the short range wake information[4].

The bunchlength in the SBLC collider is σ=300μm. The wakefield calculation takes place in the MAFIA-T2-module. The longitudinal wakepotential in a range of 13σ from the bunch head is needed. L is able to consider monopole, dipole and quadrupole wakes. The transverse wake potential is calculated by means of the Panofsky-Wenzel-theorem.

In a multibunch calculation the frequencies of the modes in the several passbands must be supplied.

Building the machine

After having defined every single element of the machine is, we continue with gluing the primitives together to a more complex structure, a so called module. In our example we take 2 accelerating structures and as well a focusing as a defocusing quadrupole and put them together in a FODO-cell.

It is possible to combine previously build modules with other elements, each of them with an arbitrary number of repetitions. In this facil manner we can construct sector 1 of the SBLC from the 193 elements within one minute.

After the modules are expanded into a structure, the misalignments to elements and classes are set by means of a random generator. Furthermore L offers the application of the slow ATL-ground motion to the final lattice.

Even in this state every single setting is accessible via the graphical user interface.

Defining the bunch

Every particle inside the bunch (1.1 10^10 particles in case of the SBLC) has different initial offsets (x, y), slopes (x', y'), energies (W), and longitudinal positions (s). In order to model the bunch with a moderate numerical effort, it is divided into several slices, distributed equidistantly over its range. Assuming no uncorrelated energy spread each particle inside one slice has the same energy. L offers the feature to include the uncorrelated energy spread by defining subslices inside one slice.

To analyze the multibunch dynamics it is often sufficient to assume the single bunches inside the bunchtrain to be pointlike charges. Nevertheless it is possible to divide every bunch into slices and to examine the combined single and multibunch effects.

Performing the calculation

The next step is starting the calculation. After 2 minutes calculation time the results of the first shot through the machine are available, such as the emittance(see Figure 3), the energy distribution (Figure 4), the phase space ellipse (Figure 5) or the trajectory of the bunch (Figure 6). The L-code calculates the beam dynamics in both transverse directions in one run. Furthermore it provides the possibility to switch single effects (e. g. all longitudinal wake

![EMITTANCE GROWTH](chart.png)  
Figure 3 The emittance growth in the transverse x direction (solid line) and the y-direction dashed line along the machine due to wakefields and misalignment.
fields or only dipole wakes) on or off right before the tracking calculation commences.

**Correction Techniques**

The code is intended not only for static analysis of emittance growth in a linac but rather for the simulation of complete linac operation. Therefore several features have been added allowing to simulate both perturbing effects occurring at machine operation and the application of advanced trajectory and emittance correction techniques. The effects perturbing machine operation include for instance random fluctuations of the bunch charge, jitter of the bunch positions or slow displacement of machine elements due to inelastic ground motion [3]. On the other hand, machine elements can be equipped with beam position monitors simulating the measurement of the transverse beam offset relative to the elements and with dipole magnets deflecting the beam. Thus the user can create his own correction procedure in the MAFIA command language, reading the beam positions or emittance profile obtained in the tracking calculation and then correct the beam emittance by adjusting any machine parameter (element displacements, deflection angles of dipole magnets ...) This feature has been applied successfully to a variety of correction techniques like Dispersion-Free and Wake-Free orbit correction, trajectory bumps and others.

**Conclusion**

The tracking code L is a powerful tool to investigate both, the single and the multibunch behaviour inside a linear accelerator. Beyond that it is able to simulate the effects of different correction schemes. The graphical user interface will guide you securely through this matter.

**References**

DESIGN STUDIES FOR THE POSITRON FACTORY

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Abstract

In the design study for the Positron Factory, a feasibility of simultaneous extraction of multi-channel monoenergetic positron beams, which had been proposed at the previous conference (Linac 94), was demonstrated by an experiment using an electron linac. On the basis of the experimental result, an efficient moderator structure, which is composed of honeycomb-like assembled moderator foils and reflectors, is proposed.

Introduction

We have been promoting design studies for the 'Positron Factory' [1], in which linac-based intense monoenergetic positron beams are planned to be applied for advanced materials characterization and new fields of basic research. A tentative goal of the slow (i.e. monoenergetic) positron beam intensity is 10\textsuperscript{10}/sec, which is larger by two orders of magnitude than those of existing strongest beams in the world. We have performed a conceptual design of a high-power electron linac of 100 kW class with a beam energy of 100 MeV and developed a newly designed electron-positron converter. We have proposed a concept of simultaneous extraction of multi-channel monoenergetic positron beams, on the basis of a Monte Carlo simulation, in a design study on a positron moderator. In this report, an experimental result to confirm the feasibility of this concept is demonstrated.

Design Studies

Linac and converter

We have performed design studies on a high-power electron linac and an electron to positron & photon converter as follows[2]:
1) An optimum electron beam energy for slow positron generation was estimated to be around 100 MeV.
2) It was calculated that a tentative goal of the slow positron beam intensity (10\textsuperscript{10}/sec) could be attained with a linac of 100 kW class with the above energy range.
3) A technical survey study confirmed a feasibility of manufacturing such a state-of-the-art linac.
4) Further detailed analyses were carried out concerning thermal deformation of the accelerator structures, beam instability, reliability of the components, down-sizing of the machine and a computer-aided control system.
5) A 'self-driven rotating converter' suitable for the high power beam was proposed and successfully tested.

A concept of the linac is shown in Fig.1. Some details of the design has been changed from that presented at Linac 94.

![Linac Diagram](image)

Fig.1 A concept of the high-power electron linac for the Positron Factory.
- Beam Energy: 100 MeV
- Beam Current: 1 mA (average)
- Beam Power: 100 kW (average)
- Pulse Width: $\sim 3.5$ $\mu$s

Multi-channel positron moderator assemblies

We have proposed 'multi-channel moderator assemblies' to supply multiple slow positron beams simultaneously as shown in Fig.2 [2]. The slow positron yield, that is a ratio of the number of slow positrons emitted from each tungsten moderator assembly to that of incident electrons onto the tantalum converter, was estimated using a newly developed Monte Carlo simulation system [3]. The result is shown in Fig.3. The contribution by energetic positrons from the converter to generate slow positrons drastically decreased at the assemblies distant from the converter. It was deduced from tracking of the particles that this is caused by spatial spread of the positron beam. On the contrary, there still were sufficient slow positron yields originating in energetic photons, even at the rear assemblies. This is because the photons go almost straightforward and cause pair production reactions uniformly in every assembly. Thus produced positrons have comparatively lower energies, which results in higher probabilities to be thermalized in each moderator foil.

To demonstrate a feasibility of the simultaneous
extraction of multi-channel slow positron beams, we fabricated a set of 2 channel tungsten moderator assemblies as shown in Fig.4. The set was composed of 18 tungsten foil layers of 25 μm in thickness. Slow positrons from each 9 layers were separately extracted by 2 tungsten mesh grids. Each moderator layer was divided into 3 parts, electrically separated and biased to drift emitted slow positrons by sloping the electric field toward the extraction grids. We observed the slow positron beam profile from the assemblies with a MCP (micro channel plate), using a 100 MeV electron beam from a S-band electron linac at Osaka University.

slow positron extraction

ergetic positrons & photons

energetic electrons (100 MeV)

tantalum (8.2mm)

1st assembly 2nd assembly 3rd assembly

tungsten(50mmX50mmX25μm)X10 foils
(gap: 8mm)

Ta converter to W moderator assembly: 27.7mm
assembly to assembly: 27.7mm

Fig.2 A concept of the simultaneous multi-channel extraction of slow positron beams by multiple moderator assemblies and the geometry for the Monte Carlo simulation.

Slow Positron Yield (slow positrons / incident electrons)

\[
\begin{array}{|c|c|c|}
\hline
\text{1st assembly} & \text{10}^{-10} & \text{10}^{-8} & \text{10}^{-6} & \text{10}^{-4} \\
\hline
\text{by positrons} & \text{by photons} & \\
\text{2nd assembly} & \text{by positrons} & \text{by photons} & \\
\text{3rd assembly} & \text{by positrons} & \text{by photons} & \\
\hline
\end{array}
\]

Fig.3 Slow positron yields (ratios of the number of slow positrons to that of incident electrons) at the multiple moderator assemblies calculated with the Monte Carlo simulation for the case indicated in Fig.2.

Contributions by positrons and photons emitted from the converter are separately evaluated.

The result is shown also in Fig.4. Three peaks were observed in the slow positron beam intensity profile. The largest one was attributed to slow positrons from the first channel which was nearer to the tantalum converter. The second and third peaks were both attributed to slow positrons from the second channel. It is assumed that back-scattered positrons and pair production reactions by photons give rise to the third peak, because thick tungsten plates were placed at the end of the second moderator assembly. This means that positrons and photons passing through the first and second assemblies still have a potential to generate slow positrons, and also that it will be efficient to place a heavy metal at the end in fabrication of moderator assemblies.

The intensity of slow positrons from the second channel was smaller only by an order of magnitude than that from the first channel, which agreed well with the simulation result. It was concluded that such an extra positron beam will be useful for preliminary or potential researches which are promoted simultaneously with main experiments using the strongest beam.

Fig.4 Experimental setup of 2-channel moderator assemblies for the demonstrative experiment of the simultaneous extraction of multi-channel monoenergetic positron beams and the intensity of extracted slow positrons observed with a MCP.

Proposal of a new efficient moderator structure

The above result suggests usefulness of a heavy metal plate for a reflector and importance of the assembly structure. To evaluate the structure effect, we calculated conversion efficiencies from energetic positrons and photons to slow
positrons for the following three cases as indicated in Fig. 5. The first structure is a usual one, which consists of ten tungsten foils of 25 μm in thickness parallel placed. The second is a set of these foils whose surrounding planes except for the positron and photon injection side and the slow positron extraction one are enclosed by thick tungsten plates. The third structure has an additional set of eleven tungsten foils crossing the above foils in the second one to make a honeycomb-like assembly of foils enclosed by the reflectors.

**Fig. 5** Proposed new structures of positron moderator assembly.

In the design study for the Positron Factory, we demonstrated a feasibility of simultaneous extraction of multi-channel monoenergetic positron beams using an electron linac, by an experiment. A more efficient moderator structure, which was suggested by the experimental result, is proposed. The world-highest monoenergetic positron beam of more than $10^{10}$/sec in intensity will be realized by the use of a high-power electron linac of 100 kW class with a beam energy of 100 MeV.

**References**


**Fig. 6** Calculated conversion efficiencies from energetic positrons and photons to slow positrons in positron moderator assemblies having different structures shown in Fig. 5.

Fig. 6 shows the calculation result. It is obvious that the structure effect is remarkable especially for higher energy projectiles. The number of the higher energy positrons and photons emitted from the converter is more than that of the lower energy ones. Therefore, the slow positron yield in the third structure is expected to increase by a few times that in a usual one. The moderator assembly with a honeycomb-like structure enclosed by reflectors proposed here is promising for realizing an intense monoenergetic positron beam of more than $10^{10}$/sec in intensity.
Engineering Design of ITEP Proton Linac for Nuclear Waste Transmutation


Abstract.

Two new mutually supporting ideas to overcome problems resulting from inevitable particles losses in ADTT linac and significantly improve reliability of its operation are discussed. To decrease induced radioactivity it is proposed to insert into linac channel material with extremely low activation cross-section and to use in main part of the linac single-gap cavities (room-temperature or SC) supplied by individual force phased low power generators. Realization of these proposals allows to overcome strong physical limitations on beam losses and to reach non-stop operation of the linac in spite of failures in one or several channels of the high-beta linac part.

Introduction

The significant and rising interest to new technologies in processing of nuclear wastes, use of weapon-grade plutonium, production of nuclear materials (Pu and Pu), and also a thorium fuel cycle development, stimulate design of 1 GeV high-current accelerators. These accelerators, as major part of electronuclear installations, are considered in different variants both proton linacs [1,2] and cyclotron complexes [3]. Beam current varies typically from 10 up to 100 mA depending on application.

Main problems under design of the high-current linac are achievement of minimum activation of its parts and long time non-stop operation. The activation level, determined by high-energy proton losses should permit hand-on maintenance of the machine.

Studies of beam halo formation as main reason of particles losses are conducted in many scientific centers of the world [4,5]. Unfortunately, despite of plenty interesting results, there is no reliable method of an estimation of small particles losses, which define actual linac activation. Our approach is based on the LAMPF beam losses data. The losses are about 0.2 nA/m at average beam current of 1 mA. We accept this beam losses level as a limit, which allows hand-on maintenance of the machine. On the basis of published results, it is difficult to assume reduction of relative losses with increasing of average current up to 100 mA. Thus, the enough quick achievement of radiation-free condition becomes very problematical.

As it is mentioned above, the second major problem of designing of high-current linac is to ensure non-stop operation of the electronuclear complex. In existing linacs uninterrupted operation depends mainly on a reliability of RF system. In our proposal the linac operation reliability does not practically depend on failure one or several RF generators and resonators of main part of the accelerator (MPA).

Supposed new ideas are the use of materials with low activation and small yield of neutrons for accelerating structures manufacture as well as application of single-gap resonators with individual RF supply and external phasing of accelerating fields for MPA.

Block-scheme and parameters of the accelerator

In majority of the projects RFQ structure is accepted as initial part, DTL structures with arrangement of quadrupoles in drift tubes or outside of resonators (BCD, CDS, etc.) are considered as the intermediate part. The 700 - 1000 MHz CCL and DAW are usually considered as MPA. However appreciable distortion of an accelerating field in CCL cells can make inconvenient of its use for acceleration of high average current beams [6]. Main lacks of DAW are relative complexity of manufacturing and tuning but also difficulty of heat remove at high average power.

Use of RF generators of high unit power (about 1 MW) in all earlier proposed projects influences on choice of length and type of focusing structure in MPA, that results in serious difficulties at feeding of high CW power in resonators and stops the operation of whole machine at failure of even one generator.

In Fig.1 the linac block-scheme is presented, in which specified proposals are introduced. The accelerator consists of injector, RFQ section, Alvarez type DTL as intermediate part and main part, consisting of 2300 single-gap resonators disposed in groups of 3 to 6 ones between focusing quadrupoles. The main parameters of the accelerator are presented in Table.

RFQ with coupling windows (4-ladder type) is used in the proposal [7]. RFQ is terminated by output dynamic match developed according to [8]. The DTL is Alvarez-type accelerating structure with PMQs. An opportunity of use PMQ in DTL-section of CW linac is provided due to application of low activation and small neutron yield graphite absorbers in an area of drift tubes apertures. The absorber thickness is chosen by constructive reasons, ensuring absorption more than 99 % of lost particles. The minimum thickness changes from 0.1 mm at 5 MeV up to 2 mm at 100 MeV.

The accelerating module at the beginning of MPA is schematically shown in Fig.2. The MPA consists of single-gap toroidal resonators groups between which magnetic quadrupoles are placed. The resonators are made of graphite. Their internal surface is covered by ~ 0.1 mm Cu-layer, that provides necessary electrical conductivity and improves vacuum conditions. The number of resonators in each group is equal to 3 at the beginning and to 6

This work supported by ISTC
at the MPA end. MPA focusing period length is $8\beta\lambda$. The ion line elements inside lenses are graphite tubes, the wall thickness of which gradually grows from 2 up to 20 mm.

The main advantage of MPA consisting of single-gap resonators is that of linac saves operation condition even at failure of several successive resonators. Even without acceptance of special measures in case of absence for any reasons of acceleration in any of resonators the beam remains stable in subsequent steps of acceleration. Thus arising output energy oscillations do not disrupt operation of target blanket complex even at presence of bend magnets in the extraction and beam distribution channel. Independent excitation of each resonator permits by means of control system to remove energy variations and longitudinal coherent particle oscillations due to change of RF field phase (and/or amplitudes), at which the beam passes accelerating gaps, following by faulty one.

Calculations show, that MPA based on 600 MHz toroidal single-gap resonators is on a par with CCL and DAW by such parameters as an effective shunt-impedance. In contrast to multi-gaps resonators there are no problems, connected with tuning and stabilization of accelerating fields in the single-gap resonator. In particular, it means, that the requirements to accuracy of manufacturing of single-gap resonators are much reduced in comparison with multi-gaps ones. Whole MPA can be constructed by using of 3-4 types of toroidal resonators, a fact that makes MPA cheaper in manufacturing. The independent phasing permits to decrease distance between gaps and reduce 20-50 % MPA length.

To excite single-gap resonators, 55 kW (for 100 mA CW beam current) RF generators are required which can be located near the resonators. Such level of RF power for resonators supply does not represent difficulties and does not require application complex and expensive feeder system. Use of single-gap resonators permits in the best way to realize idea of application of materials for lost particles absorption. Estimations, showing an opportunity of manufacturing of the MPA resonator completely from the similar material are done. For example, use fine-grain pyrolytic graphite having significant mechanical durability, high heat conductivity and ability to form with copper strong connection, permits to create the resonator for CW mode operation with characteristics are on a par with resonators constructed from usual materials, but almost without of induced activation.

An important additional feature of our MPA scheme is a fact that the distance between neighbouring gaps practically does not depend on $\beta\lambda$ due to opportunity to force required phase that allows MPA length reduce to 530 m.

The given scheme and presented proposals allow to realize linac both for CW at average beam current 100 mA, and for pulsing mode at average current 10 mA (pulse current 100 mA). At identical accelerating structure designs they differ only by RF system power.

**Conclusion**

The realization of the considered above proposals on design of high-current linac allows to overcome physical restriction on value of particle losses, representing main obstacle to increase of beam intensity from 1 mA up to 100 mA. Elimination of reliability dependence of the whole electronuclear complex on linac RF system reliability permits easily to reach a high level of non-stop failure operation. The basic advantages of the given scheme are as follows:

- opportunity of construction of the high-current linac at relative beam losses to $10^{-4} - 10^{-5}$, that will allow to have easy access to machine units,
- elimination of linac's operation stops under failure of RF generators and resonators in MPA,
- reduction of linac length down to 600 m due to increase of acceleration rate in MPA (see above this page),
- using of low power of RF generators in MPA, that opens a way to use of high efficiency solid-state generators,
- opportunity of application of PMQs in DTL,
- high degree of freedom in configuration of linac elements, first of all focusing lenses,
- simplicity of accelerating fields tuning in MPA resonators and elimination of the problem of RF power feeding into them. Both proposals supplement each other and give the greatest effect at joint application. The proposed solutions can be used both in CW and pulse linac operation modes. Application of single-gap resonators in MPA easily permits to change to SC variant of MPA, since such resonators are widely used in existing SC ion linacs.

---

**Fig. 1 Block - scheme of the 1000 MeV Linac with output beam current 10 - 100 mA**

<table>
<thead>
<tr>
<th>Injector</th>
<th>300 MHz</th>
<th>600 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>INJ</td>
<td>RFQ</td>
<td>DTL</td>
</tr>
<tr>
<td>80 keV</td>
<td>7 MeV</td>
<td>100 MeV</td>
</tr>
<tr>
<td>15 m</td>
<td>60 m</td>
<td>530 m</td>
</tr>
</tbody>
</table>
Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial part</th>
<th>Intermediate part</th>
<th>Main part</th>
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</thead>
<tbody>
<tr>
<td>Structure Type</td>
<td>RFQ</td>
<td>DTL with PMQ's</td>
<td>Single-gap resonators</td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>0.08-7</td>
<td>7 - 100</td>
<td>100 - 1000</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>300</td>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>2</td>
<td>5</td>
<td>2300</td>
</tr>
<tr>
<td>Total Length (m)</td>
<td>10</td>
<td>60</td>
<td>530</td>
</tr>
<tr>
<td>Aperture Bore Radius (cm)</td>
<td>0.8</td>
<td>0.8-1.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Average Field (MV/m)</td>
<td>ramped</td>
<td>ramped</td>
<td>2</td>
</tr>
<tr>
<td>Synchronous Phase (deg)</td>
<td>90-30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Shunt Impedance (MΩ/m)</td>
<td>-</td>
<td>35</td>
<td>21-35</td>
</tr>
<tr>
<td>RF power losses in wall (MW)</td>
<td>0.8</td>
<td>7.5</td>
<td>35</td>
</tr>
<tr>
<td>Beam Power (for 100 / 10 mA)</td>
<td>0.7 / 0.07</td>
<td>9.3 / 0.93</td>
<td>90 / 9</td>
</tr>
<tr>
<td>Number of RF Generators (%)</td>
<td>2</td>
<td>20</td>
<td>2300</td>
</tr>
<tr>
<td>Efficiency of Resonators (%)</td>
<td>47</td>
<td>55</td>
<td>72</td>
</tr>
<tr>
<td>Quadrupole Lattice</td>
<td>FD</td>
<td>FODO</td>
<td>FODO</td>
</tr>
<tr>
<td>Quadrupoles Gradient (T/m)</td>
<td>-</td>
<td>56 - 23</td>
<td>18.5 - 16.9</td>
</tr>
</tbody>
</table>

Fig. 2 Schematic view of MPA resonators

References

EXPERIMENTAL TEST OF THE ADAPTIVE ALIGNMENT
OF THE MAGNETIC ELEMENTS OF LINEAR COLLIDER

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Abstract

The first results of the experiment on the beam-based adaptive alignment of the magnetic elements of linear colliders are given in this report. This experiment has been realized on the Stanford Linear Collider at SLAC (USA) at the FFTB facility and showed the good convergence and stability of the method. It can be applied to compensate as any sharp or fluent technical displacement of quads as the seismic vibrations of the ground.

The main idea of the method

One of the greatest challenges to the development of TeV-scale e+e- linear colliders is to make particle beams with extremely small sizes up to few tens nanometers. Producing and colliding tightly focused beams requires careful control, precise alignment and stabilization of magnetic elements. The demands to precision of alignment could be from few microns till to some nanometers. However, seismic movement of the ground, technical noise and many other reasons leads to destruction of the alignment and makes our efforts to do alignment one time forever absolutely useless. Therefore, the alignment should be only adaptive, which operates simultaneously with the operating of the accelerator.

The proposed algorithm of adaptive alignment [1] is an iterative process and consists of following steps. Each quad has the beam position monitor (BPM). To shift the certain lens the method requires BPM's data from this quad and two neighboring ones (i.e. algorithm is local).

Then suggested shifts for each quad can be calculated by following formula:

$$\Delta X_i = \left( B_{i+1} \frac{a_i}{2} + B_{i-1} \frac{a_i}{2} - B_i \cdot a_i \left( \frac{1}{L_1} \frac{1}{L_2} - K_i \left( \frac{1 - \frac{1}{2} \frac{dE}{E} \right) \right) \right) \frac{L_1 \cdot L_2}{(L_1 + L_2)} + \text{Covg}$$

where dE/E - beam energy spread,

- $a_i$ - data from BPM of the quad number $i$;
- $L_1$ - distance to the previous quad;
- $L_2$ - distance to the next quad;
- $l_i$ - length of the quad number $i$;
- $K_i$ - reverse focusing distance of the quad;
- $B_i$ - coefficient, which takes into account the differences of the real optics from the thin lens approximation.

$$B_i = 1 - \frac{1}{4} \cdot K_i \cdot l_i$$

In each iterative step suggested shifts should be calculated for all quads, and then all of them should be moved simultaneously. The movement can be realized as by the shifting of the quad itself, as by changing of the magnetic field configuration with help of special additional coils.

This algorithm smoothes the sharp throttes very fastly, and more slowly - the fluent ones.

Results of the experiment

The method has been tested experimentally on the Stanford Linear Collider at SLAC.

For the first, the independence of the method from the beam oscillations was checked. For that aim two sets of suggested shifts of quads was calculated. One for normal beam passing and second - after forced deflection of the beam in vertical direction, which have leaded to the big beam oscillations. In the both cases the calculated shifts of quads were very similar. It means that the algorithm of adaptive alignment is sensitive only to the real displacement of quads, but not to the beam oscillations.

After that, the algorithm was applied to the final focus of operating accelerator to improve it alignment.

The Figure 1 shows the initial behavior of the beam, and Figure 2 - it oscillations after 7 iterations of the adaptive alignment algorithm.

![Fig. 1 Vertical component of the beam oscillations (upper part of the picture) and suggested shifts of quads (lower part of the picture) before the Adaptive Alignment.](image)

It can be seen that after the procedure of adaptive alignment the beam reduced its oscillations about 10 times. The suggested shifts are about zero. It means that the quads are in practically strait line.
Fig. 2 Vertical component of the beam oscillations (upper part of the picture) and suggested shifts of quads (lower part of the picture) after 7 iterations of the Adaptive Alignment.

Conclusion

It was experimentally confirmed that the method of adaptive alignment works enough fastly and properly and can be applied to compensate as any sharp or fluent technical displacements of quads as the seismic vibrations of the ground.

The Adaptive Alignment is a convergent process even the BPM’s null-calibrations errors take place [2].

References


RF STRUCTURE DESIGN FOR THE TBNLC*

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Abstract

This paper summarizes our ongoing effort on the design of rf-extraction structures for the rf power source of a future TeV linear collider based on using the relativistic-klystron two-beam accelerator technology to driveNext Linear Collider structures (TBNLC). Several structure configurations involving different geometries and materials are examined using 2D and 3D computer code simulations. Three-cell detuned traveling wave structures and three-cell detuned choked-mode traveling wave structures are found to be the most attractive.

Introduction

The two-beam-accelerator (TBA) concept has an inherent high efficiency for power conversion from drive beam to rf power. LBNL/LBNL has launched a study based on a Relativistic-Klystron Two-Beam-Accelerator (RTBA) [1] to provide a rf power source for the Next Linear Collider (NLC). In this concept a single intense energy electron beam is used to power a number of rf output structures. A small fraction of the beam energy is extracted in each structure, and the beam is then reaccelerated before the next structure. The use of a single beam for many rf outputs can lead to increased efficiency and lower cost.

The main goal of this work is to provide a realistic design of rf-extraction structures using 3D numerical simulations. The rf-extraction structures should have surface electric field below the electrical breakdown voltage 70 MV/m, should have high efficiency with low BBU growth over 100 structures, and should be cost effective and compact. Each rf-extraction structure must produce 360 MW for the TBNLC parameters described in Table I.

Table 1. Power Source Requirements for TBNLC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>rf frequency</td>
<td>11.424 GHz</td>
</tr>
<tr>
<td>rf current</td>
<td>1.150 A</td>
</tr>
<tr>
<td>repetition rate</td>
<td>120 Hz</td>
</tr>
<tr>
<td>peak power/structure</td>
<td>360 MW</td>
</tr>
<tr>
<td>distance between extraction structures</td>
<td>2 m</td>
</tr>
<tr>
<td>pulse length</td>
<td>300 ns</td>
</tr>
</tbody>
</table>

We perform full three-dimensional electromagnetic simulations of the complete cavity geometry, including output structures via full 3D self-consistent particle calculations and with the assumption of rigid beam. Most of the 3D calculations are performed using the 3D electromagnetic code MAFIA with the stiff beam approximations. An alternative 3D electromagnetic code ARGUS is used to cross-check the MAFIA results, while full particle simulations are used to cross check the stiff beam approximation results.

The considered geometries include multi-cell TWS, choked-mode multi-cell TWS, and structures employing pill-box cavities, reentrant cavities, tapered cavities, disk-loaded cavities, choke cavities, and Bragg Reflector or corrugated cavities. Here we present the two most promising designs we obtained.

The transverse beam dynamics of the multi-bunches are first examined against the dipole wakefield assuming one macro-particle per bunch. Then wakefield effects within a bunch are examined.

Three-Cell Inductively Detuned Traveling Wave Structure (ID-TWS)

The 3-cell TWS have the following features: (1) They are inductively detuned, i.e. the phase velocity of the electric field of the structure is greater than the beam electron velocity, to enhance the longitudinal stability, (2) TWS is chosen to reduce the surface electric field, and (3) the smallest number 3 for TWS is chosen to minimize beam break-up (BBU).

Based on 2D calculations, earlier work of LBNL/LBNL lead to a conceptual design of the 3-cell inductively detuned traveling wave structure (ID-TWS) shown in Fig. 1.

![Three-cell traveling-wave output structure](image_url)

Fig. 1. Three-cell traveling-wave output structure. The structure is cylindrically symmetric with the exception of the two WR90 waveguides connected to the last cavity. Dimensions for particle simulations were p=8.75 mm, a=8.60 mm, b=12.43 mm, and t=2.50 mm.

We carry out 3D particle simulations of the 3-cell ID-TWS for a train of 1000 Gaussian bunches of 600 A of DC current with 1150 A of rf component. A sinusoidal output power is obtained after the initial transient ramp-up phase. After the ramp-up phase the time-averaged power of 180 MW from an output waveguide, or 360 MW per structure is indeed obtained. The output power is calculated by evaluating Poynting vector over the cross-sectional area at each WR90 output waveguide exit. The 3D simulation also indicate that the detuning angle between the field and electron bunches is 60 degrees rather than 90 degrees found in the periodic 2D geometry with no output structures.

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† bk consulting, 518 Bavarian Ct., Lafayette, CA 94549
Transverse Beam Dynamics in the 3-cell ID-TWS

Beam transport over many structures is a crucial concept in a TBA. The betatron node scheme is an effective method for reducing BBU. By spacing the structures at betatron wavelengths of the focusing system, particles experience the least transverse kick. In reality there exists some mismatch of this betatron node due to errors in the focusing systems, and nonuniformity in beam energy. The beam centroid can then be driven to oscillate with exponentially growing amplitudes. Here we wish to present the transverse beam dynamics in such realistic situations.

The transverse beam dynamics can be examined either in the real space utilizing the transverse wakefield, or in the frequency space utilizing the transverse impedance. The BBU of the 3-cell ID-TWS was studied earlier, in the frequency domain, using the OMICE code [2]. Here we present the BBU calculation in the real space via MBBU code [3]. Figure 2 shows the dipole wakefield of the 3-cell ID-TWS in the 2D approximated geometry. Shown are the transverse wakefields of a 11.4 GHz Gaussian bunch with $\sigma=3$mm (solid) and $\sigma=6$mm (dotted) where $\sigma$ is the standard deviation length of a Gaussian distribution. For clarity wakefields only up to about 6 bunch spacing are shown. The filled circles and open circles indicate the wakefields at centers of bunches. Higher wakefields are seen for the shorter bunches. Since a small increase in wakefield magnitude results in a cumulative BBU over many bunches and traveling many structures, the bunch length needs to be compromised with respect to BBU.

![Fig. 2. Transverse wakefield of a 11.4 GHz Gaussian Bunch with bunch-length standard deviation of 3mm(solid) and 6mm(dotted). The wakefields at center of each bunch are indicated as filled circles(3 mm) and open circles (6 mm).](image)

The MBBU code assumes each bunch as an object, ignoring interactions between particles within a bunch. First, for simplicity, we assume one macro particle per bunch and equal spacing between bunches. The transverse displacements, $\xi_j$, of the $j$-th bunch with energy $\gamma_j$ can be represented in the following BBU equation.

$$\frac{d}{dz} \left[ \gamma_j(z) \frac{d\xi_j}{dz} \right] + \gamma_j(z) k_B^2 f_j(z) \xi_j = \frac{f_{bh} G(z)}{l_0} \sum_{k=1} W((j-k)\delta z) \xi_k,$$

where $z$ is the axial coordinate in cm, $\delta z$ is the distance between bunches in cm, $k_B$ in $cm^{-1}$ is the betatron wavenumber due to the focusing field, $W$ is the transverse wake function in $cm^3$, $l$ is the average current in $z$ in $ka$, and $l_0=mc^2e=17.05 ka$. Here

$$G(z) = 1 \quad \text{for} \quad (\ell-1)L_p < z < (\ell-1)L_p + L_g$$

$$= 0 \quad \text{otherwise}$$

where $\ell$ is structure index, $L_p$ is the periodic length of structures, $L_g$ is one structure length, and BBU is tested over a device of 100 structures. The bunches experience a transverse kick while traversing the structures, and then translate down the beam pipe. The function $G(z)$ reflects this alternating process. The numerical integration is required only in the structure region, while we utilize the transfer matrix in the drift region. We can further simply the BBU equation if $L_g \ll L_p$. In such cases we can approximate the transverse momentum kick during traversing the rf-extraction cavities as a delta-function kick; $G(z) = L_p \delta(z-\ell L_p)$. We can then transform the equation into matrix multiplication.

In Figs. 3-5 we present the BBU results using the MBBU code for the wakefield of the Gaussian bunch of $\sigma=3$mm (solid line in Fig.2). For Figs. 3 and 4 only the wakefields at the bunch centers are considered in the BBU calculation. The initial beam displacements were assumed to be uniform with no transversal momentum for all cases. An average beam current of 600 $A$ with 10 MeV beam energy, and betatron length of 2 m are considered.

![Fig. 3. BBU for 3-cell ID-TWS for various energy spread within a bunch. The betatron node scheme is used assuming a 1% error in the average beam energy from the optimum value for all cases.](image)

In Fig. 4, we show the transverse beam centroid displacements with respect to the mismatch in focusing field or the beam energy at the end of 100 structures, for the 3-cell ID-TWS with the betatron node scheme, assuming $\pm 5\%$ beam energy spread within each bunch. The 3-cell detuned TWS shows acceptable BBU with the betatron node scheme with respect to $\pm 1\%$ error in energy flatness and field accuracy. For good beam transport it is expected that a $1\%$ error in focusing field can be tolerated. The BBU in Figs. 3 and 4 show
similar results as the previously published OMICE code results [2]. Detailed comparison of the two code results are being investigated.

![Normalized Beam Centrifor Displacements at 100th RF Structure](image)

Fig. 4. Relative growths after the 100th 3-cell ID-TWS vs. focusing field or beam energy mismatch from the optimum values. The betatron node scheme is used, assuming 5% beam energy spread within each bunch for all cases.

Next we include the finite size of a bunch and the wakefield effect within a bunch. Imagine that each filled circle in Fig. 2 is stretched along the solid line over a finite length; 2σ and 0.2σ. We then divide each bunch by 11 slices uniformly over 2σ and by 3 slices over 0.2σ respectively. The BBU results are shown in Fig. 5 over 100 structures with 0% and ±5% energy spread within each slice. Shown are results for one macro particle per bunch with zero length (solid), 3 slices over 0.2σ bunch length (dashed) and 11 slices per bunch over 2σ bunch length (dotted). Landau damping effect works more effectively with finite size bunches.

![Normalized Beam Centrifor Displacements](image)

Fig. 5. BBU over 100 structures with 0% and ±5% energy spread within each bunch. Shown are for bunches of zero length (solid) and for finite sizes of 0.2σ (dashed) and 2σ (dotted).

**Three-Cell Detuned Choked-Mode Traveling Wave Structures**

In order to transport a beam over many output structures one has to damp higher order modes (HOM), that lead to BBU and degrade the beam dynamics, while keeping the fundamental mode unaffected. Narrow structures on a pill-box cavity, or choked-mode cavity, with a beam pipe can trap the fundamental mode while higher order modes propagate into an absorber. Shintake [4] has proposed using a choke cavity structure for a high energy linac. Here we apply the concept to a 3-cell traveling wave choke structure for an rf-extraction structure. The choke structure shown in Fig. 6 is cylindrically symmetric except for the two output waveguides attached to the last cavity.

![Schematic of the 3-Cell TWS with choke](image)

Fig. 6. Schematic of the 3-Cell TWS with choke. The structure is cylindrically symmetric with the exception of the two WR90 waveguides connected to the last cavity.

**Table 2. Choked-mode TWS parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>cavity height</td>
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<tr>
<td>cavity width</td>
<td>8.75 mm</td>
</tr>
<tr>
<td>choked cavity width (d2)</td>
<td>6.45 mm</td>
</tr>
<tr>
<td>choked cavity height (d1)</td>
<td>6.45 mm</td>
</tr>
<tr>
<td>choked cavity gap</td>
<td>1.00 mm</td>
</tr>
</tbody>
</table>

The transverse wakefield is smaller with the choked-mode structure than without[5]. More importantly the HOMs should damp out in a choked-mode TWS even if they do not propagate out of the cavity structure. This reduction in wake fields represents a significant advantage for a choked-mode TWS.

We wish to thank Dr. A. Sessler for valuable discussions.

**References**


Operational Experience at the Superconducting Electron Accelerator S–DALINAC


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Abstract

The S-DALINAC is a recirculating superconducting electron linac operating at 3 GHz. The accelerator delivers cw-beam to various experiments with energies from 3 to 120 MeV and currents from 1 nA to 60 µA covering a wide dynamic range. Since August 1991, some remarkable progress has been achieved:

The unloaded quality factors of the twelve niobium cavities were increased by chemical treatment, now ranging from 8-10⁶ to 2·10⁸, while the accelerating gradients of all cavities exceed 5 MV/m by far.

In 1995, all cavities were equipped with new superconducting input couplers providing variable coupling strength. In addition, a superconducting 2-cell capture cavity (β=0.85) was installed as the first element of the injector. Beam transport properties of the main linac were improved by installation of three cold quadrupoles in the cryostat. All devices operate successfully.

Further measures in beam diagnostics were taken. Diagnostic stations for the determination of transverse and longitudinal beam properties, using transition radiation emitted from a thin foil and computer graphics processing, have been developed and are used routinely now. To measure easily even small beam currents without disturbing the beam, rf cavities with low Q have been developed. Using a simple setup, currents down to some nA can be detected.

Introduction

The S–DALINAC [1] is a superconducting recirculating linear electron accelerator at Darmstadt, the layout of which is shown in Fig. 1. The electrons, emitted from a thermionic cathode are electrostatically accelerated up to 250 keV. In the Chopper/Prebuncher section (at room temperature) the continuous electron beam gets its time structure, which is necessary for the following acceleration in the superconducting S-band cavities. The injector consists of a 2-cell capture cavity (see below), a 5-cell cavity and two one meter long 20-cell cavities fabricated from RRR 280 niobium and operated in liquid helium at 2 K. Within 5 meters, the electrons are accelerated up to 10 MeV and can either be used for low energy experiments or bent by 180° for injection into the main linac. With eight 20-cell cavities the energy of the beam can be increased by 40 MeV. The beam can either be recirculated twice or extracted after each linac passage. From the first recirculation the beam can be bent and matched to the undulator of the Free Electron Laser.

Figure 1: Layout of the S–DALINAC accelerator hall.

Accelerator Operation

Since August 1991 the S–DALINAC has delivered more than 11,500 hours of beamtime for a variety of nuclear and radiation physics experiments. The electron beam produced covers a wide range of energies and currents to fulfill the different needs. Energies up to 10 MeV from the injector are used for nuclear resonance fluorescence (NRF) experiments [2], for production of channeling radiation (CR) [3] and parametric X-rays (PXR) [4]. Beam energies from 22 to 120 MeV were used for high energy channeling and parametric X-rays as well as for coincident (e,e') and single arm (e,e') electron scattering experiments. These experiments use a cw beam with a bunch repetition rate of 3 GHz or 10 MHz for time of flight applications. For the Free Electron Laser (FEL) project [5], a bunch charge of 6 pC is necessary, which is obtained at a repetition rate of 10 MHz, using a subharmonic chopper/prebuncher section. The different energies and currents produced by the S–DALINAC together with the corresponding experiments are summarized in Tab. 1. The energy spread of the accelerator is ΔE/E = ±2.5 · 10⁻⁴.

Cavity Performance

In the fall of 1993 two ceramic windows of rf feedthroughs had developed strong leaks, which caused a degradation of the unloaded quality factor of most of the cavities to the lower 10⁶ range. Due to the limited cryogenic cooling (about 100 W at 2 K) this limited the achievable energy to 50 MeV even when recirculating the beam twice. Therefore it was necessary to increase the cavity Q₀ by chemical polishing of the inner surface of all cavities. In two maintenance periods all ten 20-cell cavities and the 5-cell cavity were taken out of the cryostat, chemically treated and reinstalled. Two different cleaning methods were applied: With

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the help of DESY we were pleased to use the TTF [6] chemistry and clean room infrastructure for two cavities. After ultrasonic cleaning, a layer of 1 μm thickness of the inner surface was removed by BCP (1:1:2). The cavities were rinsed with ultra pure water (18 MΩcm) and dried in a class 10 clean room. The other cavities were treated in our laboratory. After ultrasonic cleaning the inner surface was first oxidized by HNO3, then the oxide was removed by HF. Finally the cavities were rinsed with ultra pure water and dried with filtered nitrogen. As a result the unloaded quality factors of all cavities increased by at least a factor of two, reaching now $8 \times 10^8$ to $2 \times 10^9$, but still below the design value of $3 \times 10^9$. The accelerating gradients of all cavities exceed the design gradient of 5 MV/m by far, some cavities reach 10 MV/m after a short processing. The average gradient of all cavities is presently 6.7 MV/m, while the mean quality factor is $8.9 \times 10^9$. This determines in conjunction with the limited cryogenic cooling the maximum electron energy to 120 MeV at present.

Table 1: Delivered beams from the S-DALINAC.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Energy (MeV)</th>
<th>Current (μA)</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRF</td>
<td>2.5 - 10</td>
<td>40</td>
<td>3 GHz, cw</td>
</tr>
<tr>
<td>CR, PXR</td>
<td>3 - 10</td>
<td>0.001 - 10</td>
<td>3 GHz, cw</td>
</tr>
<tr>
<td>CR, PXR</td>
<td>35 - 85</td>
<td>1</td>
<td>3 GHz, cw</td>
</tr>
<tr>
<td>(e,e'), (e,e')</td>
<td>22 - 120</td>
<td>5</td>
<td>3 GHz, cw</td>
</tr>
<tr>
<td>FEL</td>
<td>30 - 38</td>
<td>$2.7A_{peak}$</td>
<td>10 MHz, cw</td>
</tr>
</tbody>
</table>

After several warmup and cooldown periods another effect was observed. While all the cavities were not touched in any sense (not removed from the cryostat, held under vacuum), some of them show a certain time dependency of the unloaded quality factor. Directly after cooldown, some cavities start at a rather low Q0 and show field emission at a certain gradient. After simply operating the cavities at a medium gradient for 15 minutes the Q0 increases by a factor of 3 and the field emission observed before vanishes completely. This effect was observed many times for certain cavities, while other cavities show no change in the unloaded quality factor during operation.

Accelerator Improvement

Together with the replacement of the sc cavities, several new components were installed in the accelerator. All cavities were successively equipped with new rf input couplers (Fig. 2) providing variable coupling strength ($10^7 \leq Q_{coup} \leq 10^{10}$) by changing the distance between the antenna and the coaxial resonator. This variability has proven to be very useful, since it allows an optimum in matching the different beamloading and microphonic perturbation conditions. For diagnostic purposes one is able to couple critically.

As the first element of the sc injector a new 2-cell capture cavity has been installed. The cavity has an reduced phase velocity of $\beta = 0.85$ and provides an energy gain of 350 keV over a length of 8.5 cm when operated at a gradient of 5 MV/m.

Figure 2: Cut of the tuneable sc input coupler.

To improve the transverse acceptance of the accelerator four quadrupoles were installed on the main linac axis. One quadrupole is placed outside the cryostat in front of the linac, while the other three quadrupoles had to be installed inside the insulating vacuum of the cryostat. Therefore they were designed to be superconducting, using a NbTi wire (NbTi filament surrounded by Cu) and special low temperature magnetic material called CRYOPERM 10 to form the poles and return chokes. The maximum gradient is 1.5 T/m, the effective length 5.6 cm. After installation it turned out, that the cooling of these quadrupoles is not sufficient (they only reach 22-25 K). Nevertheless, the resistance of the coils becomes low enough to operate them at their nominal gradient with a dissipation of 0.5 W per quadrupole.

Beam Diagnostics

Since 1994, several new beam diagnostic stations along the accelerator have been installed. A detailed discussion of beam diagnostics at the S-DALINAC using transition radiation can be found in [7, 9]. Therefore only a short description for the determination of transverse and longitudinal beam properties is given. Moreover, a new setup measuring the beam current without disturbing the beam using a low-Q rf-cavity is reported.

Transverse Phase Space

The experimental setup for observation and analysis of optical transition radiation (OTR) is shown in Fig. 3. The radiation emitted from a 25 μm thick aluminium foil being hit by the electron beam is observed through an vacuum window with a CCD camera which is well shielded to avoid radiation damage. The signal from the CCD is digitized by a framegrabber installed in a PC. The analysis of the grabbed picture is performed on a alphasir using the special data language IDL [8]. This setup allows within seconds emittance measurements, using the three gradient method, and has been used at energies ranging from 250 keV...
to 120 MeV. Currently five OTR-setups are installed along the beamline and are used routinely.

![Diagram](image)

Figure 3: OTR diagnostic station.

The same setup is used to determine the energy spread of the electron beam in a dispersive section of the beamline. The online determination of the energy spread is an important help in optimizing the rf phases of the cavities.

### Longitudinal Phase Space

For operation of the FEL, knowledge of the bunch length, i.e. the peak current is essential. The setup shown in Fig. 4 uses the coherent part of the transition radiation in the far infrared. The radiation passes through a Michelson interferometer consisting of a mylar beamsplitter, one fixed and one movable mirror and is detected in a pyroelectric detector. Analyzing the measured autocorrelation in frequency space taking into account the spectral properties of the setup finally yields a bunch width of 4 ps in a nearly gaussian distribution, which was confirmed by a streak camera measurement using spontaneously emitted light from the undulator of the FEL. A detailed description of the setup and the analysis can be found in [9].

### Nondestructive Beam Monitoring

To measure the beam current and position without stopping the beam new rf cavities were developed. The low quality factor (1800 for the current monitor, 1000 for the position monitor) of these cavities build from stainless steel 4301 leads to a negligible temperature sensitivity. Once calibrated these monitors operate without temperature control and need no adjustment. With a simple setup using frequency modulation a sensitivity of 20 nA for the current monitor and 0.3 mm/μA for the position monitor could be achieved. Presently two monitors are installed, one in the injector and one in the extraction beamline.

![Diagram](image)

Figure 4: Interferometer setup for bunch length measurement with transition radiation.

### Outlook

For further increase of the quality factors of the sc cavities, a high pressure water rinsing system will be installed and will be available in fall of this year, which will hopefully lead to a $Q_0 = 3 \times 10^9$. The beam transport system will be further optimized which is expected to result in improved transverse stability and a reduced energy spread by making use of nonsynchronous recirculations. Beam diagnostics especially the nondestructive monitoring will be installed in every recirculation and in front of every experimental area.

### Acknowledgement

It is a pleasure to thank H. Lengeler and H.A. Schwettman for many fruitful discussions and numerous advice. The help of S. Calatroni in the production of the rf couplers is greatly acknowledged. We are very much indebted to many colleagues at DESY, in particular to A. Matheissen, O. Peters and S. Wolff for their tremendous help and support. We take the opportunity to thank H. Gaiser and the galvanic workshop at GSI, as well as the mechanical workshop at CERN, for their continuing help. For his help in numerical simulations we have to thank T. Weiland.

### References

Invited Talk Session TU1

Chairman: C.W. Schmidt

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REVIEW OF ELECTRON-POSITRON LINEAR COLLIDERS
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Abstract

This paper reviews the work performed by the International Linear Collider Technical Review Committee to examine and compare the designs and R&D status of the various e⁺e⁻ linear colliders currently under study in the world. The paper summarizes the highlights of the report issued in December 1995 and, where applicable, indicates some of the changes that have occurred since its publication.

Introduction

In June 1994 at EPAC 94 in London, the International Council of the Interlabatory Collaboration of R&D Towards TeV-scale Electron-Positron Linear Colliders created an International Technical Review Committee (TRC) consisting of close to sixty scientists, and charged it with producing a report bringing together in one document all the e⁺e⁻ linear collider designs and technologies in the world. The machines to be studied and compared were to start at c.m. energies of 500 GeV and have expansion capability to 1 TeV and above. The report [1] was completed in December 1995. The author of this paper was Chair of the TRC, T. Weiland represented the Secretariat, and E. Mitchell at SLAC was in charge of production. The TRC report is 186 pages long and only some of the highlights can be summarized here.

The particle physics community has been greatly interested in such an accelerator for some years, and, if anything, this interest has grown with the decision to proceed with the LHC. Indeed, these two machines are highly complementary in what they can contribute to the field. The linear collider will be a precision tool to study t̅t̅ production at threshold and above. If the Higgs and/or supersymmetric particles exist, the linear collider will be instrumental in discovering and/or studying them. If none of these particles exist, the machine will make it possible to explore other mechanisms to explain electroweak symmetry breaking. These are some of the most burning issues to be elucidated in the next few years. The e⁺e⁻ linear collider also has the potential of producing exciting physics from e⁺e⁻, e⁺γ and γγ collisions, and of involving other applications such as FEL's and other technologies.

The TRC report consists of six chapters. The first chapter is a description of six machines at 500 GeV c.m. energy: TESLA, SBLC, JLC (S-, C- and X-band), NLC, VLEPP and CLIC. The second chapter includes the reports of six working groups respectively describing and comparing Injection Systems, Damping Ring and Compression Systems, Linac Technology, Beam Dynamics, Beam Delivery and Experimentation for the various machines. The third chapter describes methods proposed for each machine to upgrade their c.m. energies to 1 TeV and to obtain e⁺e⁻, e⁺γ and γγ collisions. Chapter 4 describes on-going experiments and test facilities, Chapter 5 discusses present and future areas of collaboration, and Chapter 6 presents conclusions. Given that this conference is devoted primarily to linacs, the emphasis in this paper is focused on this subject.

Machine Parameters and Designs

Overall and final focus parameters for all the machines are shown in Table 1 and those for pre-linacs, damping rings and main linacs are given in Table 2. For each machine, there are two columns: the first one gives the numbers listed in the TRC report of December 1995, the second one shows new numbers where an update has taken place as of August 1996. As can be seen, all the machine designs have now reached luminosities above 10³⁵ cm⁻² sec⁻¹ which with the exception of VLEPP, are obtained by using many bunches per rf pulse. The main linacs which operate at the lower rf frequencies have the lowest gradients and are therefore the longest. For all machines, the ultimate and most challenging specification is the σ⁺' at the IP which ranges between 19 and 3 nm. For reference, the FFTB at SLAC at 50 GeV has so far reached a σ⁺ of 70 nm. Let us now characterize the various machines by dividing them into four groups in order of ascending rf frequency: 1) TESLA, 2) SBLC, JLC(S), JLC(C), 3) JLC(X), NLC (with its future TBNLC option), VLEPP, and 4) CLIC. The building blocks of the various main linac "power units" for these machines are shown in Fig. 1. The design, engineering, mass production and cost of these "power units" are crucial to the success of whichever linear collider ultimately gets selected and built because of the large quantities of identical components involved.

TESLA (Group 1)

This machine is in a category by itself because it is the only one that uses superconducting accelerator sections for the main linacs. The rf frequency is the lowest (1.3 GHz) and the beam aperture is the largest (2a = 7 cm). All the characteristics of TESLA result from these basic features. The advantages are that the rf pulse is long, the bunch spacing is wide (708 ns), the transverse wakesheds [which for single bunches vary roughly as λ⁺(a/λ⁺)²] are weakest, and corresponding alignment tolerances are loosest (by at least a factor of 5 for multibunches). As a result, emittance growth will be easiest to control. Ground motion effects may be compensated by fast feedback controls and by bunch-to-bunch steering at the end of each linac. Note, however, that the decision to reduce the repetition rate from 10 to 5 Hz has forced σ⁺ down from 64 to 19 nm to conserve luminosity. The biggest challenge for TESLA is to perfect the rf superconducting technology to the point where accelerating gradients of 25 MV/m can be attained reliably with Q₀'s of at least 5 × 10⁹, and that costs can be made affordable. The main linacs consist of 616 power units, each involving a pulsed modulator supplying an 8 MW peak power klystron which in turn drives 32 one-meter long superconducting structures in four long cryostats, incorporating HOM couplers and quadrupoles. Related


requirements are the compensation of the mechanical cavity detuning due to the Lorentz force, the absolute need to suppress field emission to avoid heat losses and captured dark current, the construction of a variable coupler, and alignment of components within the cryostats. The electron bunch train can be produced from a laser-driven gun but the positron bunch train is too intense for a conventional target to survive. Hence, the intent is to shoot the spent e⁺ beam after the IP through an undulator to produce γ's which then produce positrons in a thin rotating target. The 3.2 GeV damping rings (often called dog-bones because of their shape) must be designed to accept and damp each long train of bunches (240 km) in a “compressed” circumference (17 km). Finally, since the main linacs are already very long (32 km), the expandability to 1 TeV c.m. energy will preferably be achieved, at least in part, by an increase in gradient (say 40 MV/m). Such a gradient will require an additional 25% increase in length to 40 km. The desired luminosity at 1 TeV can be reached with a σₓ of 6.5 nm and a δₓ of 2.5%.

**SBLC, JLC(S) and JLC(C) (Group 2)**

SBLC and its close cousin, JLC(S), benefit from the most widespread and proven technology developed at SLAC and elsewhere for many years. Roughly speaking, their main linacs are equivalent to 7–10 SLAC linacs. SBLC has the next-to-largest σₓ (15 nm) after TESLA and gets its luminosity at 50 Hz repetition rate with 333 bunches per pulse spaced 6 ns apart and 1.1 × 10¹⁰ particles per bunch. JLC(S) gets its luminosity with a σₓ of 3 nm, 50 Hz, 50 bunches spaced 5.6 ns apart and 1.44 × 10¹⁰ particles per bunch. For the 500 GeV c.m. case, SBLC does not use pulse compression whereas JLC(S) uses SLED I. The respective power units are shown in Fig. 1. Because of multibunch operation, the accelerator structures are designed to detune and damp transverse wakefields. SBLC has tested 6 m-long sections with two sets of higher-order mode couplers along their length, which can also be used as pick-ups to align the sections by minimizing beam induced fields. Sputtering of a 20 μm-thick low conductivity material onto the disk edges is also being used to differentially reduce the Q of undesirable modes by a factor of 5 without affecting the fundamental mode Q by more than 5%. Initial alignment tolerances are on the order of 100 μm and sections must be mounted on girders to within a tolerance of about 30 μm rms. JLC(S) uses 3.6 m-long sections similar to the SLC. The electron and positron sources for SBLC are similar to TESLA’s, those for JLC(S) resemble those of the SLC but have not yet been designed in detail. The energies of the damping rings are respectively 3.15 and 1.98 GeV. Extension to 1 TeV c.m. for SBLC is envisaged by doubling the number of klystrons and adding pulse compressors to double the gradient within the original machine length. No upgrade option to 1 TeV has been offered for JLC(S).

JLC(C) was not considered in any detail in the TRC report because experimental work at C-band had not yet started at KEK at the time. Since then, an active R&D program has been launched on the rf components, including a 50 MW peak power klystrom, a choke-mode type, 1.8 m-long accelerator structure and a multicell coupled cavity system for a short SLED II pulse compressor. The choke-mode structure eliminates the multibunch wakefield problem and has an alignment tolerance of 30 μm. The beam characteristics are similar to those of the X-band design, except for a longer bunch length. Extension to 1 TeV c.m. energy would be obtained by doubling the klystrom output power to 100 MW and increasing the length of the main linacs by 40%.

**JLC(X), NLC and VLEPP (Group 3)**

Although VLEPP is designed for 14 GHz while JLC(X) and NLC use 11.4 GHz for their main linacs, these three
machines can be described in a single group because of their technological similarities. JLC(X) and NLC have similar luminosities, repetition rates, numbers of bunches per pulse and charges per bunch. The $\sigma_y$ at the IP for JLC(X) is 3 nm whereas that for NLC is about 6 nm, but this difference does not arise from any fundamental differences in design. There is also a slight difference in $\sigma_y$, and crab-crossing at the IP is proposed for NLC whereas it may not be needed for JLC(X). The main difference between the two machines appears in their main linac gradients (57 MV/m for JLC(X) vs. 35 MV/m for NLC) and results from the differences in their power unit designs (see Fig. 1). JLC(X) proposes to use the delay line distribution system (DLDS) whereas NLC uses SLED II, possibly to be replaced by the more efficient binary pulse compression (BPC) at a later date. The NLC klystron is planned to be a 50 MW tube (later to be upgraded to 75 MW) with periodic permanent magnet (PPM) focusing, which is currently being tested successfully at SLAC. The JLC klystron will probably be similar. R&D toward efficient and simplified modulators is crucial for eventual economy of electric power and manufacturing costs. For accelerator structures, NLC will use sections in which transverse deflecting modes are both detuned (within a Gaussian distribution) and damped to a Q of about 1000 (by coupling to four external parallel rectangular matched manifolds). First tests of this so-called DDS structure indicate that its fabrication can be achieved successfully by diffusion bonding of cups with cell-to-cell alignment better than 4 $\mu$m. It is likely that JLC(X) will use very similar sections, albeit 1.3 m long. The electron bunch trains for both machines will be produced by laser-driven photocathode guns, and the positrons by improved SLC-type sources, in combination with various L-band and/or S-band pre-accelerators. The pre-damping and damping ring energies are all at about 2 GeV.

VLEPP is based on a design with a single bunch per rf pulse which does away with the multibunch wakefield problem. This design must get its luminosity from a much greater charge per bunch ($2 \times 10^{11}$ particles) which unfortunately leads to very high backgrounds. The VLEPP rf power unit can also be seen in Fig. 1. In theory, it leads to a loaded gradient of 91 MV/m. For extension to 1 TeV c.m., JLC(X) and VLEPP would be doubled in length whereas NLC would get there by a 20% increase in length (built-in from the beginning), a doubling in the number of klystrons and an increase in their power from 50 to 75 MW. Alternatively, if the TBNLC (two-beam) technology based on drive beams accelerated by induction linacs were to become successful in the future, the NLC could have its array of klystrons, modulators and rf pulse compressors replaced by 64 sequential drivers, each 300 m-long (see Fig. 1) with reacceleration modules and transfer structures to supply the individual linac structures with the desired rf pulses.

**CLIC (Group 4)**

CLIC occupies a unique position in parameter space. The IP spots are similar to those in Group 3. The machine is characterized by the highest linac rf frequency, highest dark current capture field and potentially highest gradient. It requires many innovations, has the strongest wakefields, and therefore the tightest fabrication and alignment tolerances. The rf power is generated by an intense drive beam, accelerated by LEP-type superconducting structures, which induces the power in special transfer structures. The problem of producing thousands of klystrons, modulators and rf pulse compressors is replaced by having to create two high-current drive beams with a bunch time structure capable of generating rectangular rf pulses at 30 GHz. The problem of producing these drive beams and then conserving their phase space qualities along the full length of the linacs is a major challenge. An advantage of the CLIC two-beam scheme is that it allows all the components to be housed in one tunnel. The front end of the main e$^+$e$^-$ beam generation is analogous to the front end of the SLC. A number of design features of these drive and main beams remain to be elucidated, particularly for 20 bunches/pulse operation which has recently been chosen to bring up the luminosity within the range of the other machines. For 1 TeV c.m. energy, both the drive and main linacs would be doubled in length.

**Conclusions**

Because of lack of space, there are many topics in the TRC report that cannot be reviewed in this paper. Fortunately, many other papers at this conference deal with recent important linear collider developments. Worldwide investment in this field is spawning a vast amount of new knowledge and technologies. The SLC at SLAC and the new test facilities at DESY, KEK, SLAC, BINF, CERN and LBNL are contributing to an explosion of R&D. New laser-driven photocathode electron sources with 80% polarization have become a reality, and new positron sources and pre-linacs are undergoing design. The very small emittances that must be created by the damping rings and preserved through the bunch compressors, main linacs, beam delivery systems and final foci are giving rise to new ideas about instrumentation, alignment, stability, collimation and beam containment. New insights are being gained into beam dynamics (dispersion-free and wakefield-free steering, transient beam loading) and into the important field of ground vibrations over a wide range of frequencies ($10^{-2}$ to $10^{12}$ Hz) and coherence lengths. Finally, a whole new approach towards design for manufacturing (DFM) to decrease mass production costs while preserving tolerances, cleanliness to avoid field emission and dark current, high vacuum conditions, and above all, reliability of operation, is being introduced into the field of accelerator fabrication and pricing.

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**References**

SLC Status and NLC Design and R&D

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Introduction

In this paper, we will first review the status of the Stanford Linear Collider (SLC). In particular, we will discuss the luminosity and performance issues and the accelerator studies that relate to future linear colliders. Next, we will describe the present state of the Next Linear Collider (NLC) design and the ongoing R&D effort which is, in addition to the work at the SLC, supporting the design. This includes extensive ground motion measurements to verify the required stability, measurements of the dipole wakefields to verify the performance of the Damped-Detuned accelerator Structures (DDS), and tests of the rf structure BPMs that are needed to align the structures to the beam trajectory. It also includes the development and fabrication of the X-band structures, klystrons, and rf pulse compressors that are needed to accelerate the beams with gradients in excess of 50 MV/m.

It should be noted that much of the material reported here is described in greater detail in other papers submitted to this conference and thus the appropriate references are included throughout. In addition, because of space limitations, we only briefly describe the design of the NLC and, instead, concentrate on the R&D that is supporting the design; detailed descriptions of the NLC design can be found in Refs. [1, 2, 3].

SLC Status

The 1996 SLC/SLD physics run was not as successful in terms of luminosity as was initially expected. There were numerous operational difficulties, including a fire in the cable tray of the North Damping Ring, a dirty vacuum vent in the same ring, and poor accelerator availability. The poor availability and frequent faults made optimizing the luminosity difficult. Regardless, the average luminosity during the physics run was slightly better than that obtained during the 1994–1995 collider run; the luminosity recorded by the SLD detector per week and the integrated luminosity are plotted in Fig. 1.

Figure 1: Luminosity history in the SLC.

The increase in average luminosity was primarily due to an increase in the beam currents at the IP. The charge per bunch was increased from $N \approx 3.5 \times 10^{10}$ in 1994 and 1995 to roughly $N \approx 4 \times 10^{10}$ in 1996.

Although the 1996 collider run did not attain the luminosity desired, a new high resolution vertex chamber, the VX3, was commissioned in the SLD and an enormous amount was learned about both the operation of the SLC as well as the accelerator physics and operational issues relevant to a future linear collider. In particular, significant progress was made in the following areas:

- Beam-based feedbacks
- Beam collimation and collimator wakefields
- Beam jitter
- Sub-micron beam size diagnostics.

We will describe each of these issues in more detail subsequently.

Beam-Based Feedbacks

The SLC utilizes over 30 fast beam-based feedback loops to control and stabilize the beams and most future linear collider designs are even more heavily reliant on the beam-based feedback systems. Unfortunately, during the previous SLC runs, it was found that the gain, and thereby the frequency response, of the feedback systems had to be reduced substantially to prevent the feedbacks from oscillating [4]. This was found to be especially true in the linac where many feedbacks are "cascaded" to prevent them from interfering with each other. The principle of the cascade is that each feedback loop transmits what it measures to the next downstream loop with the assumption that the trajectory deviation will be corrected and thus the downstream feedback should not respond to it. To allow the cascade system to adapt to changes in the optics and the energy profile along the linac, the cascade transfer matrices are calculated adaptively from the natural beam jitter.

Studies during the 1994–95 and 1996 collider runs, identified three primary performance limitations:

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Feedback transfer matrices had significant errors — partly due to optics modification from transverse wakefields,

Cascade assumes purely linear transport matrices through the linac and thus the feedback loops only talk to the next downstream loop but wakefields and chromatic effects make the linac transport nonlinear,

Cascade adaption does not correctly account for the finite BPM resolution yielding incorrect transfer matrices between feedback loops.

After these problems were identified, near perfect performance was attained at low currents, where the wakefields are less important, and when the cascade matrices were calculated from dedicated oscillations where the measurements were not limited by the finite BPM resolution. This was important because it verified the feedback principles although it suggested that the algorithms need to be modified. In the future, at the NLC, the cascade matrices will likely be calculated from dedicated oscillations and the cascade system will be modified to account for the nonlinearity of the beam transport through the linac.

During the diagnostic process another important realization was made, namely, that different feedback algorithms have dramatically different sensitivities to errors. The SLC beam-based feedbacks do not use very aggressive algorithms. The cross-over frequency, below which the feedback damps rather than amplifies incoming oscillations, is $\frac{1}{\pi} f_{\text{rep}}$, where $f_{\text{rep}}$ is the sample rate. In the past, members of the linear collider community have suggested using far more aggressive feedback systems. For example, the simple double-dead-beat system, which uses the two previous measurements to estimate the next, has a higher cross-over frequency, $2 f_{\text{rep}}$, and a faster rate of damping. Unfortunately, these systems were found to be extremely sensitive to errors. In fact, even relatively small changes to the SLC feedback algorithms were seen to perform much worse when realistic errors were included. At this time, the details of the error sensitivity are not understood and this requires additional study.

Beam Collimation

During the 1994–1995 SLC run, it was noticed that optimal luminosity was found when the beams had large wakefield tails at the end of the linac. It was suggested that these wakefield dilutions were required to cancel some wakefield dilutions further downstream and this led to a study of the beam collimators [5].

Over the years, the SLC has installed a large number of collimators to reduce the backgrounds in the detector and this is also felt to be essential for a future linear collider. On inspection at the end of the 1994–95 run, it was found that many of these collimators were badly damaged. The collimators had been coated with a layer of gold to reduce the number of backscattered particles. Unfortunately the thermal contact between the gold layers and the body of the collimators was insufficient and the beam melted a very irregular channel through the gold [6]. This caused wakefields that were roughly 25–50 times larger than expected. Most of these damaged collimators were replaced for the 1996 run. To prevent similar damage, the replacement collimator jaws were coated with either vanadium or TiN. Both of these coatings have resistivities that are roughly 10 times larger than that of the gold but it was thought that they would have much better survival.

Measurements made during the 1996 SLC run [6] showed that the geometric component of the transverse wakefield was in agreement with the results of MAFIA calculations but the resistive wall wakefield of both the vanadium-coated collimators and the undamaged gold-coated collimators was roughly a factor of four higher than expected. The reasons for this discrepancy are still not explained and a facility is being planned at SLAC to test different collimator geometries and materials to gain further understanding [7].

Transverse Beam Jitter

Transverse beam jitter has two effects: it decreases the luminosity by decreasing the overlap of the two colliding beams and, more importantly, it makes the diagnostics more erratic and harder to interpret, thereby decreasing the effectiveness of the tuning procedures. During the 1994–1995 SLC run, many sources of transverse beam jitter were traced and eliminated [8]. Much of the jitter was found to arise from quadrupole vibrations induced by pressure surges in the cooling water system and vibrations from the water pumps. These were and are being corrected by modifying the quadrupole supports and the water pumps.

Another significant source of jitter on the electron beam was found to arise from the long-range transverse wakefield kicks due to the preceding positron beam. This source was reduced by changing the linac focusing lattice so that the electron and positron bunches have significantly different phase advances and thus the electron bunches are no longer driven resonantly by the positron beam [9].

Unfortunately, there still remains a 'white noise' source, that causes the vertical trajectory jitter to grow uniformly along the length of the linac by roughly $0.3 \sigma_y$, whose source was undetermined. While damaging to SLC operation, this would also be a significant concern for NLC operation. There had been a number of candidates considered for this jitter, including dark current in the linac structures that drive transverse wakefields, higher-order correlations on the injected beam that then, due to the transverse wakefields, cause the motion of the bunch centroid to increase [10], and the more prosaic effect of 10% bunch length fluctuations [11] that arise from the sawtooth instability in the damping rings [12]. This later effect, where the variation of the bunch length changes both the loading due to the longitudinal wakefield and the deflections due to the transverse wakefields, describes the observed jitter well [13]. Measurements have confirmed that there is a high degree of correlation between the linac jitter and the sawtooth signal from the damping rings [10].

Sub-Micron Beam Diagnostics

Finally, additional diagnostic tools were commissioned including the 'laser wire' [14] which was installed inside the SLD detector. The laser wire is created by focusing an intense 349 nm laser to narrow spot, about 380 nm with a Rayleigh length of
5 μm. The $e^-/e^+$ beam is then scanned across the laser and the beam size is inferred from the rate of Compton backscattering. During the end of the 1996 SLC run, the laser wire was commissioned and found to have a width of 400–500 nm, roughly 20% greater than design but still more than sufficient for SLC operation. In the NLC, such devices will be needed throughout the linacs and final focus to measure the beam emittance.

Another important diagnostic is a technique of inferring the individual beam sizes at the IP using both the beam-beam deflection scans, which just yield the convoluted size of the two beams, and the BPMs to measure the energy loss of the outgoing beams [15]. This technique will be very important at the NLC where, at present, the beam-beam deflection is the only diagnostic capable of resolving the beam sizes at the IP.

**NLC Design and R&D**

The Next Linear Collider (NLC) [1, 2, 3] is a future electron/positron linear collider that is based on copper accelerator structures powered with 11.4 GHz X-band rf. It is designed to begin operation with a center-of-mass (cms) energy of 500 GeV (which could be decreased to 350 GeV to study the top quark) and to be adiabatically upgraded to 1 TeV cms. At the onset, the entire infrastructure will be constructed for the 1 TeV cms upgrade. The upgrade to 1.5 TeV could proceed either by a straightforward 50% extension of the linac length, a trombone is incorporated into the design to facilitate this extension, or by improvements in the rf technology, increasing the accelerating gradient; the final focus and collimation sections have been designed with sufficient length to facilitate the upgrade to 1.5 TeV cms.

The initial rf system for 500 GeV cms is based on components that have been developed or can be expected in the near future. Specifically, it is composed of 50 MW X-band klystrons, SLED-II rf pulse compressors, and Damped-Detuned accelerator Structures (DDS) that reduce the long-range transverse wakefields by a combination of weak damping and detuning of the dipole mode frequencies. The upgrade to 1 TeV is based on expected improvements in the rf technology and would proceed by replacing the 50 MW klystrons with 75 MW klystrons and doubling the number of modulators and klystrons.

The NLC design, shown schematically in Fig. 2, contains all of the components found in the SLC. There are sources, damping rings, and bunch compressors to produce the low emittance beams, long linacs to accelerate the beams to the desired energies, and collimation sections and final foci to produce the small spots needed at the IP. In this paper, we cannot describe the various components of the design and instead we refer to the recent design study that was completed and documented in the “Zeroth-Order Design Report for the Next Linear Collider” [1]. This is a complete systems study with engineering support in crucial areas to verify feasibility.

The design incorporates many of the hard lessons from the SLC. Throughout the design, we have been careful to provide substantial operating margins on all the subsystems; if all of the subsystems perform as designed, then the luminosity would be roughly three times higher than that specified. In addition, the tolerances were specified to attain the design luminosity over a large range in operating parameters, such as bunch charge and beam emittance, and not just at a single point. Finally, the design includes extensive beam collimation sections and detailed diagnostic layouts and tuning procedures; all of these have been added onto the original SLC design as operational experience has been gained. The NLC design was reviewed by an external committee in March of 1996 and was presented to the 1996 DP/DPB Snowmass meeting. At this time, a larger engineering effort is being started to further study the reliability issues as well as studying the issues associated with mass manufacture of components and, ultimately, producing a cost estimate and schedule.

![Figure 2: Schematic of the NLC; from Ref. [1].](image)

As stated, detailed descriptions of the NLC design can be found elsewhere. In the next sections, we will describe some highlights of the ongoing R&D program that supports the NLC design.

**Ground Motion Measurements**

Because the NLC operates with low emittance beams which are focused to small spot sizes, there was concern that fast ground motion could cause beam jitter, leading to a significant loss in luminosity, while slower ground motion could prevent one from ever being able to properly align and tune the collider. Recent measurements at SLAC of the fast ground motion (0.01 Hz<
f < 100 Hz), using very high resolution seismographs, have confirmed the amplitude of the ground motion but have shown that the large amplitude motion is highly correlated [16]. Such motion has relatively little impact on the design and, with the exception of the final doublets which may need additional stabilization, the motion would not cause a significant (> 2%) source of luminosity loss. Of course, the design must be engineered carefully to ensure that any additional 'cultural' noise is minimized; measurements of the FFTB magnets at SLAC indicate that this is reasonable goal.

At much lower frequencies, it has been suggested that the ground has a diffusive behavior which can be described by the ATL rule [17]. This slow uncorrelated motion would cause the beam trajectory to drift with time requiring additional steering and tuning. Measurements of the motion of the magnets in the FFTB beamline at SLAC over a period of 180 hours found motions much smaller than previously reported [18]. This emphasizes the importance of site selection, although the FFTB tunnel could not be considered a quiet or ideal location. Finally, detailed simulations of the NLC linacs show that this slow ground motion should not significantly impede the operation of the collider [19].

Klystrons [20]

As described, the NLC will initially rely on 50 MW klystrons which will then be upgraded to 75 MW klystrons to achieve a full 1 TeV in the center-of-mass. At this time, the XL series of X-band klystrons are producing the required 50 MW pulses [21]. The latest klystron in the XL series, the XL4, produces 75 MW with an efficiency of 48%. The tube is very robust with stable output power and an infrequent fault rate. Furthermore, the performance of the XL series has been in close agreement with the simulation results giving confidence in our ability to design klystrons with the aid of computer simulation.

Unfortunately, the XL klystrons all use solenoidal focusing and these solenoids are both expensive and consume a significant amount of power. Thus, a Periodic Permanent Magnet (PPM) focused klystron, shown schematically in Fig. 3, has been developed [22]. In initial tests just completed, this klystron produced 1.5 μs pulses of 52 MW at 55% efficiency; this exceeds the requirements for the NLC. In addition, the klystron produced 300 ns pulses of 60 MW at 63% efficiency. At the higher power, the length of the pulse was limited due to rf breakdown and thus the klystron has been opened and the cavities are being coated with TiN. The next PPM klystron is being designed to produce 75 MW which will meet the requirements for the 1 TeV cms NLC upgrade.

Damped-Detuned Accelerator Structures [23]

To control beam-breakup of the long bunch trains in the NLC linacs, the long-range transverse wakefields in the accelerator structures must be reduced. This is done by a combination of detuning the dipole modes so that there is a ~10% Gaussian spread in the frequencies, causing the dipole modes to rapidly decohere, and damping the dipole modes with Q's of roughly 1000 to prevent the modes from re-cohering at a later time. The damping is added to the Damped-Detuned Structures (DDS) by coupling each cell to four manifolds running along the length of the structures as illustrated in Fig. 4. Recent measurements of the transverse wakefields in the DDS structures, which were in excellent agreement with theory, showed that the wakefield is damped below the limit required for the NLC [23]; additional optimization of the matching into the manifold loads should reduce the wakefields even further.

Figure 3: Schematic of PPM klystron; from Ref. [1].

Figure 4: Schematic DDS structure; from Ref. [1].

The four damping manifolds also provide a straightforward method of measuring the induced dipole modes. In the NLC, the accelerator structures, which will be mounted on remote movers, need to be aligned to the beam trajectory by minimizing these measured dipole mode signals with high resolution. Furthermore, because the frequencies of the dipole modes vary along the structure, one can determine what portion of the structure is misaligned. This technique was tested during the recent wakefield measurements [24]. The analysis of the resolution was complicated by a very large kink in the structure due to an unfortunate construction error. Regardless, the measurements reproduced the measured alignment, including the kink. Further analysis is required but the initial results look extremely promising.
NLC Test Accelerator [26]

The NLC Test Accelerator (NLCTA) [25] is designed to both test all of the rf components required for the NLC and to verify the beam loading compensation technique that is needed to control the energy spread along the NLC bunch train. It consists of a 70 MeV X-band injector, a magnetic chicane, and six 1.8 m X-band (11.4 GHz) accelerator structures that are designed to suppress the long-range transverse wakefields. The X-band injector and the six main accelerator structures will be powered with four 50 MW X-band klystrons, whose peak power is compressed with SLED-II pulse compressors, producing a 50 MV/m acceleration gradient.

At this time, the entire NLCTA beamline, except for the six accelerator structures, has been installed and is under vacuum. Beam from the gun has been accelerated to 60 MeV in the injector and transported to the final dump. Commissioning will begin this fall as the additional klystrons and accelerator structures are installed [26].

Conclusions

Although the 1996 SLC/SLD physics run did not deliver the luminosity expected, the SLD detector commissioned a new vertex chamber, the VXD3, and the run yielded a lot of useful accelerator physics. Many performance limitations were understood, giving important information for both SLC and future linear colliders. This includes experiments on beam-based feedback, collimator wakefields, a determination of the ‘anomalous’ jitter, and the laser wire.

Recently, a design study for the NLC was completed and documented in the ‘Zeroth-Order Design Report for the Next Linear Collider.’ This is a complete systems study with engineering support in crucial areas to verify feasibility. This design incorporates many of the hard lessons from the SLC and was both reviewed by an external committee in March of 1996 and presented to the 1996 DPF/DPB Snowmass meeting. At this time, a larger engineering effort is being started to estimate a cost and schedule.

In addition, the NLC R&D program has yielded very impressive results including the PPM klystron which exceeded the efficiency requirements and performed almost exactly as predicted, the DDS accelerator structure which also performed very close to expectations, and the extensive ground motion studies, which show that the highly correlated nature of the ground motion significantly reduces its impact and would cause minimal luminosity loss. Finally, the NLCTA, which is a model of the NLC linac and will verify the entire NLC rf system, is being commissioned.

Although this paper has concentrated on the SLC results and the NLC design, it must be emphasized that this is a really exciting time for all the future linear collider designs. Many of the test facilities, that have been designed to demonstrate the required technology for the different designs, are or will be commissioned soon. As these tests are completed, the next big challenge will be to complete fully engineered cost estimates for designs with the required reliability and operating margin to ensure successful operation.

References

[16] C. Adolphsen, et. al., to be published (1996); also see Appendix C of Ref. [1].
New Linac Based Free Electron Laser Projects using Bright Electron Beams

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Abstract

Due to the progress of accelerator technology in recent years it is now possible to consider the construction of a Free Electron Laser (FEL) that provides coherent radiation at wavelengths very far below the visible. In this paper, various projects are mentioned which are under way to establish the Self-Amplified Spontaneous Emission (SASE) principle at very short photon wavelengths as well as multiple harmonic generation. The basic principles are briefly explained and the expected performance is discussed.

With respect to linac technology, the key prerequisite for such single-pass, high-gain FELs is a high intensity, diffraction limited, electron beam to be generated and accelerated without degradation. Key components are RF guns with photocathodes, bunch compressors, and related diagnostics.

Once proven in the micrometer to nanometer regime, the SASE FEL scheme is considered applicable down to Angstrom wavelengths. It is pointed out that this latter option is particularly of interest in context with the construction of a linear collider, which requires very similar beam parameters.

Introduction

In a Free Electron Laser (FEL), an electron beam radiates photons at much higher power and better coherence than it does due to spontaneous synchrotron radiation. The main idea is that electrons moving in a transverse magnetic field of alternating polarity (undulator) may amplify an existing electromagnetic radiation field (see e.g. [1]). The reason is that for properly chosen phase and wavelength the scalar product of the electron’s velocity vector and the electric field vector does not vanish on average, resulting in an average energy transfer between the electron beam and the radiation field. As a consequence of this interaction, depending on the relative phase, some electrons get accelerated and others decelerated. This results in a longitudinal density modulation of the electron beam at the optical wavelength during the passage through the undulator. This, in turn, causes increased, stimulated emission at the resonant wavelength (high gain mode). The radiation power increases exponentially until, mainly because the electrons run out of resonance due to their energy loss, a saturation effect sets in. Compared to state-of-the-art synchrotron radiation sources, one expects better coherence, larger average brilliance, and, in particular, up to eight or more orders of magnitude larger peak brilliance at a pulse length of about 200 fs FWHM (see Fig. 3).

Meanwhile many FELs are under operation worldwide, several of them serving as user facilities (for an overview see Ref. [2]). Most of them are operated in the so-called oscillator mode, i.e. the radiation field is accumulated inside an optical cavity formed by two mirrors placed at the entrance and at the exit of the undulator. The major energy transfer from the electron beam to the radiation field takes place only after several electron bunches have passed the optical cavity thus generating an intense radiation field. Such operation principle only needs quite short undulator magnets and moderate values of electron beam parameters like emittance and peak current.

It is an essential advantage of the FEL principle that there is no fundamental limit in the choice of the photon wavelength. The photon wavelength \( \lambda_{ph} \) of the first harmonic is related to the period length of a planar undulator \( \lambda_u \) by

\[
\lambda_{ph} = \frac{\gamma \lambda_u}{2} \left( 1 + \frac{K^2}{2} \right),
\]

where \( \gamma = E/mc^2 \) is the relativistic factor of the electrons and \( K = e B_0 \lambda_u / 2 \pi m c \) the ‘undulator parameter’, \( e \) being the elementary charge, \( m \) the electron rest mass, \( c \) the speed of light, and \( B_0 \) the peak field in the undulator. It is seen that very short photon wavelength can be achieved if only the electron energy (i.e. \( \gamma \)) is chosen sufficiently high. However, in going to shorter and shorter wavelengths, several technical problems arise:

- For wavelengths below some 200 nm there are no good mirrors. This is the main reason why the shortest wavelength ever attained is 240 nm [3]. The solution is to operate the FEL in the amplifier mode, using an external input signal. To this end, however, a high power coherent input source (called seed laser) is necessary. Also, to achieve saturation within an undulator of reasonable length, very good electron beam quality is required. The gain length \( L_G \) (i.e. the photon power e-folding length) in the high-gain amplifier mode is given by [4]

\[
L_G = \frac{\lambda_u}{4 \sqrt{3 \pi \rho}}
\]

with the FEL parameter \( \rho \) (in this case for a helical undulator)

\[
\rho = \left( \frac{K \Omega p \lambda_u}{4 \sqrt{2 \pi \Omega_p}} \right)^{1/2}
\]

\( \Omega_p \) is the plasma frequency:

\[
\Omega_p = \left( \frac{2 \pi e I}{\gamma c \sigma^2} \right)^{1/2}
\]

\( r_c \) being the classical electron radius, \( \sigma \) the rms electron beam radius and \( I \) the peak current inside the electron bunch. Besides these formulae there are others that also take into account 3D effects like electron beam emittance,
photon diffraction[5] as well as quantum fluctuations[6], and there are various computer simulation codes. All of these indicate that, in the VUV, electron beam diameters of some $10^4$ m and peak current above 500 A are needed to achieve a gain length below 1 m and saturation within 20 m undulator length.

- Another complication arises if, in the wavelength regime envisaged, there is no seed laser. For this case it has been proposed to use the spontaneous radiation in the first part of the undulator as an ‘input’ signal [4,7]. This principle is called ‘Self-Amplified Spontaneous Emission (SASE)’. It has been demonstrated successfully in the mm wave regime[8], and it is at present the subject of several proof of principle experiments at much shorter wavelengths (see below). The reason why SASE is specially attractive is that it does not rely on any atomic system’s properties anywhere (thus allowing arbitrary tuning), and that it is the main candidate for getting into the subnanometer wavelength regime. For a diagram see Figure 1.

![Diagram of an FEL operating in the SASE mode.](image)

**Fig. 1.** Schematic drawing of an FEL operating in the “Self Amplified Spontaneous Emission = SASE” mode. The peak current in the electron bunch is very high and the undulator is long enough, so that power saturation is reached during a single passage starting from noise.

- For the high gain mode to work, a very demanding upper limit for the electron beam emittance has to be observed, see e.g. [9]:

$$\varepsilon \leq \frac{\lambda \text{ e} \hbar}{4\pi} \quad (5)$$

Fortunately it helps that the electron beam emittance decreases during acceleration - the Liouville Theorem for accelerated beams requires the normalized emittance

$$\varepsilon_n = \varepsilon \cdot \sqrt{\gamma^2 - 1}$$

to stay constant. Thus acceleration to the high $\gamma$, that is needed in order to satisfy the resonance condition (1) for short wavelengths, automatically decreases the emittance. Also, if diffraction effects are not very critical, condition (5) can be relaxed [5,6]. Nevertheless there remains a tighter and tighter tolerance on the normalized emittance of the electron source if one wants to attain shorter and shorter photon wavelengths.

**Accelerator Technology**

The way to provide the required electron beam quality at the entrance of the undulator is determined both by physical limitations and technical possibilities. By extrapolating the present state-of-the-art beam parameters by a few factors of two, one can expect beam parameters as given in Table 1. At beam energy below some 200 MeV only more relaxed beam parameters can be realized due to space charge forces. With these values, a SASE FEL operating well below 100 nanometers could be realized. Schematically, such a machine is illustrated in Fig. 2. Its essential components are:

- a low emittance photo-injector
- electron beam chicanes for longitudinal bunch compression
- accelerating structures with minimum wakefield effects
- a long undulator with very small field errors, preferentially with periodic focusing superimposed

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>beam energy</td>
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<td>&gt;200</td>
</tr>
<tr>
<td>rms energy spread $\sigma_E/\gamma$</td>
<td>$10^3$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\varepsilon_n$ (normalized emittance)</td>
<td>$\pi$ mrad mm</td>
<td>2.0</td>
</tr>
<tr>
<td>rms bunch length $\sigma_s$</td>
<td>mm</td>
<td>0.1</td>
</tr>
<tr>
<td>peak electron current</td>
<td>A</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table 1: Typical electron beam parameters envisaged for VUV FELs.

![Diagram of the first phase of the SASE FEL project based on the TESLA Test Facility at DESY[31]. The bunch length is reduced from 2 mm to 0.25 mm within two steps of bunch compression. The overall length is some 100 meters.](image)

**Fig. 2.** Schematic layout of the first phase of the SASE FEL project based on the TESLA Test Facility at DESY[31]. The bunch length is reduced from 2 mm to 0.25 mm within two steps of bunch compression. The overall length is some 100 meters.

**Electron source**

The very small normalized emittance required by the transverse coherence condition (5) came within reach due to two major achievements: The development of the rf photo-injector gun [10] and the concept of space charge compensation[11].

In an rf gun, electrons are photo-emitted from a cathode which is placed in the split plane of an rf cavity and illuminated by a laser beam. Hence the electrons experience a high electric field from the very beginning (typically about 40 MV/m in an L-band gun) and are rapidly accelerated, thus reducing space charge forces as quickly as possible.
Since electrons start with nearly zero velocity, some phase slippage occurs with respect to the rf wave. The start phase $\phi_0$ is chosen so that the electrons travel near the crest of the wave at the exit of the cavity. The start phase is an important parameter to trade off transverse versus longitudinal emittance. With a fine adjustment of the phase either the minimum transverse emittance or the minimum longitudinal emittance can be optimized.

In spite of the very quick acceleration, there is still considerable emittance growth due to space charge forces. By applying solenoid focusing, a bunch rotation in phase space can be performed, such that there is mutual compensation of space charge effects before and after this focusing [11]. Geometry and focusing strength must be chosen such that this compensation is optimum just when further acceleration sets in (ultimately eliminating emittance growth as space charge effects scale with $1/\gamma^2$).

**Longitudinal Bunch Compression**

As mentioned before, a very high instantaneous beam current is needed in the undulator to reach photon power saturation within a reasonable undulator length. A typical number is 1250 A, corresponding to 100 $\mu$m rms bunch length for a 1 mA bunch charge. This value is not attainable directly from the electron gun, because space charge forces would blow up both the transverse beam size and the momentum spread. Thus, the use of magnetic bunch compression is foreseen, in order to reduce the rms bunch length from an initial value of about 2 mm. In principle one could consider performing the bunch compression in one step at an energy level, where space charge is not critical any more (> 200 MeV or so). However, the cosine-like time dependence of the accelerating field would then impose an intolerable nonlinear correlated energy distribution along the bunch. The proposed solution is to perform bunch compression in steps.

It is worth noting that multi-mA bunch compression below 100 $\mu$m is an objective of the Accelerator Test Facility under construction at KEK, Japan [12] because it is an essential component of future linear colliders. It should also be noted that emittance conservation during bunch compression is a critical issue because of coherent radiation effects in the compressor[13,14].

**Accelerator**

The different linac concepts differ mainly with respect to the choice of rf frequency. Roughly speaking, larger rf frequencies (up to 30 GHz) offer a higher accelerating gradient, i.e., a shorter overall tunnel length, at the price of reduced power efficiency and worse beam energy distribution[27]. In contrast, low frequency linacs (down to 1.3 GHz for the superconducting TESLA linac) promise very good beam quality, because each electron bunch extracts only a small fraction of the large energy that is stored in the big cavity volume (small 'wakefield' effects)[31].

For a short wavelength FEL the highest priority is electron beam quality and large average beam current, while high accelerating gradient might be of secondary importance. Thus there is a clear preference for low frequency linacs. With respect to longitudinal wakefields of 200 fs long bunches, this preference is based on generally accepted scaling rules, because no experimental experience is yet available. Work is in progress to improve the understanding of these effects.

**Undulator**

The undulator is the most prominent FEL specific component. It has two functions:
1. It has to provide the sinusoidal field so that the FEL process can take place.
2. In order to keep the beam size small over the whole undulator length, an alternating field gradient caused by a superimposed quadrupole lattice has to be provided.

The main challenges are the total length of 10 m or more, the additional quadrupole focusing to be supplied and tight tolerances which need to be observed in order to guarantee permanent overlap of the electron beam and the photon beam.

**Projects under way**

Worldwide, several single pass FELs are either proposed or under construction to study lasing at shorter and shorter wavelengths. Table 2 gives an overview.

<table>
<thead>
<tr>
<th>Year</th>
<th>Where</th>
<th>Wavelength</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>UCLA</td>
<td>10 - 20 $\mu$m</td>
<td>start-up, growth rate [24]</td>
</tr>
<tr>
<td>1996</td>
<td>Los Alamos Ntl. Lab.</td>
<td>16 $\mu$m</td>
<td>start-up, growth rate [29]</td>
</tr>
<tr>
<td>1997</td>
<td>BNL</td>
<td>$\geq 0.9$ $\mu$m</td>
<td>start-up, growth, saturation, tapering, short bunch, superradiance, harmonics... [22]</td>
</tr>
<tr>
<td>1998</td>
<td>DESY TTF FEL Phase 1</td>
<td>50 - 100 nm</td>
<td>start-up, gain length, saturation [30]</td>
</tr>
<tr>
<td>1999</td>
<td>Spring-8 (if funded)</td>
<td>20 nm</td>
<td>start-up, gain length, saturation [23]</td>
</tr>
<tr>
<td>2000</td>
<td>DESY TTF FEL Phase 2</td>
<td>6 nm</td>
<td>start-up, gain length, saturation, superradiance, harmonics... [30]</td>
</tr>
<tr>
<td>2000</td>
<td>SLAC LCLS (if funded)</td>
<td>0.1 - 5 nm</td>
<td>dto., [25,26]</td>
</tr>
<tr>
<td>&gt;2000</td>
<td>Linear Colliders (if funded)</td>
<td>0.1 - 6 nm</td>
<td>dto., [28]</td>
</tr>
</tbody>
</table>

Table 2: Overview of linac based FEL projects relevant to pave the way towards short wavelengths.

**FEL Process**

Various computer codes have been used to investigate the start-up from noise, and the lethargy, exponential and saturation regimes, respectively, e.g. NUTMEG [15], GINGER[16], FS2R[17], TDA[18,19], FELEX[20]. There is no essential disagreement between results of all these codes.
written by different groups and based on different approaches. A critical issue for a SASE FEL is to take into account the time dependence of the input noise and the slippage effects in the theory and in the simulations. A full 3D simulation of these processes has not been done yet.

A peculiar characteristic of the SASE FEL is the strong spiking both in the temporal and spectral domain of the emitted radiation[21]. It is a consequence of longitudinal subsections inside each electron bunch radiating at statistically independent phases if the start-up is from noise instead of being „seeded“ by an external radiation field of high longitudinal coherence (i.e. by a „seed laser“). As a consequence, one expects large fluctuations of the instantaneous radiation power distribution inside each radiation pulse, changing from pulse to pulse, while the radiated power averaged over each pulse can be quite stable.

It is seen that they exceed values of state-of-the-art radiation sources by several orders of magnitude. The average brilliance is also increased (however by a smaller factor), especially if a superconducting, high average current linac is used, see Table 3.

As an alternative to the SASE concept, schemes generating harmonic content of the longitudinal electron density modulation at higher (up to the 40th) harmonics of a conventional laser have been considered (multiple stage harmonic generation). An FEL using this principle is under construction at BNL [22]. Because start-up is not from noise, improved stability and longitudinal coherence are expected, at the price of more hardware complexity and limited tunability. Experimental experience on both SASE and harmonic generation is needed to find out which scheme is the most promising one towards ultra-short wavelengths.

### Table 3: Main parameters of the TESLA Test Facility FEL (TTF FEL)[30]. The insertion device is assumed to be a planar hybrid undulator. These values should be used as a guideline only since experimental experience has still to be gained in this wavelength regime.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy</td>
<td>GeV</td>
<td>1.000</td>
</tr>
<tr>
<td>$\lambda_p$ (radiation wavelength)</td>
<td>mm</td>
<td>6.4 (193 eV)</td>
</tr>
<tr>
<td>$\lambda_u$ (undulator period)</td>
<td>mm</td>
<td>27.3</td>
</tr>
<tr>
<td>effective undulator length</td>
<td>m</td>
<td>25</td>
</tr>
<tr>
<td>rms beam size</td>
<td>mm</td>
<td>0.05</td>
</tr>
<tr>
<td>$\varepsilon_n$ (normalized emittance) in the undulator</td>
<td>mm-rad mm</td>
<td>2.0</td>
</tr>
<tr>
<td>peak electron current</td>
<td>A</td>
<td>2490</td>
</tr>
<tr>
<td>number of electrons per bunch</td>
<td></td>
<td>6.24E+9</td>
</tr>
<tr>
<td>number of photons per bunch</td>
<td></td>
<td>4E+13</td>
</tr>
<tr>
<td>rms energy spread $\sigma_v/\gamma$</td>
<td>$10^3$</td>
<td>1.00</td>
</tr>
<tr>
<td>rms bunch length $\sigma_b$</td>
<td>$\mu m$</td>
<td>50.0</td>
</tr>
<tr>
<td>$L_g$ (power gain length)</td>
<td>m</td>
<td>1.00</td>
</tr>
<tr>
<td>$P_{sat}$ (saturated power)</td>
<td>GW</td>
<td>3</td>
</tr>
<tr>
<td>average brilliance</td>
<td></td>
<td>up to 6E+21</td>
</tr>
<tr>
<td>[photons/s/mm²/mrad/0.1%]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bunch train length</td>
<td>$\mu$sec</td>
<td>800</td>
</tr>
<tr>
<td>number of bunches per train</td>
<td></td>
<td>up to 7200</td>
</tr>
<tr>
<td>repetition rate</td>
<td>Hz</td>
<td>10</td>
</tr>
</tbody>
</table>

**Perspectives for Hard X-ray FELs**

It is a most attractive feature of the SASE principle that there is apparently no wavelength limit, so that the idea came up to construct a SASE FEL operating in the Angstrom regime, i.e. on the natural scale of atomic physics and chemistry. This requires a very high quality electron beam in the energy range of 10 - 30 GeV. Since quantum fluctuation effects, which govern the electron beam size in a storage ring, are absent in a linac to a great extent, such high quality beams can only be provided by a linear accelerator. A first proposal of this kind came up at SLAC[25,26]. More recently it has been proposed to combine the construction of a future
linear collider with installation of a multi-user X-ray FEL facility[28]. A linear collider is a pair of linear accelerators (each some 15 km long) directed against each other to collide electron and positron beams at 500 GeV center of mass energy, see e.g. [27].

The key point is that a linear collider also needs accelerator components capable of maintaining excellent beam quality during acceleration, but it cannot run, mainly for power consumption reasons, at high duty cycle. Therefore, the electron pulse structure consists of trains of electron bunches, repeated at the linac repetition rate \( f_{\text{rep}} \), which is of the order of 10 Hz. It is proposed to run in an interleaved pulse mode, where rf pulses for high energy physics and those for X-ray physics alternate. For an X-ray FEL, only some 20% of the total collider length needs to be powered during the FEL pulses, so power consumption is not that much a concern - especially if a superconducting accelerator is used. Thus, the X-ray facility could utilize part of the expensive accelerator and the infrastructure of the high energy physics (HEP) lab without mutual interference, see Figure 4.

Note that such an operation mode consisting of alternating beam pulses for HEP and X-rays is different from so-called ‘parasitic’ use of HEP storage rings for synchrotron radiation users: Both users can define beam properties like energy, emittance, current, time structure etc. of their electron pulses independent of each other to a large extent, since they use different injectors and since it is no problem for rf components to change power and pulse length from pulse to pulse.

![Fig. 4. Sketch of a Coherent X-ray source based on the TESLA linear collider installation. The beam can be extracted at any energy between 2 and 250 GeV and is transferred to the X-ray lab located close to the interaction points (I.P.). Many extraction lines could be considered in parallel, so that various beam energies are available in the X-ray lab quasi-simultaneously. The X-ray FEL electron beam is provided by an rf gun followed by a sequence of bunch compressors, while the high energy pulse is served by a damping ring.](image)

References

Invited Talk Session TU2

Chairman: G.E. McMichael

Tuesday, August 27, 1996
PB INJECTOR AT CERN

H. D. Haseroth, for the Lead Ion Accelerating Facility Collaboration
CERN
1211 Geneva 23, Switzerland

ABSTRACT

For the CERN Lead Ion Accelerating Facility (achieved within a collaboration of several outside laboratories and with financial help of some member states) a new dedicated Linac has been built. This Linac has been installed in 1994 and served during two extended physics runs.

This paper reviews the main characteristics of this machine and describes the first operational experience. Emphasis is put on new features of this accelerator, its associated equipment and on the peculiarities of heavy ions.

INTRODUCTION

The Pb injector Linac is part of the Lead Ion Accelerating Facility at CERN [1] which has been described at different conferences [2,3]. This project has not been a CERN project but a joint project with several outside laboratories and helped also by outside financial contributions.

The work reported here is the result of a collaboration between different laboratories, namely GANIL (Caen, France), Legnaro (INFN, Italy), GSI (Darmstadt, Germany), Torino (University, Italy) and CERN (Geneva, Switzerland), supported by financial contributions from Sweden and Switzerland and helped with software and some hardware from India (VECC, Calcutta, TIFR and BARC, Bombay), a debuncher from IAP (Frankfurt, Germany) and manpower for installation from Prague (Czech Academy of Sciences).

The Pb injector Linac ("Linac 3") started operation in June 1994 and first results have been presented at the last Linac Conference [4], where also some papers on details of the machine were submitted [5,6,7,8].

DESIGN AND INSTALLATION OF THE LINAC

The design of this machine was decided to a large extent by the characteristics of the existing CERN machines and their auxiliary equipment and of course also by our collaborators, their experience and possibilities. Fig. 1 shows the layout of the whole facility. Several considerations determined the choice of the machine parameters. From the future experiments there was the request for a certain minimum intensity to be made available (5x10^7 ions per SPS supercycle) and the other important boundary was the cost factor. CERN had no major funds available for up-grading its machines to heavy ions and the future ion experiments were struggling with their own financial problems but several of the Institutes involved were willing to contribute in kind. The choice for the machine parameters had to be made by taking into account these conditions. It was evident that a new Linac would be needed and to minimise its cost a source with a high charge state had to be selected. Given the good performance of ECR (electron cyclotron resonance) sources, the positive experience in using them at CERN and their availability from a collaborating lab (GANIL), the choice for the future Linac was quite clear. A filter line to select the desired charge state and a RFQ for further acceleration were obvious choices (experience at INFN Legnaro). The Linac itself has been an open question for some time and was finally determined by the positive results at GSI with their high charge state injector using an interdigital H structure ("1H"). Its compact design and - for its length - modest RF power requirements and the possibility to profit from GSI's and its subcontractors experience made it an attractive choice for Linac 3. An important parameter was of course the final energy of the Linac. It has been determined by careful consideration of:

- the maximum magnetic rigidity allowed in the (complicated and expensive to up-grade) injection line to the Booster
- the charge state achievable when stripping after the Linac
- the losses when stripping at lower energies
- the losses due to charge exchange reactions in the PSB and PS as a function of energy and charge state
- the energy at the top of the accelerating cycle in PSB and PS to make transfer to the next machine not too complicated

Fig. 1: Layout of the CERN Heavy Ion Accelerating Facility
The final choice made here was 4.2 MeV/u at the output of the Linac and stripping at this energy to Pb$^{53+}$.

The ion source

The first element of the Linac is the ECR source delivering in a pulsed mode (the so called “afterglow”) a current of 120 µA of $^{208}$Pb$^{53+}$. The source is operating at 10 Hz, the frequency chosen for future operation for the LHC (CERN’s Large Hadron Collider) and compatible with all the new machine components. It may be recalled that the original specification for this source was 30 µA and during its construction phase the afterglow mode was applied pushing its performance to above 80 µA. Careful tuning and some modifications resulted in the present intensity.

The Low Energy Beam Transport

To transport the beam from the ion source into the RFQ, a special line has been designed, which does not only match the beam into the RFQ. It acts also as a high resolution spectrometer (0.3 %), that eliminates the unwanted charge states and even the unwanted isotopes, if needed.

The RFQ and the Medium Energy Beam Transport

The RFQ is of the four rod type and has symmetric supports for the vanes. It accelerates the beam from 2.5 keV/u to 250 keV/u with a very good transmission. With one buncher cavity and two quadrupole doublets matching is achieved into the first IH tank.

The IH Linac

Three cavities accelerate the beam to 1.8, 3.1 and 4.2 MeV/u respectively. The first tank operates like the RFQ at 101.3 MHz, tanks 2 and 3 at 202.56 MHz. Transverse focusing is provided by quadrupole triplets, two in tank 1, one between tanks 1 and 2, and one between tanks 2 and 3.

Stripper and Filter Line

Another magnetic quadrupole triplet is employed after tank3 to focus the beam onto the carbon stripper foil to minimise the transverse emittance blow-up. An arrangement of four bending magnets is used with a slit in the middle to analyse the beam and to select the required charge state (normally Pb$^{53+}$). The first bending magnet is stronger, such as to allow spectrometer measurements even for the (unstripped) Pb$^{54+}$ beam.

Instrumentation

Instrumentation on Linac 3 is vital, not only because several different labs were involved in the construction, which meant that beam quality checks were important at the hand-over points, but also due to the additional complications when working with heavy ions. Beam current measurements are achieved by transformers and Faraday cups. Profile measurements are done with secondary emission grids and the longitudinal beam characteristics are monitored with capacitive phase probes (some with four sectors to allow for position measurements) and a so called BLVD (Bunch Length and Velocity Detector) [9]. Apart from the existing emittance measuring lines a special multi-slit/scintillator screen device has also been set up [10].

Installation

Installation of the source had been achieved already at the end of 1992. In July 1993 the LEBT was used to measure the source characteristics. By then most of the filter line had been installed too. Tanks 2 and 3 arrived in December 1993, tank 1 in February 1994 and the RFQ in April 1994.

SETTING-UP AND OPERATIONAL PERFORMANCE

The somewhat hectic installation period in 1994 was followed by a very fast running in. This was necessary because it was clear that the subsequent machines, not used to
partially stripped heavy ions, would require a fairly extended period for setting-up.

Conditioning of the RF cavities caused no major problems. Some days were in general sufficient to overcome problems. The buncher behind the RFQ, however, suffered from operating ion pumps and even from the very low intensity beam passing through the RFQ when it was not yet powered. This beam coming from the source before the maximum of the afterglow pulse was finally suppressed to have reliable operation of the buncher. In spite of the fast running in careful measurements were done using the sophisticated equipment available for beam diagnosis. Provisional installation to measure the beam out of the RFQ and out of tank 1 were made to check the performance of the subsystems before injecting into the next unit. The BLVD in particular proved its value.

No major problems were encountered. Vacuum conditions throughout the linac were completely adequate. Some weak points on some RF amplifiers (failing HT components and insufficient cooling) have been corrected.

PRESENT PERFORMANCE AND IMPROVEMENTS

Work continued on different improvements concerning the ion source, triplet and tank alignment and also the field distribution in the tanks. Some problems with the mechanics of the stripper were also tackled.

Table 1 shows the original, the design and the present performance of Linac 3.

<table>
<thead>
<tr>
<th>Source current [μA]</th>
<th>Linac output current [μA]</th>
<th>Horizontal emittance (nm rad)</th>
<th>Vertical emittance (nm rad)</th>
<th>Energy spread [keV/μ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>design 80</td>
<td>65</td>
<td>.81</td>
<td>.80</td>
<td>2.1</td>
</tr>
<tr>
<td>1994</td>
<td>80</td>
<td>1.2</td>
<td>1.1</td>
<td>2.5</td>
</tr>
<tr>
<td>present</td>
<td>120</td>
<td>.85</td>
<td>.80</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Table 1: Linac beam characteristics (Emittances are 4x the rms values, the energy spread is given after debunching)

Although it is true that the original specifications for the minimum intensity have been exceeded by a factor of eight, future physics experiments will probably require higher intensities (e.g. the search for strangelets). In any case the LHC (Large Hadron Collider) where lead ions will be accelerated to a few TeV/μ will require higher intensities to achieve a reasonable luminosity.

Apart from intensity improvements on the source, which will reflect proportionally on the final intensities, and improvements in the transmission of the circular accelerators, several scenarios have been studied for the LHC [12]. Present planning calls for a faster (10 Hz) repetition rate of the linac and injection into LEAR (Low Energy Antiproton Ring). Accumulation of about ten pulses and electron cooling would provide for the intensities and emittances needed for the LHC [13].

First electron cooling tests were performed in LEAR with Pb53+ ions in December 1994. Considerably better lifetimes of the beam were achieved using Pb54+ ions [13]. The current after the stripper at the Linac exit for Pb54+ can be made equal to the normal Pb53+ current by optimising the stripper foil.

Another possibility, depending on ion source development [14], is a high current, short pulse, source (EBIS or Laser source) that could provide the necessary intensity and keep the required low emittance by mono turn injection into the PSB. Work in this field is going on some labs, e.g. BNL (EBIS) and CERN (laser source, in collaboration with ITEP and TRINITI, [15]).

MACHINE EXPERIMENTS

Tests with Higher RF Power

Some interesting experiments were performed in collaboration with GSI. The IH structure shows very good voltage holding capabilities in spite of the small radius of curvature on the drift tubes. Tests were made on tank 2 with considerably higher RF powers than nominal. The normal operating level requires 346 kW. Test made in 1995 with 550 kW showed excellent behaviour. In 1996 an increased power level of 800 kW was successfully applied. The conditioning of the tank took about 18 hours with a repetition rate of slightly below 1 Hz and 200 μs pulse length. The radiation values during conditioning are presented in Fig. 3. The radiation is measured 90 cm from the tank axis.

Fig. 3. Radiation levels near tank 2
The two points around 620 kW are taken at different times. Basically this figure shows the radiation increase as RF conditioning proceeds. These values are not to be taken as the values under normal operation.

The design and actually achieved fields in tank 2 are shown in Table 2. It must be stressed that these values have been realised with a very short conditioning time and are certainly not yet the maximum levels that can be obtained. These levels were determined by the maximum RF power available with the present configuration.

<table>
<thead>
<tr>
<th>Design Fields</th>
<th>Scaled to 800 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective accelerating field [MV/m]</td>
<td>6.4</td>
</tr>
<tr>
<td>Average field in gaps with highest gradient</td>
<td>15.8</td>
</tr>
</tbody>
</table>

Table 2: Accelerating fields in tank 2 for the design conditions and scaled to 800 kW

We plan to have RF power available for further tests with up to 2 MW to reach (perhaps) the breakdown limit of the tank.

"Energy Ramping" During the Pulse

Multiturn injection into LEAR, to accumulate, cool and store ions for the LHC, maybe helped by an energy variation during the beam pulse. Requirements for this scheme are: a relative momentum variation of $\pm 0.4\%$ during a Linac pulse of 20 to 60 $\mu$s whilst keeping the beam momentum dispersion within 0.02 $\%$ at 1 $\sigma$. Several machine experiments ("MDs") were made to test the feasibility of this scheme.

Dynamic ramping with the debuncher phase alone did not give the required results. Additional ramping with the tank 3 amplitude (Fig. 4) yielded the necessary variations for the energy together with the required energy dispersion. Fig. 5 shows the energy dispersion in the beginning, the middle and the end of the ramp (superimposed pictures). The variation is $\pm 40$ keV/u and the dispersion is about 10 keV/u.

Ramping with parameters of a machine, which is built to supply constant energy, means of course deviating from the optimum settings and results in a reduced stability and a more delicate operation. The best solution appears to be a dedicated energy corrector cavity:

- It allows for energy variation with a minimum alteration of other beam/machine parameters, since it can be placed close to the tank 3 output where the beam is very short. This would permit the Linac to be run with its optimum settings without spoiling its performance.
- Stripping can then be performed at constant energy, hence constant distribution of the resulting charge states.

Another important application of special and dedicated hardware for the energy ramping for LEAR is to keep the injection energy into the Booster constant in spite of changes of or on the stripper foil. Stripper foils usually show some variations in thickness and replacing one foil produces inherently a change in the energy of the stripped beam.

These changes are quite difficult to cope with on the Booster machine which requires a lengthy resetting of the injection and especially of the RF parameters. As the necessary stripper foil changes cannot always be predicted and preventive maintenance is hence excluded it is usually tried to trim the Linac energy to another value to compensate for the different stripper foil. It is clear, however, that this means - as a Linac is a fixed energy machine - deviating from the optimum settings. For this reason it is highly desirable to have a special energy corrector cavity after the Linac which allows energy corrections without touching the optimised parameters of the Linac itself. Another problem that could be eased by a dedicated cavity, is ageing of the stripper foil, which can result both in energy variations and in changes of the energy dispersion.

Tests with Pb$^{25+}$

Although $^{208}$Pb$^{24+}$ had been foreseen as “nominal ion” right from the beginning, all the initial running including the physics runs of 1994 and 1995 had been done with Pb$^{25+}$. The high intensity the source was able to provide, and the lower RF power needed for the Linac cavities, made this a good choice. However if the source can give the same (electric) current of Pb$^{25+}$ there is already a gain of some 8% in terms of number of ions. It must be remembered in this context, that the Linac accelerates to 4.2 MeV/u (by adjusting the field levels correspondingly) independent of the charge state of the ion. The output of the stripper in terms of Pb$^{24+}$ is again independent of the charge state of the incoming ion and depends solely on its energy. Hence converting the same current of Pb$^{24+}$ will result in 8% higher current after the stripper. Preliminary tests are under way to explore this possibility and have quickly produced an increase of the current by some 11%. The overall gain in terms of number of ions is hence about 20%. There is some hope that this mode of operation can be used for the physics run later this year and that further optimisation of the source can give even higher intensities.
Stripper foil ageing

The carbon stripper foils show a very good lifetime of several months. Some ageing effects have been observed that are of importance for the Booster synchrotron. Fig. 6 shows the energy spectrum (after the debuncher) with a stripper foil of a few months (note the Pb^{2+4+} on the right), fig. 7 shows the same spectrum under identical machine conditions but with a new foil. With the old foil one can clearly see a low energy tail in the spectrum. Some curling of the foil maybe the reason. This effect reduces considerably the trapping efficiency of the Booster. Fortunately it is easy, if the effect is noticed, to put in a new foil.

CONCLUSION AND ACKNOWLEDGMENTS

The CERN Linac 3 put into operation in 1994 has been working very well and exceeding most of the specifications, in particular the ones relevant for the subsequent machines. It has been demonstrated that such a machine can be built by a large collaboration of several labs from different countries without making compromises for the final performance.

It is a pleasure to acknowledge here the enormous help given to this project by our friends from the collaborating institutions, in particular from GANIL, Legnaro, GSI and Torino, but also from IAP, CAT and Prague and of course also - last but not least - the financial contribution by Sweden and Switzerland. Thanks are of course also due to the CERN people in the different groups of the PS division, and likewise from the previous AT, MT, ST and TIS divisions.

Special thanks go to several of my colleagues in the PS for supplying material for this paper especially to C. E. Hill, A. Lombardi, E. Tanke and R. Scrivens.

REFERENCES

The New GSI Presstripper Linac for High Current Heavy Ion Beams

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Abstract

The original UNILAC injector uses PENNING type ion sources and charge states up to 10\(^+\) for uranium beams. The beam intensities for very heavy ion species out of that injector are too low by almost a factor 300 to fill the Heavy Ion Synchrotron SIS up to its space charge limit. At present only ion sources like CHORDIS (1\(^+\) and 2\(^+\) charged ions) or MEVVA, which generates charge states up to 4\(^+\) above mass 180 can provide the requested beam intensities during a pulse duration of 100 \(\mu\)s.

The IH-DTL with its high acceleration efficiency offers the possibility to replace the 34 MV prestripper linac by a new 91 MV linac while keeping the positions of the pre-injectors and of the gas stripper untouched. The actual prestripper frequency of 27 MHz will be replaced by 36 MHz, being one third of the poststripper linac frequency.

The beam dynamics of 'Combined Zero Degree Synchronous Particle Sections' is applied on the two IH cavities. They generate averaged effective voltage gains of 4.3 MV/m.

The paper describes the new linac, especially focusing on the rf structures and on the beam dynamics along the IH-DTL.

Introduction

The rebuilt of the 1.4 MeV/u UNILAC presstripper linac is part of a program to extend the UNILAC capabilities [1]. Besides the traditional 25 % duty factor low intensity operation short high intensity beam pulses have to be delivered to the synchrotron SIS which is in operation since 1990. It can be filled up to its space charge limit only for ion masses below 40 at present [2]. One reason is the drastic reduction of very-heavy ion beam intensities down to around 2% by stripping processes at 1.4 MeV/u and at 11 MeV/u used for standard SIS injection.

\(^{20}\)Ne beams from CHORDIS and PENNING ion sources are used in a machine development program to define and to improve critical components along the ALVAREZ poststripper section of UNILAC and along the SIS transfer channel. Before commissioning of the new linac which is scheduled for the end of '98 an electron cooler will be installed in SIS to enlarge the efficiency of the complete system at injection (multiple multturn injection) and to improve the beam quality at fast extraction from SIS (cooling at intermediate beam energy during the acceleration cycle)[3].

This paper explains the main 1.4 MeV/u linac parameters and compares them to the synchrotron needs. Beam dynamics calculations along the new linac and a description of key components will be given.

Basic Requirements and Parameter Choice

At present the space between the dc preinjectors and the 1.4 MeV/u gas stripper along the beam axis is 43 m. A double drift buncher and 4 Wideröe tanks accelerate \(^{238}\)U\(^{160}\) ions up to the design energy. The success of generating high intensity \(^{238}\)U\(^{160}\) beam pulses out of the PENNING source was limited. On the other hand new ion sources of the CHORDIS and MEVVA type [4,5,6] were developed during the last 15 years. They provide the needed particle intensities including the beam losses at the 1.4 MeV/u gas stripper and at the 11.4 MeV/u carbon foil stripper, but at significantly lower charge states – up to 4\(^+\) above mass 180 only. That means to upgrade the 1.4 MeV/u linac voltage from 33 MV to 91 MV for the new design mass to charge ratio of 65. Extension of the accelerator length would cause considerable additional expenses for infrastructure and rebuilding steps. By use of an interdigital H-type structure it is possible to provide the needed voltage gain within the original space.

Fig. 1 shows the design particle current of the new 1.4 MeV/u linac as defined in front of the gas stripper. The space charge limit of the synchrotron is expected to range from \(4 \cdot 10^{12}\) ions for \(^{40}\)Ca down to \(4 \cdot 10^{10}\) ions for the heaviest particles like \(^{238}\)U at the standard injection energy into SIS at 11.4 MeV/u [2].

![Linac Particle Current at 1.4 MeV/u](image)

**Fig. 1.** Comparison of the High Current Injector design particle current at 1.4 MeV/u in front of the gas stripper with the estimated intensity needs to fill the SIS up to the space charge limit at the standard injection energy of 11.4 MeV/u (shaded area).
Fig. 2. Major components of the 91 MV High Current LINAC (SL = Super Lens).

Table 1: List of parameters for the 36 MHz Injector Linac with the design current of 16.5 emA at A/q = 65.

<table>
<thead>
<tr>
<th>Cavity</th>
<th>RFQ</th>
<th>Super Lens</th>
<th>IH1</th>
<th>IH2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length/m</td>
<td>9.35</td>
<td>0.8</td>
<td>9.1</td>
<td>10.3</td>
</tr>
<tr>
<td>Inner diameter/m</td>
<td>0.762</td>
<td>0.86</td>
<td>1.829</td>
<td>2.034</td>
</tr>
<tr>
<td>Energy range/keV/u</td>
<td>2.2-120</td>
<td>120</td>
<td>120-743</td>
<td>743-1400</td>
</tr>
<tr>
<td>Max. volt. between electrodes / kV</td>
<td>137</td>
<td>212</td>
<td>1150</td>
<td>1300</td>
</tr>
<tr>
<td>Aperture diam. / mm</td>
<td>11-7.6</td>
<td>13.6</td>
<td>28-42</td>
<td>46</td>
</tr>
<tr>
<td>RF power losses / kW</td>
<td>290</td>
<td>75</td>
<td>1040</td>
<td>1050</td>
</tr>
<tr>
<td>RF power into beam /kW</td>
<td>130</td>
<td>-</td>
<td>670</td>
<td>705</td>
</tr>
<tr>
<td>Norm. exit rms emittances x,y/mm mrad, z/keV ns/u</td>
<td>.05, .05, .139</td>
<td>.07, .065, .25</td>
<td>.093, .106, .39</td>
<td>.11, .116, .446</td>
</tr>
</tbody>
</table>

Taking into account the particle losses by stripping as well as an expected growth of the normalized transversal emittances by a factor of 4 along the whole linac and transport lines the estimated SIS current needs out of the new 1.4 MeV/u linac are as shown in Fig. 1 by the shaded area. 25 turns are injected into the effective horizontal SIS acceptance of 150 π mm-mrad, the corresponding filling time is 100 μs. A frequency of 36.136 MHz was chosen for the new linac, which is one third of the ALVAREZ frequency. This choice allows a good acceleration efficiency along the 1.4 MeV/u section and meets the beam specifications. At the same time the cavity diameters of the IH-DTL are up to 2.03 m which allows a convenient installation in the UNILAC tunnel. Production and in house copper plating are well established for cavities of that size.

Beam dynamics reasons and rf amplifier economy require the RFQ to be designed as one cavity while the IH-DTL consists of two cavities (Fig. 2). These cavities provide maximum voltage gains of 7.7 MV (RFQ), 40.5 MV (IH1), and 42.7 MV (IH2) respectively. Their main parameters are listed in Table 1.

Besides the high current-mode (10 Hz/100 μs pulse train) the new front end linac additionally has to allow operation at rf duty cycles up to 30 % for A/q ≤ 26 to continue the original UNILAC operation mode with a 50 Hz/5 ms pulse train out of PENNING ion sources. In that case time averaged heat losses up to 20 kW in the RFQ and up to 50 kW in each IH-DTL cavity have to be removed by cooling water.

As UNILAC was originally designed for low beam intensities, some modifications along the whole system will be necessary. The redesign of both stripper areas including the subsequent charge separation is done at present [7,8].

**Injection System**

The beam will be generated at one of the two preinjector terminals. While the existing two 320 kV terminals and the adjacent beam lines for the 11.4 keV/u beams are identical, in future at least one beam line will be optimized for high current beams from MEVVA and CHORDIS ion sources [9]. Typically ion source beam fractions above 40 % are contained in the selected charge state out of these ion sources. They supplement each other in producing the required beam intensities within normalized emittances of 0.2 π mm-mrad for a large number of elements across the whole mass range. Unbunched high intensity ion beam transport shows space charge compensation within a few 10 μs. However a stable beam transport including ion source intensity fluctuations will benefit from a layout which allows for some space charge decoupling along the injection beam line.

It is desirable to keep the charge and mass separation up to lead isotopes as included in the actual system furtheron for both beam lines. The low injection energy of 2.2 keV/u needs a careful optimization of the PENNING ion source and of the beam transport into the RFQ. Two test stands are under
construction to improve the operation with that type of ion source.

**Radiofrequency Quadrupole IH-RFQ**

Several designs for low frequency RFQ cavities were developed and partly operated with beam during the last two decades [10,11,12]. After carefully comparing the achievements with the requirements of the High Current Injector it was decided to develop a new structure - the IH-RFQ [13,14]. A simplified cross-section and a comparison with the 4 Vane RFQ are shown by Fig. 3. The design principle is explained by Fig. 4, which shows the first and second out of 10 modules of the 36 MHz IH-RFQ. Main advantages of this structure if compared to other low frequency designs are:
- Homogeneous distribution of rf power losses on the cavity surface allows for efficient water cooling
- High shunt impedance
- Short distance between electrode supports possible
- Small tank size

The beam dynamics design and the particle simulations were done at the IAP, Frankfurt University [15]. Table 1 gives the main beam and cavity parameters.

![36 MHz IH - RFQ](image)

**Beam Matching into the Drift Tube Linac**

A specific matching problem from the RFQ into the DTL for high A/q beams with high intensity arises from the fact, that the lenses and rebuncher cavities need more space or/and cause large beam envelope oscillations to get the needed focussing strengths while space charge action is controlled more easily by a focussing tool which acts in both transversal planes and longitudinally at the same time. A very compact matcher design study was described in ref. [16]. A six cell RFQ was integrated at the entrance of the IH-DTL cavity to provide both transversal and longitudinal focussing. The now improved matcher design consists of a short quadrupole doublet immediately behind the main RFQ, a 100 mm long diagnostic box and a 11 cell adapter-RFQ 'Super Lens' which is an independent cavity [17]. Its parameters are given in Table 1.

**Drift Tube Linac IH-DTL**

The total voltage gain of 83.2 MV is distributed on two cavities. This results in convenient rf power levels below 2 MW for each cavity which can be provided by tetrode driven final amplifier stages. Moreover the cavity lengths around 10 m at 36 MHz are short enough to get a sufficient frequency separation between the H_{11} and the H_{12} mode [18].

The IH-DTL uses the beam dynamics principle of 'Combined Zero Degree Sections' as operated at the GSI High Charge State Injector and at the CERN Lead Injector successfully [19]. Tank IH1 contains 4 sections while tank IH2 contains 2 sections only (Fig. 5). These sections are transversally beam matched to each other by magnetic quadrupole triplets.

The 1.6 m long coupling section between IH1 and IH2 consists of two magnetic xy-steerer pairs, a 100 mm long diagnostic box which contains a 4 segmented pick up probe and a current transformer, and a magnetic quadrupole triplet with 1.15 m length.
To get aperture diameters of 36 mm for the first and second quadrupole triplet in IH tank 1 and 48 mm for all of the other lenses down to the 1.4 MeV/u gas stripper, a cobalt steel alloy is used for the fabrication of the laminated quadrupoles which guarantees high permeability up to a magnetic flux density of 2.3 T.

Cavity Design

The principle is shown in fig. 5. Compared to previous IH cavity designs the novel design elements are summarized in the following:
- The tank consists of cylindrical modules. The modular concept is preferable at tank diameters around 2 m and tank lengths around 10 m.
- The drift tube structure is oriented in the vertical plane to minimize the influence of gravity and to ease the assembly.
- The drift tubes which house the quadrupole triplets are rf structure integrated. Their lengths in units of $\beta_\lambda$ are N+0.5, N ranging from 3 to 5. This concept becomes feasible for a large diameter ratio between tank and lens housing.

Fig. 5. IH-tank 2 consists of 4 modules. It is housing two combined zero degree drift tube sections coupled transversally by a magnetic quadrupole triplet.

The last mentioned modification was not trivial. To get rid of over voltage at the gaps in front and behind of these large drift tubes the detailed studies performed with the MAFIA-code and on a 1:5.88 scaled model were important [18]. The axially extended drift tube stem and the deep cut into the girder opposed to the large drift tube resulted from these studies (fig. 5). The tank diameters and the cavity end geometries were also determined by the MAFIA calculations. For tank IH2 these numbers were verified meanwhile with high consistency by rf model measurements. Moreover the gap to period ratio along that cavity was optimized to get agreement with the voltage distribution as used in the LORASR beam dynamics calculations.

It was also shown that two capacitive plungers per cavity are sufficient to get a frequency tuning range $\Delta f/f$ of up to $\pm 5 \cdot 10^7$.

Fig. 6. Exit particle distribution immediately behind of IH tank 2 at the design current of 16.5 emA and $A/q = 65$. The 90 % emittance values correspond to the plotted ellipses; $N_{\text{w}} = 1768$ particles.
without disturbing the gap voltage distribution. Their axial distance from the corresponding cavity end wall is around 1.2 m.

**Beam Dynamics**

The main beam parameters and design values of key components are listed in Table 1. They are derived from calculations with a unbunched 2000 particle waterbag distribution injected into the RFQ at 2.2 keV/u and transformed along the RFQ with the PARMTEQ-code [15] and successively along the matching section and the IH-DTL by the LORASR code. Fig. 6 shows the emittance plots at 1.4 MeV/u, immediately behind of IH tank 2 at the design current of 16.5 emA and A/q = 65. The averaged beam power in the 100 μs pulse corresponds to 1.5 MW, the beam power in the micro pulse with a 90% rf phase width of 15 deg is as high as 35 MW. Particle losses of around 10% are located in the RFQ while normalized r.m.s. emittance blow up of a factor 2.2 transversally and of a factor 3.2 longitudinally occurs mainly in the matcher and along the first and second zero degree sections of the IH-DTL. Especially at the design current level the particle density out of the RFQ becomes very much peaked in the centre of the longitudinal emittance plane. This is reflected by the fact that along the matcher and IH-DTL the 20% norm. emittance area is increased by a factor 3.7, while the 90% emittance area is increased by a factor 2.6 only. Nevertheless the resulting emittance areas at the exit of the new injector linac are close to the minimum permissible range of values to get an acceptable beam transport along the stripper sections and through the 4 ALVAREZ tanks. The space charge effects are still rather strong for the given beam parameters along the UNILAC and the transfer line into SIS. The destruction potential of heavy ion beams is described in ref. [20]. Great care has to be taken in the development of adequate protection systems, beam diagnostics and machine operation strategies.

**Radio Frequency Engineering**

The new frequency 36 MHz is generated by a oscillator which is phase locked to the 108 MHz reference signal of the ALVAREZ. The 36 MHz power splitter has to feed 7 amplifier chains. Four of them have a 200 kW end stage (Super Lens, two rebuncher cavities at 1.4 MeV/u and one debuncher cavity at 11.4 MeV/u) while three chains have an additional 2 MW final stage to feed the RFQ and two IH-DTL cavities. The 200 kW stages have grounded cathode circuits while the 2 MW stages are based on grounded-grid circuits. The operating point during each rf pulse can be redefined to optimize the transmitter efficiency and stability for a wide range of rf power levels and beam intensities.

**Time Schedule**

The RFQ tanks are under construction and delivery to GSI will be in Dec '96. The IH tanks will be delivered in July '97. The new 91 MV linac will be installed during the second half of 1998.

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BEAM TEST OF THE PRE-INJECTOR AND THE 3-MEV H\textsuperscript+ RFQ WITH A NEW FIELD STABILIZER PISL

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Abstract

A 432-MHz, 3-MeV radio-frequency quadrupole (RFQ) linac was developed for the Japanese Hadron Project (JHP). This four vane-type RFQ was stabilized against the dipole-mode mixing with newly devised π-mode stabilizing loops (PISLs). In order to inject a low-emittance H\textsuperscript+ beam into the RFQ, a newly designed pre-injector composed with a volume production H\textsuperscript+ ion source (VPIS) and a low-energy beam transport (LEBT) has been developed. A H\textsuperscript+ beam of 16 mA with a 90% normalized emittance of 0.41π mm-mrad was produced by the VPIS operated without cesium and injected within the design acceptance of the RFQ. The RFQ accelerated 13.2 mA of the beam with a transmission efficiency of 82.5%.

Introduction

A radio-frequency quadrupole (RFQ) linac was developed for the Japanese Hadron Project (JHP) [1]. The design values of its resonant frequency, duty factor, peak beam current, injection and final energies were determined from a beam-optics consideration of the entire system to be 432 MHz, 3% (600 μs × 50 Hz), 20 mA, 50 keV and 3 MeV, respectively [2].

Since the final energy is rather higher than common RFQs, the optimization of the beam dynamics design is important to minimize the cavity length, which relates with not only the acceleration efficiency but also the field errors and stability. Therefore, we developed a new design procedure in order to optimize the design of intermediate- or high-beam current RFQs, which is programmed in the computer code package KEKRFQ [4]. By using KEKRFQ, we succeeded in designing the RFQ with a relatively short length of 2.7 m for such a high-energy RFQ. For the stable operation with a high-duty factor of 3%, newly devised π-mode stabilizing loops (PISLs) were installed into this four-vane type RFQ in order to stabilize the field against the dipole-mode mixing due to the thermal deformation [5,6]. PISL has the following two advantages compared with vane coupling ring (VCR) [7], which is the similar field stabilizer as PISL and has been used frequently so far; (1) much easier water-cooling and (2) more uniform longitudinal electric field distribution [8,9]. By installing several pairs of PISLs to the RFQ, we obtained a uniform field distribution within ±0.75% both azimuthally and longitudinally [10]. Also for the stable operation with a negligible probability of the intercaveman discharge, the maximum surface electric-field was kept smaller than 1.8 times of Kilpatrick limit. In order to keep this restriction without reducing the acceleration efficiency, the pole-tip of each vane was cut by a rotating concave cutter into the cross-section with a curvature of 75% of the average bore radius [11]. This machining method is called as two-dimensional cutting (2DC). Since the machine setting in 2DC is easier than in three-dimensional cutting (3DC), we succeeded in constructing the RFQ with a small intercaveman distance errors of ±20 μm [12]. In order to correct the energy gain of each cell to the value produced in the ideal vane shape, each cell was machined with a slightly larger modulation factor according to Ref. [11].

In the preliminary beam test of the RFQ using a multi-cusp proton ion source and an Einzel lens, we experienced the difficulty to operate the high-voltage electrostatic lens stably with a high-duty factor. Therefore, we studied various low energy beam transports (LEBTs) using several types of magnetic lenses by simulating the beam optics with a computer code BEAMPATH [13,14]. By these studies, it was revealed that an appropriately designed solenoid magnet had the smallest lens aberration. Consequently, we succeeded in designing the LEBT without any practical emittance growth due to the lens aberration by using two short and strong solenoid magnets. We also studied how to align the permanent magnets around the arc chamber of a volume production H\textsuperscript+ ion source (VPIS) by calculating three-dimensional magnetic field distribution, in order to increase the plasma confinement efficiency. We constructed thus designed pre-injector composed with the VPIS and the LEBT in order to inject a low-emittance H\textsuperscript+ beam within the design acceptance of the RFQ.

In this paper, we represent the results of the beam test of the pre-injector and the RFQ. The detailed results of the beam test in the LEBT including the space-charge neutralization effects and the comparison of the measured results with the simulation are described in Ref. [15].

Experimental Setup

At first, the experimental setup is described in drawings. A schematic drawing of the VPIS and the LEBT viewing from the upper position is shown in Fig. 1. In the VPIS, we use three types of permanent magnets; (1) the permanent magnet for plasma confinement (PM), (2) the permanent magnet for magnetic filter (PMFM) and (3) the permanent magnet for electron suppression (PME) installed inside of the extraction electrode (EE). Six pairs of PMs, one pair of PMMs and one pair of PMEs are aligned symmetrically with the vertical plane including the beam axis. Each PM or PMM is a semicircle around the beam axis. Each PME is a
rod with a length of 40 mm aligned parallel to the symmetric plane. The sizes of the cross sections of PM, PMMF and PMES (width x height) are 8 mm x 16 mm, 10 mm x 20 mm and 5 mm x 3 mm, respectively. Since PMESs bend the electrons extracted from AC and hit almost all of them to EE, PMESs are made of Sm-Co material with a high Curie temperature in order to avoid their demagnetization due to the heat transferred from the electrons. On the other hand, PMs and PMMFs are made of Nd-Fe-B material. Each PM, PPF or PMES is magnetized normal or anti-normal to the surface of the arc chamber. The paired two PMs, PPMFs or PMESs has different magnetization direction. The neighboring two PM or PPMF has also different magnetization direction. However, the neighboring PPMF and PMES has same magnetization direction. The arc chamber (AC) with a inner diameter of 150 mm and a inner length of 150 mm is made of copper. The plasma electrode (PE) with a tapered hole of a diameter from 7 to 9 mm is made of Mo plate with a thickness of 2 mm. AC and PE are electrically isolated by separating with a ceramics plate. The bias voltage (Vb) is fed between AC and PE. We use a LaB$_6$ filament (FL; DENKA beta plus C-9a) with a diameter of 15 mm and a length of 32 mm. Arc pulse voltage is fed between FL and AC. A tapered hole of a diameter from 6 to 10 mm is bored on EE made of a copper plate with a 10 mm thickness. The extraction voltage is fed between PE and EE. The gap between PE and EE is 3 mm. The ground electrode (GE) with a hole of a diameter of 12 mm is made of stainless plate with a thickness of 5 mm. The acceleration voltage is fed between EE and GE. The gap between EE and GE is 20 mm. In order to correct the beam angle due to the dipole magnetic field produced by PMM and PMES, the steering electromagnet (STM) with a pole length of 10 mm is located 21 mm downstream from GE. The vacuum chamber just after the VPIS (CHM1) is pumped out with two 1500 l/s turbo molecular pumps (1500TMPs). The first solenoid electromagnet (SM1) is located 20 mm downstream from STM. In a space of 215 mm between SM1 and the second solenoid electromagnet (SM2), the vacuum chamber for the beam monitor (CHM2) and the gate valve (GV) are located.

Fig. 1 A schematic drawing of the VPIS and the LEBT viewing from the upper position.

Fig. 2 A schematic drawing viewing from the upper position of the diagnostic devices for the beam ejected from the RFQ.

SM1 and SM2 have the same shape with a length of 100 mm, a outer diameter of 300 mm and a bore diameter of 50 mm. A 500 l/s turbo molecular pump (500TMP) pumps out CHM2. The movable Faraday-cup (MFC) is used to measure the total beam intensity extracted from VPIS. Since MFC is connected to the ground through 50-Ω resistance, we can measure the intensity by measuring the induced voltage on the resistance (20 mV). By moving the movable slit (EMSSLH) and the Faraday-cup with slit (EMFCFLH) horizontally step by step, the horizontal emittance is measured. The vertical emittance is measured by using EMSSLV and EMFCFLV. The steps of x (y) and x' (y') were 0.2 mm and 2 mrad, respectively. Each slit used in EMSSL or EMFCFL is made of molybdenum plates with a thickness of 0.05 mm and has a gap of 0.2 mm. The distance between the slit of EMSSL and the slit of EMFCFL is 61 mm. A voltage of -1 kV was fed on each bias electrode of MFC or EMFCFL in order to suppress the secondary electrons form each Faraday-cup. The distance between SM2 and the vane end at the entrance of the RFQ is 35 mm.

A schematic drawing of the diagnostic devices for the beam ejected from the RFQ (DFQ) viewing from the upper position is shown in Fig. 2. In order to focus the beam, two quadrupole-magnets (QF and QD) are used. The distance between the vane-end at the exit of the RFQ and the pole of QF is 90 mm. The pole lengths of QF and QD are 60 and 50 mm, respectively. In a space of 118 mm between QF and QD, the gate valve (GV) is located. The energy analyzing magnet (AM) with a pole length of 90 mm is located 182 mm downstream from QD. Tow pairs of the movable slit and the movable Faraday-cup with slit (EMSSLH and EMFCFLH for the horizontal emittance and EMSSLV and EMFCFLV for the vertical emittance) are used in order to measure the transverse emittances. The steps of x (y) and x' (y') were 0.2 mm and 0.5 mrad, respectively. The distances between AM and EMDL and between EMDL and the slit of EMFCFLD are 93 mm and 205 mm, respectively. Each slit used in EMDL or EMFCFL is made of aluminum plates with a thickness of 0.1 mm and has a gap of 0.2 mm. The total beam intensity is measured with Faraday-cup FC1. The beam intensity accelerated up to 3 MeV is measured with Faraday-cup FC2, when the coil current of AM is 57.5 A (BL = 0.00483 T.m). FC1 and FC2 are also connected to the ground through 50-Ω
resistances as same as MFC. A voltage of -1 kV was fed on each bias electrode of FC1, FC2 or EMFCD in order to suppress the secondary electrons for each Faraday-cup.

**Results of the Beam Test**

The typical parameters of the operating VPIS, LEBT and RFQ are summarized in Table 1. At present, the duty of the operation of the VPIS is limited by the performance of the arc power supply. The second trace of Fig. 3 shows the VPIS beam signal measured with MFC. Since the vertical scale is 10 mA/Div., the peak intensity is 16.0 mA. When both of the coil currents for STM and SM1 was set to 0 A, the intensity measured with MFC was 16.5 mA. Therefore, the electron current accelerated up to 50 keV was 0.5 mA. The signal of the beam accelerated with the RFQ and analyzed with AM were measured with FC2 as shown in the top trace of Fig. 3. Since 13.2 mA of the injected beam of 16.0 mA was accelerated, the transmission efficiency was 82.5%. The third and bottom traces of Fig. 3 show the arc pulse voltage (125 V/Div.) and arc pulse current (50 A/Div.), respectively. The peak arc power is calculated to be 170 V × 220 A = 37.4 kW.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>VPIS:</td>
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<tr>
<td>Filament Voltage</td>
<td>8.9 V (Filament Current 69 A)</td>
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<tr>
<td>Arc Current</td>
<td>220 A (Arc Voltage 170 V)</td>
</tr>
<tr>
<td>Bias Voltage</td>
<td>12.4 V (Extraction Voltage 7.0 kV)</td>
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<tr>
<td>Acceleration Voltage</td>
<td>43 kV</td>
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<tr>
<td>H₂ gas flow</td>
<td>8.6 CCM</td>
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<tr>
<td>Arc pulse duty</td>
<td>0.76% (350 μs × 20 Hz)</td>
</tr>
<tr>
<td>LEBT:</td>
<td></td>
</tr>
<tr>
<td>Vacuum pressure of CHM1</td>
<td>1.8 × 10⁻⁶ Torr</td>
</tr>
<tr>
<td>Vacuum pressure of CHM2</td>
<td>3.7 × 10⁻⁸ Torr</td>
</tr>
<tr>
<td>Current of STM</td>
<td>3.0 A (120A/μT, 167G/cm)</td>
</tr>
<tr>
<td>Current of SM1</td>
<td>325 A (65500A/μT)</td>
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<tr>
<td>Current of SM2</td>
<td>420 A (65500A/μT)</td>
</tr>
<tr>
<td>RFQ:</td>
<td></td>
</tr>
<tr>
<td>RF power</td>
<td>480 kW for design interval voltage</td>
</tr>
<tr>
<td>RF duty</td>
<td>0.4% (25 μs × 20 Hz)</td>
</tr>
<tr>
<td>Vacuum pressure</td>
<td>1.2 × 10⁻⁶ Torr (if on, beam on)</td>
</tr>
<tr>
<td></td>
<td>7.3 × 10⁻⁸ Torr (if on, beam off)</td>
</tr>
<tr>
<td></td>
<td>5.3 × 10⁻⁷ Torr (if off, beam off)</td>
</tr>
</tbody>
</table>

In Figures 4(a), 4(b), 5(a), 5(b), 6(a) and 6(b), the measured particle distributions in the emittance phase planes are shown. Instead of the commonly used contour plot, we used a new display method of Ueno-Fujimura plot (UF-plt, see Appendix A). As described in Appendix A, the detailed structure of the distribution can be shown with UF-plt. Figures 4(c), 4(d), 5(a), 5(b), 6(a) and 6(b) shows the relationships between emittance and the beam fraction contained in the emittance. Here, the suffixes of (a) and (c) are used for the results of the horizontal emittance measurements and (b) and (d) are used for those of the vertical emittance measurements. Figures 4, 5 and 6 show the results measured at EMSLL position in the LEBT, at the entrance of the RFQ and at EMSLSD position in the DRFQ, respectively. The results shown in Figs. 5 and 6 are measured with the parameters shown Table 1. The results shown in Fig. 4 was measured by setting both of the currents of STM and SM1 to 0 A in order to measure the pure characteristics of the VPIS beam with out any unexpected affects, for example, the interference between STM and SM1 and so on. Therefore, an electron current of 0.5 mA are included in the distributions as described above. As can be seen from the figures with suffixes of (c) and (d), the 90% normalized emittances at EMSLL position, the RFQ entrance and EMSLSD position were about 0.66, 0.41 and 0.55π mm-mrad, respectively. Because of the contained electrons in the distributions measured at EMSLL, the 90% normalized emittances seem to have larger values than those at the entrance of the RFQ. The 90% normalized emittances grew during the acceleration in the RFQ by 34%. Since there is almost no filamentation in Fig. 4(a), the small filamentation in Fig. 4(b) seem to be caused by the magnetic field generated with PMESs. If the electric fields produced by the extraction and acceleration voltages caused the filamentation, both of the distributions should suffer the same affects. Since the filamentations are measured in Figs. 5(b) and 6(b), the filamentation seems to be transferred from the horizontal emittance to the vertical emittance by the rotation effect of the solenoid magnetic field.

![Fig. 3](image-url) The photograph of beam signals and arc pulse signals; top trace is the beam accelerated with the RFQ (10 mA/Div.), second trace is the beam ejected from the VPIS (10 mA/Div.), third and bottom traces are the arc voltage (125 V/Div.) and current (50 A/Div.), respectively.

We compared the beam profile measured at the entrance of the RFQ, which was generated by projecting the distribution in Fig. 5(a) onto the real axis (x), with the simulation results using the KV-distribution, Gaussian-distribution and Ueno-Yokoya distribution (UY-dst, see Appendix B) as the initial particle distributions at the exit of the VPIS. As described in Appendix B, UY-dst has understandable physical meanings; the uniform distribution in the real space led from the uniform plasma density and the gaussian distributions of x' and y' led from the thermal motion of the plasma. As shown in Fig. 7, the distribution in the real space simulated with UY-dst showed good agreement with the measured beam profile.

We measured the dependence of the accelerated beam intensity on the normalized interwave voltage (Fig. 8). Since the beam was increased by only 4% with the 12% higher interwave voltage than the design value, the H² beam seems to be lost due to the electron stripping by the collision with the following out gas in the RFQ cavity. (If the acceptance of the RFQ reduced the transmission, the larger improvement of the intensity by the higher interwave voltage was expected.) During about 150 μs after the start of the beam ejection from
the VPIS, there was no rf excitation in the RFQ due to the delay of the klystron. The large amount of out gas produced by the collision of the \( H^+ \) beam with the cavity wall should be localized around the entrance of the RFQ.

When a beam of 13.2 mA were accelerated with the RFQ, the input rf power should be increase by around 40 kW in order to keep the design rf level in the RFQ. The estimated beam current from the beam loading of \( I = 40 \) kW/(3000-50) \( kV = 13.6 \) mA showed good agreement with the beam current of 13.2 mA detected with FC2.

Conclusions

We succeeded in extracting a \( H^+ \) beam of 16 mA from a newly developed volume production \( H^+ \) ion source operated without cesium and injecting it within the design acceptance of the JHP RFQ by using the LEBT with two short and strong solenoid magnets. Although the 90\% normalized emittance (0.41\( \pi \) mm-mrad) measured at the entrance of the RFQ was about two-fifth of the design acceptance of the RFQ, the transmission efficiency of 82.5\% is rather smaller than the value of 94\% simulated with PARMTEQ [16]. Since the PARMTEQ installed at KEK simulates the beam optics by using the ideal quadrupole electric field and neglecting the effects of the image-charges, the possible causes for this discrepancy are as follows: (1) the electron stripping by the collision with the out gas produced by the lost \( H^+ \) struck on the cavity wall, (2) the higher-order components of the electric field generated by the shape of the vane-tip machined with two-dimensional cutting and (3) the effects of the image-charge induced on the vane-tip by the beam itself.

The measured 90\% normalized emittance of the beam accelerated with the RFQ was 0.55\( \pi \) mm-mrad. The emittance growth ratio during the acceleration by the RFQ was 34.3%.
Since the JHP RFQ has the excellent field uniformity and field stability produced by the field stabilizer PISL, the measured transmission efficiency (82.5%) and the emittance growth ratio (34%) will be explained by the simulations, in which the vane-tip shape effects and the image charge effects are taken into account, and the futher experiment on the vacuum pressure effects in the RFQ cavity. The arc pulse power supply will be modified for the operation with a design duty factor of 3.5%. The plasma confinement efficiency of the arc chamber will be also improved furthermore for a higher beam intensity.

Acknowledgement

The authors wish to express their sincere thanks to Mr. Kazuyuki Suzuki and the other members of the Accelerator System Design Section and the Tools Section at Hitachi Works, Hitachi, Ltd. for their technical support.

References


Appendix A: Ueno-Fujimura plot (UF-plt)

The measured particle distribution in the emittance phase plane has been commonly displayed with contour plot, so far. However, the small components of the distribution is easily neglected with the contour plot, since the number of the contour lines is limited to less than around 20 due to the resolution of the graphics. Therefore, we propose a new method of Ueno-Fujimura plot (UF-plt) in order to display the detailed stractures of the distribution, for example the filamentation due to the lens-aberration or the non-linear space charge force. When the emittance measurements was performed in the range from \((x, y') = (-0.4, -0.4)\) to \((0.4, 0.4)\) with the steps of \(dx = 0.2\) and \(dx' = 2\), an example of the beam intensity distribution detected with the emittance monitor can be shown in the way of Fig. 9(a). Here, the measured beam intensity at each \((x, x')\) is shown by the numerical figure, for example 2000 at \((0,0)\), and so on. In this measurement, each intensity represents each small rectangle composed with the four points of \((x+dx/2, x'-dx/2), (x+dx/2, x'+dx/2), (x-dx/2, x'+dx/2)\) and \((x-dx/2, x-dx/2)\). In UF-plt, the particle distribution is displayed by plotting points, whose number is proportional to the measured intensity, randomly within each rectangle as shown in Fig. 9(b).

As can be seen from the figure, it is possible to recognize the components with a very small intensity of about three-order smaller than the peak intensity. It is also noted that UF-plt is directly compared with the results of the simulation using the same number of particles.

Fig. 9 (a) An example of beam intensity distribution on x-x' plane detected with emittance monitor and (b) its UF-plt.

Appendix B: Ueno-Yokoya distribution (UY-dst) [17]

As described in the primer text of the accelerator physics, the shape of the particle distribution in the emittance phase plane at the exit of the ion source is not ellipse, except for all of four variables \((x, x', y, y')\) are distributed in Gaussian way. The Gaussian distribution of \(x\) and \(y\) has a reasonable physical meaning, since the origin of the distribution of \(x'\) and \(y'\) is the thermal motion of the plasma. However, the Gaussian distribution in the real space (concerning with \(x\) and \(y\)) is not understandable, since the plasma should be distributed uniformly around the very small hole on the plasma electrode. Therefore, we propose a new distribution of UY-dst as a most realistic distribution. UY-dst is generated with the following procedure; (1) the generation of the random distribution of \(x\) and \(y\) within a circle of a radius \(r\); (2) the generation of the Gaussian distribution of \(x'\) and \(y'\) by using the probability distribution function of \(exp[-(x^2+y^2)/2\sigma^2]/\sqrt{2\pi}\sigma\) (3) focus (defocus) with a thin-lens in order to reflect the shape of the plasma surface by using the equations of \(x' = x_0 + x/f\) and \(y' = y_0 + y/f\) and (4) iterations from (1) to (3) by changing three parameters of \(r, f\) and \(c\) in order to match \(a, b\) and \(c\) of the rms emittance to the design values or the measured values. Tow examples of UY-dst are shown in Fig. 9. It is noted that the outward form of each distribution is a lozenge.

Fig. 10 The examples of the UY-dst: (a) \(\alpha = 0\) and (b) \(\alpha = -0.91\).
RF PHOTINOJECTORS*

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Abstract

RF photoinjectors have been under intensive development for the past decade since they promise to be the high-brightness electron beam sources required for FELs. Progress has been sufficiently good to make optically switched RF photoinjectors attractive candidates as injectors for future colliders, especially those colliders which plan to use complex beam pulse structures. Although present RF photoinjectors will not today meet all the requirements of some collider designs, their potential capabilities seem greater as well as more versatile than conventional injectors. The present status and future goals of RF photoinjectors are compared. The principal problems remaining for achieving these goals while also providing high reliability for linacs during continuous, long-term operation are examined.

Introduction

The first use of rf photoinjectors was in 1985 at LANL by Fraser, Sheffield, and Gray.[1] The initial tests rapidly evolved into a working model of an rf gun at LANL for application with free electron lasers (FEL),[2] and rf photoinjectors are now routinely employed as electron sources for a large variety of FEL designs.

Very early it was realized that photoinjectors were potentially the best solution for an electron source for linacs that require a complex pulse train, since the optical system that drives the cathode is usually more suited to the time frame of the pulse structure than a fast pulser driving a grided, thermionic cathode. Numerous test linacs with rf photoinjectors are now in operation or planned that are proving this concept viable.

![Diagram of an rf photoinjector](image)

Fig. 1. Principal components of an rf photoinjector.

Finally, since a future electron-positron collider will require that the electron beam be polarized, there is hope and increasing evidence that this might be doable using an rf photoinjector.

The basic components of an rf photoinjector, illustrated in Fig. 1, consist of an rf gun with a photocathode, a laser and optical system producing the desired pulse structure, an rf source, and a timing and synchronization system.


In the sections that follow, recent progress of photoinjectors for FEL and collider applications will be examined.

Photocathodes

Until recently the LANL rf guns, which operate at L-band frequency, used CsK2Sb photocathodes, which provide lifetimes under operating conditions of some tens of hours. An S-band gun was developed at BNL that uses a metal cathode such as Cu or Mg. In the vacuum environment of the gun, a metal cathode is very robust, however the high work function and low QE associated with metal cathodes necessitates a very high-power UV laser.

Cs2Te cathodes have been developed at CERN for use with an S-band gun.[8] These cathodes maintain a QE >1% at 262 nm for many weeks in the operating gun,[9] but cannot be exposed to air. CsI cathodes can be exposed to air, but their QE is considerably lower.

The experimental effort necessary to establish the viability of an activated III-V semiconductor in a high-power rf gun for producing polarized electrons has only just begun.[10,11]

Unfortunately, the perfect photocathode, whether or not suitable for polarized electrons--one with high QE in the visible, near infinite lifetime, and able to recover readily after exposure to air--has so far eluded investigators.

FEL Applications

The universal gain parameter, $\rho$, for an FEL is a simple function of the beam brightness,[12]

$$\rho \propto \frac{B}{\text{beam}}.$$  

The appeal of rf photoinjectors for FELs is that a high brightness beam can be produced directly from the gun. This is a major advantage, especially when the electron accelerator itself is small and the whole FEL system may be less costly than alternative high-brightness injector systems, such as a pulsed, grided, thermionic gun followed by an rf longitudinal bunching system and a damping ring for reducing the transverse emittance.

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The peak normalized rms brightness is given by

\[ B_n = \frac{2I}{\varepsilon_{n,x} \varepsilon_{n,y}} \]

in units of A/(m-radians)^2, where \( I = Q \int (\sqrt{2\pi} \sigma_z) \) is the peak current, \( \sigma_z \) is the rms bunch length, and \( \varepsilon_{n,z} \), the normalized transverse rms emittance in the s-s' plane, is

\[ \varepsilon_{n,z} = \beta \gamma \sqrt{(s^2)(s'^2) - (s s')^2} \]

where s is either x or y. The mks units for \( \varepsilon_{n,s} \) are \( \pi \) m-radians, where the \( \pi \) attached to the units is used to distinguish the numerical results from those associated with the area of an ellipse which (in limited cases) bounds the phase-space domain representing the particles in the bunch.[13]

High current densities at the cathode are desirable in order to minimize the transverse emittance. Thermionic cathodes are limited to something on the order of 10 A/cm^2, whereas photocathodes can easily produce peak current densities that are much higher: more than 3000 A/cm^2 have been extracted from Cs₂Te cathodes in the CLIC Test Facility (CTF) S-band rf gun at CERN illuminated by 262-nm light from a quadrupled Nd:YLF laser system.[14] The space-charge limit is significantly higher. For a bunch length that is less than the transit time of the bunch through an rf cavity, the space-charge limit may be approximated using Gauss’ Law, \( \sigma = \varepsilon_x E_x \). For acceleration 30 degrees off the crest of an rf field of 100 MeV/m, \( \sigma = 44 \text{ nC/cm}^2 \), which translates to 5500 A/cm^2 for the 8 ps FWHM pulse as used for the CTF measurement above.

The high electric fields produced by rf guns are necessary both to extract the high currents and to minimize the effects of space charge on emittance growth while the bunch is accelerated to relativistic energies where the space-charge forces vanish. The lower limit of emittance in a gun can be approximated by the thermal normalized emittance,[15]

\[ \varepsilon_{n,th} = \gamma^2 \left( \frac{k T_e}{m_e c^2} \right)^{1/2} \]

For a laser driven photocathode, \( r_c \) is the rms radius of the laser spot on the cathode and \( T_e \) is the effective temperature of the photoelectrons.[16,17] Assuming \( r_c = 0.5 \text{ mm} \) and an effective temperature of 0.2 eV, the normalized thermal emittance for a high-gradient rf gun is about 0.3 \( \pi \) mm-mrad. This low emittance is not realized in practice because of the dominance of several mechanisms which compete to increase the emittance. The principal mechanisms are space charge and rf fields.

Analytical expressions for space-charge and rf-induced emittance growth have been derived by Kim.[18] If the aspect ratio \( A = \sigma_x/\sigma_y \) of the bunch is \( <1 \), then the transverse emittance growth due to space charge is given by

\[ \varepsilon_{n,i} = \frac{A Q}{8 \sqrt{2 \pi \varepsilon_c c \sigma_z E_0 \sin \phi_0}} \mu_i(A), \quad i = x \text{ or } y. \]

Here \( E_0 \) is the maximum rf field at the cathode, \( \phi_0 \) is the rf phase at extraction, and \( \mu_i(A) = O(1) \) for \( A \to 0 \). The rf-induced emittance growth for a bunch of negligible charge is given by

\[ \varepsilon_{n,i}^f = \frac{e E_0}{2 \sqrt{2 m_e c^2}} k^2 \sigma_z^2 \sigma_x^2, \]

where \( k = 2 \pi / \lambda \) is the wave number of the rf field. Clearly the rf emittance increases with increasing initial acceleration while the space-charge emittance decreases.

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**Fig. 2.** Measured emittances scaled to 1 nC for a sample of emittance-compensated (except BNL-1) rf photoinjectors: ELSA,[19] Boeing,[20] APEX,[21] AFEL,[22] and BNL-1.[23] The vertical range shown for BNL-2 corresponds to the estimate in reference 24.

These equations along with the practical limitations of rf cavities, photocathodes, and associated laser systems provide the basic tools needed for designing a high brightness rf photoinjector system. However, the detailed design for the rf gun is usually the product of a computer simulation using standard codes such as MASK and PARMELA. Figure 2, which follows reference 5, shows the measured emittance for a number of optimized rf photoinjectors spanning a large range of operating frequencies, v. BNL-1 (2) is an early (later) version of the photoinjector for the Accelerator Test Facility (ATF) at BNL. The emittances shown for BNL-1 and 2 have been scaled to 1 nC using the charge scaling of Rosenzweig and Colby.[12] Figure 2 shows that the beam emittance of gun designs optimized for a fixed, relatively modest charge is flat or perhaps weakly decreases as frequency increases, consistent with the scaling of reference 12. Using the same data as for Fig. 2, \( B_n \) is calculated to be 0.4, 0.2, 2.3, 6.2, 4.0, and 2.5 \times 10^{-13} \text{ (A-mm-mrad)^2 for ELSA, Boeing, APEX, AFEL, BNL-1 and 2 respectively—values that generally increase with } v, \text{ again consistent with reference 12.}

The measured emittances shown in Fig. 2 are as much as a factor of 10 lower than those predicted by Kim's equations.
emittance occurs as the bunch is accelerated inside a linac, the reduced emittance can be frozen since the space-charge forces decrease as $\gamma^{-2}$. As a practical matter, a compensating solenoid is located near the rf gun followed by a drift and a linac. Although this emittance compensation technique has been employed by a number of photoinjectors for several years, the first measurement of the relative rotation of the slice phase space distributions for various settings of the compensating solenoid were only recently reported by Qui and colleagues using the 1-1/2 cell S-band photocathode rf gun of the ATF.[27]

The success of the one and 1-1/2 cell gun developed at BNL for the ATF is evident by the frequency with which it has been copied—some dozen examples are now in use. S-band cavities can be operated at a higher accelerating gradient than L-band, thus minimizing the axial distance over which the space-charge forces are strong. A cross section of an early version of the gun is shown in Fig. 5.[28] The cavities are designed to operate in $\pi$-mode in the standard TM01 pattern.

![Fig. 5. Cross section of early BNL S-band gun.](image)

The thickness of the disks and the radius of the aperture is adjusted to linearize the radial dependence of the transverse electric and magnetic fields. RF power is coupled directly to both cells. The coupling aperture is adjusted to avoid coupling to the zero mode. The early gun featured a removable cathode plug that allowed flexibility for cathode studies, but breakdown and field emission at the associated rf choke joint necessitated operation at lower than optimum fields. The experimental results from this gun are labeled BNL-1 in this paper. Since a Cu cathode can satisfy the demands of the ATF, a new version of the gun designed to reduce the beam divergence was built with a full Cu wall, thus eliminating the rf choke.[29] The results from this gun are here labeled BNL-2.

Proposals for increasingly shorter wavelength linac-based FELs such as the VUV FEL at the TESLA Test Facility at DESY[30] and the Linac Coherent Light Source (LCLS) at SLAC[31] indicate the need for electron sources with higher brightness than presently exist. Consequently there is new motivation to understand and reduce the remaining effects of emittance growth. To this end a new 1.6 cell S-band gun that is
designed to minimize emittance growth due to multi-pole modes.\(^{32}\) is now being commissioned at the ATF.\(^{33}\) The first cell has been lengthened to increase the rf focusing. The rf side-coupling for the first cell, which was designed to suppress the zero-mode, has been eliminated in favor of a larger cell iris which increases the mode separation.

**Collider Applications**

Present designs for future high-energy colliders mostly require complex pulse trains in which the individual pulses are either very closely spaced or have high charge or both.\(^{34}\) Although all but one of the present collider designs require a transverse emittance that can only be achieved with damping rings, it has been recognized that a lower emittance from the electron source will ease the damping ring requirements.\(^{35}\) For TESLA, the desired emittance is high enough to allow for at least the possibility of using a low-emittance rf photoinjector without an electron damping ring. For the important two-beam design of the Compact Linear Collider (CLIC),\(^{36}\) the very complex pulse train required for the drive linac would be very difficult to produce other than with an rf photoinjector.

RF photoinjectors can produce the extremely high charge required in some linac applications. The L-band gun for the Argonne Wakefield Accelerator (AWA) drive linac was designed to produce 100 nC bunches from a 2-cm diameter Mg cathode. Using a picosecond UV laser, as much as 40 nC/pulse have been extracted in the linear regime. The bunch length was measured to be 27 ps FWHM at 30 nC/pulse and the corresponding emittance 17 π mm-mrad. Increasing the laser energy into the non-linear regime but staying below the explosive limit, a maximum of 56 nC/pulse has been observed.\(^{37}\)

The CTF was constructed at CERN to study the generation of 30 GHz rf (required for the CLIC drive beam) using an S-band rf photoinjector and linac. The rf gun used in 1994-95 was similar to the BNL design shown in Fig. 5. To generate the desired 30 GHz rf power, the CLIC drive beam is required to produce 1 μC of charge in a total of 48 successive S-band buckets. At the gun, a charge of up to 35 (450) nC was successfully produced in a single bunch (48 bunch train).\(^{38}\) Although this charge is nearly sufficient at the gun, the transmission through the 30 GHz rf structures remains a problem. The poor transmission is being addressed by a number of recent changes to the CTF including a new 2-1/2 cell gun\(^{17}\) with a larger iris aperture. The radial focusing is enhanced by a conical backplane around the cathode and by slightly elongating the first cell. The second and third cells are slightly shortened to reduce the energy dispersion caused by space-charge forces.

The multiple-bunch high charge in the CTF beam results in two serious problems. First, because of beam loading, the emittance-compensating solenoid progressively over-focuses the bunches as a function of distance behind the lead bunch, significantly increasing the emittance. Second, beam loading causes significant phase slippage as a function of axial position in the first cell where the bunches are still non-relativistic. This latter problem cannot be corrected by normal beam-loading compensation techniques after the gun. A novel gun design has been proposed that is expected to greatly reduce these effects.\(^{39}\) The new gun will more than triple the stored energy in the first cell. This is accomplished by designing the first cell to operate in the TM02 pattern, while the following two cells operate in the TM01 pattern. In the no-load condition, the π-mode will dominate as shown in Fig. 6(a). However, in the presence of the bunch train, the gradient in the first cell to drops due to the admixture of the zero-mode shown in Fig. 6(b). These two modes add in the first cell and subtract in the second as desired to reduce phase slippage. In addition, by adjusting the overall gradients in the gun to balance the focusing effect of the solenoid, one should be able to reduce the emittance of the bunch train to the order of the single bunch emittance. A gun of this design is now under construction at CERN.

![Fig. 6. Field patterns for 2-1/2 cell S-band gun designed for TM02 in 1st cell, TM01 in 2nd and 3rd: (a) π-mode for no load case; and (b) secondary-mode when loaded.](image)

**Polarized Electrons**

Future e\(^+\)/e\(^-\) colliders will require that one or both of the beams delivered to the interaction point be polarized. The DC-biased photoinjector at SLAC has been successfully delivering polarized electrons for all operations of the SLAC 3-km linac including the SLIC since 1992.\(^{39}\) The principal element is a GaAs photocathode photoexcited at the band gap energy. The prospects for generating polarized electrons using an rf gun were first discussed in 1993.\(^{40}\) The principal problems are the effect of a semiconductor cathode on the rf cell, the viability of an activated GaAs cathode in the vacuum of an operating rf gun, the time response of a high-QE semiconductor, and the field emission that may result when a cathode with a negative electron affinity (NEA) surface is exposed to high rf fields. The first of these problems was recently addressed in a test using the CTF gun. First a 356-μm thick GaAs crystal was glued at SLAC to a modified cathode plug using indium. After transfer to CERN, the crystal (the surface was not activated) was tested in the CTF gun with rf fields as high as 85 MV/m. The rf operation of the cavity, including the field emission, appeared normal.\(^{9,10}\)
There is an international effort now underway to study the remaining problems. A 2-1/2 cell gun of the CERN design with the TM02 pattern in the first cell is being constructed at Nagoya/KEK to be used at the CTF. Special fabrication techniques will be employed that should significantly reduce dark current. Since dark current is probably the major source of vacuum degradation that will affect an NEA crystal, this gun may prove to be an important test platform for the generation polarized electrons. Finally, there is rapid progress in determining the photoemission response time of GaAs. Recent measurements are consistent with a response time of ≤10 ns for a high-polarization (80%) III-V crystal with a 100-nm epilayer.

Conclusion

Rapid progress is being made to develop higher brightness rf photoinjectors in response to the requirements of proposed short-wavelength FELs. Likewise, rf photoinjectors have been successfully optimized for high charge and/or complex pulse profiles for use with colliders and other linac applications. The possibility of producing polarized electrons with an rf photoinjector is being investigated.

References

[16] The effective temperature of the photocathode can be derived from Schottky effect measurements. For high QE cathodes, a value near 0.2 eV is found. For GaAs, see H. Tang, Proc. of the 1993 Particle Accelerator Conference, 17-20 May, 1993, Washington, DC, p. 3036; for GaTe, see reference 17.
[41] The collaboration was initially formed in early 1996, by CERN, KEK/Nagoya, and SLAC.
[42] T. Nakashish (Nagoya) and H. Matsumoto (KEK), private communication.
MEASUREMENT OF SHORT BUNCHES

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Abstract

In recent years, there has been increasing interest in short electron bunches for different applications such as short wavelength FELs, linear colliders, and advanced accelerators such as laser or plasma wakefield accelerators. One would like to meet various requirements such as high peak current, low momentum spread, high luminosity, small ratio of bunch length to plasma wavelength, and accurate timing. Meanwhile, recent development and advances in RF photoinjectors and various bunching schemes make it possible to generate very short electron bunches. Measuring the longitudinal profile and monitoring bunch length are critical to understand the bunching process and longitudinal beam dynamics, and to commission and operate such short bunch machines. In this paper, several commonly used measurement techniques for subpicosecond bunches and their relative advantages and disadvantages are discussed. As examples, bunch length related measurements at Jefferson Lab are presented. At Jefferson Lab, bunch lengths as short as 84 fs have been systematically measured using a zero-phasing technique. A highly sensitive Coherent Synchrotron Radiation (CSR) detector has been developed to noninvasively monitor bunch length for low charge bunches. Phase transfer function measurements provide a means of correcting RF phase drifts and reproducing RF phases to within a couple of tenths of a degree. The measurement results are in excellent agreement with simulations. A comprehensive bunch length control scheme is presented.

Introduction

Interest in short bunches is driven by many applications such as short wavelength FELs, linear colliders, advanced high frequency accelerator development such as laser or plasma wakefield accelerators, and Compton backscattering X-ray sources [1-3]. Much progress has been made on photoinjection and different magnetic and RF bunching schemes, and with simulation tools to produce very short bunches [4-7]. Electron linacs have the advantage of producing shorter bunches compared to circular machines. Bunch lengths less than 100 fs have been reported for low charge bunches [7-8]. Subpicosecond bunches with high charge per bunch have also been achieved [6, 9]. Recently a 1 ps bunch was reported for the circular machine at ESRF [10].

In this paper, several commonly used techniques for measuring short bunches are briefly described. Then several bunch length related measurements at Jefferson Lab: phase transfer function measurement, zero phasing measurement, and monitoring CSR, are presented in detail, followed by a summary. The bunch length is defined by the rms size of the longitudinal distribution and subpicosecond bunches are referred to as "short".

Measurement Techniques

One conventional technique uses transverse deflecting RF cavities or a streak camera to measure short bunches in the time domain [11]. This method provides bunch length and longitudinal profile information. Using dual sweeping options, bunch-to-bunch resolution can be achieved at the expense of single bunch resolution. Using a L-band RF deflecting cavity, a few tenths of a picosecond resolution has been reported by the LANL group [6]. High resolution is reported for commercially available streak cameras by the vendor specifications [11]. Though the resolution of streak cameras is continuously improving, their high cost is still a primary concern. Also, due to their operational complexity these devices require significant amount of experience and special equipment for calibrations.

Another recently developed method utilizes coherent radiation to determine the frequency components of the longitudinal profile. Though coherent radiation has long been studied theoretically [12-13], it was not until 1989 when CSR was first observed experimentally by Nakazato's group at Tohoku University with a linac machine [14]. Since then, coherent radiation has been extensively studied at Tohoku University and Osaka University for various radiation mechanisms [15]. Meanwhile, Coherent Transition Radiation (CTR) was first measured by the Cornell group in 1991 [16].

In general, the total radiation power is the summation of the power from each individual electron with a phase factor, and is given in Eq. (1).

\[ P(\lambda) = P_{\text{inc}} \sum_{\lambda=1}^{N} \frac{2\pi}{\lambda} \right| = P_{\text{inc}} (\lambda) \cdot (N + N(N-1) \cdot F(\lambda)) \quad (1) \]

where \( P_{\text{inc}} \) is the radiation power from an individual electron, \( N \) is the number electrons per bunch, and \( \lambda \) is the wavelength of the radiation. \( F \) is a bunch form factor given by

\[ F(\lambda) = \int S(z) e^{-\frac{2\pi i}{\lambda} z} dz \quad (2) \]

where \( S(z) \) is the normalized longitudinal density distribution and the integral is over a single bunch. The first term on the right side of Eq (1) is the incoherent power proportional to the number of electrons and the second term is the coherent power proportional to the square of the number of electrons. The form factor is nearly zero in regions where the radiation wavelength is much shorter than the bunch length and becomes close to one when the wavelength is much longer than the bunch length. In between is a transition region. This is illustrated in Fig. 1, where the CSR power spectrum is plotted for bunches with a Gaussian distribution. The dashed line is the incoherent term. The coherent enhancement is clearly seen and the location of the transition region is determined by the bunch length.
Measurements at Jefferson Lab

A very stringent demand on final energy spread, with a design goal of 2.5 \(10^{-4}\) (rms), requires short bunches at the Continuous Electron Beam Accelerator (CEBA) of Jefferson Lab [5, 20]. CEBA is routinely operated within its bunch length specification of 0.5 picosecond, and a bunch length as short as 84 fs has been achieved. Three bunch length related measurements have been performed and systematic studies of longitudinal bunching process have been carried out with the assistance of simulation tools. A block diagram of the CEBA injector layout is given in Fig. 2. A 0.1 MeV CW electron beam is chopped by a pair of RF chopper cavities into a bunch train with variable length from 0 to 100 ps separated by 2 ns. The beam is bunched and accelerated to 0.5 MeV by RF buncher and capture cavities. Then the beam is further bunched and accelerated to 5 MeV by the two Superconducting RF (SRF) cavities, followed by 16 SRF cavities to accelerate the beam to the final injection energy of 45 MeV.

A phase transfer function measurement has been proposed and utilized routinely over the last a few years [21-22]. A relatively narrow chopper slit is used and the phases of the chopper cavities are modulated, equivalent to sampling a small portion of the nominal bunch piece by piece. The arrival phases of the sampled beam are measured by two longitudinal pick up cavities at strategic locations downstream, operating at fourth harmonic of operating RF frequency of 1497 MHz. A particular measurement result of a phase transfer function at the first pick up cavity is shown in Fig. 3(a). Such measurements can give a time resolution to better than one tenth of a picosecond. However, since this measurement only quantifies phase compression, the effects of initial energy spread and space charge are not determined. Therefore, the profile that can be obtained from projection of the phase measurement is only valid for bunches with small initial energy spread and low charge per bunch. PARMELA simulation results are in good agreement with the measurements (see Fig. 3(b)), where the initial energy spread and space charge were turned off. When a significant initial energy spread and both energy spread and space charge were turned on, the simulation results show rather obvious effects (see Fig. 3(c) and (d), respectively). Nevertheless, the measured patterns of phase provide unique signatures of RF cavity parameters [22]. A distinguishable slope change of the measured pattern results from a fourth tenth of degree phase change of the capture cavity (see Fig. 3(e)) while a vertical slip of the pattern is displayed (see Fig. 3(f)) due to a two degree change of chopper gang phase. These pattern recognition techniques have been proven to be invaluable to operate the machine and are routinely used to correct RF
phase drifts and reproduce RF phases to within a couple of tenths of a degree.

![Images of plots](image)

Fig. 3 Plots of phase transfer functions, a relation between modulating phase (input phase) and detected phase (output phase): (a) is measured phase pattern optimized at the first pick up cavity; (b) is simulation result with the initial energy spread and space charge off; (c) is simulation with a significant initial energy spread turned on; (d) is simulation with both energy spread and space charge turned on; (e) is measurement with 0.4 degree phase change of the capture cavity; (f) is measurement with 2 degree of chopper gang phase change.

A zero phasing measurement was employed to measure bunch length and obtain longitudinal profile information [23-24]. The measurement requires several RF cavities (zero-phasing cavities), a spectrometer, and a transverse profile measuring device. The RF cavities operated at zero-crossing of the accelerating gradient impart a time correlated momentum tilt along the beam bunch. Then the spectrometer translates the longitudinal momentum spread into a horizontal position spread. By measuring the horizontal profile, the bunch length and longitudinal profile can be determined. Namely, 16 SRF cavities in the first and second SRF modules are running on crest to achieve maximum energy gain and minimum energy spread. During the measurement, the last 8 SRF cavities are phased to 90 degree off crest. A wire scanner is used to measure horizontal profile at spectrometer. The relation between the bunch length and the transverse beam width at the scanner is given in Eq. (3),

$$\sigma(p) = \frac{1.86}{\pi} \sqrt{\frac{x_{rms}^2 - x_{0rms}^2}{D} \frac{E}{\Delta E}}$$

where \( \sigma \) is the rms bunch length, 1.86 is unit conversion factor between RF degrees and ps, \( D \) is the dispersion of the spectrometer, \( E \) is beam energy with the zero-crossing cavities off, \( \Delta E \) is the energy gain at crest of the zero-crossing cavities, and \( x_{rms} \) and \( x_{0rms} \) are horizontal rms widths at the scanner with the zero-crossing cavities on and off, respectively. This relation and measurement procedure were tested using a simulation where the zero-phasing measurement is performed and compared to the actual bunch length. The results shows good agreement over bunch length of 0.1 to 0.4 ps range except a 10 fs offset.

The bunch length was systematically changed by varying the second SRF cavity phase, resulting in longitudinal phase space rotations. Excellent agreement has been achieved between the measurement and simulation, shown in Fig. 4. It was observed that plus and minus 90 degree off the crest gave different measured bunch lengths, as shown in Fig. 5a and b, which is also consistent with the simulation results. The reason is that in general, the longitudinal phase space ellipse of the incident beam has a slope, \( dE/dt \). The RF wave has slope of \( +/- 2\pi \Delta \Phi \) at the zero-crossings. When these two slopes have the same sign, the measured horizontal profile will be wider, giving a longer bunch length. Therefore, the average bunch length of the two should be used. A relation between the phase space slope and measured bunch length is found to be

$$\frac{dE}{dt} = \frac{\sigma^2 - \sigma}{2\pi \Delta \Phi}$$

where \( \sigma^\pm \) are the measured bunch length with zero-phasing cavities at plus and minus 90 degree off crest, respectively, and \( \sigma \) is the average. The left side of Eq (4) is plotted from simulation in the solid line while the right side of Eq (4) is displayed from measurement in circles in Fig. 6, as the phase of the second SRF bunching cavity is varied. They agree pretty well. It is noted that the zero value point represents the upright position of the ellipse in the phase space, where the shortest bunch was obtained in both experiment and simulation. There is a steep slope around the zero point where the slope of the ellipse changes sign, corresponding to the transition from under compression to over compression. The zero phasing measurement gives bunch length with high precision. The main shortcomings are that the measurement is destructive and time consuming.

![Graph showing bunch lengths versus phase change](image)

Fig. 4 Bunch lengths versus phase change of the bunching cavity, where circles are from measurement while solid curve is from simulation.

![Graph showing horizontal profiles](image)

Fig. 5 Horizontal profile measured by wire scanner. (a) is for zero-phasing cavity minus 90 degree off crest, resulting a longer bunch length while (b) is plus 90 degree off crest, giving a shorter bunch length.
antenna structure the diode is insensitive to the background black body type radiation. The bandpass feature also makes it less responsive to background radiation outside of the interesting wavelengths. CSR signals were measured (see Fig. 8) and calibrated by the zero-phasing measurement shown above. The bunch length as short as 84 fs or 25 μm was achieved, and found simply by peaking the CSR signal (see Fig. 9). The measurement was done with a 513 μm diode plus a 20% bandpass mesh filter [31], for 3x10^4 electrons per bunch. With 200 sample average, the CSR signals after amplification have a signal to noise ratio of 450 for the 84 fs bunch and 100 for a bunch length of 0.6 ps. The main limitation on the resolution in our experiment is due to a slow signal fluctuation of about 20 mV with a few minute time scale. At typical operating conditions, the CSR signal changed from 4 V to 2 V as the bunch length increased from 0.45 ps to 0.6 ps, so a bunch length change of a few fs may be resolved for Gaussian bunches. The monitor is noninvasive and has high resolution. It is also compact (3 cm in size), relatively inexpensive (a few thousand US dollars), and operates at room temperature. Potentially such a monitor can be integrated into a feedback of a control system to lock the operating bunch length. Its main shortcoming is that it cannot provide an absolute value of bunch length. Therefore, it needs to be calibrated with a precise bunch length measurement such as the zero-phasing [26-27].

Fig. 6 Relation given by Eq. (4) is plotted for different bunching SRF phases, where the circles are the right side of the equation and from measured bunch lengths while the solid curve is the left side and from phase space of simulation.

Fig. 7 Schematic diagram of the whisker contacted GaAs Schottky diode assembly

To combat the shortcomings of the previous methods, a noninvasive CSR bunch length monitor has been developed [25-27]. Comparing two CSR power spectrum curves in Fig. 1, the spectrum for the shorter bunch length covers the spectrum for the longer bunch length at long wavelengths, but has extra power at short wavelengths. Therefore, the output signal from a CSR power detector with an arbitrary "bandpass" characteristic will always increase as the bunch length becomes shorter, until such power changes take place at wavelengths outside the range of the detector. Such a monitor was installed after the first chicane dipole. The key component of the detector is a state-of-the-art whisker contacted GaAs Schottky diode developed and fabricated at the Semiconductor Device Lab of the University of Virginia [28-30]. The diode assembly, shown in Fig. 7, consists of a 1/4 mm GaAs chip, a 90 degree polished corner reflector, and a 1 mil whisker wire. The whisker acts as a four wavelength traveling wave antenna with a 90 degree bend inductively cutting off the induced current to the open end. Its tip is etched to less than 1 μm and contacts one of thousands of 1 μm “honey-comb” Schottky diodes on the chip (see the right side of the drawing). The corner reflector is introduced to sharpen radiation pattern around the antenna. The radiation is focused on to the diode by a parabolic reflector following a single crystal quartz vacuum window. The diode is connected to a DC current supply providing a typical 1 μA operating current. Due to its nonlinear properties, a small voltage change, proportional to the incident radiation power, is generated and can be measured as the CSR signal. The diodes have high sensitivity. Unlike thermal detectors, due to its

Fig. 8 Experiment result of CSR power versus rms bunch length where CSR power was measured by the Schottky diode and bunch lengths were measured by zero-phasing technique.

Fig. 9 Measurement results of CSR power and bunch lengths versus relative SRF phase changes. As expected, the shortest bunch length corresponds to the highest CSR power signal.

The strategy of bunch length control at Jefferson Lab is: use zero-phasing measurements as the primary standard to
characterize the longitudinal beam dynamics and calibrate the CSR monitor with the assistance of PARMELA simulations as cross-checks, use the CSR detector to monitor bunch length during beam delivery, and when the CSR signal varies outside of acceptable bounds indicating the bunch length has changed, use the phase transfer function measurement to correct the RF phase drifts that have occurred.

Summary

Several bunch length related measurement in the subpicosecond parameter regime have been discussed. The conventional streak camera or fast deflecting cavity can be employed in the subpicosecond regime with some significant capital investment and operating expertise. Coherent radiation detection techniques offer a very attractive alternative, which is relatively easy to operate, much less expensive, and has excellent performance for shorter bunches. The uncertainty of extracting the longitudinal profile from measured power spectrum needs to be experimentally resolved.

At Jefferson Lab, a phase transfer function measurement is used to correct and reproduce RF phases to a couple tens of degree, which is easy to implement and gives high sensitivity. The zero-phasing method was employed to characterize the bunching process; bunch lengths as short as 84 fs have been measured. Excellent agreement has been achieved between experiment and simulation, and simulation has been very helpful in understanding the measurement results. A noninvasive CSR bunch length monitor using a Schottky diode has been developed. The diode provides very high sensitivity, which means it is able to detect bunch length changes of order 1 fs and for charges as low as $10^6$ per bunch at a bunch length of 0.5 ps. It is compact, inexpensive, and operated at room temperature. The shortest bunch was found experimentally by peaking the CSR signal from the diode.

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A HIGH PERFORMANCE SPOT SIZE MONITOR


Abstract: Beam size estimates made using beam-beam deflections are used for optimization of the Stanford Linear Collider (SLC) electron-positron beam sizes. Beam size and intensity goals for 1996 were 2.1 x 0.6 μm (x,y) at 4.0 x 10^10 particles per pulse. Conventional profile monitors, such as scanning wires, fail at charge densities well below this. Since the beam-beam deflection does not provide single beam information, another method is needed for Interaction Region (IP) beam size optimization. The laser based profile monitor uses a finely focused 349 nm wavelength, frequency-tripled YLF laser pulse that traverses the particle beam path about 29 cm away from the e+/e- IP. Compton scattered photons and energy degraded e+/e- are detected as the beam is steered across the laser pulse. The laser pulse has a transverse size, (σ_0), of 380 nm and a Rayleigh range of about 5 μm. This is adequate for present or planned SLC beams. Design and results are presented.

Introduction

The Stanford Linear Collider (SLC) is the first of a new generation of colliding beam machines that rely on micron sized beams colliding at a relatively low repetition rate [1]. The ultimate performance of the collider is limited by the control of emittance dilution effects that increase the transverse beam size (σ_x,y) at the interaction point (IP), where the two beams meet each other. A useful estimate of σ_x,y is obtained from the deflection seen when sweeping one beam across the other [2]. The two principle drawbacks of the deflection technique are its sensitivity to shifts in beam centroid and a lack of indication of which beam is changing.

The latter has the most significant impact on emittance dilution and optics related optimization. A single beam (e+ or e-) diagnostic that can operate over the full range of SLC beam intensities from 0.3 x 10^10 to 4 x 10^10 particles per bunch is needed. Unfortunately, wire scanners cannot be used for beam sizes smaller than 1.4 μm or for intensities greater than 0.6 x 10^10. A wire scanner equipped with 4 μm diameter carbon wire is used to measure σ_x,y for beams safely away from these thresholds. If either threshold is exceeded, the energy deposited in the wire from a single pulse severs it. The wire scanner is installed deep inside the solenoidal SLC Large Detector (SLD) system and is virtually inaccessible, so routine replacement of the carbon wires is not practical.

The SLC IP laser based beam profile monitor will be used to measure σ_x,y of individual beams inside the SLD over the full range of operating intensities with about 10% accuracy. Some key features of the device are similar to the laser based beam size monitor developed for the FTFB at SLAC [3][4]. A finely focused laser pulse is brought into a 90° crossing angle collision with the electron and positron beam and the Compton scattered photons and degraded beam particles are detected. As the e+/e- beams are steered across the laser pulse on a succession of pulses, the amplitude of the scattered radiation is recorded and used to estimate the beam sizes, in a manner similar to that used with SLC wire scanners [5].

Future linear colliders (LCL) will employ beams of higher charge density than those of SLC [6]. In most designs, conventional wire scanner limits will be exceeded for all damped beam regions. Sets of laser based monitors will serve as emittance monitors. Lessons learned from the operation of the device described in this paper will be useful for the development of NLC beam profile monitors.

Principle of Operation

We considered three basic `optical scattering structures`, 1) a diffraction limited, finely focused waist (TEM'00 mode), 2) an interference fringe pattern similar to that used at FTFB and 3) the finely focused waist of a first order transverse mode laser beam (TEM'01 mode).

The minimum transverse size, σ_0, of a diffraction limited laser beam is [7]:

$$\sigma_0 = \frac{\lambda f}{4\pi\sigma_{in}}$$

where λ is the wavelength of the light, f is the focal length of the lens and σ is the gaussian beam sigma as defined by the photon density. The effective length of the focused section is twice the Rayleigh range (z_R).

$$2z_R = \frac{8\sigma_0^2}{\lambda}$$

The incoming beam size, σ_in, and f combine to give an 'f/#', with the aperture roughly ±3 σ_in giving σ_in ~ 1/2 f/# λ . For typical SLC parameters, with the required beam stay clear distance of 25mm and an f# of 2, λ must be shorter than 500 nm in order to have σ_in < σ, and z_R < 5μm. This is the option selected.

The second 'optical scattering structure', the interference fringe pattern, is useful for much smaller beam sizes than those expected for SLC and, unless the pattern pitch is controllable, can be used to measure only a small range of beam sizes. Scanning with this system involves measuring the modulation depth of the scattered radiation as the beam is moved across the pattern. We could not find room in the confines of SLD for fringe pitch control.

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The third option mentioned above, the TEM ‘01’ mode laser beam, with a field null at the center of the spot, may prove useful. It is easy to implement since the mode would be generated at the laser and the modest increase in \( \sigma_m \) is accommodated in the transport and IP optics. A double lobe result is generated from a ‘01’ mode scan and the spacing between the lobes can be used a laser beam diagnostic.

As the particle beam is swept over the laser beam with a varying impact parameter \( y_0 \), the number of scattered photons, \( N_x(y_0) \), is given by:

\[
N_x(y_0) = \frac{PN_x \sigma_x}{c\hbar\nu(2\pi \sigma_x)^2} \exp\left(-\frac{y_0^2}{2\sigma_x^2}\right)
\]

where \( P \) is the power of the laser beam intercepted by the particle beam (\( \sigma_x=750\mu m \)), \( \nu \) is the frequency of the laser light, \( N_x \) is the number of electrons in the beam, \( \sigma_x \) is the Compton scattering cross section and \( \sigma_x \) is the overlap size (\( \sigma_x^2 = \sigma_{x1}^2 + \sigma_{x2}^2 \)). For peak laser power of 10MW and with \( \sigma_x = 1\mu m \) and \( N_x = 10^{10} \), \( N_x \) is \( 5000 \). A correction, nominally about 12%, is required since the particle beam has an aspect ratio (\( \sigma_x/\sigma_y \)) ~ 5 and the laser beam does not have an elliptical cross section.

The energy distribution of the scattered photons and degraded beam particles is relatively flat and, for \( \lambda = 350 \) nm (3rd harmonic YLF), has a peak gamma radiation energy of 29GeV for SLC. Detectors for monitoring the gamma rays and the degraded e+/e- particles are located along the beamline that extends to the beam dump area [8],[9]. Backgrounds in the degraded particle detectors are typically about 50 particles per beam crossing.

Figure 1. Cutaway elevation view of the inside of the SLD.

The new vertex detector [10], surrounding the e+/e- IP with the wire scanner on one side (not shown) and the laser profile monitor on the other, is itself surrounded by the 13 inch inner cylinder of the SLD central tracking drift chamber (CDC). Access is not available beyond a few inches from the end of the cylinder. The laser transport line (shaded) enters from the bottom right of the figure and passes through two bellows before terminating in the IP optics bench. The numbers along the central axis indicate the distance in cm from the e+/e- IP.

### Optics

Optics design goals were to achieve the minimum \( \sigma_0 \) with the highest transmitted power and the lowest possible aberrations. The most important mechanical constraints were the minimum beam transport diameter of 25mm, the available beamline length of 52mm and mass and density restrictions. Figure 1 shows an elevation view of the IP layout. Within the cone subtended by active SLD segments, the mass of the optics and related supports must cause minimal scattering of the decay particles the SLD is intending to analyze.

The IP f/2 optics (figure 2) are catadioptric, with minimal geometric aberrations, in which a diverging meniscus lens is coupled with a spherical reflector [11]. Two such systems are required, for measuring both \( \sigma_e \) and \( \sigma_r \). For laser pulse lengths longer than about 150ps, the particle beam will also scatter some of the incoming photons before they reflect from the spherical mirror.

The incoming laser beam has \( \sigma_m \) of about 2.5mm. As \( \sigma_m \) is increased, diffraction scattering from the edges of the input optic produces non-gaussian tails effectively increasing \( \sigma_m \). For small \( \sigma_m \), the effective f/ of the IP is increased, resulting in a larger \( \sigma_m \). At the end of the transport, in the IP 'optics bench' (fig. 3), a compact switch system is used to select which of the two possible paths through the IP the laser will follow. A brewster polarizer is used in conjunction with a linear polarizer at the laser to do the selection. A compact construction was required in order to minimize the mass obscuring the SLD end cap detector segments and in order to fit around SLD internal masking and supports.

An estimate of the deviation from diffraction limit caused by surface figure distortions yielded a per element mirror and lens surface figure tolerance of \( \lambda/40 \).

### Laser Induced Optical Component Damage

Since we require reliable operation for several years, about 100 million pulses, and since much of the system is sealed and inaccessible, considerable design effort was concentrated on damage prevention. In order to prevent inadvertent high power density related damage, no lenses or other focusing elements are present in the transport line that carries the light from the laser room to the IP.

The most threatening source of damage is from chemical contaminants. Studies of damage in sealed laser systems (typically infrared lasers) have shown that organic chemical contaminants are a leading cause[12]. Trace contaminants, such as silicone sealers, have been pinpointed as root causes. There is little information available concerning the long term operation of UV lasers where it is possible that the sensitivity to trace organic chemicals will be greater. For this reason, our design transport \( \sigma \) is as large as possible and all IP, IP bench and transport assembly took place in class 100 clean rooms. Non-ultra high vacuum (UHV) volumes are purged with an Ar/O\(_2\) (90/10) mixture as suggested in the report noted above.

Bulk multi-photon damage is another serious concern for long term operation of the UV system with several transmissive optics. Darkening in fused silica has been seen following long term exposure to high fluence, short wavelength light [13]. We interpolated between results at

309
248nm and at 550nm and set our tolerance a factor 5 away from the threshold where these effects are first seen.

**Mechanical**

Three subsystems, the IP and its mirror bench, the 17m transport line and the laser itself comprise the profile monitor. The laser is housed in a external clean room. The transport line passes through the beamline radiation shielding and then along the superconducting quadrupole triplet before entering the SLD vertex area.

The beam enters the IP, (figure 2), from the right or from the bottom, for y or x scans respectively, and passes through the UHV fused silica window that separates the gas filled optics bench from the beamline vacuum. A seal design was developed that allowed the window surfaces to be ground to λ/40 surface quality after attaching the weld ring. The window is coated with a graded index ‘Solgel’ anti-reflective [14] coating. Conventional dielectric layer coatings were rejected since their application would be made after the attachment of the weld ring.

![Figure 2. Central cross section of IP Optics. The parallel laser beam (ω₀>> 20m) enters at right or from underneath with a σ₀ of about 2.5mm. The four 8mm thick UHV seal windows with their weld rings are placed on each side of the IP, with the precision optics installed inside the vacuum chamber. 1% of the light is transmitted and re-imaged on the far side of the IP for diagnostic purposes.](image)

After passing through the focal point the spent laser light is absorbed using glass absorbers located both inside and outside the vacuum system. This prevents possible reflection from metal surfaces that might make secondary ghost images or sputter nearby metal surfaces and thereby cause damage to optical components. The spherical reflector coating allows 1% of the incident light to pass through. Its rear surface, together with a second spherical reflector outside of the vacuum chamber, generate an image of the IP spot that is used as a diagnostic.

The IP optics bench directs the light from the transport to the IP using one controllable and 4 fixed mirrors. It terminates the 1 inch diameter laser transport line. The transport line is evacuated for 90% of its length (10⁻⁶ Torr) and slightly pressurized, along with the optics bench, for the remaining 10%. This section is flexible, to be compliant in seismic events, and removable, to allow servicing SLD luminosity components.

The IP housing has a required vacuum performance of 5 nano-Torr. The cathodioptic optics are most sensitive to lens and mirror centering and coplanarity errors which lead to machining tolerances of 5µm.

![Figure 3. IP Optics Bench Machining. The bench contains 5 mirrors and a Brewster angle polarizer. It has 2.2cm diameter machined internal passages for light transport. The IP is in the top right of the figure, shown without the diagnostic re-imaging optics installed. Eight mirror retaining cap mounting holes are clearly visible in the front of the figure.](image)

A gimbaled moving mirror mount was developed for the transport line that has angular stability of 30µrad and compensated bellows vacuum forces. Fine alignment adjustments are made remotely using compact piezo-electric motors [15].

**Diagnostics**

Steering and alignment diagnostics are provided by 4 miniature CCD profile monitors located behind transport line and IP bench mirrors. They view the laser light directly through the partial transmission of the mirror. A frame grabber based video analysis system is used to monitor the position and size of the spot at each of the monitors.

At the monitor beyond the IP, where reliability and camera radiation damage are concerns, the 50µm spot generated by the re-imaging optics is transmitted by a 10,000 fiber fused silica bundle [16] from the high radiation area to a monitor table. The coherent fiber bundle fluoresces and shifts the UV into visible. It has a diameter of 0.5mm and a single fiber diameter of 10µm. The IP assembly also has two fast
diodes and a beam pickup electrode that are used for finding the relative timing of the laser and particle beams.

The transport line is protected from stray laser light using a CW He-Cad 350 nm λ alignment laser that is mode matched to the high power laser on the laser table. The 1mW He-Cad laser is ideal for this purpose since it’s wavelength is very close to the tripled YLF wavelength. If the signal from the CW laser at the monitor beyond the IP is lost, the high power laser shutter will be closed in order to protect the transport from mis-steered high power laser pulses.

Laser

The laser system consists of a mode-locked 119MHz, 150ps pulse length, YLF oscillator seed laser and a YLF regenerative amplifier laser. Both lasers are lamp-pumped. The oscillator is locked to the 119MHz accelerator clock frequency with a acousto-optic amplitude modulator operating at the first sub-harmonic. A single 1nJ pulse from the oscillator is switched into the amplifier using two Pockels cells.

The amplifier has a gain of 10⁶ in 20 passes and produces 10mJ pulses of 1047nm λ light at a repetition rate of 40Hz. After tripling, we observe 2mJ at 349nm λ with the same pulse length. We chose YLF as the lasing material because of its reduced thermal lensing compared to YAG. After frequency tripling, a pinhole spatial filter is used to improve the beam shape. A small fraction of the light is diverted into a phase space monitoring diagnostic, consisting of a transport of roughly equal length to the main transport and a camera used for measuring beam size, before the entrance to the transport line. The laser beam quality, characterized by M², the deviation from diffraction limit, is measured to be M²=1.1.

Performance

The number of detected gamma rays and degraded e+e⁻ is reduced about a factor of 20 from N, due to the finite acceptance of the detectors and transmission losses in the laser transport and IP system. Thus the expected signal at optimum overlap was about 800 degraded particles. The most difficult aspect of commissioning the monitor was establishing collisions for the first time. Laser timing and e+e⁻ beam x and y position must be adjusted in order to establish collisions. Since the e+e⁻ bunch length is short (σₓ~ 2mm), the overlap is dominated by the laser pulse length. The initial timing setup done with the pickup and fast diode was accurate to about 0.5ns. The search strategy we adopted was to scan perpendicular to the laser beam direction (up and down in fig. 2) with an un-focused e⁻ beam (one with the waist at the e+/- IP, 29cm away). A signal of a few counts over background was visible for ±1mm along the laser path. Once collisions were established, they could easily be re-established using the timing signals and the beam position monitors that surround the IP.

Scanning is done using controls similar to those used for the beam-beam deflection. With this system, the 120Hz beam is steered across the laser spot on a succession of pulses, with detector data recorded on each pulse. A typical background-subtracted scan is shown in figure 4. A scan like this one takes about 30 seconds to complete.

An accurate calibration procedure is required in order to get an estimate σₓ from the measured σ. Unfortunately, it is not possible to directly measure, using an independent technique, the high power laser σ₀ in the IP. The technique chosen for obtaining an estimate of σ involves operating the SLC at intensities 20% of nominal, performing all emittance and IP σₓ optimization using the beam-beam deflection and comparing the results with σ. This test provided e+/- beams with a beam-beam deflection overlap σₓ of 2.9 x 1.0μm (which, for equal e+/⁻, should give actual σₓ of 2.1 x 0.7 μm). Laser profile measurements done at that time yielded 2.0 x 0.85μm σ₀. The results are consistent with a 0.4 to 0.5μm laser σ₀, 20% larger than design expectations but adequate for SLC use.

![Figure 4. A typical profile monitor scan showing σₓ. The horizontal scale is determined using the transfer matrix (Rₓ) for the scan coils to the laser IP. The collision signal in this case is detected using the SLD polarimeter degraded e⁻ detector, located after the first large bend in the outgoing beamline. Each data point is the average of 3 beam pulses with the laser on, with the average of 6 pulses with the laser off subtracted.](image-url)
Figure 5. A typical laser-waist scan. The plot shows the measured $\sigma_y^2$ vs e-beam x position. A parabola is used for a fit.

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Invited Talk Session TU3

Chairman: N. Holtkamp

Tuesday, August 27, 1996
CONSTRUCTION, COMMISSIONING AND OPERATIONAL EXPERIENCE OF THE ADVANCED PHOTON SOURCE (APS) LINEAR ACCELERATOR


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Abstract

The Advanced Photon Source [1] linear accelerator system consists of a 200-MeV, 2856-MHz S-band electron linac and a 2-radiation-thick tungsten target followed by a 450-MeV positron linac. The linac system has operated 24 hours per day for the past year to support accelerator commissioning and beam studies and to provide beam for the user experimental program. It achieves the design goal for positron current of 8 mA and produces electron energies up to 650 MeV without the target in place. The linac is described and its operation and performance are discussed.

Introduction

The Advanced Photon Source [1] linear accelerator system consists of a 200-MeV, 2856-MHz S-band electron linac and a 2-radiation-thick tungsten target followed by a 450-MeV positron linac. The linac is designed to accelerate 30-nsec-long pulses containing 50 nC of electrons to an energy of 200 MeV at 48 pulses per second. The 480-W beam is focused to a 3- to 5-mm diameter spot on a 7-mm-thick water-cooled tungsten target that serves as a positron converter. A 1.5-T pulsed coil immediately downstream of the target refocuses the bremsstrahlung-pair-produced (BPP) positrons and electrons and directs them into the positron linac. Electrons and positrons can be accelerated to about 450 MeV. Final optimization is achieved by rf phasing combined with focusing corrections to optimize matching into the Positron Accumulator Ring (PAR). Electrons transported directly from the gun to the end of the positron linac can reach an energy of 650 MeV.

Initial commissioning of the APS injector and storage ring was performed using primary electrons from the linac. Commissioning then proceeded for several months using BPP electrons in order to ensure that the linac reliability would be adequate for positron production. Linac reliability was good, and magnet polarities in the PAR, synchrotron, and storage ring were reversed in July of 1996. The APS facility has operated with positrons since that time, serving the scientific user community and accelerator physicists and engineers. Use of positrons avoids ion-trapping problems.

Equipment - rf

Figure 1 shows the basic features of the linac. For clarity, the electron and positron linacs are drawn parallel to each other in the figure. Electrons are produced by an

Fig. 1. Schematic view of the linac. The electron and positron linacs are shown parallel to each other for clarity, and the two scales are slightly different.
electron gun with a thermionic cathode. They are transported with the aid of focusing lenses to a single-gap prebuncher and a constant impedance (\(v_p = 0.75\)c) buncher, both of which operate at 2856 MHz.

The beam then enters a 3-m-long, SLAC-type accelerating structure surrounded by Helmholz magnets and is accelerated to 50 MeV. Further acceleration to 220 MeV is accomplished by four additional accelerating structures in the electron linac. The five accelerating structures in the electron linac and nine in the positron linac are powered by five 35-MW TH2128 pulsed klystrons. The upstream accelerating structure in each linac is directly powered by a klystron, while the remaining 12 structures are powered in groups of four by a klystron and SLED cavity assembly as indicated in Figure 1. Coupling cells at the output ends of the structures direct rf power into water-loads to be dissipated as heat. Power to the klystrons is provided by 100-MW line-type pulse modulators [2].

Accelerating structures, SLED cavities, and waveguide components are kept at constant temperature (± 0.1°F) to maintain cavity dimensions and energy stability. To find the operating temperature, the SLED cavity assembly is detuned, and beam energy is measured while the temperature of the accelerating structures and other rf components in that sector is varied. The operating temperature is reached when maximum beam energy is achieved. The SLED is tuned to achieve maximum beam energy at that temperature. Optimum temperatures are different for each sector and also must be re-established when changes are made to building temperature setpoints or air-flow patterns.

The modulator and SLED trigger timing in each sector are individually adjusted to achieve maximum energy gain. A basic operation in setting up the linac is to establish the correct phase between rf components. Phase is initially set using diagnostic lines at the end of each of the two linacs (see Figure 1). A dipole magnet bends beam out of the linac and into a separate beamline equipped with a beam position monitor (BPM) [3], fluorescent screen [4], and a Faraday cup.

Phase is optimized by maximizing beam energy and minimizing energy spread, while viewing changes in the beam image. Some effort has been devoted toward automation of the phase optimization process. The image width on the fluorescent screen varies with the energy spread and its position varies with energy. Proper phase is maintained by automatic phase-control software [5]. The auto-phase control screen is shown in Figure 2. Phase and amplitude of the buncher and prebuncher are adjusted to maximize transport efficiency in the electron linac and minimize energy spread in the positron beam.

Additional information about the rf instrumentation is provided in a separate paper in these proceedings [6].

### Beam Diagnostics

Linac beam current is measured by a toroidal coil and three wall-current monitors. Beam position is measured by eleven 4-button stripline BPMs that also measure the beam current [3]. Diagnostic instrumentation performance is discussed elsewhere in these proceedings [6].

Electrons and positrons are simultaneously accelerated in the positron linac. If phasing is chosen to optimize positrons, the electrons then fall into the next available bucket and are accelerated, but have lower energy and larger energy spread than the positrons. Unfortunately, readouts from the wall-current monitor and BPMs in the positron linac are unreliable during positron runs, due to the mixed nature of the beam. A harmonic BPM [6,7,8] currently under development will enable us to differentiate between the two species.

![Beam Diagnostics](image)

**Fig. 2.** The automatic phase control screen allows storage of all measured phase values in memory, individual phase adjustment, calculation of positron phase from electron phase and vice versa, and fast loading of pre-recorded phase values.

The positron linac diagnostic line, shown in Figure 3a, was used to simultaneously measure beam energy and energy spread of the positrons and electrons in our mixed-species beam after it had been optimized for positrons. Data in Figure 3b were obtained by using sddssexperiment
[9] to sweep the mixed beam across the Faraday cups at the end of the positron linac. Other sdds [9] routines were used to process and present the data.

Beam profile information is obtained by inserting fluorescent screens [4] that are viewed by cameras into the beam. Real-time beam images are visible in the control room, and digitized information can be collected and analyzed via the controls system. Experience with CID cameras has been fairly good thus far, even in the high radiation area near the target. CCD cameras have not fared as well, and some have degraded noticeably within days.

Fig. 3. Diagnostic line at the end of the linac (a), showing Faraday cups (FC), dipole magnet, and a BPM. Electron and positron energy and energy spread with beam optimized for positrons (b). Data were collected by sdssexperiment [9].

Fourteen gas-filled particle detectors run the length of the linac and allow areas of high beam loss to be localized.

Real-time beam current, position, and profile information are used to optimize settings for the 42 focusing and 38 steering magnets throughout the linac. Magnets can be controlled singly or in groups by simple scripts. For example, transport efficiency from the gun to the target was improved from 60% to greater than 85% after a systematic algorithm to optimize focusing and steering in the first sector was developed and applied.

Beam position information, rf power measurements, and corrector magnet response matrices are used as input to any of several automatic trajectory control programs for beam within the linac and to energy control programs for beam injected from the linac into the PAR [10].

Trajectory control is also extremely useful during beam tuning and optimization of new linac configurations.

**Radiation Measurements**

The linac shielded enclosure is constructed of 2-m-thick concrete along the entire length between the linac and the klystron gallery. The shield is modified in the vicinity of the positron target, where 0.4-m-thick steel plates are embedded within 1.6-m-thick concrete to further reduce photon radiation levels in the klystron gallery. Calculated unshielded x-ray dose rates inside the linac tunnel 1 m downstream of the positron target are as high as $7 \times 10^5$ mrem/h. Unshielded neutron dose rates are on the order of $10^6$ mrem/h at that position.

Measurements of radiation from the target were made in normally occupied areas of the klystron gallery using gamma and neutron instruments. The measured data are compared to computations of the estimated radiation leakage [11] at the nominal operating power, as shown in Figure 4. The linac safety envelope is set at 1 kW of beam power. It can be defined in terms of beam power since production yields of secondary radiation, including positrons, neutrons, and gamma rays, are proportional to beam power within the linac's energy range. Measured radiation fields were due only to gammas, and no detectable neutron radiation has ever been found.

Fig. 4. Calculated radiation field in the klystron gallery at the nominal 480 W operating power, and measured gamma radiation at 225 and 390 W.
Penetrations in the shield wall that permit passage of transmission waveguides, cables, water, and other utilities are individually shielded and are frequently monitored to ensure that there is no abnormal radiation leakage.

Since radiation levels near the linac are extremely high during operation, all linac systems capable of producing or accelerating beam are interlocked to the personnel safety system. These systems are deactivated by two independent chains by doubly redundant methods whenever the tunnel is open for access or when beam permissive is removed for any reason.

Radiation levels in all potentially occupied areas near the linac are within DOE guidelines.

**Performance**

Table 1 summarizes the achieved linac performance to date.

<table>
<thead>
<tr>
<th>Electron Linac</th>
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<th>Goal</th>
<th>Achieved</th>
</tr>
</thead>
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<tr>
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<td>200 MeV</td>
<td>240 MeV</td>
<td></td>
</tr>
<tr>
<td>Pulse Length</td>
<td>30 ns</td>
<td>30 ns</td>
<td></td>
</tr>
<tr>
<td>Target Spot Size</td>
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<td>φ ≤ 5 mm</td>
<td></td>
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<td>Power on Target</td>
<td>480 W</td>
<td>390 W</td>
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</tr>
<tr>
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<td>60-Hz rate rf: 60 Hz</td>
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</tr>
<tr>
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<td></td>
</tr>
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<td>Energy Spread</td>
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<td>≤ ± 8 %</td>
<td></td>
</tr>
<tr>
<td>Emittance</td>
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<td>≤ 1.2</td>
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<td>(mm mrad)</td>
<td></td>
<td></td>
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<table>
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<td>14 mA</td>
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<tr>
<td>Energy Spread</td>
<td>± 1 %</td>
<td>≤ ± 1.6 %</td>
<td></td>
</tr>
<tr>
<td>BPP e^+</td>
<td>Unplanned</td>
<td>&gt; 400 MeV</td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td>Unplanned</td>
<td>&gt; 17 mA</td>
<td></td>
</tr>
</tbody>
</table>

**Control and Monitoring**

The linac is controlled by the Experimental Physics and Industrial Control System (EPICS) [12]. EPICS is extremely flexible and, when combined with the sdds toolkit [9], provides a powerful environment for monitoring as well as active and passive control of the accelerator and its various subsystems.

A powerful save, compare, and restore (SCR) tool allows a detailed record of any given accelerator configuration to be created and stored. Previously recorded configurations can be restored, in part or totally, and an existing accelerator configuration can be compared to any previously recorded files to within predetermined tolerance levels.

Extensive data are recorded by the Archiver and are readily available for further analysis, a feature that is extremely useful for long-term problem debugging. Records are kept of all standard process variables (PVs) as well as PVs that are calculated relationships between other PVs, such as the klystron perversance. An alarm logger maintains a comprehensive record of all alarms, and those data are also available for processing.

**Planned Improvements**

The APS facility plans a 95% or better availability; thus the equipment reliability is critical. Several improvements are underway to increase the overall reliability of the linac.

Transmission waveguide vacuum has been less reliable than desired due to fragile braze joints. Most waveguide sectors have temporary patches and indium-coated gaskets. New waveguide has been procured and will be installed in the next few months.

Accelerating structure removal and cleaning procedures are well known as a result of an accident at the beginning of linac commissioning; however, we wish not to repeat the exercise. Additional rf windows are being installed along with the new waveguide in order to isolate all water loads. This will prevent flooding should a water load fail for any reason in the future.

Efficient positron production and acceleration requires all modulators and klystrons to be functional, thus a sixth klystron and modulator that will act as a switchable spare is being constructed. This system will enable normal linac operation to continue after a short switching delay.

The use of constant current power supplies [13] to replace some modulator components is being actively pursued as a means to improve modulator reliability. One of these supplies is now being installed in the sixth modulator for testing.

**Future Plans**

**LEUTL**

Plans are underway to add a separate electron source in the linac capable of significantly lower normalized emittance and higher peak current than the present DC gun. To implement this, we initially plan to install a thermionic rf gun source and alpha magnet pulse compressor combination, but ultimately we plan to upgrade to a photocathode-based rf gun. This new, high quality source forms the heart of the Low-Energy Undulator Test Line (LEUTL) [14].

The LEUTL has a number of different purposes. One is to allow for the testing of specialized undulators before
their possible installation into a storage ring. Yet another example is to explore such beam/ undulator operating modes as that expected during self-amplified stimulated emission (SASE) below 100 nm.

**Slow Positrons**

The linac can be used for various purposes between injection cycles, including slow positron production [15]. The nominal beam power of 480 W can be greatly increased for slow positron production by detuning the SLEDs and increasing the beam pulse length. Target design simulation studies are underway at this time. Safe operation of the facility must be assured and radiation issues must be addressed in detail. A possible layout of the slow positron area and the LEUTL beamline is shown in Figure 5.

![Figure 5. A possible layout of the slow positron target area, beam transport, and experimental area. The upstream end of the LEUTL is also shown.](image_url)

**Conclusions**

The linac has met its design goals and reliably produces positrons for injection into the PAR. Injection efficiency for positron operation is still being improved, but has been as high as 65%. Improvements to the linac are planned, and future plans include a low energy undulator test line and SASE FEL, and a slow positron source.

For information about the Advanced Photon Source, and about Argonne National Laboratory, please check our Web Page at [http://www.aps.anl.gov/welcome.html](http://www.aps.anl.gov/welcome.html) and the links therein.

**Acknowledgments**

Work supported by the U. S. Department of Energy, Office of Basic Energy Sciences under the Contract W-31-109-ENG-38. We would particularly like to acknowledge M. Douell, D. Fallin, C. Gold, J. Goral, J. Hoyt, D. Jefferson, T. Jonasson, M. Lagessie, D. Meyer, S. Pasky, L. Peterson, V. Svirtun, and D. Yuen for their efforts in constructing the linac; J. Haumann for overseeing design and construction of the modulator controls; and Mr. F. Onesto for expediting. We thank G. Mavrogenes for his valuable insight and experience. Slow positron target simulations are carried out by E. Lessner. We also acknowledge the efforts of the entire APS staff who constructed, commissioned, and now operate the facility. Lastly, we greatly appreciate the expertise of D. Haid in graphics manipulations for this document.

**References**


Poster Session TU

Chairman: N. Holtkamp

Tuesday, August 27, 1996
SLC–2000: A LUMINOSITY UPGRADE FOR THE SLC

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Abstract

We discuss a possible upgrade to the Stanford Linear Collider (SLC), whose objective is to increase the SLC luminosity by at least a factor 7, to an average $Z$ production rate of more than 35,000 per week. The centerpiece of the upgrade is the installation of a new superconducting final doublet with a field gradient of 240 T/m, which will be placed at a distance of only 70 cm from the interaction point. In addition, several bending magnets in each final focus will be lengthened and two octupole correctors are added. A complementary upgrade of damping rings and bunch compressors will allow optimum use of the modified final focus and can deliver, or exceed, the targeted luminosity. The proposed upgrade will place the SLC physics program in a very competitive position, and will also enable it to pursue its pioneering role as the first and only linear collider.

Introduction

The goal of the SLC–2000 proposal [1] is to upgrade the Stanford Linear Collider (SLC) in order to produce 3 million polarized $Z$s in less than four years, and to embark on the rich physics program accessible in future high-luminosity SLC runs [2]. In this document, we outline an upgrade path for the accelerator that will increase the SLC luminosity by roughly a factor of seven and point to related documents for more information.

The average $Z$ production rate during good months of the 1994/95 SLC running cycle was 5000 $Z$s per week. Assuming 30 week physics runs each year and a 25% reduction of the integrated luminosity due to PEP-II (B factory) operations, then the peak luminosity must be increased from its 1994/95 value by a factor of seven to attain the desired complement of $Z$s. It should be noted that we have based our luminosity extrapolation on the good performance during the 1994/95 run. If, instead, the luminosity estimate is scaled from the average performance during either 1994–1995 or 1996, where we had numerous operational difficulties, the upgrade would only yield 2 million $Z$s in four years.

To gain the factor of seven increase in luminosity, we propose to decrease $L^*$, the free length at the interaction point (IP), by moving the final lens closer to the IP and to decrease the horizontal emittance by 30% at the IP. We considered a number of other approaches such as increasing the bunch charge, the number of bunches per train, or the repetition rate, or decreasing the emittance more substantially, but felt they were all too costly, difficult or uncertain. On the other hand, the optics and aberrations in the final foci are well understood, as demonstrated by studying the operation of the collider at low beam current where the emittance dilutions and pulse-to-pulse orbit variations are small.

At a bunch charge of $5 \times 10^8$, the measured IP spot sizes are roughly 2.1 $\mu$m by 400 nm, in complete agreement with the expected values [3]. Thus, although the proposed upgrade will increase the optical aberrations slightly, we believe that we can accurately calculate these and compensated them with additional octupoles in each final focus.

Unfortunately, at high currents, there are dilutions that are not well understood. For example, with a bunch population of $3.5 \times 10^{10}$, the measured vertical IP spot size is typically 50% larger than expected. Fortunately, any emittance dilutions or jitter at high current will get demagnified by the new final lens, and the ratio of actual and expected luminosity will stay constant. Thus, the predicted relative luminosity increase due to the change in $L^*$ is valid at both high and low currents.

The reduction of the horizontal emittance is more difficult to predict because we do not fully understand the emittance dilutions and the luminosity reductions at high current. Fortunately, the horizontal spot size, and thereby emittance, is significantly larger than the vertical and much closer to the expected value giving confidence in our ability to predict a small reduction. In the upgrade, we reduce the horizontal emittance in the damping rings and bunch compressors by a factor of three. Given the known sources of dilution, we would expect this to reduce the IP horizontal emittance by a factor of 50%. Assuming some additional sources, we are conservatively designing for an emittance reduction of only 30%.

Table 1 lists IP beam parameters for the SLC-2000 upgrade. The upgrade rests on the following assumptions: First, the luminosity limits in the present SLC are due to purely geometric effects, i.e., transverse wakefields, magnetic errors, transverse jitter, etc., that dilute the projected horizontal and vertical phase space densities upstream of the final triplet. In this case, the limiting dilutions will be demagnified by the new final doublet along with the spot sizes. This assumption is believed to be true because all known chromatic and chromo-geometric sources which can partially negate the chromatic correction have been estimated to be negligible. Second, the chromatic properties of the present SLC final focus agree with predictions, giving confidence that we can predict the chromatic properties of the new design. Experimental data which support this are summarized in [4, 5]. Third, the required 500 $\mu$m bunch lengths at the IP can be produced and collided with acceptable backgrounds. It should be noted that the SLC operated with 750 $\mu$m bunch lengths at the IP during the first half of the 1994-1995 run. Fourth, the horizontal emittance reduction at the IP can be accomplished. This assumption has been verified recently by operating the present damping ring coupled, decreasing the extracted horizontal emittance.
by roughly 50% at the expense of the vertical. Further evidence for it arises from the behavior of the vertical emittance which was decreased substantially by operating the damping rings off the coupling resonance, and from studies of emittance growth in the collider arcs [5, 6]. Fifth, the luminosity is not limited by collision related backgrounds, i.e., background sources that arise from the electromagnetic interaction of the two bunches.

**Final-Focus Upgrade**

The centerpiece of the final-focus upgrade is a pair of new LHC-style superconducting final doublets with a field gradient of 240 T/m. These doublets will replace the present SLC final triplets which have gradients of about 100 T/m. The free length to the IP, \( L^* \), will be reduced from 2.2 m in the present final focus to 70 cm in the upgrade. In addition, three new bending magnets and two octupole correctors will be installed in each final focus, to reduce the effects of synchrotron radiation and higher-order aberrations.

At present the SLC final focus operates with flat beams. IP beta functions are about \( \beta_x \approx 7 \text{ mm} \), \( \beta_y \approx 2-3 \text{ mm} \), and the high-current emittances are \( \gamma_e \approx 5.6 \times 10^{-5} \text{ m} \), and \( \gamma_y \approx 1.0 \times 10^{-4} \text{ m} \). Under good running conditions, the spot size can be 2.1 \( \mu \text{m} \times 0.7 \mu \text{m} \) at high current (bunch charges larger than \( 3.5 \times 10^{10} \)). The upgrade is designed to reduce the spot size to 1.15 \( \mu \text{m} \times 0.25 \mu \text{m} \) for horizontal and vertical beta functions of 2.1 mm and 500 \mu \text{m}, respectively. This corresponds to a luminosity of 500 Zs per hour, which increases to more than 1000 Zs per hour, if the horizontal emittance is reduced to \( \gamma_e \approx 4.0 \times 10^{-5} \text{ m} \), and the rms bunch length shortened to 0.5 mm.

The present IP spot size is limited by three different effects [3, 7]: linear optics, nonlinear aberrations—primarily due to the interleaved sextupoles—and synchrotron radiation in the bending magnets. The latter increases both the horizontal spot size, due to the induced emittance growth, and the vertical spot size by virtue of the large triplet chromaticity. To reduce these limitations, we have considered the following improvements to the final focus: First, the three last bending magnets will be replaced by 50% longer magnets. Sufficient space for the new dipoles is available. Second, two octupole magnets, on remotely controlled movers, will be added to each final focus. These will correct the dominant nonlinear aberrations, and improve the energy bandpass of the system. It will also be advantageous to mount the four main sextupoles in each final focus on remote movers, and to install additional 1-\( \mu \text{m} \) resolution BPMs, as used in the Final Focus Test Beam. The last two items are relatively minor modifications, which will facilitate operation. Third, as stated, the heart of the final-focus upgrade is the installation of a new superconducting final doublet. In order to fit into the detector at the reduced \( L^* \) of 70 cm, the maximum outer radius of the new doublet cryostat is about 20 cm. To provide sufficient beam stay clear, the inner radius is chosen as 2.54 cm. These dimensions closely resemble those of the superconducting quadrupoles fabricated for the LHC [8] and proposed for the TESLA final focus [9], which have an effective pole-tip field of 6 T. To achieve such a high pole-tip field, and to make use of LHC technology, the cryogenics system must be upgraded to 1.8-K operation. For comparison, the present SLC triplet, which operates at a temperature of 4 K, has an effective pole-tip field of only 2.2 T at a similar radius. The quadrupole design for TESLA [9] would meet all the SLC-2000 requirements.

A reduced \( L^* \) alone already alleviates all three effects limiting the IP spot size: it allows higher IP beam divergence, providing a larger acceptance, and thus facilitates a squeeze of \( \gamma_x, \gamma_y \). Next, it reduces the chromaticity of the system, thus reducing the effect of synchrotron radiation on the vertical spot. The beta function at the exit of the last quadrupole is about \( \beta_y \approx L^* / \beta_y \). If the quadrupole strength is changed in proportion to the divergence, i.e., \( K_{Q1} \approx \beta_y \), the chromaticity \( \xi \approx \int \beta_y(s) K_{Q1} ds \) scales as \( \xi \sim L^2 / \beta_y^{3/2} \). Hence, a reduction of \( L^* \) roughly implies a reduction of \( \beta_y \) by about the same factor. In addition, a reduced \( L^* \) leads to reduced nonlinear aberrations since the strength of the sextupoles, which generate the aberrations, scales in proportion to the chromaticity.

We have also studied a more ambitious option for SLC-2000, namely to substitute the present final focus by an FFTB-like system with noninterleaved sextupoles. The performance of such a system would be superb. However, it is thought to be more (too) expensive, and we do not further discuss it here.

IP beam parameters for the present and the upgraded final-focus systems have been summarized in Table 1. The table shows that the luminosity improves by about a factor of 3.5, when only the final focus is upgraded, and that it further increases, by a total factor of 7, if damping rings and bunch compressors are also modified. It should be emphasized that the actual average luminosity delivered in the 1994/95 SLC run was about 60 Zs per hour, and thus short by a factor of 2–3 compared

<table>
<thead>
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<th>parameter</th>
<th>present</th>
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<th>FF+DR+BC</th>
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<td>( N )</td>
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<tr>
<td>( \sigma_B )</td>
<td>52 MeV</td>
<td>166 MeV</td>
<td>482 MeV</td>
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</table>

Table 1: Estimated IP beam parameters and predicted peak luminosity for the present final focus, for only the final-focus upgrade, and for the complete SLC-2000 upgrade involving final focus, damping ring and bunch compressor. The symbol \( L_0 \) (\( L \)) denotes the luminosity without (with) pinch and hourglass effect. The last four parameters refer to the spent beam and were obtained using the code GUINEA-PIG [10].
with the ideal estimate of Table 1. The origin of this discrepancy is not fully understood. Regardless, since the aberrations and dilutions will be demagnified by the new doublet, the ratio of expected and actual luminosity is believed to stay the same for the upgrade, so that we expect exactly the predicted factors of 3.5 or 7 improvement in luminosity.

Table 1 also shows average energy loss and energy spread of the spent beam, which both increase by a factor 10–20 to values of the order of one percent for the upgrade. The number of beamstrahlung photons and the average photon energy are increased by a similar factor. The parameters for disruption and beamstrahlung are very close to, if not larger than, those expected for the Next Linear Collider (NLC).

Ref. [11] describes the optics of the upgraded SLC final-focus system. The peak of the vertical beta function in the final doublet is reduced by about a factor of 5 from its present value, while the maximum of the horizontal beta function is about a factor 3 larger. The dispersion function is the same as in the current system. The total momentum bandwidth of the final-focus upgrade is larger than ±0.3% (defined by a doubling of the beta function), which is sufficient for an expected beam-energy spread of about 0.2%. The effects of synchrotron radiation and nonlinearities are still small for these beta functions, and there is, hence, a potential for further decreasing the IP spot size, until the hourglass effect, the physical aperture in the final doublet, or the beam stay-clear for the spent beam will finally set a limit. Another fundamental limit on the spot size is due to the Oide effect (synchrotron radiation in the final doublet) which, for emittances of \( \gamma \epsilon_x \approx 4 \times 10^{-5} \) m and \( \gamma \epsilon_y \approx 1 \times 10^{-5} \) m, imposes a minimum horizontal and vertical spot sizes of 700 nm and about 100 nm, respectively. Thus, this limit will not be important for SLC-2000.

The 10-\( \sigma \) beam envelopes of the incoming beam in the final doublet are comparable to, or better than, the present situation, and the beam stay-clear in the doublet is more than sufficient. The stay-clear of the spent beam in the high-dispersion points of the CCS is of some concern, because the energy loss and energy spread are largely increased due to enhanced beamstrahlung [12].

For SLC-2000 the background from synchrotron radiation in the final doublet looks considerably improved, thanks to the shorter \( L^* \) [12]. As regards synchrotron-radiation generated upstream of the final doublet, there is no significant difference between SLC-2000 and the present design [11]. Furthermore, masks can be installed to intercept most of this radiation.

Damping Rings, Bunch Compressor, Linac

In addition to the final focus upgrade, the SLC-2000 scenario requires a smaller horizontal emittance. This is produced by modifying the present damping rings to use combined function bending magnets as described in [13, 14]. Here, a single 70 cm combined function magnet replaces two 30 cm bending magnets and a defocusing quadrupole located between the bending magnets. This decreases the horizontal dispersion in the magnet and increases the horizontal damping partition to 1.7 with a net effect of decreasing the horizontal emittance by a factor of three to \( \gamma \epsilon_x = 0.9 \times 10^{-5} \) m.

To further improve the collider performance, we also plan to modify the bunch compressors which immediately follow the damping rings. Presently the bunches are compressed in transport lines which are corrected chromatically through second order. Unfortunately, these have proven difficult to tune and operate and are a possible source of beam halo which could cause backgrounds in the detector. In the upgrade, we will add a short magnetic chicane after injection into the SLAC linac. The bunch compression is then performed using the chicane and the old compressor beam lines simply transport the beams from the rings to the linac.

Finally, the upgrade requires shorter bunch lengths at the IP. These are obtained by decreasing the bunch lengths in the linac from roughly 1.1 mm to 0.9 mm and inducing a correlated energy deviation along the bunches which causes them to be further compressed in the arcs that transport the beams from the linac to the IP. To achieve sufficient compression, the energy spread must be increased from 0.1% to 0.2–0.3%.

Conclusion

The SLC-2000 upgrade encompasses a new final lens, a smaller horizontal emittance, produced by a modified damping ring, and shorter bunches at the IP. Based on the performance during good months of the 1994/95 run, the upgrade should produce 3 million \( Z \)s in 4 years. Of course, the upgrade scenario presented is still preliminary and a number of additional calculations and experiments are needed before the design can be completed with full confidence. Finally, the upgrade is expected to cost roughly 20 M$.

References

Pencil-like mm-size Electron Beams Produced with Linear Inductive Voltage Adders (LIVA)

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Abstract

We present the design, analysis, and first results of the high brightness electron beam experiments currently under investigation at Sandia National Laboratories. The anticipated beam parameters are the following: energy 12 MeV, current 35-40 kA, rms radius 0.5 mm, and pulse duration 40 ns FWHM. The accelerator is SABRE [1], a pulsed LIVA modified to higher impedance, and the electron source is a magnetically immersed foilless electron diode [2]. Twenty to thirty Tesla solenoidal magnets are required to insulate the diode and contain the beam to its extremely small sized (1 mm) envelope. These experiments are designed to push the technology to produce the highest possible electron current in a millimeter radius beam. Design, numerical simulations, and first experimental results are presented.

Introduction

The particle beam which drifts through the multiple cavities of conventional induction linacs is replaced in a LIVA by a metal conductor which extends along the entire length of the device and effectuates the addition of the accelerator cavity voltages. The present experiments were motivated by the success of converting RADLAC II into a linear inductive voltage adder fitted with a magnetically immersed foilless diode (RADLAC/SMILE [3]). Annular beams of 50-100 kA, 1-cm radius were produced with very sharply defined 3-mm thick annulus and low transverse velocities ($B_z = 0.05$).

The SABRE accelerator is also a LIVA. It has 10 inductively insulated cavities each rated to maximum voltage of 1.2 MV. This experiment operated SABRE at ~12 MV with a reduced current of 100 kA.

The major modification of the pulse forming network was the reduction of the total number of pulse forming and transmissions lines by half (from 20 to 10). Thus, each cavity was fed by a single pulse forming line, doubling the accelerator impedance. To maintain an additional capability of further increasing the voltage, a new, smaller diameter magnetically insulated transmission line (MITL) [4] cathode electrode was designed and constructed whose 120-ohm impedance is 40% higher than the sum of the impedance of the cavities.

SABRE High Impedance MITL and Diode

The cathode electrode geometry is shown in Fig. 1. The tapered sections face the cavity gaps and provide an impedance increase which follows the voltage axial gradient. The constant radius segments correspond to MITL sections without axial electric field. This design assures constant current flow over the entire length of SABRE. The cathode electrode is 9.6-m long and includes the voltage adder (6-m long) and a constant radius (2.2 cm) extension 3.2 m in length.

Fig. 1. Line drawing of the new high-impedance cathode electrode.

The magnetically immersed foilless diode is similar to that of RADLAC II/SMILE. However, SABRE diode impedance and solenoidal magnetic field are much higher, and the cathode is a needle on axis (Figs. 1-2), unlike the annular diode in RADLAC II. To generate beams of millimeter sizes, the diode must be immersed in solenoidal fields of 20-30 Tesla [5,6,7]. Figure 2 shows a schematic diagram of the diode design, including the solenoidal magnet. The shape of the fringe field is tailored by a 2-cm thick aluminum cylinder of 25-cm inner radius coaxially enclosing the entire diode assembly.

Simulation Results

The MITL voltage adder (Fig. 1) and the foilless diode (Fig. 2) were designed with a large number of particle-in-cell simulations. Figure 3 shows an electron map of the MITL voltage adder at 60 ns following the arrival of the voltage pulse at the first cavity ($t = 0$). The line is magnetically insulated with the self-field ($B_z$) of the current flowing along the voltage adder.

Fig. 2. Schematic diagram of diode design and transition region.

Figure 4 is a simulation of the transition region. In this region all the sheath electrons are lost to the anode. The losses occur at the point where the self field $B_z$ becomes equal to the

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Fig. 3. Electron map for the high-impedance cathode electrode obtained with a PIC code at 60 ns following the arrival of the voltage pulse at the first cavity ($t = 0$).

Fig. 4. PIC simulation of the transition region. The losses near the conically tapered section are due to the transition from $B_z$ insulation (left side) to $B_y$ insulation in the immersed diode ($0 < Z < 20$ cm); see Fig. 5.

$B_z$ component of the applied field. The simulation's resolution is not fine enough to give the precise beam parameters. The Fig. 5 simulation was done with the above concern in mind, so only the immersed diode was included. A beam of 36 kA with 0.44-mm rms radius is produced. This simulation represents an ideal situation assuming no cathode plasma radial expansion, perfect cylindrical symmetry without instabilities, and negligible beam perturbation due to possible beam-stop plasma blow offs. The cathode plasma expansion problem has been simulated with IPROP [8]. The result is that the effective size of the cathode tip may increase by up to 40%.

Preliminary theoretical analysis and numerical simulations with IVORY suggest two-stream ion hose instabilities between the primary electron beam and the ions extracted and accelerated from the target [8]. This instability causes the beam to oscillate and appear larger. Later in the pulse, the beam breaks up to a number of filaments which move apart, further increasing the electron beam size. According to IVORY, the apparent beam spot size decreases inversely with the diode magnetic field. A 30-T or higher field should control these instabilities in the linear regime and allow 0.5- to 1-mm radius beams. Experimental results appear to agree with the above predictions.

**Experimental Results**

We experienced two major difficulties: a severe decrease in the diode impedance near the peak of the voltage pulse and a larger than predicted beam size. We discovered that the impedance decay was due to a 100-kV prepulse 200 ns before the main pulse. A prepulse suppression switch solved the problem; a 3-cm long plastic preceding the transition region adequately isolated cathode needle from the prepulse. The main pulse was able to flash the plastic surface, propagate downstream and ignite the cathode tip. For the switch to be effective, the diode chamber pressure must be below $10^{-2}$ torr.

The beam cross section was measured destructively with an x-ray framing camera. The beam spot on a tantalum x-ray converter was imaged through eight lines of sight onto discrete sealed microchannel plate detectors which were pulse biased to provide sequential 6-ns frames spanning the SABRE power pulse. In addition, two lines of sight are statically biased to provide time-integrated beam size measurements. Figure 6 shows one time-integrated image and the film spectrally dense profiles along two directions. It is obvious that there is an intense center core surrounded by a tenuous and asymmetric halo. In this particular shot, the cathode needle was misaligned relative to the magnetic field axis, with the tip displaced approximately 5 mm. The FWHM of the x-ray spot size is 2 mm. We are in the process of analyzing the data and implementing a number of corrections to the photograph: namely, the film and microchannel response and aperture modulation response which is calculated with monte carlo radiation transport codes. In addition, to estimate the electron...
beam size from the x-ray spot size, a correction must be made for electron scattering in the target material [9].

The IVORY simulations suggest a ~2-mm beam spot size for a 30-Tesla confining magnetic field. The results appear to agree with the simulation predictions. In addition, a cursory analysis of a number of shots with different magnetic field suggests a beam size decrease as the magnetic field intensity increases.

The halo problem may be unrelated to the ion-hose instability. In the higher Bz shots (> 20 T), we can clearly distinguish the halo from the main beam. In addition, the relative location of core and halo remains unchanged from frame to frame in contrast with observation in the lower Bx shots.

The beam temperature was evaluated by comparing the thermoluminescent dosimeter (TLD) obtained polar diagrams with numerical simulation predictions. The beam temperature is in the range 0.1 < βx ≤ 0.2, higher than predicted without ions (Fig. 5) but in excellent agreement with simulations which include proton emission from the anode target.

Summary

We have designed, constructed and experimentally tested an immersed diode and a high impedance voltage adder for SABRE which should generate a very intense high brightness electron beam of millimeter size. In our first experimental validation of the design, halo and ion hose instabilities have imposed a lower limit of 2-mm radius to the beam. An increase of the Bz to ~ 30 T minimized the ion hose effect and reduced the beam radius to 1 mm.

Acknowledgments

We thank H. C. Ives and T. Wagoner for modifying and setting up the fast-framing x-ray pinhole camera and designing and fielding the diode diagnostics; P. J. Pankuch and K. Law for designing the 9.6-m MITL cathode electrode; R. Wavrik for designing the magnetically immersed foilless diode and magnet support structure; R. S. Coats for calculating the magnetic field profile; K. Shrimp and J. Puissant for building the coils; R. L. Westfall and the SABRE crew for technical support; Dusty Ervin for his motivation and promptness in providing machine shop support; M. Cuneo and W. Fowler for providing design and technical support for the RF target cleaning; D. Nielsen and J. Armijo for refurbishing the diode chamber and target following each shot; and A. W. Sharpe for his technical and management support of the SABRE facility. We would like to extend special thanks to D. L. Cook for his continuous encouragement and vigorous support.

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References

Operation and Improvements of the Fermilab 400 MeV Linac

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Abstract
The 400 MeV Fermilab Linac Upgrade commissioning began August 28, 1993. High energy physics collider operation (run 1b) began in November 1993 and ended March 1, 1996. The Linac, operating at 98% reliability, provided 400 MeV H+ beam to the Booster and 66 MeV H+ beam to the Neutron Therapy Facility. During this time, the beam intensity, which initially was administratively set to 35 mA, rose to a peak of 50 mA while losses decreased significantly. This paper discusses the Linac operation and reliability since the Upgrade.

Introduction
Commissioning of the high energy part of the Linac started August 28, 1993. Prior to this the entire system was installed in the Linac tunnel, along side the drift tube cavities and operated without beam for one year. The last four cavities (116 to 200 MeV) of the original Linac were removed three months before commissioning, and the new side-coupled structure (116 to 400 MeV) was moved into place and reconnected.

When commissioning begun low intensity coating beam was achieved in about eight hours. Once the low energy linac was properly matched, beam coated through the high energy linac with little loss. Good transmission required empirical tuning of the high energy trim magnets and quadrupoles.

Tuning of the accelerating gradients and phases began immediately, starting with the first of seven side-coupled modules and the longitudinal matching sections. The new high energy structure is composed of two small longitudinal matching sections to match from 201.25 MHz into the new 805 MHz system followed by seven side-coupled accelerating modules. Each accelerating module is composed of four cavities with each cavity having 16 cells. A 12 MW klystron feeds each module [1]. The RF amplitude and phase to each module was determined by a process called phase scan signature matching [2] where the phase difference between two beam detectors is measured as the RF phase of the module is scanned through 360 degrees and compared to the calculated curve. Beam measurements and RF studies required seven days and the first low intensity 400 MeV beam was accelerated on September 4, 1993 [3].

Shielding assessment studies, to verify the radiation integrity of the Linac enclosure, were required and done before increasing the intensity. Commissioning of the Booster 400 MeV line, injection and Booster acceleration proceeded in concert until the Main Ring and Tevatron began operations.

Steady improvement in the beam intensity, losses and stability were made during this time. At the time of Main Ring startup, early October 1993, the Linac was providing the design intensity of 35 mA with >98% transmission through the high energy linac.

While commissioning, the Fermilab Linac Department was augmented by several people from the Superconducting Super Collider Linac Group, the Institute for Nuclear Physics, Moscow, and the Institute of High Energy Physics, Beijing.

During 1994 the linac group worked to increase intensity and lower losses. Much of this involved adjustment of the ion source parameters to operate at 65 mA and above [4]. On the high energy linac, studies continued to refine the longitudinal and transverse tunes. This represented small changes to RF phases and amplitudes of the system, adjustment of individual quadrupoles, and much tuning of the high energy trim magnets. All combined, the Linac output intensity increased from 35 mA to 44 mA.

During the February 1995 shutdown the low energy buncher RF system was upgraded and the cavity began operating at 30% higher gradient. This resulted in higher capture (72%) into the low energy linac and the intensity improved to 48 mA. This also appeared to help the high energy linac transmission with a resulting increase in the Linac output to 47 mA.

Operation
Chart 1 shows the monthly average intensity at 400 MeV through the period of the Collider Physics run. The general trend is up with dips caused by ion source aging and differences in the two ion sources. Ion source improvements were implemented in September 1994 and gave a significant increase in intensity. The smaller increase from March 1995 is a result of the work on the low energy buncher. These are monthly averages not peak intensities. During the period of March 1995 to the end of the run it was not uncommon to operate for days at 47 to 48 mA and a record of 50 mA for H+ ions was achieved during studies at the end of the run.

* Operated by the Universities Research Association under contract with the U.S. Department of Energy.
Normalized losses in the accelerating section of the high-energy linac changed very little as the intensity rose. Losses would rise briefly until the best tune was found for that intensity and often decreased to a level lower than the starting point. The 750 keV line tuning has a large effect on the high energy linac losses. A different trim setting is needed for each ion source. Settings have been found which allow both ion sources to provide equivalent beam intensities and losses.

A major improvement in the losses occurred in February 1995. Studies which culminated in a new high energy linac quadrupole tune reduced the losses everywhere in the high energy linac by a factor of two. As the source current increased new quadrupole settings were necessary in the high energy linac. New setting were found using TRACE3D and beam profiles measured at three locations in the transition section and at nine locations along the side coupled structure. Beam profile measurements at the transition section, with TRACE3D analysis, provided Twiss parameters of the beam from the low energy linac. This provided new transition quadrupole settings which produced a waist at the entrance to the high energy linac. After new settings for the transition section were installed, tuning of the trim magnets was done to minimize losses through the high energy linac. At this point an attempt was made to set the rest of the quadrupoles for a FODO structure however the losses with these setting were too high at the ends of modules 2 and 3 so less radical quadrupole settings for modules 1 and 2 were tried. These settings, as 'suggested' by TRACE3D, had the smallest beam size in modules 2 and 3 with clean transmission through the rest of the linac. A best solution was found after several iterations. Chart 3 shows the decrease in the losses during the month of February when these studies were performed.

Chart 4 is a TRACE3D display for the final setting of the linac quadrupoles. The low beam losses in the Linac, good running conditions for the Booster and other operational requirements have forced us to accept these settings and give up on a FODO structure.
Reliability

Reliability in the entire Linac was better than 98% before the Upgrade. In the first three months of 400 MeV operation reliability averaged 94.7%. Except for one klystron problem this increase was due to problems with the low energy linac. This is because people were too busy, during the shutdown, with installation of the Upgrade to do normal maintenance on the low energy systems. As the run progressed the reliability of the Linac as a whole returned to the 98% level with the majority of problems requiring less than five minutes to correct. After the first three months of running the linac downtime was much less than 2% except for a failure every three to four months requiring several hours to repair.

Chart 5, Percent of the total Linac downtime caused by each major system.

The 805 MHz, 12 MW klystrons, a major part of the Upgrade system, has operated extremely well. Of the 7 large and 3 small (200 kW) klystrons, none has yet to fail and many are approaching 30,000 hours operation.

Keeping in mind that the total linac downtime is about two percent, the major reliability problems are the RF modulators in both the high energy and low energy linacs (Chart 5). Subsystems with smaller but significant downtime are: the preaccelerator high voltage supplies, the low energy RF power amplifiers, the low energy cavities, and the high energy low-level RF components.

The low energy linac modulator problems are almost exclusively due to the tubes in use. The tubes are old designs and many are no longer made by the original manufacturer. Of the fifteen switchtubes to control the power tube high voltage, three per a RF station, 28 were replaced over this two year period. These tubes typically fail in one of two modes: voltage breakdown and instabilities. They are used as a linear amplifier and the current manufacturers have trouble making tubes that work in this mode. This requires working with the manufacturers to produce tubes that meet our application.

The high energy linac modulator problems are more varied but a majority of the failures concern the HV SCR switches for the charging supplies and pulse forming networks. Several of these switch banks have been replaced and work continues to improve their reliability. Other problems include the SCR firing circuits and high voltage cable breakdowns.

Current Performance

The Linac is now running at intensities between 45 and 48 mA. The ion source provides approximately 65 mA of H+ beam through the 750 keV line and to the entrance of the Linac. Of this 70-72% is captured in tank 1 and accelerated through the low energy linac to 116 MeV (tank 5). Transmission through the high energy linac is greater than 98% with usually less than 1 mA lost between the output of the drift tube linac tank 5 and the output of the coupled cavity structure (400 MeV). Most of this loss is in the 805 MHz coupled cavity modules 1 and 2 due to the inability to longitudinally capture all of the beam from the 201.25 MHz drift tube linac.

References

Longitudinal Emittance from the Fermilab 400 MeV Linac

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Abstract. The measurements which characterize the longitudinal emittance of the Fermilab 400 MeV Linac beam are presented. These measurements are made by determining the momentum spread and the bunch length of the beam using wall-current monitors, bunch length detectors and a spectrometer.

1. Introduction

Accurate measurement of the length of a bunched ion beam with velocities less than c is difficult. In the Fermilab 400 MeV Linac (the Linac), we have made this measurement using wall-current monitors (WCM), and with a special-purpose device known as a Bunch Length Detector (BLD). The momentum spread can also be determined from the BLDs, as well as from a spectrometer magnet. These methods are discussed, the resolution of these devices is calculated and/or measured and measurement results on the Linac are presented.

2. Overview of the Linac

The Linac is described in detail in the references [1, 2]. For the purpose of this paper, it is sufficient to know the following. The first half of the Linac, low-energy linac (LEL), is a 201.25 MHz drift-tube structure which accelerates the beam to 116.5 MeV. It is followed by a 4-meter transition section which contains two 805 MHz non-accelerating bunching cavities, the “buncher” and the smaller “vernier.” The second half of the Linac, the high-energy linac (HEL), consists of seven 805 MHz modules which each consist of 28 side-coupled cavities in four sections, which accelerates the beam to 401.5 MeV. Each module is followed by a WCM. The Linac beam travels approximately 70 m for injection to the 8 GeV Booster synchrotron. A spectrometer magnet sits at 401 MeV to dump the beam which Booster does not need.

3. Monitoring of Wall Currents

A WCM is a multipurpose device, providing beam toroid signals, beam phase signals and bunch-length information from a resistive gap in the beam pipe. The bandwidth is a compromise between the low-frequency toroid requirements and the high-frequency bunch length requirements. The $\beta=1$ bandwidth of this device is measured to be 6 GHz.

Formulae

For a charged beam with $\beta < 1$, the image charges on a conducting beam pipe spread ahead and behind the beam bunch by an angle $-\gamma^2$. The electric field at the surface of the conducting beam pipe for a particle of velocity $\beta$ is [3]:

$$D_r(t) = \sum_n \left( J_1(\alpha_n^r r / r_0) / J_1(\alpha_n^r)^2 \right) e^{-\alpha_n^r x / r_0}$$

with:

$$x = \gamma \beta ct \quad \text{and} \quad J_0(\alpha_n^r) = 0.$$ 

$D_r(0)$ is taken to be 0.663. At the energies of the Linac, 116 MeV to 401 MeV:

$$0.0154 \ t < x < 0.03054 \ t \ [\text{cm}], \ t \ \text{in picoseconds}.$$ 

Using these formulae, the delta-function response of a 40 mm aperture WCM to a 116.5 MeV beam produces a signal whose apparent length is 100 psec, or about 30° at 805 MHz. A beam length of 100 psec yields a signal on a 116 MeV WCM of about 135 psec, 40°.

Measurements

The WCMs have been used as follows: to observe adjacent buckets for stray beam (only every fourth RF bucket is used at 805 MHz), to estimate the bunch length and to measure the phase of the beam with respect to the RF reference line. During the initial commissioning of the 805 MHz part of the Linac in 1993, beam was observed in adjacent 805 MHz buckets from LEL, and the match was adjusted. Bunch-length changes were observed at WCMs as longitudinal parameters were tuned. Also, the phase and amplitude of the 805 MHz modules was adjusted based on these beam phase signals [1].

For large bunch lengths at higher $\beta$, as obtained following the long drift to the Booster, a WCM is satisfactory. The bunch length is accurately measured at a WCM 41 meters downstream of the Linac. Also, the stability of the Linac beam velocity is tracked with this device.

Figure 1. Measurement results from Wall-current Monitors

WCM measurements have been made of the bunch length vs. position in the Linac and time in the Linac 30 μsec macropulse. (The center of the macropulse is called “2000 μsec”. The results are presented in Fig. 1. The average of several measurements of the bunch length is used. The measured WCM signals are compared to a test distribution,
convolved with the above formulae. These measurements are consistent with a constant bunch length of 159 ± 15 psec (46 ± 4°) through the HEL. This is the average of the measurements, with the uncertainty being the standard deviation on this average combined with the error bars on the measurement. Systematic errors are believed to be large and are not quoted here. The average of the bunch length measurements at the beginning of Module 1 is 185 ± 18 psec (54 ± 5°).

4. The Bunch-Length Detector

A BLD accurately measure the length of a low-β bunched beam. These devices also work well for a high-β beam, but the far simpler WCM is sufficient there. Based on the work of Witkov [3], Feschenko has further perfected this device [4]. Details of the design are presented in the ref. [5]. The BLD gets its signal from a prompt secondary electron beam, created when the primary ion beam hits a target wire, biased to -10 kV. The electrons are collimated by a slit in front of the RF deflector. They are deflected transversely by this RF cavity, which is excited with RF power proportional to the accelerating RF in the Linac. This time-dependent deflection sweeps the electrons across the detector slit at the far end of the BLD. The RF cavity doubles as a focusing einzel lens. The phase of the deflection is varied, and the resulting electron signal vs. this phase is the longitudinal bunch shape.

Resolution

The resolution of the BLD is predominantly determined by: (a) the temporal distribution of the electron beam when it reaches the deflector (related to the 3D emittances of the beam), (b) the strength of the deflection and (c) by machining tolerances [4].

The transverse emittance of the electron beam is determined by the size of the wire, the size of the collimator slit and the temperature of the electrons as they are ejected from the wire’s molecular lattice. The longitudinal emittance is dominated by the time it takes for the secondary electrons to be ejected from the wire—a parameter of some interest to atomic physics. The best measurement to date puts this number at no more than 6 psec [7]. Combined with the other temporal effects, the resolution is degraded less than 10 psec, which corresponds to 2.9° of 805 MHz phase.

The strength of the deflection determines how quickly the image of the wire passes across the detector slit, and this can be measured directly:

\[ \delta \phi = 2 \arcsin(\sqrt{\sigma_{beam}^2 + w_{slit}^2 / 2X_{max}}) \]

\[ = \sqrt{\sigma_{beam}^2 + w_{slit}^2 / X_{max}} \]

for small angle values, where \( \sigma_{beam} \) is the width of the image of the electron beam on the slit, \( w_{slit} \) is the width of the slit and \( X_{max} \) is the extent of the deflection on the plane of the electron detector and is proportional to the electric field in the RF deflector. Without RF deflection, a DC voltage on one of the einzel lens/deflector plates can be changed until the image of the wire is no longer seen in the detector.

\[ V_1 = K\sqrt{\sigma_{beam}^2 + w_{slit}^2} \]

Then, with the RF on, a similar measurement is performed, being careful to measure the maximum deflection of the RF voltage:

\[ V_2 = K(X_{max} + \sqrt{\sigma_{beam}^2 + w_{slit}^2}) \]

Therefore, for small angle values,

\[ \delta \phi = \frac{V_1}{V_2 - V_1} \]

The resolution of the three BLDs installed in the Fermilab Linac have been measured in this manner:

<table>
<thead>
<tr>
<th>BLD Position</th>
<th>V1</th>
<th>V2</th>
<th>Res</th>
<th>Est Res</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition section, 1</td>
<td>80</td>
<td>1200</td>
<td>4.09</td>
<td>5.02</td>
<td>5.78E+10</td>
</tr>
<tr>
<td>Transition section, 2</td>
<td>90</td>
<td>550</td>
<td>11.21</td>
<td>11.58</td>
<td>2.50E+10</td>
</tr>
<tr>
<td>400 MeV Area</td>
<td>120</td>
<td>500</td>
<td>18.09</td>
<td>18.32</td>
<td>1.68E+10</td>
</tr>
</tbody>
</table>

V1 and V2 are in Volts, the resolutions are expressed as degrees of 805 MHz phase, and the bandwidth is in Hz. The “Res” column represents the resolution measured here; the “Est Res” column is an estimate of the overall resolution, which is equal to \( \alpha \text{Res}\^2 + (2.9\text{°})^2 \), taking into account the estimated 10 psec of temporal effects, discussed above.

The resolution on the initial BLD (400 MeV Area BLD) is the poorest, and as we gained experience in building them, the resolution improved. The “Transition section 2” BLD has a smaller, higher-loss cable than “1”, and thus a lower value for V2. All measurements are made at the maximum obtainable power in the RF deflector, estimated at tens of watts.

Figure 3, Typical bunch-length measurement.

Measurements

Typical data from the two BLDs in the transition section are shown in Fig. 3. The second BLD has been used to determine the proper gradient of the 805 MHz buncher cavity. The bunch length as a function of the buncher gradient has also been measured. The bunch length at the BLD upstream of module 1 is 25° when the buncher is off, and 11° when the buncher is set optimally.

Another interesting measurement, made with each of the BLDs, is the length variation during the pulse. The bunch length is measured at various intervals through the macropulse by changing the sample time on the A/D module.

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These results are shown in Fig. 4.

Figure 4, Bunch Length through the macropulse.

Measurement limits

The beam in the Linac has been as high as 50 mA, peak. This corresponds to $1.6 \times 10^9$ particles per bunch, or a charge of $2.5 \times 10^{-10}$ Coulombs. When the BLD target wire is placed in the middle of the beam bunch, the measurement is destroyed. This may be due to a change in the potential seen by the secondary electron beam as the ion beam passed through the target wire. The electrons created in the center of the distribution have a significantly higher potential than the electrons created at the trailing edge. Moreover, the electrons created at the beginning of the bunch are subjected to the passage of the ion beam.

This effect is estimated as follows. The least damaging (and the easiest to calculate) ion beam distribution is a uniform spherical beam. The potential of a test charge along a line is proportional to the distance from the center of the beam, $z$, and the radius of the beam, $R$, is:

$$ V = \frac{\rho}{2e_0} \left[ R^2 - \frac{3}{4z} \left( (R + z)^3 - (R - z)^3 \right) \right] $$

As $z \to 0$, the potential is finite, and for the Linac beam, with $R=10$ mm, $Q = 2.5 \times 10^{-10}$ C, we have:

$$ V_{\text{center}} = 339 \text{ volts} $$

With a primary potential on the BLD target of 10 kV, the secondary electron beam has a velocity of $\beta=0.1950$. This perturbation produces an electron velocity of $\beta=0.1981$ when the ion beam is directly over the wire. Over the 10 cm the electrons must travel to the RF deflector, where their temporal distribution is marked, these faster electrons are 0.750 advanced from the normal electrons.

Further study is needed because (a) there is still a large resolution-killing effect visible on the 400 MeV BLD, (b) the bunch length is much greater than the beam radius and (c) the beam distribution is not uniform. (b) and (c) affect the potential oppositely—longer bunch length lowers the central potential, but non-uniform charge distribution raises it.

5. Momentum Spread

The momentum spread is measured in the Linac by the BLDs at 116 MeV and at 401 MeV, and verified with the spectrometer magnet at 401 MeV.

The bunch length out of Tank 5 is measured by the first BLD to be 14°; the bunch length at the second BLD, 3 m downstream, with buncher cavity off is 25°. This change in the bunch length is due at least partially to the momentum spread, but since the orientation of the longitudinal ellipse is unknown from this measurement, it can only be estimated. Assuming that all of the bunch spreading is from the momentum spread of the beam, $\Delta p/p = 0.17\%$. This puts an upper limit on the longitudinal emittance out of the LEL of $1.6 \times 10^3$ eV-sec. Similarly, the longitudinal emittance is estimated from the change in the bunch lengths from the last BLD to the last WCM, 41 m downstream of the Linac, for the output of the last HEL module to be $7.8 \times 10^3$ eV-sec.

An upper limit on the momentum spread is obtained with the 401 MeV spectrometer magnet. The edge effects of this magnet are poorly understood. The smallest size beam which can be achieved at the focus of this magnet is 32 mm. If this is all due to momentum spread, then this would correspond to $\Delta p/p = 0.005$. The BLD measurement yields $\Delta p/p = 0.0055$.

6. Conclusions

The length of the Fermilab Linac bunched beam has been measured using wall-current monitors and bunch-length detectors. Both of these devices yield interesting and useful results. A well-constructed and carefully implemented BLD can have a bandwidth of almost 60 GHz. The longitudinal emittance can be estimated with these devices.

7. Acknowledgments

Petr Ostroumov and Alexandr Feschenko, from the Institute for Advanced Studies in Moscow, were fundamental in the construction and assembly of these devices. H. S. Zhang, of the Institute for High Energy Physics in Beijing, China, contributed many of the ideas in the understanding of the resolution of the BLD. Our thanks go out to them.

8. References

Emittance Measurement Techniques Used in the 1 MeV RFQ for the PET Isotope Linac at Fermilab

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Abstract: Beam emittance measurements have been performed on the 3He+ beam at the PET-isotope production accelerator, being commissioned at Fermilab for the Biomedical Research Foundation in Shreveport, Louisiana, USA. Emittances have been measured at injection to and extraction from the first RFQ, at 20 keV and 1 MeV, respectively. A single slit followed by a 48-electrode collector is used in the standard way to measure the divergence of the 3He+ beam as a function of position. Noise reduction operations have been developed, both in hardware and software. These techniques and the emittance measurement results are presented.

1. INTRODUCTION

Fermilab, in collaboration with Scientific Applications International Corporation (SAIC), the University of Washington and the Biomedical Research Foundation (BRF), is commissioning a linac to produce an average 200 particle µA of 3He+ at 10.5 MeV for the production of the radioisotopes needed for PET, positron emission tomography [1]. Since isotopes with half-lives on the order of minutes are desired, a small accelerator which can exist in a hospital environment is being constructed. 3He is interesting because it may reduce neutron radiation and the shielding requirements, thereby reducing the cost, the complexity and the weight of the accelerator. The purpose of this effort is to explore the overall practicability of this approach.

| Component   | Energy | Description | 10
---|---|---|---
1 Ion Source | 20 keV | Duoplasmatron | 0 m
2 Transfer Line | 20 | Solenoid | 0.7
3 212 MHz RFQ | 1.0 MeV | | 1.024
4 Transfer Line | 1.0 | 540° bend | |
5 425 MHz RFQ A | 5.047 | Tightly coupled | 1.371
6 425 MHz RFQ B | 8.025 | | 1.461
7 425 MHz RFQ C | 10.539 | | 1.485
8 Target Area | 10.539 | Solid or Liquid | |

Table 1, Components of BRF PET Linac.

The components in this accelerator are summarized in Table 1 and shown schematically in Figure 1. The basic layout of this accelerator is as follows: 25 mA of singly-charged 3He is extracted from a duoplasmatron source at 20 keV into a 0.7 m transfer line and injected into a 212 MHz RFQ. This RFQ accelerates the beam to 1.0 MeV at which energy the 3He+ is stripped by a gas jet to doubly-charged 3He. Following the stripper, a 540° isochronous bend rebunches and injects the beam into the beginning of three tightly-coupled 425 MHz RFQs. The bend has the added benefit of folding the accelerator back onto itself, reducing the length of the accelerator. The beam is accelerated to 10.5 MeV and terminated at the target area where the isotopes are created. The repetition rate of this accelerator is \(\leq 360 \text{ Hz}\), for a maximum duty factor of 2%.

Extensive test of the first RFQ, including tests of the gas stripper, have been conducted. The remaining parts of the accelerator will be commissioned in the Fall of 1996. Delivery to BRF in Louisiana, USA, is scheduled for early 1997.

![Figure 1, The BRF PET Linac](image)

Further information on this project is available from our web site: [http://www.linac.fnal.gov/pet](http://www.linac.fnal.gov/pet), and in Reference [1], in this conference.

This paper is organized as follows. The hardware and software components used in this measurement are presented. Then the unique features of this measurement are described, in particular, the way in which noise is eliminated from the data, both programatically and manually. Finally, specific results are presented.

2. SETUP

2.1. Hardware.

The emittance probe which has been used at Fermilab for a number of years is used here [2, 3]. The probe consists of a 0.075 mm slit in a thin tungsten plate, followed at a distance of 55 or 98 mm by a bank of 48 copper strips, separated by mylar insulators. The probe is adjustable in length for beams of differing divergence. Each strip subtends 3.34 mrad or 1.87 mrad respectively with respect to the slit. A stepping motor on a precision drive moves the probe through the beam. The resolution of the stepping motor and drive is 0.05 mm. Only one probe is available, so the opposite plane is measured by removing and rotating the probe assembly by 90-degrees. The wire signals are sampled synchronous to the beam at 10 Hz.

To minimize RF and ground noise, the collector strips are fully shielded by the emittance probe assembly, the cables are shielded, and the cables pass through high-μ metal tape cores outside the vacuum chamber. Each of the 48 signal cables is terminated in 50Ω at a bank of low noise amplifiers. These amplifiers have a gain of 200 with common mode noise reduction. The amplified signal is sampled, held and digitized by the local controls computer. The digitization resolution is 14 bits or 1 mV for signals of -10 to +10 V. Typical peak signals are a few volts. Noise levels and off-

* Fermilab is operated by the Universities Research Association under contract by the Department of Energy, contract number DE-AC02-76H030000.
sets are less than a few tens of mV, which causes some problems, see below.

2.2. Software.

There are five software components used in the emittance measurement. All except the first are run on a host console, an 85 MHz Sun SPARCstation 5 running the Solaris 2.4 operating system.

1. A local control algorithm is run in the local controls computer, the IRM (Internet Rack Monitor) [4], to manage the movement of the emittance probe through the beam. Parameters to this local application (LA) include: the start and stop positions, the step size and the minimum acceptable beam current. The LA provides binary status on data validity, i.e., when the probe has completed a step and the beam current is adequate.

2. The data acquisition program is responsible for setting the parameters for the LA according to the desires of the experimenter, and for collecting the valid emittance data. This program writes the raw emittance data to a disk file on the host console when the measurement is complete.

3. An analysis program reads the file generated by program 2 and converts the raw data into analyzed emittance data and writes a fixed-format data file suitable for display. It also prints the emittance of the beam in several ways: the RMS emittance and the geometric emittance for 60%, 90% and 95% of the beam. (All emittance levels are contained in the program; only these are presented.) These percentage emittances are calculated by appropriately adding up the pixels of beam in $x'z'$ phase space. Cuts on the data and noise reduction, described below, are carried out here. Note that the raw data file is unaffected.

4. Several options for the display of the data are possible. The one used here is LabVIEW [5].

5. Utilities for viewing or manipulating the raw data are available.

In addition to these fundamental programs, simple launch programs have been created using TCL/TK and LabVIEW to orchestrate the running of these programs. The LA is written in the C programming language; the programs in 2, 3 and 5 are written in C++, and the display program is written in LabVIEW.

3. MEASUREMENTS

Measurements have been made at two energies for the $^3$He$^+$ beam: at injection to the RFQ at 20 keV and at extraction from the RFQ at 1.0 MeV. The low-energy measurements are made by replacing the RFQ with the emittance hardware at the entrance to the RFQ.

3.1. Data Reduction

An uncut measurement is shown in Figure 2a. With noise and offset levels amounting to a few percent of the peak signal, it is clear that noise reduction is needed. Noise elimination has been performed by algorithm and by hand.

Algorithmic noise reduction consists of first removing obvious offset levels for each wire. Then all values less than a user set "NoiseValue", typically tens of mV, are set to zero. If the noise is not adequately eliminated, specific noisy wires may be removed from the calculation.

![Figure 2, Before (left) and after application of noise cuts.](image)

Small, non-zero readings on the edge of the distribution, where there is clearly no beam, unrealistically enlarge the calculated RMS emittance. (These extraneous signals also increase the 100% emittance, but this is of less concern.) To eliminate this effect, a further cut may be applied to the data. The RMS emittance is calculated from the noisy data, after passing through the background subtraction described in the previous paragraph. All data outside of an $X\sigma$ ellipse (where $X$ is a value supplied by the experimenter, usually about 8.0) of the same aspect ratio and tilt as the calculated emittance are removed, and a new RMS emittance is obtained. This cut may be repeated with the new RMS emittance, but it is found that only the first iteration is necessary. For highly elongated or distorted ellipses this cut may actually chop off real beam at the ends of the distribution. The effect of these operations is shown in Fig 2b.

The beam in these measurements does not fill a regular phase-space ellipse, so the cut described above does not eliminate noise uniformly. So, manual reduction has been done on a few measurements. A procedure has been developed where the raw data are exported into a spreadsheet program. First, the data are corrected and zeroed as in the computer algorithm method. Next, the edges of the beam are identified visually within the spreadsheet, and all data outside of this edge are manually zeroed. Then the RMS emittance is computed by hand or the raw data are written back into a (new) data file, and analyzed programatically with no further cuts. After some practice, the raw data can be manipulated in this manner in about two hours.

Manual reduction of the data gives significant insight into the sensitivity of various noise components. Small noise points near the real emittance distribution are of little or no significance to the RMS emittance calculation. However, a single noise point some distance from the real distribution has a strong effect on increasing the calculated RMS emittance. RMS emittance and twiss values obtained by hand from the raw data gave good (better that 10%) agreement with the computer reduced data.

3.2. 20 keV Emittance

Properties of the transport line and the effect of the solenoid magnet on the beam parameters at injection to the first RFQ have been measured. Beam parameters are measured at approximately the entrance point of the RFQ for magnet currents from zero to 300 A. Figure 3 shows the $x'z'$ phase
space plot for the beam near a waist at the emittance probe (225 A in the solenoid, 3181 Gauss). The simulation program TRACE-2D is then used to match parameters to the expected beam conditions from the ion source and these data. To obtain a match, full neutralization of the 3He beam is assumed. The ion source emittance is taken to be 160 to 200 mm mrad. The beam at the emittance probe is 400 mm mrad with an 80% core of 200 mm mrad. Using twiss parameters from this analysis allows a calculated match to the RFQ for the core of the beam. The normalized RMS emittance near the 20 keV entrance of the RFQ is 0.6 mm mrad.

![Figure 3, 20 keV Emittance contour plot.](image)

It would be useful to measure the emittance immediately at the exit of the ion source with the present equipment as information of the ion source beam is based on much earlier and lower current studies and on EGSUN calculations.

### 3.3. 1.0 MeV Emittance

The emittance of the 1 MeV 3He beam has been measured as a function of the orientation and sample time within the 70 µsec beam pulse. For these measurements the beam current at 20 keV is similar to above, but the injection line is configured differently and with a weaker solenoid so only 5.5 mA is seen at the exit of the RFQ. For different orientations and sample times through the macropulse, there is essentially no change in the emittance or the twiss parameters of the beam: the beam at 1 MeV appears symmetrical and uniform in time. Thus the emittance for a 5.5 mA 1 MeV 3He beam is measured to be:

<table>
<thead>
<tr>
<th>Normalized-RMS Emittance</th>
<th>0.20 mm mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>beta</td>
<td>1.7 m/r</td>
</tr>
<tr>
<td>alpha</td>
<td>-6.9</td>
</tr>
<tr>
<td>95% emittance</td>
<td>43 mm mrad</td>
</tr>
<tr>
<td>90% emittance</td>
<td>34 mm mrad</td>
</tr>
<tr>
<td>60% emittance</td>
<td>13 mm mrad</td>
</tr>
</tbody>
</table>

A typical run as seen through the LabVIEW interface is presented in Fig. 4.

![Figure 4, Emittance of 1 MeV beam, as seen through LabVIEW interface.](image)

### 4. SUMMARY

A set of hardware and software components have been assembled for the BRF PET accelerator, being commissioned at Fermilab. These components have been used before, but the 3He beam in the environment in which this accelerator sits has proven to be significantly noisier than previous emittance measurements (on H-minus ions and on protons). This is due in part to the close proximity of the RF stations and poor grounding and cabling procedures in the initial accelerator layout. Techniques to deal with this extra noise have been developed and successfully applied to this experiment.

### 5. REFERENCES

[1] P. Young, et. al., "Progress Update on the Development of the 3He Linac for PET Isotope Production". This conference, paper number SPP01.
CONTINUED CONDITIONING OF THE FERMILAB 400 MeV LINAC HIGH-GRADIENT SIDE-COUPLED CAVITIES

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Abstract
The high-energy portion of the Fermilab 400 MeV Linac is made of high gradient (37 MV/meter surface field) side-coupled cavity sections which were conditioned over a 10 month period before their installation in August of 1993. We have continued to monitor the conditioning of these cavities since that time while the cavities have been in operation, and those results are presented here. The sparking rate and the X-ray production are measured and compared with the 1992/3 pre-operational and 1993/4 early-operational measurements. These rates are consistent with a continued diminishing of these phenomena. Predictions and spark management strategies presented in earlier reports are evaluated in light of present experiences. We also have been measuring the sparking rate within this structure with and without our 50 mA peak beam. We find that the sparking rate is 20% higher with beam in the accelerator.

Introduction
During the fall of 1993, Fermilab commissioned seven side-coupled linac cavities as replacements for four of its original drift-tube cavities, resulting in a doubling of the linac's output energy. Achieving the acceleration necessary in the available space required gradients of up to 8 MV/m which led to maximum surface gradients of nearly 40 MV/m. These high fields raised concerns for RF breakdown, resulting in beam loss, and X-ray production, resulting in material degradation of surrounding components and possible personnel exposure in the conditioning area. Therefore, these two properties were monitored carefully [1, 2]. We have continued to monitor these quantities throughout their lifetime and report on them here.

The fundamental concern with RF breakdown is lost beam pulses. If the rate of RF breakdown were too high, it would impact the amount of beam delivered for p-bar production or for fixed target physics. Being the first accelerator of the Fermilab complex, it was desired that the losses be very low. The goal for the beam loss rate at the time of commissioning was 10^{-3}.

Conditioning History
The conditioning of the cavities started in the summer of 1991 in a separate shielding cave apart from the linac tunnel. The modules were placed in the cave individually and operated for a month or two until their sparking and x-ray characteristics were understood. In the fall of 1992 they were placed in the linac tunnel alongside the still running drift tube linac and operated there for about seven months. In August 1993, the old linac cavities were removed and the new ones were put into position and powered once again. From 27 August to 4 September of 1993 the new linac was commissioned with beam and has been running since.

Since it has the highest gradients, module 1 was conditioned first and has the most extensive information. Module 7, having the lowest fields, was never operated in the separate cave and has the least information. Daily logging of sparking data started in April 1994 and continues. Data were also collected during each modules initial turn-on in the separate cave, during February, and October-November of 1993.

During its initial conditioning in February of 1992, module 5's x-ray production was carefully measured. This was repeated in March of 1996.

RF Breakdown
Figure 1 shows the spark rate for module 1 as a function of total accumulated pulses. The rate is shown as sparks per million RF pulses. One can see that initially there was a rapid cleanup. This cleanup has a characteristic time, \( \tau \), of of eleven days to decrease by 1/e with the cavities running at the nominal 15 Hz. The later measurements show that once the initial cleanup is done, a slower conditioning rate is evident.

Table 1 shows the maximum surface gradients for the modules. We assume the conditioning rate is dependent on the strength of the fields in the cavities and the quality of the surface of the high field regions. For module 1, \( \tau \) of the long term conditioning is 365 days. (The cavities accumulate \( 1.3 \times 10^6 \) RF pulses per day.) For module 3, \( \tau \) is 630 days and for module 6 it...
is 8.8 years. Looking again at Table 1 the decrease of the sparking rate as the surface field decreases. In a previous report [1] we noted that within a single cavity the sparking rate varied with the field to the 19.5 power. The data here indicates that more than just the field strength is at work as the reduction should only be a factor of 2.5 from module 1 to 7.

Table 1: Maximum surface field (MV/m) and average spark rate (sparks per $10^8$ RF pulses) for the Fermilab Side-coupled Cavities. The sparking rate is corrected for pulse length variation (see section on Pulse Length Dependence).

<table>
<thead>
<tr>
<th>Module</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Fld.</td>
<td>36.5</td>
<td>36.2</td>
<td>35.8</td>
<td>35.5</td>
<td>35.2</td>
<td>35.0</td>
<td>34.9</td>
</tr>
<tr>
<td>Spk. rt.</td>
<td>36</td>
<td>37</td>
<td>40</td>
<td>21</td>
<td>9</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

The much larger reduction evident here probably represents our learning to construct the cavities more cleanly as time passed. The tuning of the cavities also became more efficient as we gained experience. This meant that the cavities were open to the ambient air for shorter periods of time.

The above results refer to all cavity sparks recorded. The Fermilab linac pulses at 15 Hz whether or not beam is present. The question remains whether or not the presence of beam affects the sparking rate. We looked at this for data collected during a three week period of stable running in January and February of 1996. The raw sparking rate during that time was $273 \pm 15$ sparks per million RF pulses. The rate of lost beam pulses during that time was $328 \pm 26$ per million beam pulses. This indicates that the presence of beam increases the sparking rate by 20%.

**Pulse Length Dependence**

In a previous report [2] we reported on seeing a dependence between the length of the flat-top of the RF pulse and the sparking rate. We noted that the sparking rate increased as the fourth power of the pulse length. The performance of the systems continues to be consistent with this finding. The break in Figure 1 at $1.4 \times 10^9$ shows the increase in sparking rate for module 1 when the flat top was increased from 45\mu sec to 80\mu sec. A thorough study of this phenomenon was not completed in time to produce statistically significant results for this report.

**X-ray Production**

At the time of initial conditioning, we made a thorough measurement of the relationship between the cavity power (and therefore the maximum surface field) and the x-ray production. Recently we repeated that measurement. Figure 2 displays the results. The topmost set of data points are the 1992 data. These were taken by a single detector placed by the middle of the module. The lower groups are the 1996 data, taken by four detectors each placed near the middle of each section of the module. The lines on the plot show the Fowler-Nordheim equation for the RF case [3].

$$j_F = \frac{5.7 \times 10^{-12} \times 10^{4.526 - 0.5 \phi^{1.75}}}{\beta E_a^{2.5} \exp\left(-\frac{6.53 \times 10^9 \times \phi^{1.5}}{\beta E_a^2}\right)}$$

The lines represent different values of beta which is a measure of the enhancement of the electric field due to geometrical effects on a microscopic level compared to the measured macroscopic surface electric field. To make absolute comparisons, we would have to know the area of the emitting surfaces as a function of the field in that area. We do not know this, but we feel that the curvature of the lines and the plotted data gives an indication of the average beta of the field-emitting surfaces. The change in the shape of the plots would indicate that the effective average beta has been reduced by approximately a factor of two. In addition, comparing the actual x-ray measurements we see a reduction of an order of magnitude after the three years of running which would indicate that the area associated with these high microscopic fields is being reduced.

![Field-Emitted Current (arb units)](image)

**Figure 2:** Beta dependence of x-ray production.

**Summary**

The new side-coupled cavities of the Fermilab linac upgrade have performed very well. The beam loss rate due to sparking of .03% is well below our target of .1%. The sparking rate continues to improve, indicating that conditioning is continuing. This is also evident in the measurements of the X-ray production. Measurements indicate that the field emission sites are getting cleaner and are getting smaller in area.

**Acknowledgments**

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**References**


BUNCHING SYSTEM OF THE KEKB LINAC

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Abstract

At present, the KEK 2.5-GeV Linac is being upgraded as the injector of the KEK B-factory (KEKB). One of the most important changes is to increase the intensities of positron beams injected into a KEKB ring; it is, therefore, required to accelerate high-intensity single-bunch electron beams to high energy, 3.7 GeV, where they are converted to positron beams. For the purpose, the primary electron bunch should have more than 10 nC. Furthermore, the bunch lengths must be limited as short as 10 ps, in order to achieve narrow energy spreads of primary electron beams, and produce positron beams of short bunch lengths, as well. The bunching system has been designed to meet these requirements, introducing subharmonic bunchers (SHB).

This paper describes the upgrade of the bunching system and the results of simulations of bunching using PARMELA. The designs and RF test of SHB cavities are described.

Introduction

The KEK PF 2.5-GeV Linac is now being upgraded for the KEKB project [1]. The pre-injector of the KEKB Linac must provide beams with various charge contents for the KEKB rings and PF ring: single-bunch electron beams of 10 nC for the positron beam production, and 1 nC for direct injection to the KEKB electron ring. The demands to the bunching section lies in the primary electron beams for the positron production; the pre-injector must produce single bunch electron beams of more than 10 nC, furthermore, there exist the optimum bunch lengths according to the charges of the bunches to minimize the energy spreads in subsequent acceleration, determined by the contributions of bunch length and longitudinal wake fields to energy spread. According to calculation results [2], bunch lengths about 10 ps at FWHM are desirable in the case of single bunches of 10 nC.

To meet these requirements, the pre-injector system has been designed to introduce two subharmonic bunchers (SHB). The frequencies of the two SHB’s was chosen to be 114.24 MHz and 571.2 MHz [3].

We will describe the design of the whole bunching system, and the bunching characteristics, together with the design, fabrication, and RF test results of subharmonic bunchers.

Design of Bunching System

The acceleration studies on high intensity single-bunch electron beams for the KEKB Linac have been carried out at KEK PF 2.5-GeV Linac for a couple of years [3, 4], using one subharmonic buncher (476 MHz). And it has been clear from those studies that one more subharmonic bunchers was necessary to produce single bunches with no satellite bunches if the charge about 10 nC or more [4]. The frequencies of subharmonic bunchers were chosen to be 114.24 MHz and 571.2 MHz [3].

As mentioned above, the electron charges required for the production of positron beams KEKB are 10 nC. We, however, have designed the bunching system with PARMELA so that it could produce single bunches up to 15 nC. The layout of the newly designed bunching section is shown in Fig. 1. The bunching system with one subharmonic buncher was described elsewhere [3]. We will briefly describe the new bunching system and bunching behaviour below, mainly for the case of 15 nC. To get 15 nC single bunches at the end of the pre-injector, we assumed 20 nC from the electron gun considering charge losses in the bunching processes. In this case, the space charge force is so large that it was necessary to shorten the drift space after the beam was tightly bunched, to minimize debunching. Since the counteracting forces of the space charges make the beam energies convergent with bunching, there exists the minimum possible beam pulse length. In the drift space downstream SHB1, this is about 1000 degrees in S-band or little longer, which corresponds to almost half the wavelength of the rf of SHB2. Furthermore, the SHB1’s frequency is so low that the tremendous power is required to provide large modulation. We, therefore, set low the bunching field at SHB1, about 50 keV. To compress the above beam pulse length to shorter than one wavelength of the S-band prebuncher, further bunching is required at SHB2 wit the peak electric field of 100 kV. In this design, the first prebuncher

![Fig. 1. Pre-injector of the KEKB Linac](image)

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was removed since debunching occurred in drift space between the prebunchers, and thus the main bunching components of the final system include two subharmonic bunchers of standing wave types, and prebuncher (the old PB2) and buncher. The preinjector is to strengthen the electric field of the buncher; the power of the klystron for the pre-injector will be increased twice to provide the electric field of 20 MV/m for the buncher (present: 15 MV/m). More efficient bunching was confirmed from the results of the simulations in the case of high intensity beams.

Figure 2 shows the parameters of a bunched beam of 15 nC at the exit of the buncher. About 70% of the initial charges are contained in 15 degrees around the peak. It is shown that single bunches of about 10 ps at FWHM could be obtained. The energy spread is rather broad, but a short bunch length is more important than this energy spread in the bunching section, since the energy dispersion due to the bunch length during subsequent acceleration dominates the total energy spread. In this case, two tiny satellite bunches on each side of the main bunch were formed containing charges of 6 percent of total initial charges. For other charges, shorter bunch lengths and narrow energy spread was obtained in simulations; 5 degrees and 1.2 MeV for 1 nC bunch, and 10 degrees and 2.0 MeV for 10 nC, all at FWHM.

Simulation on charge 15 nC showed that the optimization of focusing magnetic fields of maximum 1400 G, full capacity of the present focusing coils, could hold the normalized RMS emittance below 150 π.mm.mrad[6].

Subharmonic Buncher 1 (SHB1)

The 119 MHz subharmonic buncher cavity [7] is available with the removal of the positron beam line according to the end of the TRISTAN experiments. To examine its usability as the SHB for the KEKB Linac, we measured the main parameters of the cavity and calculated the parameters for the same geometry with SUPERFISH. The results of SUPERFISH showed that minor changes of the acceleration gap structure make the cavity usable as SHB1 of the KEKB Linac as far as the frequency is concerned. But the measured shunt impedance (0.54 MΩ, compared to the calculated value 0.79 MΩ) is so low that it requires a very large peak power for bunching high intensity beams. For example, as mentioned in the previous section, a peak modulation of 50 kV will be necessary for a beam of a pulse width 2 ns and 20 nC in this design. In this case, the peak voltage will be as high as 77 kV. The shunt impedance value shows that the cavity should be supplied a peak power as high as 11.2 kW to sustain the peak voltage. The shunt impedance of this cavity is made low by large nose tip radii and beam duct diameter near the gap. We designed a new SHB1 cavity and as its shunt impedance is above 1 MΩ, we can fabricate a cavity with the shunt impedance value larger than 0.7 MΩ, and if this is the case, the required peak power becomes 8.6 kW.

Subharmonic Buncher 2 (SHB2)

Design and low power RF test. The structure of the SHB2 cavity newly fabricated is shown in Fig. 3. The structure of the cavity is similar to that of 476 MHz SHB cavity [3]. In the case of 476 MHz cavity, a ceramic covering was used over the input coupling loop to isolate vacuum from the atmosphere. By doing so, the coupling of the cavity can be changed keeping vacuum. In this case, we did not use a ceramic covering to prevent electric discharges which may occur in high field operations. The power input connector is joined to the cavity by a rotatable ICP flange, and therefore the coupling can be changed if needed, though it damage cavity vacuum during change.

Fig. 2. Characteristics of the bunch of 15 nC at the exit of the buncher. (a) bunch shape; the horizontal axis denotes the phase of a particle with respect to the fundamental wave in the buncher. (b) the distribution of particles in longitudinal phase space. (c) energy spread

Fig. 3. Structure of SHB2 cavity.
The main parameters of the SHB2 cavity are shown Table 1. The Q value was measured by both the reflection method and the impedance method[8]. The temperature of the cavity was kept constant at 31±0.2 °C by circulating the cooling water used in actual beam line, and vacuum was kept by a turbomolecular pump, lower than 10^{-2} mbar. The cavity has a Q value of 83 % of the calculated one. The shunt impedance of Table 1 was obtained from R/Q values measured by Slater's bead perturbation method[8]. The measurements were done using aluminum spheres of diameter 2,3,4 mm as perturbaters. It is the value obtained when these values are extrapolated to the limit of zero volume. This R/Q value is nearly the same as the one by SUPERFISH. Figure 4 shows the electric field distribution on the beam axis near the acceleration gap. The agreement between measured curve and the calculated one is good. From this shunt impedance value, it can be seen that a peak power 6.7 kW is necessary to get the peak electric field, 100 keV, required to be provided by the SHB2 cavity to bunch 20 nC beams. A SHB2 power source capable of peak power 10 kW is now being fabricated. It will be a solid state amplifier and completed in this fiscal year.

<table>
<thead>
<tr>
<th>Table 1. Main parameters of the SHB2 cavity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity Length</td>
<td>117 mm</td>
</tr>
<tr>
<td>Gap Length</td>
<td>12.2 mm 12.48 mm</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>571.2 MHz</td>
</tr>
<tr>
<td>Tuning Range</td>
<td>570.44 - 572.32 MHz (total stroke of tuner: 30mm)</td>
</tr>
<tr>
<td>Q, value</td>
<td>10,870 9010</td>
</tr>
<tr>
<td>Coupling Parameter</td>
<td>1.4</td>
</tr>
<tr>
<td>Shunt Impedance</td>
<td>1.83 MΩ 1.50 MΩ</td>
</tr>
</tbody>
</table>

Fig. 4 Electric field distribution on axis near the acceleration gap of SHB2.

**High Power Test.** Since a high power source of 571.2 MHz is not available to us at present, as a preliminary test, we performed a high power test of the newly fabricated cavity using the 476 MHz power source which is installed in the present beam line. To adjust the resonant frequency of the cavity to 476 MHz, we inserted a copper spacer of thickness 26.7 mm in the cavity and lengthened the cavity.

The test was done at 31±0.2°C, and 3x10^{-7} mbar. The electric discharges by multipactoring has been observed during initial rf aging, and we performed the high power tests at various levels through two days. We finally put peak power 4.2 kW into the cavity, though this is not a sufficient level. We confirmed a stable operation without continuous electrical discharge up to this level except for initial stage discharges. Figure 3 shows the power pulses observed by an oscilloscope.

When a 571.2 MHz power source becomes available, we will perform again high power test through the full range at the resonant frequency.

![Power Pulse Forms in High Power Test](image)

Fig. 3. Power pulse forms in high power test observed at power source (above) and cavity monitor(below)

**Conclusion**

We designed the bunching system for the KEKB Linac by simulation code PARMELA. The result showed that the newly designed bunching system can produce bunched beams required for the KEKB pre-injector. We fabricated a new SHB cavity and confirmed that it has required properties. Another SHB cavity will be fabricated in the near future.

**References**

MEASUREMENT OF PRECISE PARTICLE DISTRIBUTIONS IN EMITTANCE PHASE PLANE IN THE JHP LEBT

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Abstract

A low energy beam transport (LEBT), in which any practical emittance growth due to the lens-aberration would not be caused, was developed for the Japanese Hadron Project (JHP). In the LEBT, we measured the precise distributions in the transverse emittance phase plane of the particles, which were extracted from the volume production H⁻ ion source (VPIIS) operated without cesium. The measured results showed good agreements with the simulation results using the initial particles at the exit of the VPIIS generated with Ueno-Yokoya distribution (UY-dst), in which the particles are distributed uniformly in the real space (concerning with x and y) and distributed in Gaussian way concerning with x' and y'. We also detected the unexpectedly strong space-charge neutralization effect only with the residual H₂ gas with a pressure of 3.7 × 10⁻⁶ Torr. In this condition, 93% of the beam intensity was neutralized with almost no beam loss due to electron stripping by collisions with H₂ gas.

Introduction

In order to inject a low-emittance H⁻ beam into a 432-MHz radio-frequency quadrupole (RFQ) linac, a low energy beam transport (LEBT) was developed for the Japanese Hadron Project (JHP) [1, 2]. By the beam dynamics design studies with a computer code BEAMPATH [3], it was revealed that an appropriately designed solenoid magnet had the smallest lens aberration in LEBTs [4]. Therefore, we succeeded in designing the JHP LEBT without any practical emittance growth due to the lens-aberration by using two short and strong solenoid magnets. A new volume production H⁻ ion source (VPIIS) was also developed at the same time with the LEBT. We succeeded in extracting a H⁻ beam of 16 mA from the VPIIS operated without cesium [5].

In this paper, we present the results of the measurement of the precise particle distributions in the emittance phase planes in the LEBT and the measured space-charge neutralization effects produced by the residual H₂ gas. Instead of a commonly used contour plot, we use a new display method of Ueno-Fujimura plot (UF-plt) [5], in order to display the measured particle distributions in the emittance phase plane. In UF-plt, the particle distribution is displayed with light and shade by plotting points, whose number is proportional to the intensity measured at (x, x'), randomly within the rectangle composed with the four positions of (x+dx/2, x'+dx'/2), (x-dx/2, x'-dx'/2), (x-dx/2, x'+dx'/2) and (x+dx/2, x'+dx'/2). Here, dx and dx' are the steps of the measurements.

Experimental Setup

A schematic drawing of the experimental setup viewing from the upper position is shown in Fig. 1. The vacuum chamber (CHM1) just after the VPIIS is pumped out with two 1500 l/s turbo molecular pumps (1500TMPs). The first solenoid electromagnet (SM1) is located 90 mm downstream from the plasma electrode of the VPIIS. In a space of 215 mm between SM1 and the second solenoid electromagnet (SM2), the vacuum chamber for the beam diagnostic (CHM2) and the gate valve (GV) are located. SM1 and SM2 have the same shape with a length of 100 mm, an outer diameter of 300 mm and a bore diameter of 50 mm. A 500 l/s turbo molecular pump (500TMP) pumps out CHM2. By moving the movable slit (EMSLLₘ) and the Faraday-cup with slit (EMFCLₘ) horizontally step by step, the horizontal emittance is measured. The vertical emittance is measured by using EMSLᵥ and EMFCLᵥ. Each slit used in EMSL or EMFC is made of molybdenum plates with a thickness of 0.05 mm and has a gap of 0.2 mm. The distance between the slit of EMSL and the slit of EMFC is 61 mm. Since the alignment error of each slit is ±0.1 mm, which is the error of the real space of the emittance phase space, the error of x' or y' space is calculated to be ±0.07 mm. The beam intensity was measured with the Faraday-cup (FC). A voltage of −1 kV was fed on each bias electrode of EMFC or FC in order to suppress the secondary electrons formed each Faraday-cup. EMSL is located almost the same position of the vane-end at the entrance of the RFQ, when the LEBT is connected with the RFQ.

Fig. 1 A schematic drawing of the experimental setup viewing from the upper position.
Results of the Measurements

The measured particle distributions in the horizontal phase space at the entrance of the RFQ displayed with UP-plots are shown in Fig. 2; (a) when the vacuum pressure in CHM2 was $3.7 \times 10^{-5}$ Torr and (b) when it was worsened up to $3.7 \times 10^{-5}$ Torr by closing the gate valve located between CHM2 and 500TMP. In these measurements, a $\mathrm{H}^-$ ion beam of 16 mA was extracted from the VPIS. Ellipses drawn in Fig. 2 show the design acceptance of the RFQ. The TWISS parameters and the normalized emittance of the acceptance are $\alpha = 1.05$, $\beta = 0.0473$ mm/mrad and $\epsilon_n = 1.5\pi$ mm-mrad, respectively. The TWISS parameters and the 4 times of the normalized rms emittance of the measured particle distributions are listed in each figure. By tuning the currents of SM1 and SM2 to the values shown in Table 1, the TWISS parameters of the measured beam was matched with the design value with a matching factor of around 1. By comparing Fig. 2(a) with Fig. 2(b), we can estimate the space charge neutralization factor in the typical operating condition shown in Table 1 by the following way. At first, we estimated the TWISS parameters at the exit of the VPIS by inversely tracing the beam shown in Fig. 2(b) up to the exit of the VPIS by using a simulation code BESAMPATH [3], in which both of the two nonlinear effects of the realistic field and the non-uniformly distributed space charge force are taken into account. In this estimation, we assumed that all of the beam intensity was neutralized by the residual $\mathrm{H}_2$ gas. That is, the equivalent beam current was assumed to be 0 mA. This assumption was considered to be valid because of the following two reasons; (1) the observation of the fluorescence produced by the beam which was not observed in a good vacuum pressure of $3.7 \times 10^{-6}$ Torr, (2) the coil currents of SM1 and SM2 were close to the design values estimated with a design initial particle distribution at the exit of the VPIS for the zero current beam; $I_{\text{SM1}}(0) = 323$ A and $I_{\text{SM2}}(0) = 382$ A. On the other hand, the design coil currents of SM1 and SM2 for the beam with a current of 16 mA are 382 A and 424 A, respectively. In this inverse trace, the KV-distribution beam with TWISS parameters listed in Fig. 2(a) was used as the initial beam. The TWISS parameters at the exit of the VPIS were estimated to be $\alpha = -0.90$ and $\beta = 0.050$ mm/mrad. By using thus estimated initial beam at the exit of the VPIS, we simulated the beam optics in the normal direction with various beam currents. The result using the beam with a current of 1.1 mA well represented the TWISS parameters of the particle distribution shown in Fig. 2(a). Therefore, the equivalent current of the beam in the typical operation condition can be thought as 1.1 mA. Since we worsened the vacuum pressure largely (by 10 times) in the measurement shown in Fig. 2(b) compared with it of the typical operation shown in Fig. 2(a), the validity of the assumption of the perfect neutralization in the measurement shown in Fig. 2(b) was also proven with the very small equivalent current of 1.1 mA.

From the two beam currents of $I_0 = 16$ mA and $I = 14$ mA measured in the two different vacuum pressures shown in Table 1, we can estimate the cross section of the electron stripping reaction of $\mathrm{H}^-$ collided with $\mathrm{H}_2$ by using the following equation.

$$\sigma_{eH} = \ln(I_0/I)/Nl$$

By substituting the beam length of $l = 51.5$ cm and the target density of $N = 1.31 \times 10^{21}$ 1/cm$^2$ calculated from the vacuum pressure of $3.7 \times 10^{-5}$ Torr, we estimated the cross section as follows.

$$\sigma_{eH} = 1.98 \times 10^{-15} \text{ (cm$^2$)}$$

Fig. 2 Particle distributions in the horizontal emittance phase space measured at the entrance of the RFQ; (a) when the vacuum pressure in CHM2 was $3.7 \times 10^{-5}$ Torr in the typical operation and (b) when it was $3.7 \times 10^{-5}$ Torr.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Parameters of the LEBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (keV)</td>
<td>(Typical) (500TMP-GV close)</td>
</tr>
<tr>
<td>Vacuum pressure in CHM1 (Torr)</td>
<td>1.6 x 10^{-5} 1.6 x 10^{-5}</td>
</tr>
<tr>
<td>Vacuum pressure in CHM2 (Torr)</td>
<td>3.7 x 10^{-5} 3.7 x 10^{-5}</td>
</tr>
<tr>
<td>Beam Intensity at FC (mA)</td>
<td>16 14</td>
</tr>
<tr>
<td>Coil current of SM1 (A)</td>
<td>335</td>
</tr>
<tr>
<td>Coil current of SM2 (A)</td>
<td>360</td>
</tr>
<tr>
<td>4 times normalized rms emittance ($\pi$ mm-mrad)</td>
<td>0.4116 0.3751</td>
</tr>
</tbody>
</table>

Comparison of Measurements with Simulations

We measured both of the two particle distributions in horizontal and vertical emittance phase planes [5]. However, it is practically impossible to find out the correlation of these two distributions, since the enormous number of the same precise measurements with different conditions are necessary.

Therefore, we compared the measured particle distribution shown in Fig. 2(a) with the simulation results using the three types of theoretical initial distributions with TWISS parameters and 4 times of normalized rms emittance of $\alpha = -0.90$, $\beta = 0.050$ mm/mrad and $\epsilon_n.4\text{rms} = 0.41\pi$ mm-mrad at the exit of the VPIS; Gaussian distribution, KV distribution and UY distribution. The beam profiles of the measurement and the simulated results are shown in Fig. 3(a). As can be seen from this figure, the result using UY-distribution well represents the measured profile. The profile simulated with Gaussian-distribution has a higher peak and it with KV-
distribution has a lower peak than the experimental result. Also the relationship between emittance and the beam fraction containing in the emittance simulated with UY-distribution showed a good agreement with the experimental result. Figures 4(a) and 4(b) show the particle distribution generated with UY-distribution at the exit of the VPIS and the particle distribution at the entrance of the RFQ simulated with the initial UY-distribution. By comparing Fig. 2(a) with Fig. 4(b), there are two agreements in these two distributions; (1) each distribution has a lozenge shape and (2) a pair of two opposite sides of each lozenge has lighter distribution compared with the other pair of sides. It is noted that the measured shape of the distribution is not an ellipse. On the other hand, the simulated phases of the sides with light distribution in the emittance phase space is slightly different from the measured results. Since we did not include the focusing effects of the extraction and acceleration gap, this focusing effects seem to cause this discrepancy.

0.4π mm-mrad. By plotting the measured particle distributions with a new display method of UF-plt, the detailed structure of the distributions were revealed. The measured distribution showed good agreements with the simulation results using the newly proposed initial distribution of UY-distribution, in which the particles are distributed uniformly in the real space (concerning with x and y) and distributed in Gaussian way concerning with x' and y'.

We detected the unexpectedly strong space-charge neutralization effect only with the residual H₂ gas with a pressure of 3.7 × 10⁻⁶ Torr. In this condition, 93% of the beam intensity was neutralized with almost no beam loss due to electron stripping by collisions with H₂ gas. By worsening the vacuum pressure and measuring the total beam intensities, the cross section of the electron stripping reaction of H⁻ collided with H₂ was also estimated to be 1.98 × 10⁻¹⁰ cm².

Acknowledgment

The authors wish to express their sincere thanks to Dr. Y. Batygyn (Institute of Physical and Chemical Research in RIKEN) for his offer of the computer program BEAMPATH and several useful advice.

References


Conclusion

The particle distributions at the entrance of the RFQ were measured with the errors of ±0.1 mm in real space and ±1.6 mrad in x' or y' space. The 4 times of the normalized rms emittance of a H⁻ beam of 16 mA was measured to be
DESIGN OF INPUT AND OUTPUT COUPLERS FOR LINEAR ACCELERATOR STRUCTURES

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Abstract

The input and output couplers for 2m-long S-band linear-accelerator structures for the KEKB linac upgrade have been designed and tested. The dimensions of the coupler cavities were estimated by a simulation of the Kyhl method using the MAFIA code, and determined by low-power tests using the Kyhl method. It has been shown that the coupler dimensions can be predicted with precision to be less than 0.5 mm. The asymmetry of the electromagnetic field (amplitude and phase) in the couplers has been corrected by a crescent-shaped cut on the opposite side of the iris. The total performance of the accelerator structures with these couplers is also described.

Introduction

A reinforcement of the PF linac at KEK is now under way for the KEKB project.[1] The beam energy of the linac is being upgraded from 2.5 GeV to 8.0 GeV. For this energy upgrade, about seventy new accelerator structures (54 cells, 2m-long, S-band, quasi-constant gradient, 2π/3-mode, electroplated and no dimpling) are to be fabricated. The input and output couplers for the new accelerator structures have been redesigned, because the existing couplers have insufficient performance concerning the reflection, phase shift, asymmetry of electromagnetic fields and RF breakdown limit. Fig. 1 shows a cross-sectional view of the coupler. The adjustable parameters are W (iris width) and 2b (inner diameter). So far, the coupler dimensions have been determined by trial and error.

A method for estimating the coupler dimensions by a numerical simulation using the MAFIA T3 module has been proposed [2]. In this paper, we present a new method to estimate the coupler dimensions by simulating the Kyhl method [4] using the MAFIA E module.

A correction for the asymmetry of the electromagnetic fields in the coupler cavities was performed by making a crescent-shaped cut on the opposite side of the iris.

Simulation of the Kyhl method

The simulation of the Kyhl method was carried out as follows:
1. Generate a mesh structure constructed with the coupler cavity, half cell and waveguide (Fig. 2). Although the curvature, (R) of beam hole edge (see Fig. 1) had been 3 mm for the existing couplers, it was changed to be 7 mm in order to improve the vacuum-breakdown limit.

Fig. 2. MAFIA geometry for the Kyhl method simulation.

2. Obtain the resonant frequency (f(res)) and external Q (Q_ext) for this structure by simulating the Slater's tuning curve method[4].
3. Determine f(res) and Q_ext for various W and 2b. Fig. 3 shows f(res)(W,2b) and Q_ext(W,2b).
4. Obtain W and 2b at the cross point of two lines (Fig. 4): one is

\[ f_{res} = f_{res}(W^{2b} + f_{res})^{1/2}. \] (1)
The other is

$$Q_{\text{ext}} = Q_{\text{target}}.$$ \hspace{1cm} (2)

This set of $W$ and $2b$ is the design value of coupler cavities. Here, $f_{\text{res}}$ (resonant frequency for the $\pi/2$ mode) were obtained by a dispersion curve measured using 6 cell accelerator structures (standard cavities). $Q_{\text{ext}}$ was determined as follows:

Let $Q_{\text{ext}}$ be inversely proportional to $v_{s}$.

$$Q_{\text{ext}} \propto 1/v_{s}.$$ \hspace{1cm} (3)

The relation between $2a$ and $v_{s}$ is given by the following equation, which is obtained by the dispersion curves for several standard cavities:

$$v_{s}/c = 0.959887 \times 10^{-2}(2a)^{2} - 0.514516 \times 10^{3}(2a)^{2} + 0.0105696(2a) - 0.0735666.$$ \hspace{1cm} (4)

From equations (3) and (4), and data for a coupler with good matching and tuning characteristics ($2a = 26.3$ mm, and $Q_{\text{ext}} = 96.195$), $Q_{\text{ext}}$ is given as a function of $a$ as follows:

$$1/Q_{\text{ext}} = 4.36109 \times 10^{-6}(2a)^{3} - 3.1082 \times 10^{-4}(2a)^{2} + 4.74707 \times 10^{-3}(2a) - 0.033040.$$ \hspace{1cm} (5)

From this equation, the target value of $Q_{\text{ext}}$ can be obtained.

The coupler dimensions were determined by cold tests based on the Kyhl method. A very few iterations of machining were required before an optimal configuration could be obtained. A comparison between the measured and predicted values of the coupler dimensions is shown in Fig. 5 for three types of couplers with different $2a$.

![Comparison between the predicted and measured values of $W$ and $2b$.](image)

It is shown that the coupler dimensions ($W$ and $2b$) can be predicted with an accuracy of less than 0.5 mm.

**Correction of the Field Asymmetry in Couplers**

The asymmetry of the electromagnetic field (amplitude $E$ and phase) in a couplers was corrected by a crescent-shaped cut...
(depth of the cut is C) on the opposite side of the iris (see Fig. 1) using following procedures:
1. Measure the electric-field distribution for two couplers with different values of C. The field distribution has been measured by the bead pull method based on the non-resonant perturbation theory [7].
2. Obtain a relation between C and the factor k, defined as follows: (Fig. 6)

\[ k = \Delta E/E_{X=0} \text{[\%]}, \]
\[ \Delta E = E_{X=X_0} - E_{X=0}, \]
\[ X_0=4,8,12 \text{ [mm]}. \]

\[ (6) \]

![Graph showing k as a function of C.](image)

Fig. 6. \( \Delta E/E \) as a function of C.

3. Obtain the optimum value of C by interpolation or extrapolation.

Fig. 7 shows the field distributions (amplitude and phase) for a coupler with an optimum value of C.

![Graph showing field distributions.](image)

Fig. 7. Effect of the correction of an electromagnetic-field asymmetry by a crescent-shaped cut.

With this correction, the asymmetry of amplitude (\( \Delta E/E \)) and phase was reduced from 8% to 1% and 1.3° to 1.1°, respectively at \( X=8 \text{mm} \).

**RF characteristics of the accelerator structure**

The phase distribution for the accelerator structure with new couplers was measured using a nodal-shift technique (Fig. 8). A standard deviation of 0.9° was achieved (note that our accelerator structure was fabricated without dimpling). The SWR was 1.07.

![Phase distribution graph.](image)

Fig. 8. Phase distribution for the accelerating structure after electron-beam welding of the couplers.

**Summary**

The design of the coupler dimensions was achieved by a simulation based on the Kyhl method. The dimensions obtained by this method are in good agreement with those determined by cold tests. It has been proven that the asymmetry of the electromagnetic fields in the coupler can be corrected by a crescent-shaped cut.

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**References**

LINAC LU-20 AS INJECTOR OF NUCLotron

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1. Abstract

The linac LU-20 created as an injector of Synchrophasotron and Nuclotron is described. Tables of main parameters and beam intensities are included. The functional diagram of LU-20 is shown. Injection channels, diagnostic and control systems are described also. The scheme of beam transport line is also provided.

2. Introduction

Nuclotron injector at present time is the linac LU-20, which was built in 1974 as a proton injector for Synchrophasotron with output energy of 20MeV [1]. In fact from the beginning it was used as a proton accelerator and as an accelerator of light element nuclei and ions at the second drift ratio with output energy of 5MeV/nucleon. Nuclei of such elements as deuterium and helium (the duoplasmatron was used as a nucleus source), 3Li\(^+\), 4Li\(^+\), 11B\(^+\), 12C\(^+\), 14N\(^+\), 16O\(^+\), 18F\(^+\), 24Mg\(^+\), 26Si\(^+\)\(^+\) (the laser ion source[2]), 19Ne\(^+\), 20Ne\(^+\), 27S\(^+\), 28Ar\(^+\), 34Kr\(^+\) (electron beam ion sources “Krixon”[3] and “Krixon-S”[4]) were accelerated. Polarized deuteron beams were accelerated using cryogenic source POLARIS[5].

So, the spectrum of accelerated in LU-20 nuclei and ions is provided by four ion sources:
- the duoplasmatron;
- the laser ion source (LIS);
- EBIS KRION-S;
- the polarized deuteron source POLARIS;

Accelerated beam intensities are shown in Table 1. In 1993 the Nuclotron was built in Dubna. Since then LU-20 has been also used as the Nuclotron injector.

3. Pre-injector

The pre-injector is powered by 700 kV pulse transformer. The low voltage winding is fed by a form line with distributed parameters. The maximum duration of a HV pulse is 600 μs. The stability of high voltage is within ±5-10\(^{-4}\). The accelerating tube consists of 56 aluminium diaphragms separated by porcelain rings. The diaphragms are connected to a high voltage water divider. A grid with an aperture diameter of 220 mm is installed at the 28-th diaphragm. The ion sources are mounted on a HV terminal of the accelerating tube and have ion optic systems for initial forming of beams.

<table>
<thead>
<tr>
<th>Particle type</th>
<th>Intensity at the output of LU-20</th>
<th>Source</th>
<th>Pulse duration (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>1×10(^{14})</td>
<td>Duoplasmatron</td>
<td>500</td>
</tr>
<tr>
<td>d</td>
<td>3×10(^{15})</td>
<td>Duoplasmatron</td>
<td>500</td>
</tr>
<tr>
<td>d(^+)</td>
<td>3×10(^{10})</td>
<td>POLARIS</td>
<td>500</td>
</tr>
<tr>
<td>α</td>
<td>6×10(^{12})</td>
<td>Duoplasmatron</td>
<td>500</td>
</tr>
<tr>
<td>α(^+)</td>
<td>1×10(^{9})</td>
<td>LIS</td>
<td>30</td>
</tr>
<tr>
<td>α(^+)</td>
<td>5×10(^{10})</td>
<td>LIS</td>
<td>30</td>
</tr>
<tr>
<td>C(^{33+})</td>
<td>2×10(^{10})</td>
<td>LIS</td>
<td>20</td>
</tr>
<tr>
<td>O(^{18+})</td>
<td>3×10(^{9})</td>
<td>LIS</td>
<td>10</td>
</tr>
<tr>
<td>O(^{18+})</td>
<td>2×10(^{9})</td>
<td>LIS</td>
<td>10</td>
</tr>
<tr>
<td>Mg(^{13+})</td>
<td>1×10(^{9})</td>
<td>LIS</td>
<td>5</td>
</tr>
<tr>
<td>Si(^{14+})</td>
<td>1×10(^{8})</td>
<td>LIS</td>
<td>5</td>
</tr>
<tr>
<td>Si(^{14+})</td>
<td>2×10(^{8})</td>
<td>KRION-S</td>
<td>100</td>
</tr>
<tr>
<td>Ar(^{18+})</td>
<td>2×10(^{8})</td>
<td>KRION-S</td>
<td>100</td>
</tr>
<tr>
<td>Kr(^{36+})</td>
<td>1×10(^{8})</td>
<td>KRION-S</td>
<td>100</td>
</tr>
</tbody>
</table>

Note: * - after stripper

The ion sources on the high voltage terminal are powered by a generator separated by an insulating driving shaft. It has output power of 10 kW.

The pre-injector tube is pumped by a vapour oil pump with a trap. The pump has the total performance of 5000 l/sec. The tube is connected to the linac cavity by a vacuum line on which an axial symmetric matching lens, a buncher, a double magnetic corrector, a beam current transformer and a Faraday cylinder are placed.

The sources are controlled via an optic fiber line from the LU-20 control room.

4. The accelerating-focusing system of LU-20

The linac LU-20 is an accelerator of Alvarece type. It has the following main parameters (see Table 2).

Drift tubes are fastened inside the resonator using two rods and contain quadrupole lenses working in continuous
mode. Precise tuning of field strength distribution along the resonator is made by disks placed at the drift tubes.

While working at the second drift ratio field distribution is changed by a bottom tuner, that allows to create field subsiding to the resonator end.

To increase the intensity of accelerated deuterium and helium nuclei, the injection is made into the 5th gap. The voltage on the accelerating tube of the preaccelerator is increased in two times, that results in emittance improvement of the injected beam [6].

**Table 2**

<table>
<thead>
<tr>
<th>Main parameters of LU-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>injection energy: protons</td>
</tr>
<tr>
<td>injection energy: ions</td>
</tr>
<tr>
<td>output energy: protons</td>
</tr>
<tr>
<td>output energy: ions</td>
</tr>
<tr>
<td>working frequency</td>
</tr>
<tr>
<td>resonator diameter</td>
</tr>
<tr>
<td>resonator length</td>
</tr>
<tr>
<td>number of drift tubes</td>
</tr>
<tr>
<td>resonator quality</td>
</tr>
<tr>
<td>synchronous phase</td>
</tr>
<tr>
<td>focusing system</td>
</tr>
<tr>
<td>quadrupole lens gradients</td>
</tr>
<tr>
<td>characteristic parameter</td>
</tr>
<tr>
<td>aperture</td>
</tr>
<tr>
<td>acceptance</td>
</tr>
<tr>
<td>energy dispersion with</td>
</tr>
<tr>
<td>debunker</td>
</tr>
<tr>
<td>min. charge to mass ratio</td>
</tr>
</tbody>
</table>

To reach this a solid metal wall is installed at the 4th drift tube, and quadrupole lenses of the first four accelerating periods are used for beam transportation. While accelerating ions with Z/A = 0.5 the beam is injected into the first gap. It was experimentally proved that the highest field strength reached without breakdowns allows to accelerate ions with Z/A ≥ 1/3. The flat peak duration of RF-pulse equals to ≈30 μs. The reached field strength values and maximum allowed gradients in the existing lenses are far from the required values. So accelerating of ions with Z/A = 1/3 is not effective.

At the output of the linac a carbon stripper with the average mass to square ratio ≈60 μg/cm² is installed. Usage of the stripper for ions with energy of 5 MeV/nuc is useful only for light nuclei up to Ar.

To increase accelerating beam intensities a buncher is installed at the input of LU-20 and a debunker is used to decrease dispersion of beams injected into Nuclotron.

5. **RF-power system**

The RF-power system of LU-20 is intended to excite in the resonator, buncher and debunker powerful electromagnetic fields, which are stable in frequency, amplitude and phase. The peculiarity of the RF-power system consists in the wide range of required exciting power, because LU-20 can accelerate ions with Z/A equal to 0.3...1. The exciting power can vary from 2 MW on accelerating of nuclei with Z/A of 0.5 up to 5.5 MW on accelerating of ions with Z/A of 0.3. In Fig. 1 a functional diagram of the RF-power system necessary to receive maximum output power in the resonators is shown. In this case the resonator is excited by two autogenerators "Rodonit". Both generators have positive feedback loop through the resonator. To excite main mode $TM_{010}$ suppression of the highest modes $TM_{011}$ and $TM_{012}$ is made. To do so, power is entered via exciting loop, which is placed at the middle of the resonator. Besides, positive feedback loops are located at places where the highest modes are absent, i.e. at the lengths equal to 1/4, 1/2 and 3/4 of the resonator length.

where PC is Phase Changer, A1, A2 are generators (1st and 2nd channels of "Rodonits"), IA is intermediate amplifier, L is 75 Ohm load, PB is phase bridge, A4 is generator of debunker, DG is defining generator.

Fig. 1

One of the problems of resonator excitation is resonance RF-dischargemultiplication. The most probable place of resonance RF-dischargemultiplication appearance is the initial part of the resonator. To suppress it an additional positive feedback system entered at the input of the main generator is used. This system consists of a standalone generator with low output power (up to 500 W), a phase changer and a connection loop. When the resonance RF-dischargemultiplication appears by some reasons, the main positive feedback system level becomes too low to excite the powerful generators. The extra positive feedback system doesn't depend on resonance RF-dischargemultiplication strongly, because its connection loop is located at the end of the resonator. So this system provides RF-field excitement.

The buncher is fed from the LU-20 main resonator by the connection loop via the cable and the phase changer. The buncher requires about ≈25 kW of RF-power.

To feed the debunker a standalone RF-amplifier with output power of ≈250 kW is used.

To suppress resonance RF-discharge, in the gaps of buncher and debunker resonator electrodes are installed with negative voltage on them.

6. **Beam transport channel**

LU-20 has two beam transport lines. The first one is intended to inject beams into Synchrophasotron and the
second one is intended to inject beams into Nuclotron. The initial part of the channel is common to Synchrophasotron and Nuclotron. This part consists of the first triplet of quadrupole lenses, an additional lens and dipole bend magnet 1BM, which turns a beam in vertical by 15.6°. During injection in Synchrophasotron 1BM is off. The beam transport channel with installed diagnostic and control systems are shown in Fig. 2.

The channel of injection into Nuclotron [7] was designed to provide compatibility with the channel of injection into Synchrophasotron. Besides, it should be taken into account, that median plane of Nuclotron is 3760 mm below than the LU-20 axis and beam injection is made vertically. The channel allows to make achromatic injection on the median plane and to position a beam on Nuclotron orbit. In horizontal plane the channel coincides beam axis with linear part of the Nuclotron axis. The channel also coincides the beam dispersion.

To protect superconductive elements of Nuclotron from warming up, a deflector is placed in the channel. The deflector creates beam pulses with the required duration. The pulses have fronts of 100ns. Unused pulse part is adsorbed by an adsorber installed at the debuncher input.

Vacuum in the channel is provided by magnet-discharging pumps with total performance of 800 l/min. After magnet 1BM a nitrogen trap is installed to separate general part of the channel having vapour oil pumping. It allows to obtain vacuum value of $\approx 5 \times 10^{-8}$ torr.

7. Diagnostic and control systems

In the transport line Faraday cylinders, transformers of current, collector current profilometers and scintillation observation stations are used as diagnostic and control elements.

To measure beam charge distribution a fully adsorbing spectrometer with silicon detectors is installed in the Synchrophasotron injection channel after 1BM magnet. Moreover, another method is used to identify accelerated in LU-20 ions. In this case an analyzed beam passes through the stripper and then is analyzed using the bending magnet of Synchrophasotron channel. This method can be applied to identify middle and heavy ion beams.

The transformers of current are used for high intensity beam measurements. Beam currents of $\approx 0.5$ mA are measured by the Faraday cylinders having maximum sensitivity of $\approx 10^7$ elementary charges/pulse. High intensity beam ($\approx 10^7$ elem. charges/pulse) profiles are obtained using the collector current profilometers. There are two scintillation observation stations with maximum sensitivity of $\approx 10^7$ elem. charges/pulse to measure different intensity beams. Each station has a set of five targets. The targets are made as grids to estimate beam parameters.

Low intensity beams are observed using electronic amplifiers.

All parameters of the linac (the potential in the pre-injector, RF-field in the linac, buncher, debuncher resonators, currents in the drift tube lenses, currents in the magnet elements of the transport channel and so on) are processed by computers and displayed on the linac control room monitors.

8. References


![Fig. 2](image)

The beam transport channels

where PI is the pre-injector, BM the bend magnets, ML the magnet lenses, Trip the triplets, DB the debuncher
Upgrades of the Nuclotron Injector for Acceleration of Ions with \( Z/A = 0.28 \) *

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1. Abstract
An upgrade for the front section of the Nuclotron Injector is presented. The aim of this upgrade is to decrease the minimal charge-to-mass ratio of ions accelerated from 0.33 to 0.28. It consists of a transverse wall placed 1.1 m from the front flange of the linac, separating the 14.4 meter tank into two distinct RF cavities, and replacement of the 11 drift tubes in the first cavity, extending the transverse acceptance of the linac. This upgrade makes possible the acceleration of iron, cobalt, copper and krypton ions in the Nuclotron. Upgrades to both Laser and EBIS sources are also planned, to increase the linac output current and the atomic number of accelerated ions.

2. Introduction
The mass limit for the LU-20 Nuclotron Injector is currently set by the requirement that ion charge-to-mass ratio \( Z/A \) must be equal to or greater than 1/3. An upgrade of the linac front section has been proposed, and has now in fact been carried out, allowing for acceleration of ions with \( Z/A = 0.28 \). This paper describes the upgrade; commissioning experiences are detailed in a follow-on paper.

The LU-20 linac was originally constructed as a proton injector. For ion acceleration, operating in the second harmonic mode is necessary, leading to unfavorable transit-time factors for the original drift-tube geometries. Electric fields needed for efficient acceleration are shown in Fig. 1, requiring either a very large tank tilt, or a general increase of field levels.

As producing the required field distribution is not possible with the present RF system, operation in the second harmonic mode to date has been achieved by increasing the overall strength of the accelerating field to a level where capture of particles can take place. This choice is not optimum: in addition to not being able to reach the most desirable gradients for the front end of the tank, the extra RF power is wasted on the largest part of the linac tank. Moreover, the existing quadrupole lenses in the front end of the linac are unable to supply the gradients required to effectively focus ions with \( Z/A < 0.5 \), leading to further beam losses throughout the linac. By placing a diaphragm at the location of the 11th drift tube, the tank is divided into two separate resonators that can be excited to different levels. By replacing the first 11 drift tubes, as well, and improving the quadrupole magnets in them, better accelerating and focusing efficiency can be achieved. Note, no changes are required to the remainder of the linac.

3. The accelerating-focusing system of the first compartment

3.1. Accelerating structure.
To provide the greatest energy gain of a particle, the gap factor \( \alpha = g/L \) (\( g \) is the gap between drift-tube faces and \( L \) is the length of the accelerating cell) should be as small as possible and constant. The tuning of each accelerating cell to the resonant frequency is realized by selecting the drift tube diameter.

Operational experience for linacs in our frequency range (145 MHz) indicates that stable operation is possible if electric field gradients do not exceed 11MV/m on the axis of the accelerating gaps (\( E_a \)) and 25MV/m on the surfaces of the drift tubes (\( E_s \)) [1]. From these considerations, we have selected a gap factor \( \alpha \) of 0.2 and have set the rounding radii of the drift tubes at \( R_s = 12 \text{mm} \) and \( r_s = 8 \text{mm} \) (see Fig. 2). To characterize the accelerating structure, it is necessary to know the dependence of the transit-time factor \( T \) (at the harmonic number \( k \)) on the velocity of an accelerating particle. As a first approach, for the simplified model of the accelerating period (\( R_s = 0 \) and \( r_s = 0 \)) the dependence of the diameters of the drift tube on particle velocity was determined by the method of partial areas [2]. Then using the results of these calculations and the chosen geometric parameters \( 2a, R_s, r_s \) and \( \alpha \), a full-scale model of an accelerating period was made (see Fig. 2). It has a movable bottom and changeable drift semitubes, and so can be configured to make measurements for any of the relevant accelerating periods.

Fig. 1

![Diagram](image1)

Fig. 2

![Diagram](image2)
The calculation of the accelerating structure was carried out by the method of sequential approaches using experimental dependences of $T(\beta)$, $d(\beta)$ [3]:

$$\int_{\beta_{\min}}^{\beta_{\max}} \frac{d\beta}{\varphi_{\beta}} = \int_{\beta_{\min}}^{\beta_{\max}} \frac{z^2}{A^2} \frac{keE_0}{m_0c^2}$$

The new drift tubes differ in construction from the old ones by the omission of tuning disks. The new drift tubes are also not vacuum-tight. The drift tubes are fastened using two rods; the principal one is used to feed and cool the quadrupole lenses, the second one located under 90° prevents mechanical vibration of the drift tubes. The ends of the rods are fixed in special adjusting devices for precise alignment.

A special tuning unit (cylindrical piston) is installed at the input wall of the first tank section to provide exact tuning to the resonant frequency of the main compartment. The frequency range allowed by this tuner is 100 kHz, two times wider than expected detuning.

### 3.2. Focusing system

A FODO focusing periodicity was selected for the new drift tubes, to match that in the main tank.

![Fig. 4](image)

To obtain acceptable values of the gradients in the quadrupole lenses and not to decrease significantly the throughput of the linac, a compromise value of $\cos \mu$ equal to 0.6 was taken, where $\mu$ is the average phase advance. For ions with $Z/A=0.3$, the maximum gradients reach values up to 100 T/m. Fortunately, because of the very low duty factor required for the LU-20, these magnets can be run in a pulsed mode. A Brookhaven concept [4] with a trapezoidal pole configuration has been adopted for the magnet design, based on simplicity of manufacturing and assembly, and on a pole profile which provides good field gradient with acceptable nonlinearities. A schematic of this design is shown in Fig. 4. The full aperture of the quadrupole lens is set at $2r_m=2.2$ cm, the size of the flat pole is chosen according to the recommendations of Plotnikov [5], to suppress the sextupole component of the magnetic field. The magnet cores are assembled from sheet electrotechnical steel, and consist of two halves joined by a metal ring.

This construction allows a greater number of turns in the winding and hence greater field gradient, and also simplifies assembly of the quadrupole magnets.

Each quadrupole magnet is an integral part of its drift tube, so the magnetic axis of the lens is rigidly connected to the aperture of the drift tube. The misalignment of the geometric axis to the lens magnet axis does not exceed 0.05 mm. The lens median planes are adjusted using a special fixture to an accuracy of ±30'. After assembly, the magnetic characteristics of the new drift tubes were measured on a test stand. The dependence of the field on the exciting current in lens number 3 is shown in Fig. 5. The dependence of the magnet field nonlinearity on radius at the working current in the exciting winding is shown in Fig. 3.

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy (ions)</td>
<td>$W_0$ = 150 keV/nucleon</td>
</tr>
<tr>
<td>Output energy (ions)</td>
<td>$W_k$ = 496 keV/nucleon</td>
</tr>
<tr>
<td>Minimum ratio Z/A</td>
<td>0.3</td>
</tr>
<tr>
<td>Working frequency</td>
<td>$f$ = 145 MHz</td>
</tr>
<tr>
<td>Resonator length</td>
<td>$L$ = 1.15 m</td>
</tr>
<tr>
<td>Number of drift tubes</td>
<td>$N$ = 10+2 semitubes</td>
</tr>
<tr>
<td>Resonator quality</td>
<td>$Q$ = 10000</td>
</tr>
<tr>
<td>Avr. amplitude of field on axis</td>
<td>$E_0$ = 2.2 MV/m</td>
</tr>
<tr>
<td>Synchronous phase</td>
<td>$\varphi_s$ = -29°</td>
</tr>
<tr>
<td>Aperture</td>
<td>$2a$ = 20 mm</td>
</tr>
<tr>
<td>Structure of focusing period</td>
<td>FODO</td>
</tr>
<tr>
<td>Characteristic parameter</td>
<td>$\cos \mu$ = 0.6</td>
</tr>
<tr>
<td>Gradients of quadrupole lenses</td>
<td>$H'$ = 100...40 T/m</td>
</tr>
<tr>
<td>Acceptance</td>
<td>$A$ = 220 mm mrad</td>
</tr>
</tbody>
</table>

The main parameters of the accelerating-focusing structure of the new first tank are shown in Table 1.

### 4. RF-power system

A block-diagram of the RF-power system is shown in Fig. 6. This system provides maximum excitation in the linac tanks. The main resonator tank is powered by two “Rodonir” autogenerators, each with an output power of 3 MW. Both generators have a positive feedback loop through the tank. To excite the main mode $TM_{010}$ the highest modes $TM_{011}$ and $TM_{012}$ are suppressed.
frequency up to 5 Hz at an output pulse peak power up to 25 MW and a beam divergence of less than 5-10⁻⁴ rad. The planned laser beam focusing system with a parabolic mirror will provide a flux density up to 3·10¹¹ W/cm² on the target. The up-dated laser ion source is expected to produce Fe²⁺ ion beams at an intensity of more than 10¹⁰ ion/pulse.

5.2. Electron beam ion source (EBIS)

The "Krion-2" EBIS source [7] will also be upgraded. A new electron optics system will provide an 8 keV, 2.5 A electron beam with about 200 A/cm² beam density. To reach these electron beam parameters with a magnetically immersed Pierce type gun, a 5 T superconducting solenoid will be manufactured using a high precision winding technology. Design of the electron collector and the ion beam optics, based on IGUN [8] simulations, has been performed. The electron collector design provides satisfactory formation of about 1 mA of ion beam with 1.5 keV electron beam energy on the collector surface. The upgraded "Krion-2" EBIS will provide a variety of ion species with high and moderate charge states. For example, iron ion beams of Fe⁶⁺ and Fe⁵⁺ will have intensities of 3·10⁹ ion/pulse and 1·10⁹ ion/pulse respectively. Note, to inject solid materials into the EBIS trap, an external MEVVA-type ion source will be used [9].

6. References

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MODEL FOR HALO DYNAMICS IN ACCELERATING BUNCHED BEAMS

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Abstract

Beam halo is a critical issue in the design of high-intensity ion accelerators for neutron spallation, materials studies and transmutation technologies. A new particle-core model, which treats accelerating bunched beams, is described. The core is a uniformly-filled 3-D ellipsoid in an azimuthally-symmetric linac with linear, continuous transverse focusing. The envelope equations are solved for the length L and radius R of the core, by treating the average longitudinal focusing forces as linear and continuous also. Core mismatch yields coupled oscillations of L and R with two distinct frequencies. The Hamiltonian for test-particles near the core is derived, including the oscillating space charge forces and a realistic Fourier expansion of the accelerating fields. Changes in linac parameters and beam energy are assumed adiabatic.

Introduction

Beam losses of as little as 1 part in $10^8$ per meter can lead to unacceptable activation levels in beamline components for proposed high-current, high-intensity ion linacs. Because of the finite number of macroparticles that can be used in a realistic beam dynamics simulation, it is only possible to set an upper bound on the levels of particle loss, and it is unlikely that such numerical simulations can resolve beam losses at this very low level.

Given this fundamental limitation, simple models are very important for obtaining physical insight into the causes of beam halo and particle loss. The well-known particle-core model [1], for example, has been used to illustrate how beam mismatch can lead to halo development. However, the particle-core model is limited to coasting unbunched beams, which is a significant departure from the actual problem of bunched beams in the accelerating fields of a linac.

We propose a longitudinal analog to the particle-core model for the purpose of studying the halo dynamics of test-particles interacting with a bunched beam in an RF linac. This model will be useful primarily for exploring regions of phase space outside of the core that are sparsely populated. Such regions can become populated at the low-energy end of a linac: for example, ~10% of the beam from a typical ion source exhibits strong transverse aberrations, and bunching of the beam in an RFQ can lead to a tenuous longitudinal halo.

Overview of Method and Approach

The core is assumed to be an azimuthally symmetric 3-D ellipsoid with a uniform distribution of particles, which leads to linear space charge fields inside the core. The transverse and longitudinal focusing forces are assumed to be linear and continuous. To further simplify the form of the space charge fields, free space boundary conditions are assumed and the condition $0.8 < \gamma L / R < 4$ is imposed, which is consistent with moderately relativistic ions with typical bunch shapes in large-bore cavities (see Ref. [2] for further discussion).

The core is treated as though it were moving with constant velocity; energy and velocity increases are treated as adiabatic changes. Space charge fields inside the core are linear and have the form (see e.g. Ref. [2]):

$$E_x(x,t) = \frac{31 x}{2\beta^3 \gamma^3 I_0} \left[ \frac{1}{R^2(t)L(t)} - \frac{1}{3\gamma R(t)L^2(t)} \right] ;$$

$$E_z(z,t) = \frac{1}{\beta^3 \gamma^2 I_0} \frac{(z - \beta ct)}{R(t)L^2(t)} .$$

Eq. (1)

where $I_0$ is the characteristic current. Space charge fields outside the core fall off nonlinearly.

In treating the RF fields, the geometry of a DTL is used, and the Fourier expansion of the RF fields is assumed to be symmetric between the drift tubes. The accelerating component of the RF fields is assumed to be small so the beam energy increases adiabatically. The longitudinal field has the form:

$$E_z(r,z,t) = \cos(\omega t + \phi_z) * \left[ E_0 I_0 (\kappa_0 r) + \sum_n E_n I_0 (\kappa_n r) \cos(2\pi n z / \beta \lambda) \right]$$

Eq. (2)

where $\kappa_n = (2\pi / \beta \lambda) / (n^2 + \beta^2)$, $I_0$ is the zeroth order modified Bessel function, and we are assuming a DTL geometry as shown below in Fig. 1. The radial electric field and azimuthal magnetic field have similar forms.

![Fig. 1. DTL geometry for the RF field expansion.](image)

Given the assumed uniform transverse focusing fields, the space charge defocusing, the average longitudinal focusing calculated from Eq. (2), and the beam emittances, the dynamical equations for the core length L and radius R are readily obtained, as is shown on p. 449 of Ref. [2]. The transverse and
longitudinal equations are coupled by space charge, and the
equilibrium values, L_0 and R_0, must be obtained numerically.

**Numerical Results**

We integrated the resulting test-particle equations of motion for a few trajectories through 500 DTL gaps, assuming physical parameters appropriate for a high-current D^+ DTL, as shown in Table 1. The trajectories are plotted as Poincaré surfaces of section, with the phase space locations shown each time the trajectory reaches the center of a gap.

<table>
<thead>
<tr>
<th>Parameters used in Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Kinetic Energy</td>
</tr>
<tr>
<td>Relativistic factors: β; γ</td>
</tr>
<tr>
<td>Cell length: ββ</td>
</tr>
<tr>
<td>Phase advances: σ_x0; σ_x</td>
</tr>
<tr>
<td>σ_z0; σ_z</td>
</tr>
<tr>
<td>Bunch size: L_0; R_0</td>
</tr>
<tr>
<td>RMS emittance: ε_x</td>
</tr>
<tr>
<td>ε_z</td>
</tr>
<tr>
<td>ETL: T; φ_s</td>
</tr>
</tbody>
</table>

Figure 2 shows a surface of section for four trajectories. The innermost trajectory is well inside the core; the second one has an amplitude just less than L_0; the third oscillates well outside of the core; and the outermost trajectory is near the boundary of stable motion. Each trajectory is moving along the accelerator axis, with no transverse motion. In this and following figures, the spatial variables X and δZ have been normalized to ββ, V is has been normalized to β, and δVz is the relative momentum spread δp/p.

Figure 3 shows surfaces of section for four trajectories with the same longitudinal initial conditions, but each with an initial value of X=0.6R_0. The two trajectories inside the core and the outermost trajectory remain stable, but nonlinear coupling between the transverse and longitudinal motion of the remaining trajectory have resulted in chaotic motion. As it spirals in longitudinally (upper plot) it spirals out transversely (lower plot) to large amplitudes.

![Poincaré surface of section](image)

**Fig. 2.** Poincaré surface of section (longitudinal phase plane) for a well-matched beam and no transverse motion.

**Fig. 3.** Poincaré surfaces of section for a well-matched beam, and initial values of X=0.6R_0 and Vx=0.

Assuming small beam mismatch, the actual values of R and L differ from the equilibrium values as follows:

R(t) = R_0(1 + r(t)); L(t) = L_0(1 + l(t)); \hspace{1cm} \text{Eq. (3)}

where \( r(t), l(t) \ll 1 \). Linearizing and solving the coupled differential equations leads to coupled mismatch oscillations of the form:

\[
\begin{align*}
\dot{l}(t) &= C_+ A_+ \cos(\omega_+ t - \phi_+) + C_- A_- \cos(\omega_- t - \phi_-); \\
r(t) &= A_+ \cos(\omega_+ t - \phi_+) + A_- \cos(\omega_- t - \phi_-); \hspace{1cm} \text{Eq. (4)}
\end{align*}
\]
where $C_+$ and $C_-$ are complicated functions of the physical parameters, while $A_+$ and $A_-$ are determined by the initial values of $r$ and $l$.

![Diagram](image)

Fig. 4. Poincaré surface of section (longitudinal phase plane) for a 10% mismatched beam and no transverse motion.

Figure 4 shows the result of mismatching the beam, when there is no transverse motion. The initial values of $r$ and $l$ were 0.1 and -0.1, respectively. For this case, the space charge coupling is relatively weak, and $l$ oscillates approximately once every 3 RF periods, while $R$ oscillates approximately once every 25 RF periods. Figure 4 shows that these oscillations have broken the third ring into a chain of 26 islands.

Figure 5 shows surfaces of section for four trajectories with the same longitudinal initial conditions, but each with an initial value of $X=0.6R_0$. Only the innermost trajectory remains stable under the combined effects of beam mismatch and transverse/longitudinal coupling. The other three trajectories spiral inward longitudinally as they are driven outward transversely to maximum radii of 20 times the beam radius.

**Discussion**

At present, the test-particle equations of motion for our proposed longitudinal particle-core model have only been studied numerically, but a limited analytical treatment should be possible. The transverse motion is predominantly linear, at least initially. Also, the transverse motion is much faster than the longitudinal motion, and this separation of time scales can be used to develop a perturbative treatment of the coupling between transverse and longitudinal motion. A third time scale exists, because change in the physical parameters is slow compared to the longitudinal motion. The two primary difficulties are the treatment of 1) space charge nonlinearities outside of the core, and 2) the rapidly oscillating (i.e. nonresonant) components of the RF fields.

The model studied here requires further testing and refinement. For simplicity, acceleration was ignored, but slow acceleration might play a stabilizing role by making resonances between the transverse and longitudinal motion temporary. The trajectories we studied had no motion in the $y$-plane, which implies zero angular momentum; finite angular momentum might also play a stabilizing role. Finally, the dynamics may be sensitive to the detailed treatment of the RF fields. We considered only 4 Fourier modes.

![Diagram](image)

Fig. 5. Poincaré surfaces of section for a 10% mismatched beam, and initial values of $X=0.6R_0$ and $V_x=0$.

**Acknowledgments**

The author thanks Michael F. Reusch and John R. Cary for useful discussions. This work is supported by Northrop Grumman Corporation.

**References**


END-TO-END PARTICLE SIMULATIONS OF A 1.76 MEV ELECTROSTATIC PROTON LINAC FOR CONTRABAND DETECTION

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Abstract

We present detailed end-to-end particle simulations of a 10 mA, 1.76 MeV electrostatic proton linac designed for a contraband detection system based on the principle of gamma resonance absorption. A 10 mA, 40 keV H- beam is matched by a space-charge-neutralized single-solenoid LEBT into the first column of a tandem accelerator. The resulting 0.9 MeV H- beam is then focused by a quadrupole triplet to a tight waist in a gas stripper. The emerging H+ beam is matched by another quadrupole triplet into the second column of the tandem. A HEBT consisting of two quadrupole doublets and an 81 degree dipole directs the final 1.76 MeV H+ beam downward to a carbon 13 target, where a horizontal fan of resonant gamma rays is generated. The Northrop Grumman TOPKARK code is used to model the linac, including nonlinear space charge forces and the magnetic and electrostatic fringe fields. Our results include the extent and location of beam loss, as well as the evolving shape of the beam distribution.

Introduction

The Contraband Detection System (CDS) uses a 10 mAmp, DC, 1.76 MeV Tandem proton accelerator. CDS is being built by Northrop Grumman and TRIUMF under the auspices of DARPA. The purpose of the device is to detect explosives and/or illicit drugs in luggage through the use of gamma ray resonance absorption techniques.

A 40 keV H- beam from a volume ion source, with a normalized emittance of 0.1 mm-mR, is extracted into a space charge neutralized, single solenoid LEBT and matched into the first column of the tandem accelerator, in whose fringe field, positive ions are reflected and a 10 mA current appears. Figure 1 shows 2 RMS Trace 3D envelopes. Trace3D is being run in a 2D mode. The 0.86 MeV H- beam coming out of the first column is then focused by a quadrupole triplet to a tight sub millimeter waist in a gas stripper. The emerging H+ beam is matched by another quadrupole triplet into the second column of the tandem which accelerates it to 1.76 MeV. A HEBT consisting of two quadrupole doublets and an 81 degree dipole directs the final 1.76 MeV H+ beam unto a thin carbon 13 target, where a horizontal fan of resonant gamma rays is generated. The total length of the beamline is less than 10 meters.

Simulation Method

Modifications to the Northrop Grumman ray tracing code "Topkark" and other codes have been developed for application to CDS. These modifications encompass a capability to vary charge and current as a function of length and various models of the Tandem field. We report on the results of these applications, complete end to end studies of the device, from ion source, through the LEBT, first tandem stage, H- to H+ stripper, second tandem stage and the HEBT. Our principle aims are to avoid beam scraping in the Tandem and to provide a wide variety of on target beam shapes.

The Northrop Grumman Topkark code exists in two versions, a map code, which uses automatic differentiation and a complementary ray tracing code that simulates individual particle trajectories. The present study used the latter code and a standard Runge-Kutta integrator although Topkark is also equipped with canonical integrators. Topkark implements several 2D and 3D space charge models, a uniform Trace3D-like model with linear forces, a Gaussian model, azimuthally symmetric "Parmila" and Gauss Law models, and a generalized ellipsoidal model due to Garnett and Wangler.

One critical aspect of modeling CDS is the form of the radial focusing in the fringe field of the first electrostatic column as the low velocity, 40 keV beam is rather sensitive. Hence, we have studied several models for the fringe field, a hard-edge, impulse model, a model in which the longitudinal field rises linearly in the fringe region and a model in which the longitudinal field is a cubic polynomial in the fringe region. In the fringe, the radial field is given by

\[ E_r = -\frac{r \partial E_z}{2 \partial z} \]

In the central portion of the Tandem the
longitudinal field is effectively constant. Fig. 2 illustrates the near axis fringe fields as calculated with a charged ring model. The oscillations in Er are due to the finite ring spacing.

Fig. 2 - Tandem fringe fields

Simulation Results

End-to-end simulations of the baseline 10 mA case with Topkark yield almost no beam loss despite significant space charge induced nonlinearities. This is not surprising given that the physical apertures in the device are six times the RMS beam size. Optically, the CDS device is quite robust. Scenarios departing significantly from baseline are typically apertured limited in the tandem. Fig. 3 shows the horizontal phase space at the center of the stripper where the narrowest, 3.5 mm radius aperture is had.

Fig. 3 - Horizontal phase space at stripper center

The HEBT is capable of producing a variety of on target elliptical beam shapes. Figure 4 gives a 3D profile of one spot geometry. Nonlinearities contributed by the quadrupole fringe fields are quite small but there is some flattening of the profile due to space charge forces.

Fig. 4 - CDS on-target beam density profile

We are also studying ways to increase the cost effectiveness of CDS, including decreasing the size and complexity of the device and increasing the output gamma ray intensity. Figure 5 shows 1 RMS beam envelopes for a doubled current, 20 mA case as produced by the Topkark code. The small discontinuity just after Z equals 1 meter is caused by a 2 RMS scraper. Although the 20 mA beam tends to be generally larger in the tandem, the current CDS configuration should be capable of transporting this larger current without much difficulty.

Fig. 5 - RMS envelopes for a 20 mAmp case

Currently we are conducting end-to-end simulations with beam input parameters measured at the end of the LEBT. Future simulation plans include modeling the emittance and divergence increments caused by the gas stripper.

OPERATIONAL EXPERIENCE WITH THE CERN HADRON LINACS

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Abstract

The present CERN proton linac (Linac2) was commissioned in 1978 and since that date has been the primary source of protons to the CERN accelerator complex. During the past 18 years, the machine has had a very good reliability record in spite of the demands made upon it. Modifications have been made with the view of maintaining this reliability with reduced resources and new requirements from the users. Further demands will be made in the future for LHC operation.

In 1994, a new linac for heavy ion production was put into service replacing the original CERN proton linac. As this machine was built within an international collaboration, operation had to take into account the novelty of the techniques used and the variety of equipment supplied by outside collaborators. Even so, the new machine has also had very good reliability.

Linac1

Proton Operation

Although the original CERN proton linac (Linac1) no longer exists, from the operational point of view it is interesting to review the changes made to the machine since its construction [1,2]. Major performance improvements came about quite early with the change of the grid focusing in tank 1 with pulsed quadrupoles. Later, an easy access to these quadrupole power supplies was invaluable in tuning beam intensities for other particles. Further improvements in performance came with the addition of transient beam loading compensation for the RF systems and pre-accelerator HT systems, the installation of a high gradient HT column with a duoplasmatron ion source and improved matching in the LEBT.

Linac1 was commissioned in 1958 and was built with the technology of that age. It was very much a hands-on, manpower intensive machine with little scope for modern control technology. A considerable effort had to be expended to maintain operational availability throughout its life. The technology of the tanks, RF liner inside a vacuum envelope, made alignment unstable and the constructional methods were not of good vacuum engineering standards. The unstabilised RF structure also gave rise to instabilities that had to be dealt with on an ‘‘ad hoc’’ basis. These are some of the reasons the machine became unsuitable for the performance demands of the new CERN accelerators, hence the construction of Linac2.

Development Era

Following the commissioning of Linac2, the old machine became available for development work. Linac 1 had already accelerated light ions in the $2\beta\lambda$ mode and more extensive studies were carried out on the production and acceleration of alphas. The success of a gas target stripper in the LEBT enabled useful quantities of D and $\alpha$ particles to be accelerated and stored in the ISR.

The presence of a spare accelerator also gave rise to an interesting operation where Linac1 acted as a cheap source of particles for cooling and set-up tests for LEAR. Opportunity was also taken to replace the aging, and increasingly unreliable, SAMES high voltage generators and the pre-injector by an RFQ [3]. This exercise was successful with an improvement in injection reliability.

Light Ions

The positive experience with very light ions encouraged the users to demand other ions. Experiments demonstrated that it could be just possible to increase the accelerating fields in the tanks by 33%. Achievement of these levels on an old machine required more access for maintenance and repairs than was possible during normal PS operation. To overcome these difficulties, the linac was moved to allow the installation of a shielding wall. Surprisingly, the linac worked after this move supplying LEAR again with protons.

Installation of an O$^+$ injector [4] followed some time later with the proton injection line entering at 30° to the ion line. The use of the linac with these two particles was mutually exclusive but free time could be used to commission ions. This proved to be a difficult process due to sparking in tank 1. Eventually, with a computer controlled formation program reliable operation of the tanks was achieved and O$^+$ accelerated and passed to physics. Operationally, the linac proved to be much more reliable than had been hoped for. Even so much effort had to be expended in keeping all component performance at its peak but the failure rate could be held below 10% for these short experimental periods.

After beams of milliamps, beams of microamps proved much more difficult to measure and diagnostics remained a major problem. This was not helped by an inherent instability in the ion source. With the demand for S$^{33}$ with higher mass but lower intensity, the problem was aggravated. Linac1 finished its active life in 1992 after 33 years of service. It was a labour intensive machine which required considerable attention but which was sufficiently flexible so as to allow considerable abuse of its original components. Many more problems were experienced with modern ones.
Linac2

Reasons for a New Linac

The demands made on the old linac following the commissioning of the PSB and ISR machines proved difficult to satisfy reliably and efficiently. The input matching, low injection energy, the FFDD focusing structure and instabilities in the RF at high currents made the old machine much more difficult to handle. Thus a new machine capable of accelerating 200 μs pulses of up to 150 mA of protons was designed. Improvements built into this machine were a higher injection energy (750 instead of 500 kV), a post coupled stabilised RF structure, feedback stabilised RF amplifiers and better diagnostics. Advantage was taken of the technology of the era to simplify wherever possible and to add remote computer control [5].

Initial Experience

The linac was commissioned in stages with extensive testing between them. When in 1978, the linac was deemed ready it was used for one physics period for injection into the PSB. At this time Linac 1 was held in reserve in case of problems but not used. The improved intensity, energy stability and reproducibility gave immediate benefits to the other users. From 1979 it became the proton workhorse of the CERN accelerator complex. Reliability was high and over the next ten years a 5% downtime would give rise to concern.

Improvements

Some problems were experienced with the high voltage holding of the original 750 kV high voltage column but after a rigorous program of cleaning and electrode polishing, acceptable to good sparking rates were achieved. In the period 1983 to 1992 the sparking rate varied from 1 to 3.5 sparks per day. However, there were intensity limitations with the high gradient column and although the requirements for LHC could be just met, it was felt that more margin was needed. The success of RFQ1 on Linac1 and the promise of better injection into Linac2 from a RFQ led to the decision to replace the Cockroft-Walton system by a RFQ [6] with an injection energy of 90 kV. This was installed in 1993. Problems related to damage to vacuum pumps during HT flashovers did cause some vacuum pollution in the RFQ and a general increase in its sparking. Long term conditioning has rectified the situation.

Performance

Table 1 shows typical performance figures for 1994 both for standard operation and for high performance, LHC type, beams. For the moment, the high performance beam is used only for test purposes as some upgrading of the RF would be needed for longer beams required by some users.

For comparison, in 1995 the linac ran for 6630 hours with 98.5% availability, all sources of beam loss included.

<table>
<thead>
<tr>
<th>Operation</th>
<th>LHC (50% duty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current source</td>
<td>250</td>
</tr>
<tr>
<td>Into Linac</td>
<td>155</td>
</tr>
<tr>
<td>Linac out</td>
<td>140</td>
</tr>
<tr>
<td>Into PSB</td>
<td>130</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>20 - 120 μs</td>
</tr>
<tr>
<td>Rise Time</td>
<td>20</td>
</tr>
<tr>
<td>H Emittance</td>
<td>1.7 μm</td>
</tr>
<tr>
<td>V Emittance</td>
<td>1.2 μm</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>±170 keV</td>
</tr>
<tr>
<td>Operation</td>
<td>6250 hours</td>
</tr>
<tr>
<td>Availability</td>
<td>97.6%</td>
</tr>
</tbody>
</table>

Table 1. Performance figures for 1994.

Light Ions

Although Linac2 was designed entirely for protons, it did prove possible, with little effort to accelerate deuterons in the machine. About 20 μA of deuterons were sent to the PSB and proved invaluable in the commissioning of the early light ions in the accelerator complex in 1985. With the RFQ this facility has now been lost.

Linac3

History

The Light Ion programme was initiated as a collaboration between CERN, GSI and LBNL. Following the success of this experiment and the impossibility of further upgrading the venerable Linac1 for heavier ions, a study was launched into the possibility of building a new linac dedicated to heavy ions. A cost / energy analysis based on possible source technology, restrictions from other machines and interest from physics indicated that a linac capable of accelerating Pb²⁰ to 4.2 MeV/u with stripping to Pb²⁶ was feasible in the existing hall. The project [7] came to fruition as an international collaboration between CERN (infrastructure and 200 MHz RF), GANIL Caen (source), INFN Legnaro (LEBT, RFQ and MEBT), GSI (100 MHz RF and IH linac), INFN Torino (HEBT including ion filter), IAP Frankfurt (debuncher). Additional assistance was furnished by the Czech Republic, India, Sweden and Switzerland. In spite of the variety of equipment supplied by the collaboration, the new linac was ready on time to supply beam to the next accelerators in summer 1994. Beam was supplied to physics for nine weeks of operation later that year [8].

First Operation

There had been some fears that the diversity of the equipment would lead to reliability problems as CERN staff learn to use it. Experience with ions in Linac1 had shown the
importance of beam diagnostics for such low intensity beams (80 eµA from the source, 20 eµA after stripping). Faraday cups, SEM grids, beam transformers and phase probes proved to be invaluable during the commissioning. Also temporary 100 MHz amplifiers had to be adapted to CERN controls for two operational periods.

During the physics period, the fault rate was maintained at under 2% influenced mainly by mains instabilities. However, at the end of this period when the machine was supposed to deliver ions to LEAR for cooling experiments major problems, which are still not yet fully resolved, with the microwave generator for the source caused a considerable delay.

Consolidation

As the next physics period was not scheduled until the end of 1995, time was spent in consolidating the machine for operation. Tests were carried out on the source improving the output current to 120 eµA. However, new problems with the microwave generator arose requiring major repairs. The first of the 100 MHz amplifiers from industry was delivered and commissioned for the 1995 run but although it worked without fault during this period, the reliability has not been as good as expected. The second amplifier was delivered in 1996 to replace the equipment borrowed from GSI which had worked well, in spite of its age, until the end of 1995. The new 100 MHz amplifier is still undergoing debugging by the manufacturer.

Between the IH structures, quadrupole triplets are installed which in their initial configuration made alignment of the linac very difficult. Modifications were made by the collaborator but problems still exist in this area.

Another cause for concern, the life of the 100 µg/cm² stripper foils turned out to be unfounded. Although statistics are not readily available, it has been found that a foil which resists the > 100 eµA 4.2 MeV/u beam for more than a few hours, will resist for months.

The Future

Linac2 has been the supplier of protons to CERN for 18 years and during that period has showed a remarkable reliability. However, it has recently started to show signs of fatigue especially at the level of the vacuum seals. Major works are envisaged to change and improve vacuum sealing in the next years. Also during its life no re-alignment has been carried out and there are indications that due to settlement of its building this would be desirable. The demands of the LHC era will require more performance from the linac and thus some refurbishment of the machine will be needed to maintain reliability.

Ion beams will continue to be in demand. In the short term, the reliability can be maintained with manpower effort but some improvements are still needed. The use of LEAR as an intermediate ion store for LHC ion beams will require operation at 10 Hz. Most of the components are already suitable for this but the impact on reliability has yet to be assessed. Already Linac3 has shown itself to be a flexible machine capable of changing ion species at fairly short notice. When its teething problems have been overcome, it will be a very useful tool.

Acknowledgments

In the history of the CERN hadron linacs the people who built these machines should not be forgotten. Service groups provide us with the equipment and the repair service that keeps the machines running with high reliability. The authors would like to thank them all.

This paper is also dedicated to Pierre Tetu, who left us with linacs that work and who's knowledge of them is sorely missed.

References

COMMISSIONING AND EXPERIENCE IN STRIPPING, FILTERING AND MEASURING THE 4.2 MEV/U LEAD ION BEAM AT CERN LINAC 3

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Abstract

The new CERN Heavy Ion Linac (Linac3) accelerates a Pb³⁺ beam to 4.2 MeV/u. The beam is then stripped to Pb²⁺ by a carbon foil, and, after stripping, a 12 m filter line prepares the beam for the injection into the Proton Synchrotron Booster (PSB). The filter line eliminates the unwanted charge states, checks the beam quality (energy, energy spread, transverse emittance and intensity), and finally transports the beam in the lines leading to the PSB.

The paper summarises the transverse beam dynamics of the line, and reports on its commissioning, especially focusing on the experiments that led to the stripper choice, and on the measurements performed with a specially developed single pulse multislit emittance device. The operational experience is also reported.

Introduction

At the end of Linac3, the Pb³⁺ ions are stripped to obtain a beam with a magnetic rigidity of 1.16 Tm, only 16% higher than the 50 MeV protons, which have in common with the ions (on pulse-to-pulse basis) the long transfer line and the injection into the PSB. This allows the use of the same magnetic elements for both particles. Optimum charge state and energy giving the required rigidity after stripping from Pb³⁺ have been determined as Pb²⁺ at 4.2 MeV/u [1].

A filter-stripper line (see Fig.1), 12 meters long, between the end of the linac and the shielding wall that separates Linac3 from the transport line to the PSB, is used to select and optimise for injection into the PSB the desired charge state after stripping, and to measure the parameters of the different lead ion beams (27° and 53° with the adjacent charge states). Measurements have to be performed independently from PSB operation, and on single pulse basis, to observe the ion beam stability. The design and realisation of the line has been done at CERN in collaboration with the INFN-Torino [2].

After the linac interdigital-H tanks, a quadrupole triplet focuses the beam on the stripper, then a four bending magnet sequence eliminates the unwanted charge states on a slit. At the end of the line, a debunching cavity (made at IAP-Frankfurt) minimises the energy spread for injection into the PSB. Longitudinal beam parameters are measured at the exit of the linac by a Bunch Length and Velocity Detector (BLVD), made at INP-Moscow [3], and by using the first bending magnet as a spectrometer. Horizontal and vertical emittances are measured in a straight line after the first bend with a single pulse emittance measurement device of the multislit type [4]. Five SEM-grids at different positions in the line allow the measurement of the horizontal and vertical beam position and profile, and two phase probes check the phase profile. Finally, beam currents for the different charge states are measured with two transformers, placed before and after the slit.

Figure 1. Layout of the filter - stripper line.

Beam Dynamics of the Filter-Stripper Line

The optics of the line have to take care of some critical points. First of all, position and transverse size of the beam should not exceed the foil dimensions (20 mm diameter) in the 100 mm long longitudinal region where the four stripper supports are located. Then, the filter resolution has to be considered, because the transverse width of the beam spot at the slit has to be smaller than the distance between two adjacent charge states. Moreover, the four bending magnets have to form an achromatic system with minimum emittance increase. The matching, done with the code TRACE-3D [5], is shown in Fig.2. It takes into account the emittance increase at the stripper, as well as the change of charge state.

Fig. 2. Emittances in 3 positions and beam envelopes (TRACE-3D).
Stripper Measurements

The first stripping tests were done with carbon foils of surface density 100, 200, 300 and 400 µg/cm². Fig. 3 shows the corresponding charge state distributions measured after the spectrometer. They are all centred around 53°, in excellent agreement with the predictions of Baron’s formula[6].

This indicates that the equilibrium thickness is already reached with the 100 µg/cm² foil. Straggling is responsible for the larger energy spread across thicker foils. For Pb²⁺ and a 100 µg/cm² foil we measured an increase in energy spread of 11% (±33 against ±30 keV/u (2σ)) after stripping. This is acceptable for beam transport, since the energy spread for PSB injection is mainly defined by the deblending cavity. Therefore 100 µg/cm² (thickness of 0.5µm) has been kept as the nominal stripper surface density. The beam energy loss across this foil, measured at the spectrometer, is ΔW = (130 ± 10) keV/u, in good agreement with the Firsov formula [7].

![Figure 3. Charge state distribution after stripping for increasing stripper thickness.](image)

A Model for Stripper Breaking

Since the first experiments, we noticed that foils thicker than 200 µg/cm² broke down after only a few minutes. For the 100 µg/cm² foils, direct observations through a quartz window showed that increasing the focusing on the stripper made the beam visible on the foil as a red spot. As the focusing was further increased the spot turned white and the foil broke. These observations can be explained by a calculation of the temperature T reached by the foil during the beam pulse. The energy that the beam loses inside the foil, as consequence of scattering with the foil atoms, goes first to heating of the foil material (only about 0.1% goes to the stripping of electrons), and then is dissipated by radiation from the small beam spot on the foil, the conductivity contribution through the 0.5 µm thickness being negligible. We can represent the three contributions with the equation:

\[ ΔW I = mc \frac{dT}{dt} + 2εσS(T - T_0) \frac{1}{4} \]

i.e. the power produced by a beam of current I that loses the energy ΔW is equal to the sum of the increase in thermal energy of the stripper material (mc being its mass and specific heat) and of the radiated power, expressed by the Stefan-Boltzmann relation for the emission from a surface S. ε is the emissivity (0.75 for Carbon) and σ the Stefan-Boltzmann constant. The factor 2 takes into account the fact that energy is radiated from both sides of the foil. After a time usually shorter than the beam pulse length, T converges to the equilibrium temperature \( T_0 \) can be neglected if \( T\approx T_0 \):

\[ T = \left( \frac{ΔW I}{2εσS} \right)^{\frac{1}{4}} \]  (1)

The highest temperature is reached at the centre of the beam distribution, where the current density \( dI/dS \) is maximum. Considering a gaussian beam distribution in the transverse plane, \( dI/dS \) converges to \( I/2πσ(x)σ(y) \), with I the total beam current and \( σ(x)σ(y) \) the rms dimensions of the beam. Introducing this value into (1), one obtains the maximum stripper temperature as:

\[ T_{\text{max}} = \left( \frac{ΔW I}{4πεσ(x)σ(y)} \right)^{\frac{1}{4}} \]  (2)

Taking the Linac3 beam parameters, 80 µA of Pb²⁺ and 130 keV/u energy loss, for a round beam of rms radius \( r_{rms} \), we obtain the temperature as function of beam radius of Fig. 4. TRAC3-3D calculations give \( r_{rms} = 1.6mm \), indicating that the temperature of the stripper of 100 µg/cm² comes close to the temperature of Carbon sublimation, 4100 K, assumed as the maximum that the foil can stand. Small reductions in beam size or imperfections in the foil would break it, while only a small increase in beam size brings the temperature down to a safe value. Since the energy loss ΔW is proportional to the stripper thickness, thicker foils reach higher temperatures. The colours observed on the foil before breaking correspond well to the peak emission wavelength at the calculated temperatures. In conclusion, one has to find a compromise
between the lifetime of the foil, requiring a large beam size, and the minimisation of the emittance growth due to the increase in divergence, that instead requires a small beam size. This compromise has been found easily at Lina3 since emittance growth is not a very critical issue (large PSB acceptance), and foil lifetimes are now of the order of 2/3 months.

The formula (2), with the needed changes in the parameters, indicates as well that an Al$_2$O$_3$ stripper (melting T=2345 K, ε=0.2), considered as an alternative to Carbon because it is easier to produce and more homogeneous in thickness, would not withstand the temperatures induced by the Lina3 beam.

![Figure 4. Lina3 stripper temperature from (1) as function of rms beam radius for two different Carbon foils.](image)

**Single Pulse Transverse Emittance Measurements**

A single pulse emittance measuring device was required to check the pulse to pulse stability of the linac. We choose a multislit plate with a scintillator screen and CCD camera readout. Particles traversing the slits produce light on the scintillator and a special triggered CCD camera captures and digitises the image every 1.2sec, the repetition rate of the linac. Special software reconstructs the emittance from the digitised image and calculates the Twiss parameters [4].

Starting from nominal emittance values and orientations, preliminary simulations were needed to transport the beam to the multislit (see Fig.1). Final adjustments, especially with the steers, were made by working experience.

CCDs’ saturation was avoided using a fast exposure time (150 µs) and stopping down the iris. The scintillator, a CERN Cromox type 6 Al$_2$O$_3$ + 0.2% Cr$_2$O$_3$, showed linearity in our beam current range (up to 80 µA of Pb$^{27+}$) and no substantial degradation in performances in 30 hours operational time.

To obtain the Twiss parameters at Lina3 output we made backward TRAC-3D simulations taking as input the values measured at the detector and as output the Linac output parameters. We checked the measurement with different optics, confirming both the reliability of the device and the good pulse to pulse stability of the Linac. The multislit plate with 4 mm slit spacing and 0.2 mm slit width is a good compromise to obtain the best resolution.

![Figure 5. Emittance plots at detector position for Pb$^{27+}$.](image)

An emittance plot at the detector position is shown in Fig. 5 and a summary of the measured values for Pb$^{27+}$ is in Table 1. Measurements for Pb$^{58+}$ are not very precise, since the detector is placed before the ion separation, nevertheless the total (4 x rms) horizontal emittance after stripping has been estimated to be ~10.5 π mm mrad.

<table>
<thead>
<tr>
<th>ε$_x$/π (unnorm.)</th>
<th>ε$_y$/π (unnorm.)</th>
<th>ΔW</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.7 mm mrad</td>
<td>9.9 mm mrad</td>
<td>±30 [keV], 2σ</td>
</tr>
</tbody>
</table>

Table 1: Measured beam parameters at Lina3 output (Pb 27$^+$).

**Conclusion**

The matching of the line and the stripping were easier than foreseen, the best results being obtained with a 100µg/cm$^2$ carbon foil. The current transmission of the line is almost 100% (max. 80 µA of Pb$^{58+}$), and the beam quality is good for the injection to the PS Booster. The linac shows an excellent pulse-to-pulse stability.

**Acknowledgements**

Our thanks go to C.Dutriat, L.Bernard, G.Martini and G.Molinari for their continuous assistance during the commissioning, to J.M.Quesada who provided us with some theoretical background and to K.Langbein for helping during measurements.

This paper is dedicated to the unforgettable P.Tetu. His legacy of scientific and human experience was essential to accomplish successfully the work that he had started.

**References**

EXPERIMENTS ON A 14.5 GHZ ECR SOURCE

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Abstract

The 14.5 GHz ECR4 source supplied to CERN in the framework of the Heavy Ion Facility collaboration provided Pb^{27+} operational beams to a new custom built linac in 1994. This source, which operates in the pulsed "afterglow" mode, quickly met its design specification of 80 nA and now provides currents >100 nA regularly. Early source tests showed the existence of extremely stable modes of operation. In the search for higher intensities a number of experiments have been performed on plasma gas composition, RF power matching, extraction, beam pulse compression and a biased dynode. The results of these tests will be presented along with further ideas to improve source performance.

Introduction

CERN's original proton linac was shut down in 1992 after a final light ion period with sulphur ions. It was dismantled and construction started, on the site, of a new heavy ion linac (Linac3) intended for the acceleration of lead ions. This machine was built by an international collaboration involving GANIL, Caen (ion source); INFN, Legnaro (low energy beam transport and RFQ); GSI, Darmstadt (Interdigital-H linac and some RF systems); INFN, Torino (high energy transport and filtering); IAP, Frankfurt (debuicheer), and CERN and assistance from Sweden, Switzerland, the Czech Republic, India. In June 1994 the first beam was passed to the next accelerator in the injector chain, (the booster synchrotron) and in October beam was given to the physics experiments for a nine week operational period.

An ECR (Electron Cyclotron Resonance) ion source was chosen for the project. Although the ECR was originally developed for continuous operation, the afterglow phenomenon can be exploited to give short pulses suitable for synchrotron operation of high charge state ions [1]. In the optimisation of the design of the new facility the output energy of the linac was defined to be 4.2 MeV/u for Pb^{34+}, a charge state that is beyond the reach of normal ECR sources. Thus stripping at the end of the linac was necessary. Further design optimisations indicated that at least 80 nA of Pb^{27+} would be required from the source.

GANIL performed tests on their ECR4 (Fig. 1) source and showed that enhanced intensities of highly charge lead ions could indeed be obtained at 2.5 keV/u (approximately 20 kV total) in the afterglow mode of operation which satisfied the criteria of: a) intensity >80 nA; b) adequate useful beam length; c) pulse to pulse stability; d) emittance. In fact, to limit the X-ray emission from the linac cavities which were designed for 25+, the charge state 27+ was chosen for operational purposes whilst still meeting the intensity criterion.

![ECR 4 LEAD SOURCE (GANIL)](image)

Fig. 1. The ECR4 source used at CERN.

Early Tests

After commissioning of the source at CERN using the GANIL test settings, 65 nA of Pb^{27+} was measured in a Faraday cup after analyser magnets. Improvements to the vacuum of the beam line and an extensive optimisation of the source showed that about 100 nA could be obtained (Fig. 2(a)). During a search of the source parameter space, a new operating point was found. At lower magnetic fields, the afterglow pulse became very smooth and stable with a decay

![Graph](image)

Fig. 2. Different types of afterglow: a) optimised initial, b) stable mode, c) typical operational beam

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tail of several milliseconds (Fig. 2(b)). The pulse rise time was of the order of 500 µs and the plateau acceptable. Although the intensities were somewhat lower than the GANIL mode, a compromise could be found which retained the extreme stability on a pulse to pulse basis whilst keeping a good plateau (Fig. 2(c)). This stability proved to be invaluable in the setting up of the following accelerators [2]. A reproducible operating current of around 80 µA was adopted as standard during the first (1994) physics run.

**Extraction Gap**

Initially an extraction gap of 42 mm was was used in the source. Various tests have been carried out to investigate the optimum gap. In each case the source, and beam transport, was optimised for maximum intensity and stability of the beam. The results of these tests are summarised in figure 3. During the 1995 physics run the 47 mm gap, with 120 µA of Pb²⁺, was retained. Further tests on the gap are needed for other extracted currents and charge states.

![Fig. 3. Pb²⁺ current variation with extraction gap.](image)

**Gas Mixing.**

It had been suggested [3] that the replacement of oxygen as the pilot gas by neon should give rise to an improved intensity and an increase in the mean charge state. Extensive tests showed that the current of Pb²⁺ could not be increased using neon. Currents approaching those obtained with Pb/O₂ operation could be reached, however the stability and duration of the afterglow pulse were reduced.

After a long period of operation with pure neon it became evident that at least a small amount of oxygen is required for Pb/Ne operation: after approximately 24h it was not possible to start the discharge at the pressure required for high charge state production.

A significant difference between Pb/O₂ and Pb/Ne operation was found when the source parameters were optimised on Pb²⁺ production (Fig. 4). In both cases the current of Pb²⁺ was 70µA. The maximum of the CSD was increased to 29+ for neon operation, while it remained at 27+ for oxygen. Initially a similar result was found for an optimisation on the Pb⁵⁺ peak. The maximum of the CSD was moved to Pb²⁺ for Pb/Ne and to Pb⁴⁺ for Pb/O₂ operation. However, after a period of four weeks of operation with oxygen it could be shown that the maximum of the CSD can be shifted to 31+ for Pb/O₂ operation (discharge optimised for 32+). The Pb²⁺ current was 80µA in this case while the best result for Pb/Ne was 50µA.

![Fig. 4. Comparison of charge state distributions (CSD) of lead ions a) using oxygen as carrier gas, b) using neon and residual oxygen as carrier gas. (Source parameters optimized for maximum current of Pb²⁺ in both cases)](image)

**RF Tuning Effects**

Microwave power is injected into the source via a tuned waveguide to co-axial transition. To obtain the best output and stability from the source, the optimum tuning of the transition was not necessarily that which gave the minimum reflected power. Additionally, other tuning points could be found which gave similar, or reduced, performance within the range of the tuner. Certain operating points also gave rise to increased X-ray emission from the source.

Fig. 5 shows a comparison of the current during the afterglow with the current during the main pulse for the full tuning range. In a first approximation the two curves are complementary, i.e. if a high afterglow peak is obtained the current is low during the heating phase and vice versa. This is especially pronounced at position 4920 in Fig. 5. The maximum for the afterglow is found at position 4968,
although the base current also goes through a maximum at this position.

It should be noted that the shape and duration of the afterglow are also a function of the tuner position, so that a peak on Fig. 5 does not necessarily indicate a stable operating point. Furthermore the curve is influenced by the various source parameters and it changes with time, so that an optimisation is required at regular intervals.

**Dynode Bias**

The inner conductor of the co-axial transition which contains the sample oven and which penetrates into the plasma chamber (see Fig. 1) is known as the dynode. In another ECRIS for sulphur ions, the presence of a biased electrode in the plasma gave improved performance and stabilised the afterglow [4]. It had been reported that biasing the dynode in an ECR4 source also enhanced the yield of ions [5]. The original lead source dynode was a 6/8 mm copper tube but became a 10/8 mm tube in a biased configuration. Initial tests showed that it was impossible to control the source output using the oven heating as a parameter. The oven temperature is influenced by RF losses on the dynode, RF heating of the oven and resistive heating. There were indications that the lead neutral pressure in the source was too high and examination of the sample showed that it had been overheated, giving rise to a too high lead vapour pressure in the plasma chamber.

The dynode bore was reduced to 6 mm, as in the original electrode, and a much improved control of the oven was obtained. The source was optimised with zero bias, new RF tuning points and magnetic fields had to be found. It was immediately obvious that the source was much more temperamental and that all parameters had a very much reduced tolerance. The optimum RF tuning was now very sharp and just off the limit of stability. Satellite tuning points whilst more stable gave only 50% of the peak intensity.

Although it proved possible to optimise the source under these conditions, no gain in Pb$^{31+}$ current was observed. Application of a negative bias to the dynode resulted in a loss of current, an increase in instability and beam breakup and a change in beam shape when the bias exceeded 50 V. These instabilities were also present in the microwave reflected power. As the bias increased above 200 V, the current appeared to climb again but isolation and sparking limited the bias that could be used reliably. Positive bias reduced the beam dramatically. However, it did prove possible to find a low magnetic field setting which reduced instabilities but without an improvement in intensity.

It was noted that for O$^+$, the current in the afterglow, which is not very pronounced relative to that in the main discharge, tended to decrease whilst the main discharge current increased. It may be asked if the bias was insufficient relative to the ionisation potential of Pb$^{31+}$ (874 eV).

**Future Plans**

Further tests are desirable (subject to operational restrictions) to examine the effects of various ideas to increase the yield of the Pb$^{31+}$ and Pb$^{32+}$ ions. Experiments are only interested in particles not electrical intensity so an increase in charge state from the source is not of interest unless the intensity gain is dramatic. Going to lower charge states is excluded in the linac design. Investigations that could be of interest are:- extraction gap with current and ion species, continuation of the biased electrode tests, plasma chamber wall materials, sample composition and plasma gas effects.

**References**


A LINAC GENERATOR PROGRAM AS PRE-PROCESSOR FOR THE SIMULATION CODE DYNAC

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Abstract

A linac generator program, GENAC, has been developed, capable of generating an accelerating structure through interpolation of SUPERFISH output files. GENAC can handle long and complex accelerating elements, such as asymmetric ones or elements consisting of several accelerating gaps in one go. GENAC is a pre-processor to the beam simulation code DYNAC [1]; both programs are based on the same set of quasi-Liouville beam dynamics equations.

With the DYNAC code one has the possibility of using multistep space-charge calculations [2],[3],[4] within the accelerating elements of a linac. Therefore, the combination of the linac generator GENAC with the simulation code DYNAC constitutes a powerful tool for the development of new types of accelerators.

Introduction

New types of accelerators, such as ones devoted to medical or industrial applications or nuclear waste transmutation, often consist of long cells generating complex (multi-gap) fields including asymmetric ones. The simulation program DYNAC and its pre-processor GENAC, both based on the same set of quasi Liouvilleian equations, can handle such long complex fields, including asymmetric ones. It is important to note that codes such as PARMILA [2] and MAPRO [3] assume symmetric fields and assume the accelerating gaps to be short (i.e. the velocity of the particles are assumed constant across the gap). Such codes are therefore not suited for the new types of accelerators mentioned above.

Short description of GENAC

GENAC needs two types of input files: firstly an input file giving the basic linac parameters such as input and output energy, particle type and synchronous phase; and secondly a set of SUPERFISH files for different relativistic \( \beta \) corresponding to different points along the accelerator.

GENAC reads the axial field distributions \( E_x(z) \) from the SUPERFISH files and interpolates for the actual \( \beta \) ( or \( \beta_\alpha \) ) in a way similar to one described in [5]: the two fields in the SUPERFISH files nearest to the actual \( \beta \alpha \) are found and a logarithmic interpolation on the field is made such that:

\[
E_x(i) = E_x(i)
\frac{E_{2\alpha}(i)}{E_x(i)}
\]

where \( E_x \) is the interpolated field at the position \( i \) between the given SUPERFISH fields \( E_x \) and \( E_{2\alpha} \), and \( R \) is defined as:

\[
R = \frac{\beta \lambda_x - \beta \lambda_{\alpha}}{\beta \lambda_{\alpha+1} - \beta \lambda_x}
\]

Given the field thus obtained, the transit time factors are computed as in [1] and a first value for the energy gain is obtained. From here starts an iterative process, acting on the field based on the following three criteria: the synchronous phase, the accelerating field \( E_x \) and the cell length.

Once the criteria have been met, GENAC will start generating the next accelerating field and this process continues until the final energy wanted has been reached.

It is important to note that the previous set of quasi-Liouvillean equations [6], used by MAPRO and PARMILA, needs the value of the synchronous phase and velocity at the middle of the accelerating gap. These values can only be obtained through supplementary computations as the synchronous phase and velocity are only known at the input of the accelerating element. This makes the linac generator complicated. The beam dynamics equations used in GENAC and DYNAC make use of an equivalent travelling wave for which the phase can be obtained at any point; it is sufficient to have the above mentioned values at the input of the accelerating element. These analytic equations also allow any beam parameters at any given point along the accelerating element to be obtained. Another important difference is that GENAC can generate cells containing a single accelerating gap as well as ones containing two or more accelerating gaps. An example will be shown later.

GENAC produces three sets of output. During the generation process, the total length and obtained energy are printed on the terminal. At the same time an output file is written containing more detailed information of the linac generated through the iterations. Finally an output file, containing a description of the generated linac, is written to serve as input file to DYNAC.

Application to a proton linac design

A typical application is the generation of a linac containing long asymmetric fields such as in [7]. In this design, each superperiod consists of two periods, which in their turn contain two cells of three gaps each, arranged in a...
FODO lattice (see Fig.1). The electric field distribution for one of such cells is shown in Fig.2.

Fig.1. Layout of a superperiod of the LANL medical linac

Axial field distribution $E_z(z)$

![Graph](image)

Fig. 2. The axial field distribution of a three gap cell in the LANL medical linac. One notes the asymmetry in the first and third field.

To generate a linac consisting of such multi-gap elements one can either generate gap by gap or several gaps in one go. The linac section studied here has an energy range from 10 to 30 MeV over a length of 9.1 m and is operated at 1300 MHz. Table 1 shows some results from the output file corresponding to the first three accelerating elements of the linac for a generation made gap by gap.

**ACCELERATING ELEMENT N : 1**

**CHARACTERISTICS AT THE OUTPUT OF THE ACCELERATING ELEMENT**

BETA $dW$(MeV) ENERGY(MeV) TOF(deg) TOF(sec)

REF .14546 .086544 10.087 .23399E+03 .49999E-09

**ACCELERATING ELEMENT N : 2**

FREQUENCY : .13000E+10 Hz
GAP LENGTH : .33537E+01 cm
FIELD FACTOR : .10107E-01

**CHARACTERISTICS AT THE INPUT OF THE ACCELERATING ELEMENT**

BETA GAMMA ENERGY(MeV) TOF(deg) TOF(sec)

REF .14546 .10108E+01 .10087E+02 .21069E+03 .45019E-09

**CHARACTERISTICS AT THE MIDDLE OF THE EQUIVALENT FIELD**

BETA GAMMA ENERGY(MeV) SYNCHRONOUS PHASE (deg)

REF .14592 .10108E+01 .10152E+02 -.30014E+02

**CHARACTERISTICS AT THE OUTPUT OF THE ACCELERATING ELEMENT**

BETA $dW$(MeV) ENERGY(MeV) TOF(deg) TOF(sec)

REF .14613 .093969 10.181 .57069E+03 .12194E-08

**ACCELERATING ELEMENT N : 3**

FREQUENCY : .13000E+10 Hz
GAP LENGTH : .25236E+01 cm
FIELD FACTOR : .10413E-01

**CHARACTERISTICS AT THE INPUT OF THE ACCELERATING ELEMENT**

BETA GAMMA ENERGY(MeV) TOF(deg) TOF(sec)

REF .14613 .10109E+01 .10181E+02 .57632E+03 .12315E-08

**CHARACTERISTICS AT THE MIDDLE OF THE EQUIVALENT FIELD**

BETA GAMMA ENERGY(MeV) SYNCHRONOUS PHASE (deg)

REF .14657 .10109E+01 .10244E+02 -.29969E+02

**CHARACTERISTICS AT THE OUTPUT OF THE ACCELERATING ELEMENT**

BETA $dW$(MeV) ENERGY(MeV) TOF(deg) TOF(sec)

REF .14674 .087411 10.268 .84632E+03 .18084E-08

Table 1: Typical data from the GENAC output file. The total length after three gaps is 8.33 cm.

Table 2 shows results for the first three gaps as in table 1, this time treating the three gaps as one long accelerating element. Note that in this case the phase law is slightly different.

**ACCELERATING ELEMENT N : 1**

**CHARACTERISTICS AT THE INPUT OF THE ACCELERATING ELEMENT**

BETA GAMMA ENERGY(MeV) TOF(deg) TOF(sec)

REF .14485 .10107E+01 .10000E+02 -.35999E+02 -.76904E-10

**CHARACTERISTICS AT THE MIDDLE OF THE EQUIVALENT FIELD**

BETA GAMMA ENERGY(MeV) SYNCHRONOUS PHASE (deg)

REF .14501 .10107E+01 .10024E+02 -.29990E+02

**CHARACTERISTICS AT THE INPUT OF THE ACCELERATING ELEMENT**

BETA GAMMA ENERGY(MeV) TOF(deg) TOF(sec)

REF .14485 .10107E+01 .10000E+02 -.30.100E+02 -.66667E-10
CLOSEST CHARACTERISTICS AT THE MIDDLE OF THE EQUIVALENT FIELD
BETA GAMMA ENERGY(MeV) SYNCHRONOUS PHASE (deg) REF .14586 .1010E+01 .10144E+02 -.30013E+02

CLOSEST CHARACTERISTICS AT THE OUTPUT OF THE ACCELERATING ELEMENT
BETA dW(MeV) ENERGY(MeV) TOF(deg) TOF(sec) REF .14605 .283081 10.283 .86007E+03 .18418E-08

Table 2: Typical data from the GENAC output file. Treating the 3 gaps as one long accelerating element a total length of 8.29 cm is obtained.

Conclusion

The combination of the linac generator GENAC with the simulation code DYNAC constitutes a powerful tool for the development of new types of accelerators. The automatic adjustment of the quadrupoles in presence of space charge can be included using the fast and accurate new space charge method in reference [4].

Acknowledgements

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References

DYNAMICS OF BEAM HALO IN MISMATCHED BEAMS

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Abstract

High-power proton linacs for nuclear materials transmutation and production, and new accelerator-driven neutron spallation sources must be designed to control beam-halo formation, which leads to beam loss. The study of particle-core models is leading to a better understanding of the causes and characteristics of beam halo produced by space-charge forces in rms mismatched beams. Detailed studies of the models have resulted in predictions of the dependence of the maximum amplitude of halo particles on a mismatch parameter and on the space-charge tune-depression ratio. Scaling formulas have been derived which will provide guidance for choosing the aperture radius to contain the halo without loss.

Introduction

High-intensity proton linacs are being proposed for new projects around the world, especially for tritium production, and for pulsed spallation neutron sources. Typical requirements for these linacs include high peak beam currents of about 100 mA, and final energies of about 1 GeV. For these applications high availability is demanded. High availability requires very low beam-loss to avoid radioactivation of the accelerator and to allow hands-on maintenance that will keep the mean repair and maintenance times short. This challenge will require a greater understanding of the evolution of the beam distribution, including the low-density beam halo.

Particle-Core Models

Numerical studies have established rms mismatch as a major cause of emittance and halo growth.\textsuperscript{1,2,3} The particle-core model\textsuperscript{4,5,6} for a continuous beam has contributed to an understanding of the underlying causes of halo formation from mismatched beams. We have recently developed a particle-core model for the case of a spherical bunch. In these models the space-charge field from a mismatched beam core, propagating in a uniform linear focusing channel, is represented by a hard-edged, spatially-uniform density distribution that oscillates radially in the symmetric breathing mode. The amplitude of the breathing mode is directly related to the initial rms mismatch of the beam. The dynamics of the outer halo particles are determined by the external focusing force and the repulsive space-charge force from the oscillating core. The behavior of these particles is studied in the model by representing the outer halo particles with single particles that oscillate through the core, and interact with it. We will restrict our treatment to particles with zero angular momentum. The equations for the models can be expressed in a dimensionless form. The equation of motion of the core radius is the envelope equation

\[ \frac{d^2 r}{dt^2} + r - \frac{n^2}{r^3} - (1 - \eta^2) \left[ \frac{1}{r^2} \right] = 0. \]  \hspace{1cm} (1)

The matched beam size is the solution of Eq.1 when \( d^2 r/dt^2 = 0 \). The equation of motion of a particle inside the core radius is

\[ \frac{d^2 x}{dt^2} + x - (1 - \eta^2) \left[ \frac{x}{r^2} \right] = 0, \quad x < r. \]  \hspace{1cm} (2a)

and outside the core is

\[ \frac{d^2 x}{dt^2} + x - (1 - \eta^2) \left[ \frac{1}{x^2} \right] = 0, \quad x \geq r. \]  \hspace{1cm} (2b)

The upper expression in the bracket for each of the above equations is the space-charge term for the continuous beam and the bottom expression is for the spherical bunch. The quantities \( r \) and \( x \) are dimensionless displacements taken relative to the radius \( R_0 \) of the matched core, the independent variable is \( \tau = k_0 z \), where \( z \) is the axial distance and \( k_0 \) is the zero-current phase advance per unit length without space charge, and \( \eta = k_0 R_0 \) is the space-charge tune depression. It can be shown that \( \eta = 4 \pi \varepsilon/k_0 R_0^3 \), where \( \varepsilon \) is the unnormalized rms emittance. For the cylindrical beam, \( 1 - \eta^2 = K/k_0 R_0^2 \), where the quantity \( K \) is the generalized perversance, related to the particle charge \( q \), mass \( m \), velocity \( \beta \), relativistic mass factor \( \gamma \), and beam current \( I \), by \( K = q I / 2 \pi e_0 mc^2 \gamma^2 \beta^2 \), and for the spherical bunch with number of particles \( N \) per bunch, \( 1 - \eta^2 = k_0 x R_0^3 \), where \( x = q^2 N / 4 \pi e_0 mc^2 \beta^2 \gamma^3 \). The degree of mismatch is measured by the mismatch parameter \( \mu \), defined as the ratio of the initial beam radius to the radius of the matched beam; an rms matched beam has \( \mu = 1 \).

The particle phase-space motion is complicated, because of the time-dependent space-charge force, which is nonlinear when the particles are outside the core. The particles can either gain or lose energy, depending on the phase of the particle motion relative to the phase of the core oscillation. The particles slowly gain or lose energy as a result of a series of kicks. It has been found that a parametric resonance exists\textsuperscript{5} such that the largest energy transfer occurs when the particle frequency is about one half the core frequency. The particle frequencies depend on the amplitude, because of the nonlinear space-charge force, and not all particles can be locked into resonance. The motion is most conveniently described by showing a strobeoscopic or Poincare map, shown in Fig.1, in which \( x \) and \( x' \) phase space for the continuous beam with \( \mu = 1.5 \), and \( \eta = 0.5 \), and is plotted for an initial array of test particles, once per core oscillation cycle. An initial distribution of halo particles is distributed regularly along the \( x \) and \( x' \) axes, and the strobe time is taken when the core radius is minimum. In Fig.2 we show the corresponding strobeoscopic plot for the mismatched spherical bunch. Three distinct regions are observed in Figs.1 and 2, defined by a separatrix. First, there is the inner region, which may be called a core-dominated region. Particles with trajectories in this region spend most of their time inside the core, where the frequencies of motion are too small for a strong resonant energy transfer with the core. There is an outer region, which
may be called the focusing-dominated region, in which the
particles spend most of their time outside the core. The motion
of these particles is mostly determined by the external focusing
force, and these particles have an oscillation frequency too high
to have resonant energy transfer with the core. Finally, there
are the regions surrounding two fixed points on the x axis, one
on each side of the origin. In these regions the particle
oscillation frequencies are close to one half the core frequency,
and the parametric resonance produces large energy transfers.
The amplitude growth for the resonant particles is self-
limiting, because of the nonlinearity. A maximum resonant-
particle amplitude exists, which depends on the amplitude of
the core breathing mode, which is related to the initial rms
mismatch of the beam. The general features of the particle
dynamics appear to be insensitive to the details of the assumed
core distribution. For example, a similar stroboscopic plot is
obtained, if the distribution of the core is changed from
uniform to Gaussian.7 The appearance of the stroboscopic
plots is found to be very insensitive to the tune depression η.
Chaos, observed as a breakup of the separatrix, can be seen for
values of the space-charge tune depression ratio, below about
0.4.

![Stroboscopic plot](image1)

**Fig. 1.** The stroboscopic plot from the particle-core model for a
continuous beam with μ = 1.5, and η = 0.5.

![Stroboscopic plot](image2)

**Fig. 2.** The stroboscopic plot from the particle-core model for a
spherical bunch with μ = 1.5 and η = 0.5.

Our hypothesis is that if we inject a realistic beam with a
tail that is rms mismatched to the focusing lattice, the
particles in the tail that fall under the influence of the
parametric resonance with the breathing mode will be driven to
large amplitudes, and produce the halo. We cannot rule out the
possibility that beam instabilities might also cause additional
particles from the core region to move across the separatrix
into the resonance-dominated region and add to the halo. That
only a small percentage of the particles comprises the halo in a
real beam, can be explained because the percentage of the
particles in the tail of the injected beam that fall within the
resonance region is small. Low tune depressions and
accompanying chaos can be expected to increase the population
of the halo, because then, more particles in the injected beam
can be influenced by the resonance.

A significant prediction of the particle-core model is that
for given values of μ and η, there is a maximum amplitude for
the resonantly-driven particles that form the halo, given by the
location of the outermost point of the separatrix. The
maximum amplitudes have been calculated as a function of μ
and for η = 0.5 and 0.9 from the numerical solution of Eqs. 1
and 2, and are shown in Fig. 3. Figure 3 shows that the
spherical bunch case leads to larger maximum amplitudes than
for the continuous beam. We interpret the results of the two
models as upper and lower limits in a smooth approximation
for the average values of the maximum amplitudes of
ellipsoidal bunches, because in proton linacs, the longitudinal
semiaxis of the bunches is usually larger than the radius. From
Fig. 3, it can be seen that the maximum amplitude, as
described in the normalized or dimensionless form, is very
insensitive to η. The normalized maximum amplitude is well
described by an approximate empirical formula

\[ x_{\text{max}} / a = A + B |\ln(\mu)|, \]

where \( x_{\text{max}} \) is the maximum resonant particle amplitude, \( a \) is
the matched rms beam size, which is identified in the model
with the rms size of the core, and \( A \) and \( B \) are weak functions
of the tune depression η. In the range 0.500 ≤ μ ≤ 0.952, and
1.05 ≤ μ ≤ 2.00, we obtain least-square-fitted values of \( A \) and
\( B \). These are given in Table 1.

![Graph](image3)

**Fig. 3.** Maximum amplitudes versus μ for particles in the
resonance regions for the cylinder, and sphere models: a) sphere,
η = 0.9, b) sphere, η = 0.5, c) cylinder, η = 0.9, and d) cylinder, η = 0.5. The solid points represent the smoothed PARMILA
simulation results for comparison with the models, and the open
points represent the maximum amplitudes including quadrupole
flutter.
Table 1

<table>
<thead>
<tr>
<th>Core</th>
<th>$\eta$</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical</td>
<td>0.5</td>
<td>3.97</td>
<td>3.83</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>0.9</td>
<td>3.91</td>
<td>4.25</td>
</tr>
<tr>
<td>Sphere</td>
<td>0.5</td>
<td>4.87</td>
<td>5.30</td>
</tr>
<tr>
<td>Sphere</td>
<td>0.9</td>
<td>4.81</td>
<td>5.56</td>
</tr>
</tbody>
</table>

Equation 3 is not a good approximation for mismatches very close to $\mu = 1$, where, as $\mu$ approaches 1, $x_{\text{max}}/a$ rapidly approaches 2 for the continuous beam, and $\sqrt{2}$ for the spherical bunch.

We have determined a characteristic time scale from the particle-core model for particle motion in the resonance region. Unambiguous results are obtained by calculating the period for small-amplitude oscillations about a stable fixed point on the axis of the stroboscopic plots. Particle periods for the continuous beam, obtained for $\mu = 1.5$, are about 10 breathing-mode periods for $\eta < 0.4$, and for $\eta > 0.6$, the particle period increases rapidly with $\eta$. If we interpret the particle periods from the particle-core model as the characteristic growth time for the halo, we observe that the growth time for the halo is reduced significantly as $\eta$ decreases from 0.9 to 0.6. The wavelength $k_b$ for the breathing mode can be obtained from the expressions for the phase advance per unit length, $k_b^2 / k_0^2 = 2(1 + \eta^2)$ for the continuous beam, and $k_b^2 / k_0^2 = 3 + \pi^2$ for the spherical bunch.

In a real linc, additional effects that are not included in the particle-core model, must be accounted for, such as beam-envelope flutter associated with a quadrupole focusing system, acceleration, and the influence of other modes of the mismatched beam. We have conducted a test of the predictions of the particle-core model, by carrying out PARMILA simulations, using an r-z space-charge mesh with individual runs at $10^5$ particles per run. The linc used for the test was a 217- to 1700-MeV section of a superconducting proton linc with variable tune depressions and with transverse focusing from a singlet quadrupole FODO lattice. An initial 6-D waterbag distribution (uniformly-filled 6-D ellipsoid) was used, and the beam was given the same initial mismatch parameter $\mu$ in all three planes, which was varied from run to run. Simulation studies of beam mismatch have shown that this type of mismatch appears to produce the most extended halo. The maximum particle displacement was determined at the center of every quadrupole, and the largest of those maxima for each $\mu$ was plotted in Fig.3. Because of the flutter associated with the periodic quadrupole lattice, the models should be compared with the maximum displacement smoothed or averaged over the lattice period, which we have also presented in the Figure. The smoothed PARMILA points in Fig. 3 are observed to lie between the sphere and cylinder models, as would be expected for beam bunches that are approximate prolate ellipsoids. Considering the simplicity of the models, we believe that the agreement of the maximum amplitudes from the models and the simulations is remarkably good, and it supports the hypothesis that the breathing mode is a main driver of the beam halo in a linc. As a further test of the importance of the breathing mode, we have plotted the rms transverse cross-sectional area of the beam as a function of energy along the linc, to search for the area oscillations that would be expected if the breathing mode was excited. Indeed, area oscillations are observed with a period that is consistent with the theoretically expected breathing-mode values. We note that these simulations should be repeated using a 3-D mesh to ensure that we have not excluded any modes in the r-z simulations that may be important.

Conclusions

Work during the past several years has led to the hypothesis that beam mismatch will be the main cause of beam halo in the new linacs. If we assume that the breathing mode, is mainly responsible for the halo, we can use the particle-core models to make quantitative predictions about the halo that is formed. The particle-core models, one for a continuous beam and one for a spherical bunch, predict that the halo will be limited to a maximum amplitude, which depends mostly on the strength of the initial mismatch. We interpret the predictions of the two models as establishing lower and upper bounds of the halo amplitude for a prolate ellipsoidal bunch in a linc. Simulation results for a realistic linc are found to produce smoothed maximum amplitude values that are consistent with the models, and provide additional evidence that the breathing mode is the most important mode producing the halo. To keep the halo small, one needs to match the beam as well as possible, and keep the rms beam size small by keeping $\epsilon$ small and $k_0$ large. We note that additional effects can contribute to beam halo, such as intrabeam scattering, beam-residual gas scattering, and image-charge effects. However, these effects are expected to be usually less serious than beam mismatch.

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References

A NEW APPROACH TO SPACE CHARGE FOR LINAC BEAM DYNAMICS CODES


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Abstract

Apart from very computer time consuming PPI routines (Particle to Particle Interaction, e.g. [1]), all previous space charge routines require some kind of symmetry. A new routine, not requiring symmetry, is being developed. It offers fast computation and is little sensitive to statistical noise. It could become a good tool for studying halo formation phenomena.

Introduction

Almost all presently available space charge routines require some form of symmetry. The common SCHEFF routine [1][2], transforms the density distribution into a rotationally symmetrical one, where the field is computed and linearly corrected inside an elliptical cylinder. The outside density distribution is obtained using a different method, and discontinuities appear. Moreover it is very sensitive to statistical noise. In the SC3DELP [3] and MAPRO [4] routines, the bunched beam is assumed to have an ellipsoidal symmetry. The former SCHERM routine [2], represents the non-symmetrical longitudinal shape of the bunch with two or three ellipsoids. However it keeps in the transverse direction an elliptical profile. The MOTION routine [5] treats the two transverse directions x and y independently.

The present work suggests a new type of approach, offering fast computation without the need of strict symmetry.

Three dimensional representation of the bunch

The three dimensional representation of the charge distribution of the bunch is made with Hermite expansions.

As shown in [2], one can obtain the integrated charge density along one axis in the form of a Hermite series expansion:

$$\rho(x) = \sum_i A_i H_i \left( \frac{x}{a} \right) \exp \left( - \frac{x^2}{a^2} \right)$$  \hspace{1cm} (1)

is the r.m.s. dimension of the bunch along the x axis and $A_i$ is defined as:

$$A_i = \frac{q}{i! \sqrt{2\pi}} \sum_{n=1}^{N} H_i \left( \frac{x_n}{a} \right)$$  \hspace{1cm} (2)

where q is the charge of the macro-particle. Analogous relations are valid in the y and z directions, with b and c as respective r.m.s. dimensions. In these expressions the coordinates are taken with respect to the centre of gravity of the bunch; N is the number of particles in the bunch. As $H_1(u) = u$ and $H_2(u) = u^2 - 1$ it turns out that $A_1 = A_2 = 0$.

Most functions of a coordinate can be represented with a Hermite series expansion. For instance, one may be interested in the variation a(z) of the transverse r.m.s. dimension in x of the bunch along the z axis. To do so one can compute the following function of z:

$$H_2 \left[ \frac{x(z)}{a} \right] \rho(z) = \frac{q}{k} \sum_{k=1}^{N} A_{2,k} H_k \left( \frac{z}{c} \right) \exp \left( - \frac{z^2}{2c^2} \right)$$  \hspace{1cm} (3)

where

$$A_{2,k} = \frac{q}{k! \sqrt{2\pi}} \sum_{n=1}^{N} H_2 \left( \frac{x_n}{a} \right) H_k \left( \frac{z_n}{c} \right)$$  \hspace{1cm} (4)

One obtains:

$$a^2(z) = a^2 + a'^2 \frac{A_{2,k} H_k \left( \frac{z}{c} \right)}{A_{k} H_k \left( \frac{z}{c} \right)}$$  \hspace{1cm} (5)

$A_k$ is given by:

$$A_k = \frac{q}{k! \sqrt{2\pi}} \sum_{n=1}^{N} H_k \left( \frac{x_n}{a} \right)$$  \hspace{1cm} (6)

Similarly, one could compute the variation of the centre of gravity in z along the x axis (ditto for the y axis). One gets:

$$z_0(x) = c \frac{\sum_i A_{i,1} H_i \left( \frac{x}{a} \right)}{\sum_i A_{i} H_i \left( \frac{x}{a} \right)}$$  \hspace{1cm} (7)

with

$$A_{i,1} = \frac{q}{i! \sqrt{2\pi}} \sum_{n=1}^{N} \frac{z_n}{a} H_i \left( \frac{x_n}{a} \right)$$  \hspace{1cm} (8)

and analogous relations for z(y). An example is given in Fig.1.

![Fig.1. Projection on the (y,z) plane of the particle distribution in a bunch at the output of the 200 mA proton CERN RFQ2B. The variations of the y r.m.s. size along the z-axis and the centre of gravity in z along the y axis are shown.](image-url)
In the above derivation the terms $A_{jk}$ and $A_{i}$ of a two dimensional Hermite series expansion have been introduced. Such an expansion can be extended to three dimensions, giving the local density distribution $\rho(x,y,z)$:

$$\rho(x,y,z) = \sum_{i,j,k} A_{ijk} H_i(\frac{x}{a}) H_j(\frac{y}{b}) H_k(\frac{z}{c}) \exp\left(-\frac{x^2}{2a^2} - \frac{y^2}{2b^2} - \frac{z^2}{2c^2}\right)$$  \hspace{1cm} (9)

with

$$A_{ijk} = \frac{q}{(2\pi)^{3/2} i! j! k!} \sum_{l=1}^{\infty} H_l(\frac{x}{a}) H_j(\frac{y}{b}) H_k(\frac{z}{c})$$  \hspace{1cm} (10)

As above one has $A_{i00}=A_{0j0}=A_{00i}=A_{i00}=A_{00i}=A_{000}=0$. If the three axes are chosen such that $xy=yz=xz=0$, the corresponding terms $A_{i00}$, $A_{0j0}$, and $A_{00i}$ are also zero. This last condition is not necessary; it would be needed one could straighten up the axes by rotation. The main term $A_{000}$ is such that:

$$A_{000} = \frac{q N}{(2\pi)^{3/2}}$$  \hspace{1cm} (11)

**Computation of the field distribution**

The charge density distribution in a bunch can be considered to be a Gaussian:

$$\rho_0(x,y,z) = A_{000} \exp\left(-\frac{x^2}{2a^2} - \frac{y^2}{2b^2} - \frac{z^2}{2c^2}\right)$$  \hspace{1cm} (12)

corrected by various terms (coefficients $A_{ijk}$ in eq.9), each of them of total charge zero. In practice most of these terms are in the range of a few per cent or less of the fundamental term $A_{000}$, only a few ones are slightly above 10 %.

The field due to the Gaussian term (eq.12) is computed by numerical integration as explained in [2], but the macroparticle charge density contains a single term only and therefore computer time remains small. For the other terms the method introduces approximate expressions of the field, good in the part of the bunch where most of the particles lie, but less correct at large distances where the field is anyway very weak. According to the Laplace-Poisson relation:

$$\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} = \frac{\rho(x,y,z) - \rho_0(x,y,z)}{\varepsilon_0}$$  \hspace{1cm} (13)

and the following property:

$$\frac{d}{du}\left[H_i(u) \exp\left(\frac{-u^2}{2}\right)\right] = -H_{i+1}(u) \exp\left(\frac{-u^2}{2}\right)$$  \hspace{1cm} (14)

one can take for the charge term, with $A_{ijk} \neq A_{000}$:

$$A_{ijk} H_i(\frac{x}{a}) H_j(\frac{y}{b}) H_k(\frac{z}{c}) \exp\left(-\frac{x^2}{2a^2} - \frac{y^2}{2b^2} - \frac{z^2}{2c^2}\right)$$

yielding to the following field components:

$$E_x = -\frac{q}{\varepsilon_0} A_{ijk} H_i(\frac{x}{a}) H_j(\frac{y}{b}) H_k(\frac{z}{c}) \exp\left(-\frac{x^2}{2a^2} - \frac{y^2}{2b^2} - \frac{z^2}{2c^2}\right)$$  \hspace{1cm} (15)

$$E_y = -\frac{q}{\varepsilon_0} A_{ijk} H_i(\frac{x}{a}) H_j(\frac{y}{b}) H_k(\frac{z}{c}) \exp\left(-\frac{x^2}{2a^2} - \frac{y^2}{2b^2} - \frac{z^2}{2c^2}\right)$$  \hspace{1cm} (16)

$E_z = -\frac{q}{\varepsilon_0} A_{ijk} H_i(\frac{x}{a}) H_j(\frac{y}{b}) H_k(\frac{z}{c}) \exp\left(-\frac{x^2}{2a^2} - \frac{y^2}{2b^2} - \frac{z^2}{2c^2}\right)$

$$\frac{q}{(2\pi)^{3/2}} \sum_{i,j,k=1}^{\infty} H_i(\frac{x}{a}) H_j(\frac{y}{b}) H_k(\frac{z}{c}) \exp\left(-\frac{x^2}{2a^2} - \frac{y^2}{2b^2} - \frac{z^2}{2c^2}\right)$$ (17)

a, b, c define the r. m. s. size of the bunch, and $\alpha + \beta + \gamma = 1$.

These $\alpha$, $\beta$, and $\gamma$, which depend on $a$, $b$ and $c$ but also on $i$, $j$, and $k$, have to be optimized for each term. At large distance the real field vanishes as $r^{-n}$ (with $n>2$) instead of exponentially. However, the error made is not significant.

A difficulty appears in the eq.(15), (16) and (17) for $i, j$ or $k = 0$: the integral of $H_0(\frac{x}{a}) \exp\left(-\frac{x^2}{2a}\right)$, which corresponds to the error function, does not go down to zero at infinity. It is therefore replaced by a polynomial equivalent to the above integral over most of the interval, but going to zero at infinity.

**Preliminary results of the new method**

Since the major interest of this new method is to compute space charge fields in the absence of any symmetry, comparisons have been made with a PPI routine in order to check its validity.

In order to explain the differences which could arise in these comparisons, it is essential to examine the limits of the PPI routine such as its sensitivity to statistical noise and to the so-called "stopping distance", which avoids that the field becomes infinite when the macroparticles are too close to each other.

In Figures 2, 3 and 4 comparisons between the new space charge routine and previous ones for the CERN proton linac at 200 mA are shown for different positions along the machine for 5000 particles. In Fig.4 one clearly observe the differences in particle distributions between the results obtained with the new space charge routine and SCHEFF at the output of the CERN proton linac. The emittances and transmissions, however, yield to very similar values.

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Fig. 3 The transverse impulse as a function of $z$ in the bunch at a given point in the machine for the new routine (a), a PPI routine (b) and SCHEFF (c). The curves shown correspond to the differences between the total impulse and the Gaussian contribution for the $(x,z)$ plane with $x=0,+a,-a$.

Fig. 4 The beam is shown in the $(x,x')$ plane at a given point in the machine for the new routine (a) and for SCHEFF (b). In (c) and (d) the beam is shown in the longitudinal plane for the new routine and SCHEFF respectively.

**Conclusion**

This new space charge method is very promising and may help in the estimation of tolerances necessary for the design and operation of high intensity linacs. The computing time needed with the new method is significantly shorter than any other presently available routine. Some possible refinements of the present method are still being studied. This routine might also be used for cyclotrons.

**Acknowledgments**

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**References**

HIGH CHARGE-STATE ION BEAM PRODUCTION FROM A LASER ION SOURCE


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Abstract

The high current, high charge-state ion beam which can be extracted from a laser produced plasma is well suited, after initial acceleration, for injection into synchrotrons. At CERN, the production of a heavy ion beam using such a source is studied.

A 60 mA pulse of a mixture of high charge state tantalum or lead ions of 5 μs duration has been extracted at 59 kV. The resulting beam emittance and energy spread were measured.

A Low Energy Beam Transport system (LEBT) consisting of two pulsed solenoids is used to match the beam to a four-rod Radio Frequency Quadrupole (RFQ).

Preliminary results are given for the acceleration of the beam by an RFQ, designed for the acceleration of 10 mA of Ta10+ to an energy of 100 keV/u.

Introduction

The demand for high intensity, high charge-state heavy ion beams for HEP experiments has prompted the study of a Laser Ion Source (LIS) at CERN since 1989 [1-3]. In recent publications the creation and extraction of a high charge-state heavy ion beam [2] and the acceleration of an aluminium 9+ and 10+ beam using a four-vane RFQ [3] have been reported.

In 1996 a new LEBT and a new four-rod RFQ designed for the acceleration of heavy ions have been installed. The first results of this device are presented here.

Apparatus

A schematic of the layout of the LIS and pre-accelerator is shown in Fig. 1.

Source

A free running CO2 laser (λ=10.6 μm), produces an output pulse of 30 J. Approximately half the energy is present in the first peak of 50 ns (FWHM).

The beam is focused onto the tantalum target with a spot size of 35 μm (calculated [4]), where the first temporal peak is responsible for the generation of the ions of high charge-states in the hot dense plasma.

The plasma expands through a hole in the mirror and an expansion region to the extraction region. The target chamber and expansion region are isolated from ground and can be held at voltages up to 80 kV.

The extraction system consists of an accel/decel system with 3 plane electrodes with apertures of 30 mm and an extraction gap of 30 mm.

Low Energy Beam Transport and Matching line

The beam is matched to the RFQ using a simple LEBT consisting of two pulsed magnetic solenoids, with effective lengths of 350 mm. A large inner-diameter (120 mm) is used to reduce spherical aberrations. The maximum magnetic field on axis is 1.4 T. The inner diameter of the vacuum chamber is 100 mm.

A profile harp and a Faraday cup between the solenoids are used for beam analysis. Two dipole magnets are included for trajectory correction.

RFQ

The four-rod RFQ [5] is designed to accelerate ions with charge to mass ratios higher than 0.0865 (applicable for tantalum charge-states ≥16+), with up to 60 mA of a mixture of charge states. It operates at a frequency of 101 MHz and accelerates ions from 6.9 to 100 keV/u. The input acceptance is 300 mm.mrad.

Medium Energy Beam Measuring Line

After the RFQ there is a line of measuring equipment including a Faraday cup and beam current transformers. Two quadrupoles allow the full beam current to be transported through a magnetic spectrometer. A phosphor screen is positioned after the spectrometer for measurements of the energy dispersion and charge-state distribution (CSD).
Results

Tantalum Plasma Charge State Distribution

An electrostatic spectrometer has been used to measure the abundance of different charge-states in the un-accelerated plasma which pass through the extraction electrode apertures. Due to the large energy spread of ions in the plasma, ions with the correct energy per charge ratio for the spectrometer exist for many charge-states. As the production time for all ions is less than 1 µs, a time-of-flight (TOF) spectrum can be recorded using a Secondary Electron Multiplier (SEM) tube positioned after the spectrometer (see Fig. 2).

![Graph showing TOF spectrum](image)

Fig. 2. TOF spectrum of the unaccelerated plasma, measured with an electrostatic analyser 2.5 m from the target.

TOF spectra are recorded over a range of different spectrometer voltages and the data are processed to produce a CSD. Fig. 3 shows the CSD of tantalum ions which pass through the 30 mm extraction apertures during the time interval 3-8 µs after the laser pulse (target to extraction distance: 0.9 m). At present no precise secondary electron emission coefficients ($\gamma$) exist for CuBe (the SEM material) for bombardment by high charge-state Ta ions at energies in the range 0.5-10 keV/q. Therefore the processed data (a) after scaling to the total current of 60 mA have been corrected assuming that $\gamma$ is only a function of the ion kinetic energy ($E$) [6], and a function of the potential energy ($V$) [7]. The first qualitative measurements of $\gamma$ suggest the energy range 0.5-10 keV/q lies between the regions (b) and (c).

![Graph showing charge-state distribution](image)

Fig. 3. Charge-state distribution of the unaccelerated plasma. Measured data processed under the assumption that a) the secondary electron emission coefficient ($\gamma$) of CuBe is independent of charge-state and kinetic energy, b) $\gamma$ scales with ion kinetic energy, c) $\gamma$ proportional to charge-state.

The group of lower charge-states (centered around Ta$^{7+}$) can be explained by the reflected laser pulse (reflected from the plasma, to the laser cavity and back to the plasma). This is confirmed by simulations [8].

Extracted Ion Beam

Measurements of the total current, current per charge-state and emittance of the extracted ion beam have been made. The current measured with a Faraday cup placed 24 mm after the ground extraction electrode is shown in Fig. 4.

![Graph showing beam current](image)

Fig. 4. Beam current measured with a 30 mm aperture Faraday cup positioned 24 mm after extraction. High charge-state Ta beam is indicated from 3-8µs after the laser pulse.

During the time window from 3-8 µs after the laser pulse, during which the high charge-state ions are expected, the average current is 64 mA. After this time the beam consists mainly of lower charge-state ions.

The beam emittance was measured using a pepper-pot, phosphor screen and CCD camera arrangement. The CCD camera is gated from 3 - 8 µs to measure only the high charge-state group. A typical reconstructed phase space plot is shown in Fig. 5, where the total combined emittance for all extracted ions in the horizontal plane is 250 mm.mrad. The beam was extracted at 59 kV in order to match the RFQ input energy of 6.9 keV/u for Ta$^{2+}$.

Measurements of the CSD of the high charge-state group after extraction, show a distribution similar to that measured in the plasma.

![Graph showing phase space](image)

Fig. 5. Horizontal phase space plot of a Ta beam measured 79 mm after extraction. The 4 x rms emittance was 250 mm.mrad.
Beam Matching to the RFQ

Before the installation of the RFQ, measurements were made of the beam transported through the LEBT line. The extraction voltage was set to 59 kV to match the most abundant charge-state, Ta\(^{3+}\), to the RFQ input energy.

The total beam current was measured behind an aperture of 6.5 mm using similar focusing conditions to those used for RFQ injection (Fig. 6).

The size of the focal spot was measured at the end of the LEBT with a phosphor screen and CCD camera (Fig. 7). The different focal length for different charge-states leads to a "long" beam waist of the order of 50 mm.

The charge-state distribution in the focal spot was estimated from measurements with the magnetic spectrometer, phosphor screen and CCD camera. Percentages for each state are Ta\(^{9+}\):11%, Ta\(^{10+}\):17%, Ta\(^{11+}\):20%, Ta\(^{12+}\):20%, Ta\(^{13+}\):19%, Ta\(^{14+}\):13%.

![Fig. 6. Beam current (average of 3 shots) measured at the RFQ input plane with a 6.5 mm aperture Faraday cup.](image)

![Fig. 7. a) Image of the beam focal spot on a phosphor screen positioned at the RFQ input plane (recorded using a gated CCD camera) b) Horizontally integrated intensity plot.](image)

Accelerated Beam Current

An output beam current of 2 mA (5 μs average) was measured with a Faraday cup at the RFQ exit (see Fig. 8), containing five charge-states with intensity ratios of Ta18+: 4%, Ta19+: 15%, Ta20+: 39%, Ta21+: 30% and Ta22+: 12%.

The average energy is 97 keV/u for all charge-states and the total energy spread is 5 keV/u for Ta\(^{26+}\).

The transverse emittance has been measured as 22 mm.mrad (4 x rms un-normalised) using the pepper-pot and phosphor screen arrangement.

![Fig. 8. RFQ output beam current (average of 3 shots) measured with a Faraday cup behind the MEBT quadrupoles.](image)

Conclusion

The first results of the CERN laser ion source show 1-2 mA (peak current) in each of 3 charge-states around Ta\(^{3+}\), accelerated to 97 keV/u, within a transverse emittance of 22 mm.mrad (4 x rms). The experimental system consists of a free-running CO₂ laser providing 15 J in the first peak, 59 kV at ion extraction from the plasma, a simple 2 solenoid beam transport and an RFQ designed for high charge-state heavy ions. The optimization of the full ensemble has just begun.

Acknowledgments

The work detailed in this report would not have been possible without the aid of CERN's survey team, RF group, vacuum group, magnet group and mechanical support.

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RF AND CONSTRUCTIONAL ISSUES IN THE RFQ FOR THE CERN LASER ION SOURCE

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Abstract
An expandable RFQ has been designed and built. Its length can be modified in steps to match the different phases of the Laser Ion Source (LIS) study. This paper describes the basic design approach, the field simulations using MAFIA, the establishment of a lumped-element equivalent circuit using PSPICE, model measurements, RF cold measurements and the strategy to trim longitudinal field flatness. Results of RF power tests are also given.

Introduction
This RFQ serves the double purpose as a test item for the ion beam from the experimental laser ion source as well as a reserve item for the operating RFQ in Linac3 that has been designed and built by the laboratory of INFN Legnaro/Italy. This determines the outer dimensions flange-to-flange and also the basic electrode support structure tilted 45 degrees from vertical since a set of "Legnaro" spare electrodes should be usable in the new RFQ.

Mechanical Engineering and Vacuum

Basic Principles. The RFQ (see Fig. 1) is conceived such that it can be lengthened by adding an extension to its extremity. The total length can vary between 2.5 and 3.5 m.

The vacuum tank and the electrode support are independent elements.

The assembly and adjustment of the electrodes on their support are made outside the tank, with the support fixed in three places on a surface table in the same configuration as that foreseen in the tank. The electrodes are then put in place with respect to their references, fixed on the surface table (alignment tolerance ± 0.03 mm/2500 mm).

The sighting line, offset from the beam, is fixed with respect to the entry and exit centre line of the electrodes. This is transferred as a reference to the exterior by two targets and a transverse level. Three alignment jacks allow positioning of the completed assembly.

Vacuum tank. The vacuum tank is made from a mild steel "thick cylinder", allowing the machining from solid of the flat sealing surfaces for the metal toroidal joints.

The tank is electrolytically copper plated. This operation is facilitated by use of one material only for the tank, along with its simple geometry.

Electrode Support. The electrode support comprising 13 cells is made of mild steel. Its module of elasticity is well known and its thermal conductivity is relatively good. The assembly takes the form of a ladder, where the rungs serve as supports for the electrodes.

All machining is done before the final assembly is completed by MIG welding. This type of welding limits deformation to the order of 0.5 mm/2500 mm. The welds are vacuum tested to guarantee good copper plating. The finished support is stabilised by thermal treatment.

The copper plating of the support is performed in several steps. A first copper layer of 10 μm is applied globally followed by tinning of the faces that will receive the cooling circuit. The cooling circuit is then soft soldered to the ladder. A second copper plating of 50 μm (certain precision surfaces being protected) is then applied.

Water cooling reduces the forces induced in operation between the electrode and its supports due to differential thermal expansion.

The ladder assembly is fixed inside the tank on 3 points reproducing the support conditions that have served outside for adjusting the electrodes.

Electrodes. The electrodes are drawn from square copper bars OFE 4/4 (hard) The transverse profile is obtained by planing, the longitudinal modulation by a C.N.C. machine and profiled milling cutters.

The electrodes are fixed to the support with intermediate copper shims (to guarantee good heat transfer) and stainless steel keys. One central dowel pin per electrode assures the longitudinal position. This system allows one to absorb up to ± 2 mm of positioning tolerance.

The contact between electrodes and their support is achieved with the aid of commercial RF finger contacts attached to a flexible copper element permitting the absorption of possible deformations. They do not interfere
with the positioning of the electrodes and are fixed both sides with partially copper plated stainless steel screws.

The contact between the ladder and the tank is made using commercial RF contacts mounted on a retractable assembly permitting the introduction (in a vertical position) of the ladder with its assembled electrodes, into the tank.

Vacuum. The nominal pressure of the system is $10^{-4}$torr. The RFQ is equipped with a 240 l/s turbo molecular pump for the pre pumping and two 400 l/s ion pumps.

All the joints in direct contact with the vacuum tank are aluminium coated toroidal joints. $6 \times 10^4$ torr have been reached with particle source disconnected.

Electromagnetic Field Computations

Finite element representation of the resonators. The cylindrical RFQ tank consists of 13 cells. A single cell of 2 * 96.1 mm length = 2500mm/13 has been modelled with program MAFIA (Fig. 2) for the geometry of existing RFQ electrodes (compatibility). The radius has been varied until the frequency of 101.28 MHz was obtained for $r=281$mm.

![Fig. 2. Single RFQ-cell geometry representation.](image)

One can see how the 4 quadrupole electrodes or “vanes” which focus the beam are supported by stems with holes. These are the rungs of the ladder mentioned earlier. The 4 vanes pass through all holes but only 2 are fixed to the upstream stem and 2 to the downstream stem producing a 72kV quadrupole field. Subsequent holes are turned ±45° in order to make their inductances equal. This destroys all symmetries in x, y and z and increases computing time because the full cell of 61*55*14= 46970 mesh points has to be computed. Assemblies of 13 cells have been modelled. MAFIA's choice of elements is limited: “bricks” (rectangular parallelepipeds) and only on boundaries, “prisms” (diagonally halved bricks). Moreover all bricks are aligned in x,y,z-planes. Since one needs small spacing for the vanes (3.5mm distance from axis) the latter limitation leads also to very thin, long bricks on the periphery where less resolution is needed. One easily exceeds the safe 1:10 limit ratio of rectangle sides. This is why modelling of heavy ion RFQ's with their large, low- frequency cavities and closely spaced vanes is difficult with this program.

As the electrode capacity (and frequency) is sensitive to meshing it has been computed independently with finer meshes in MAFIA's static solver, MAGNET and POISSON. Then the coarser RFQ- meshes have been readjusted to yield the same precise capacity values.

Higher modes have been predicted at 268 and 272 MHz.

Many coupled cells and end effects. After establishment of the geometry of the fundamental cell for an infinitely long RFQ, finite element models with 1 - 13 coupled cells and closed end covers have been computed. Figure 3 illustrates that 1 cell with end covers resonates at a higher frequency than 2, 3, 6, 13 ... $\infty$ cells and $f$ [MHz] is higher for odd n than even n (explainable by field plots).

![Fig. 3. Frequencies of RFQ models with n cells.](image)

These computations have been confirmed by measurements on a model and equivalent- circuit analysis with PSPICE.

The program predicted vane voltage variations between centre and ends of a cell, particularly in end cells:

![Fig. 4. Voltage variations along 13-cell RFQ.](image)

Figure 4 shows also that overall variations along a 13-cell RFQ (which were large initially) can be made as small as variations within cells by slight geometry changes near the end covers which match this slow wave structure.

RF aspects

3-cell model. A short full-scale model equipped with unmodulated vanes was constructed. The possibility to implement a 1, 2 or 3 cell configuration allowed to study different combinations of a regular cell and end cells, and to separate the impact of different perturbations.
Errors due to electrode misalignment had to be taken into account. Theoretical studies had shown that the *sum* of the four interelectrode distances determines to first order the total vane capacitance hence the resonant frequency. This dependence was experimentally verified and then used to correct the raw frequency measurements. The measured parameters for 1, 2 and 3 cells laid the basis for a PSPICE equivalent circuit model of the full RFQ.

A rapid way of measuring r/Q was found in passing. It consists of measuring the change in admittance ΔY of a vane as a function of frequency offset Δf by direct connection of a network analyser: r/Q = (ΔY/Δf)*2/(2/fresent). This method is only valid for short geometries where feeding a single point does not perturb the field pattern.

**PSPICE simulation.** Figure 5 shows the equivalent circuit for inner and end cells. The vane pairs are represented by the usual LC low-pass ladder whose parameters CV,2 and LV,2 can be derived from the known electrode capacitance. The surrounding tank structure and the electrode supports for end and inner cells are modelled by the inductances LCAV, LEXT and LSTEM, the window and end cell stray capacitances by CWIN and CSTEM respectively.

![Diagram](image)

**Fig. 5.** PSPICE equivalent circuit.

All circuit parameters are fitted on the basis of the model measurements. An essential ingredient is the coupling factor K_{amb} between the two supports in a cell to take the magnetic field perturbations in the asymmetric end cells into account.

**Low power RF measurements.** The RF properties of the RFQ were measured in different phases of completion. The Q-factor Q= 4230 of the fully equipped RFQ is only about 35.6% of the theoretical value; this can be attributed to less than perfect copper plating and ill-directed surface roughness due to machining perpendicular to the RF current path.

The vane voltage developed for a given RF power level was measured by a calibrated capacitative pickup to determine directly the r/Q parameter. Its value of r/Q=3.64 Ohm corresponds very well to theoretical predictions. The diagnostic probes were adjusted and calibrated accordingly.

The longitudinal field pattern was measured by a bead pulled longitudinally through the RFQ and supported by the electrodes themselves. The initial pattern was strongly tilted (18.6%) as well as concave (13%) in addition to the unavoidable variation within a cell (1%).

**Field correction strategy.** Provisions had been made to mount either “flaps” between the stems and electrodes or to add “plates” on the girder. The former allow to decrease, the latter to increase the local resonant frequency.

The PSPICE model proved to be a very convenient and rapid means to simulate arbitrary capacitive or inductive perturbations. It was not possible to establish a 13*13 Jacobian matrix to relate field errors linearly to cell perturbations because of the simultaneous frequency changes involved. However, qualitative rules for the effects of perturbations on field pattern were found:

- In uniform structures the *difference* in end cell loading determines the tilt. Capacitive loading increases the field at the respective end, in the present case by 3.7% per pF.
- In uniform structures the *sum* of end cell loading determines the field curvature and the resonance frequency. Capacitive loading leads to a concave, inductive loading to a convex pattern. The respective factors are here 0.9% per pF for the bump and 120 kHz per pF for the frequency.
- Arbitrarily perturbed structures can be corrected by first fitting the field pattern to a polynomial of degree 2, then placing corrective elements iteratively at spots of maximum deviation to get the equivalent of a uniform structure. Remaining bump and tilt are finally removed as above.

Here the field pattern was corrected to 2.5% bump and zero tilt by placing 16mm plates in the upstream and 4mm plates downstream end cells. The resonant frequency was too high since the influence of bulkier RF contacts had been underestimated. PSPICE runs show that the frequency can be brought to nominal with less than 0.6% field distortion by placing four sets of “flaps” in stems 2/3, 4/5, 9/10 and 11/12. Since the RFQ frequency is not important in this application that correction was postponed.

**High power test.** Nominal field level of 72.1 kV (~ 1.9 Kilpatrick) was reached after one weekend of conditioning. The RFQ finally held 115% field with virtually no breakdowns at a vacuum of 2.5 *10^-7 torr (less than ideal due to the connected ion source). Operation at 7% and 28% field levels for proton and helium beam tests was perfectly possible in closed-loop operation where the multipactor level was broke through at the beginning of each pulse. The beam tests proper are reported elsewhere [1].

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DESIGN AND BEAM TESTS OF AN RFQ TO ACCELERATE A LEAD ION BEAM FROM A LASER ION SOURCE

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Abstract

A Radio Frequency Quadrupole (RFQ) for acceleration of a 10 mA lead 18+ ion beam from 6.9 keV/u to 100 keV/u has been designed, built and tested in the framework of the CERN Laser Ion Source (LIS) study. The challenge of the RFQ design was to deal with a lead ion beam that includes about 10 charge states with an overall current of some 100 mA. A new RFQ design, intermediate between the two standard high-intensity and low-intensity designs, has been applied in order to have a compact structure giving small longitudinal emittance and high transmission.

The transport and matching line from the source to the RFQ is made of two solenoids. The unwanted charge states are not filtered and will enter the RFQ mis-matched. In order to test the RFQ performance proper it was decided to operate it with an equivalent mono-species proton beam during the first stage of the commissioning.

The design criteria for this intermediate current RFQ, the problems involved in dealing with a mixture of different charge states, as well as the results of the first test with an equivalent proton beam are presented in this paper.

RFQ Design

The general criteria for designing the RFQ were a high transmission (>90%) and good output beam quality: in particular the r.m.s. longitudinal emittance should not exceed the value of 18 deg keV/u at 100 MHz. Other limitations were given by the length (fixed to 250 cm) and the output energy, which had to be in the range of 100 keV/u to match the downstream analysing magnet.

The beam coming from the laser ion source is composed of a mixture of about ten charge states [1] of varying energies. The overall current was estimated to be 100 mA, of which 10 mA represent the design particle. The unwanted charge states are not filtered out prior to entering the RFQ and will contribute considerably to the degradation of the beam quality, even considering that the beam will eventually be partially filtered by the RFQ itself. The challenge, then, was to design a machine which could stand a rather high beam current and preserve the beam quality but without reaching prohibitive lengths. For RFQ design, two standard "recipes" are normally used: the "high current" design [2] and the "low current" design [3]. However, neither of these approaches could be successfully applied to the current problem: the first would result in an excessively long structure and the latter would give poor beam quality and low transmission rates. The solution which proved to be successful was to treat the beam as low-current when it is continuous and as high-current as soon as the longitudinal current density starts to increase. This strategy gave the rough design for the intermediate current RFQ; subsequent modifications were made on the low energy section to meet the requirement of an output r.m.s. longitudinal emittance inferior to 18 deg keV/u at 100 MHz. Three techniques have been tried in our case for limiting the longitudinal emittance from the start: 1) to have a very long shaper; 2) to prebunch the beam with an independent RF cavity before injection in the RFQ; and 3) to keep the synchronous phase at -90 deg, while increasing the accelerating component for about 20 cm at the low energy end. This last method is equivalent to having a series of about 30 bunchers with a voltage adiabatically increasing. This was also the selected approach as it provided a resulting longitudinal emittance remarkably small with respect to the others. In Table 1 the RFQ characteristics are summarised and in Fig.1 the main RFQ parameters are represented as a function of length. In Fig. 2 the evolution of the beam emittance for a nominal matched beam is reported.

Table 1

<table>
<thead>
<tr>
<th>RFQ Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Ion: Charge 18+, Mass 208 a.m.u</td>
</tr>
<tr>
<td>Frequency: 101.28 MHz</td>
</tr>
<tr>
<td>Vane voltage: 71 kV (1.8 Kilp)</td>
</tr>
<tr>
<td>Power losses (at 90 kΩ-m): 70 kW</td>
</tr>
<tr>
<td>Maximum electric field: 27 MV/m</td>
</tr>
<tr>
<td>Vane Length: 253.18 cm</td>
</tr>
<tr>
<td>Number of cells: 287</td>
</tr>
<tr>
<td>Minimum bore radius: 0.2 cm</td>
</tr>
<tr>
<td>Modulation factor (max): 2.1</td>
</tr>
<tr>
<td>Transmission: 94%</td>
</tr>
<tr>
<td>Current: 10 mA</td>
</tr>
<tr>
<td>Input energy: 6.9 keV/u (extrac. volt. 80 kV)</td>
</tr>
<tr>
<td>Output energy: 100 keV/u</td>
</tr>
<tr>
<td>Input acceptance: 300π mm mrad (tot.unnorm)</td>
</tr>
<tr>
<td>Transv. emittance growth: 0</td>
</tr>
<tr>
<td>Output long. emittance: 12π deg keV/u</td>
</tr>
</tbody>
</table>
Fig. 1. Variation of RFQ aperture, modulation and phase vs. length. Phase and modulation are tapered down in the last section in order to limit the output energy to 100 keV/u for the first phase of the experiment.

Fig. 2 Transverse and longitudinal emittance evolution for a mono-species beam.

Owing to the 4-rod structure the RF field pattern is different in the horizontal and vertical plane [4]. Longitudinally the beam undergoes a voltage difference on axis equal to half the operating voltage. The input region has been modelled with MAFIA and the beam trajectories have been integrated in the MAFIA calculated field in order to estimate the effect on the beam dynamics. The effect on the transverse plane (asymmetry between the x and y focusing field component in the RMS) turns out to be negligible in our case, and the 1-2% energy spread resulting from the non-zero longitudinal field does not have any effect on the final beam quality.

Due to the complexity and the uncertainties of the beam parameters at the output of the LIS, it was decided to test the performance of the RFQ itself with an equivalent proton beam. The equivalent proton beam has an energy equal to the energy per nucleon of the lead ion beam and a current scaled like the ratio of charge to mass (11.56 in our case). The RFQ is run at a voltage equally scaled like the ratio charge to mass.

Measurements on the Pb Equivalent Proton Beam

The source used for the equivalent proton beam test is a duoplasmatron source designed to produce a 90 keV 250 mA proton beam [5]. As the beam required for the test is a 6.9 keV 20 mA proton beam the source was operated in a regime very far from that of standard operations, giving rise to some instabilities as well as a reduced proton yield. More specifically in normal operation protons represent 70% of the total current, composed also of $H^+_2$ and $H^+_3$; in the low energy regime the protons are only 45%. Operating the source with Helium 1+ provided a cleaner beam with only few percent of unwanted particles.

Before testing the performance of the RFQ in the experimental set-up as in Fig. 3, various beam parameters were measured at the position corresponding to the RFQ input plane and the solenoid settings giving the match to the RFQ were found.

Fig. 3 The experimental set-up consisting of a proton source, two solenoids, the RFQ, and a measurement line. Dimensions are in mm.

As there was margin to increase the RFQ power from the nominal level, several tests in different equivalent "rescaled" conditions were performed. These provided insight to the RFQ dynamics in areas that could not be explored before. The configurations tested are reported in Table 2; the values underlined are the "nominal" values for that configuration (i.e. the value that corresponds to the design operation for lead 18+).

<table>
<thead>
<tr>
<th>Configuration Tested</th>
<th>Charge/mass</th>
<th>Extraction Voltage (kV)</th>
<th>RFQ Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton 1/1</td>
<td>7.14,21</td>
<td>6.2 to 19</td>
<td></td>
</tr>
<tr>
<td>$H^+_2$ 1/2</td>
<td>7.14,21</td>
<td>6.2 to 19, 12.4</td>
<td></td>
</tr>
<tr>
<td>$H^+_3$ 1/3</td>
<td>7.14,21</td>
<td>6.2 to 19</td>
<td></td>
</tr>
<tr>
<td>Helium 1/4</td>
<td>28</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>
What is expected is that each configuration when operated with the nominal settings gives the same output beam. The measuring line shown in Fig. 3 - two quads, a beam transformer, an emittance measurement device and a spectrometer - allows the measurement of the RFQ transmission, of the output transverse emittances and of the output energy spread. The measured performances of the RFQ for the nominal settings are summarised and compared to the calculated ones in Table 3, Fig. 4 and Fig. 5.

Table 3

<table>
<thead>
<tr>
<th></th>
<th>calculated</th>
<th>measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>transmission</td>
<td>94%</td>
<td>88%</td>
</tr>
<tr>
<td>energy (keV/u)</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td>rms, un, x-emitt (mm mrad)</td>
<td>7.9</td>
<td>7.6</td>
</tr>
<tr>
<td>rms, un, y-emitt (mm mrad)</td>
<td>7.9</td>
<td>8.0</td>
</tr>
<tr>
<td>total energy spread (keV/u)</td>
<td>5.6</td>
<td>5.1</td>
</tr>
</tbody>
</table>

The difference between the calculated and measured transmission can be explained by a non-perfect matching due to the solenoid field limit.

- transmission and energy spread vs. rf voltage: the output current grows with rf voltage till the nominal level is reached, then it stays constant till the rf voltage is about 3 times the nominal voltage. Above this value the transmission drops very rapidly to zero as the transverse focusing becomes excessively high and causes cross-over. The output energy spread is at a minimum for the nominal voltage and grows for higher-than-nominal voltage due to longitudinal mis-match.

- transmission versus input energy: when the extraction voltage was set for protons (7 kV) for any RF level the other species (H⁺ and H3⁺) were not accelerated through the RFQ. However, when the extraction voltage was set to the nominal values for H⁺ or H3⁺, protons were always transmitted with a rate depending on the rf level. This result shows that, as calculated, the energy acceptance of the RFQ is quite large due to the very adiabatic design in the first part of the machine. In fact, particles which enter the RFQ outside the longitudinal stability region can be reabsorbed in the stable bucket after the bunching process is completed.

Conclusion

An RFQ for acceleration of a 300pi mm mrad, 18+ lead i-1 beam from 6.9 keV/u to 100 keV/u with high transmission and excellent output beam quality has been designed and constructed at CERN in the framework of the LIS study. The first beam test with an equivalent proton beam confirmed the theoretical prediction of transmission and output beam quality.

Acknowledgements

We feel very indebted to W. Pirkl for his support and guidance and to F. Neddam for the many beam measurements he has performed. We also thank H. Charmot, C.E. Hill and J.P. Romero for their interest and support.

References

CONCEPTUAL DESIGN OF BEAM DUMP FOR HIGH POWER ELECTRON BEAM

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Abstract

A high power CW (Continuous Wave) electron linac has been developed at PNC and its injector section has been completed in 1996. This paper presents the conceptual design of beam dump for a high power low energy beam (200 kW of 10 MeV electron). It has a Ring and Disk structure. The thermal analysis, stress analysis showed that 200 kW electron beam could be securely stopped in the beam dump. The temperature rise at highest position was estimated to be 343 degree.

Introduction

Design and construction of a high power CW electron linac to study feasibility of nuclear waste transmutation [1] was started in 1989 at PNC. The injector has been completed and started its operation at 3.5 MeV beam energy in summer 1996 and the whole facility is planned to be commissioned at 1997. Main specification of the accelerator is shown in Table 1.

Table 1

Main specification of the electron linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>10 MeV</td>
</tr>
<tr>
<td>Maximum Beam Current</td>
<td>100 mA</td>
</tr>
<tr>
<td>Average Beam Current</td>
<td>20 mA</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>100 ms ~ 4 ms</td>
</tr>
<tr>
<td>Pulse Repetition</td>
<td>0.1 Hz ~ 50 Hz</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>0.001 ~ 20%</td>
</tr>
<tr>
<td>Norm. Emittance</td>
<td>50 π mm mrad *</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>0.5%*</td>
</tr>
</tbody>
</table>

* estimated value by simulation

As the beam is a considerably high power and of low energy electron, the average power density of heat generation due to the energy deposition is quite large, so that it is of extreme importance to realize the beam dump to be secure by removing the heat very efficiently. At the same time, radiation shielding of the beam dump is also of the major concern.

Design

The conceptual design of the beam dump is based on the following design criteria:

1) to disperse the beam by magnet in front of the beam entry
2) to stop the beam part by part in spatially separated blocks
3) to minimize the induction of radioactivity

The first criteria is for making the power density smaller by defocusing/spreading the beam. It is also assuring to avoid mishaps of the pin point beam hitting the component. The second criteria makes also a reduction of power deposition in a small region of the beam dump. The third criteria eliminates the use of water to stop the beam. Liquid target does necessarily increase the total inventory of the radioactive materials.

The concept of the present design is, as shown in Figure 1, Ring and Disk (RD) system. The part where energy is deposited consists of 17 rings and 5 disks (thickness of 5 cm). Each plate is made from OFHC (Oxygen Free High-purity Copper). All the rings have different inside diameters (the beam runs inside this ring). The frontmost ring has the inside diameter of 19.6 cm and other rings have smaller diameter with increment of 1.2 cm from upstream to downstream.

Fig. 1. Beam Dump in cross-section.

The beam enters into the cylindrical vessel through a dispersion magnet which is located 2 m front of rings. Since the beam has spatially a Gaussian profile, the inner front edges of rings stop the narrow annular lobe of the beam, from outside as going to the backward. Finally the beam is stopped by the disk set at the backend of the block. Figure 2 is a front view of the inner front edges.

These rings and disks are formed into 4 modular units. Each module is electrically insulated from each other in order to measure the beam current deposited on them. It can be replaced/exchanged as a unit. In a module a cooling water flows in series from ring to ring. In order to reduce radiolysis of cooling water and to eliminate the vacuum window between the beam dump (target) and the accelerating tube, cooling water is not exposed to direct incident electron beam.
Thermal and Stress Analysis

Several computer codes were used in order to estimate the temperature rise and the stress of rings with full beam power. This calculation assumed that the transverse beam intensity is Gaussian distribution and the electron is injected to the target block with the angle of incidence varied between 0° and 3°.

Firstly, the power density in the target block is calculated using the EGS4 [2] code. The EGS4 code performs Monte Carlo simulations of the radiation transport of electrons, positrons and photons in any materials. Then we applied the PRESTA algorithm (Parameter Reduced Electron-Step Transport Algorithm) [3], which was developed by Bielaw and Rogers to improve the electron transport in EGS4 in the low-energy region. The maximum power density was estimated to be 2.2 kW/cm².

Using the power densities from the EGS4, we proceeded to the thermal analysis using the finite element method code ANSYS [4]. Examples of the results of the analysis are shown in Figures 5 and 6. They are cross-sectional views of a ring in which stress is estimated to become maximum. The results predicted that the maximum temperature rise in the ring is at the inner front edge of ring and is 343 degree, and peak stress of 2.3 kg/mm².

The problem of connecting between the beam dump and the accelerator (the pressure difference between 1 x 10⁻³ torr and 1 x 10⁻⁷ torr in the accelerating tube) was solved by using a differential pumping stations and a low conductance beam transport tube.
Since the Von Mises stress exceeds the yield stress of copper (0.63 kg/mm²), a plastic deformation might be induced over a major portion of the ring. As it is considered that the thermal stress cracking could be generated by this deformation, we design the beam dump such a deformed disk is easily replaced with a new one.

Photon Production

The energy distribution of photons (γ-rays) generated by incident electrons in the target block are studied using the EGS4 code. Figure 7 shows the relationship between its energy E and the scattering angle θ of the photon, where θ is the angle from the incident direction of electron beam.

Electrons are particularly susceptible to a large angle deflection by scattering from nuclei and they are backscattered out of the target block. In this context, Figure 7 shows the concentration of backscattered photons in the direction of 180°. A preliminary estimate of the absorbed dose rate in the backward direction (180°) at 1 m is 9000 Gy/h with full beam power.

Conclusion

A beam dump at PNC, employing the Ring & Disk system, has been designed for the high power low energy beam (200 kW of 10 MeV electron). The beam could be stopped at the inner edge of the rings which are cooled by water.

The maximum power density in the target block is 2.2 kW/cm² with full beam power assuming Gaussian distribution of the transverse beam intensity. The maximum temperature rise in the ring (at the inner front edge of ring) is estimated to be 343 degree.

Fig. 7. Correlation between the photon energy E and the scattering angle θ.

References

ANALYSIS OF WAKE FIELDS ON TWRR ACCELERATOR STRUCTURE IN PNC

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Abstract

A high power CW (Continuous Wave) electron linac has been developed so as to accelerate 10 MeV–100 mA beam, and its injector section has been completed in 1996 at PNC. It is essential for higher beam acceleration to reduce the beam instability caused by the space charge effect and the beam-cavity interaction. Both are important for PNC linac, because an accelerator with a high beam loading generally has a low accelerating gradient.

In this paper, beam induced fields for the regular section with PNC accelerator structure are examined by means of a numerical wake field analysis. The BBU start current is estimated in the relationship of the wake potential to space charge force in injector section.

Introduction

The development of a high current electron accelerator is being carried out to target to treat high level nuclear wastes via photo-nuclear reaction which is selective and clean more than the spallation reaction. The elementary design and the experiments [1–3] for the high current linac are in progress using L-band RF source which is effective to a high beam loading. The traveling wave accelerator with an RF feedback called Traveling Wave Resonant Ring (TWRR) is employed to get higher energy transfer with a shorter accelerator length, the reasonable cost, and the ease of the maintenance. The accelerator structure has a constant gradient disk loaded type and accelerate 80 pC charge per bunch for 100 mA average current. The accelerating gain from PNC structure is 1.3 MeV which is so low compared with S-band linac that the effect on the beam such as a microwave instability may cause undesirable beam broadening in longitudinal and transverse direction at lower than usual beam current.

In the regular section which beam energy is over than 3 MeV in PNC linac, the beam instability originates from the interaction with the accelerator structure. The analysis for this interaction is recently developed by means of a wake field approach for both circular and linear accelerators. Monopole and dipole components of wake field a nd related loss factors were calculated by ABCI [4] and MAFIA [5] T3 in order to have the potential and voltage compared with the accelerating condition. Finally, the BBU start current was estimated by the scaling of the wake potential with the voltage and the space charge parameter of the behavior in the envelope equations.

Definition and Calculation

When charged particle passes through a structure with the speed of light c, it produces the electromagnetic field. The wake fields \( W_0 \) and \( W_\perp \) [6, 7] both for monopole and dipole components are described as

\[
W_0 = -\frac{1}{Q} \int dz E_z (r, \theta, z, (z + s)/c) ,
\]

\[
W_\perp = -\frac{1}{Q} \int dz (E_\perp + c \times B)(r, \theta, z, (z + s)/c)
\]

where \( E_z, E_\perp \), and \( B \) are the electric and magnetic fields produced inside the cavity, and \( Q \) and \( s \) are the bunch current and the bunch coordinate, respectively. The coordinate inside the cavity is represented in cylindrical in this case. The associated loss factors \( k_0 \) and the induced voltage \( \Delta V \) are presented as

\[
k_0 = -\frac{1}{Q} \int ds \lambda(s) V_z(s) ,
\]

\[
k_\perp = -\frac{1}{Q} \int ds \lambda(s) V_\perp(s) ,
\]

\[
\Delta V = 2Q k_0
\]

where \( \lambda \) is a bunch distribution. \( V_{z,\perp} \) is the wake voltage derived by the total beam bunch and the wake potential for the longitudinal and transverse in each. These quantities except the induced voltage are ready to several codes for numerical calculation.

The actual parameters for the calculation used for the beam and the accelerator structure is summarized in Table 1. The typical dimensions of the accelerator structure used are \( a = 50 \), \( b = 90 \), \( t = 8 \) and \( D = 24 \) mm, which are exactly or approximately equal to the actual structure dimensions for PNC linac. The beam bunch shape is assumed filamentary and gaussian shape in the longitudinal direction. Numerical calculation was done mainly by ABCI because of the less demand of cpu time, while MAFIA was used for 3-dimensional structures which is not available for ABCI. In the case of off-centered beam, MAFIA is suited because of the symmetry free input for the beam parameter.

Monopole and dipole component were estimated to examine the dependence of the bunch shape, the cell distance and cell shape distance.

Characteristics of Wake Fields for PNC linac

The analysis was carried out for the cases of a single cavities and the accelerator structure consists of many cells in order to make the effects in PNC linac clear.
Table 1 Parameters of wake field analysis

<table>
<thead>
<tr>
<th>Iris (a)</th>
<th>90 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boa (b)</td>
<td>50 (mm)</td>
</tr>
<tr>
<td>Disk thickness (t)</td>
<td>8</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>0.3 - 200 (mm)</td>
</tr>
<tr>
<td>Periodic distance(D)</td>
<td>24 - 64 (mm)</td>
</tr>
<tr>
<td>Charge of single bunch (Q)</td>
<td>80 (pC)</td>
</tr>
<tr>
<td>Bunch length</td>
<td>0.3 - 200 (mm)</td>
</tr>
<tr>
<td>Beam displacement</td>
<td>0 - 20 (mm)</td>
</tr>
</tbody>
</table>

Case of Single cavity

In the case of 2.5 mm bunch seen in Fig. 1, there exists one down warding swing which is essentially only a spike in this situation. This picture is magnified for an only shot to display the potential on the beam bunch. Figure 1 has the abscissas which is presented by volt. The gradient of the curve has a down swing at first which means the gradient of the wake field is negative, which can cause to have an attractive force on particles in the right-shoulder in the bunch. The bias is changed around 10 cm bunch length. The wake potential for 10 cm and 1 cm are 10 V and 50 V in each for each 80 pC of the single bunch. The voltages are small enough to consider the stability for PNC linac.

![Fig. 1 Wake voltage from single cavity.](image)

The analysis of the potential dependence for an off-cantered beam shows that there is basically only a spike both in the longitudinal and transverse wake fields. But MAFIA calculation may neglect calculation of higher frequency area, because of lack of cpu time. This picture notices also that the beam bunch gets an attractive force for the longitudinal wake field at first and a repulsive force for the transverse. The shapes of the potential are the same but the amplitudes are different. The loss factor normalized to a single bunch current and an induced transverse voltage is summarized in Table 2. The deflection voltage for 1 cm off-centered filamentary beam with bunch length of 0.3 cm is almost -200 V which corresponds to 6 KV/m in the beam pipe. This potential is not so strong compared with the potentials in the beam pipe in present colliders like SLC and designed value for SSC. Total loss of a wider beam is reduced for transverse case, while the factor is enhanced for the longitudinal. The energy emission is clearly mainly by longitudinal process. Effectively there is no significance for such a small energy loss into cavity for PNC linac.

Table 2 Loss factor and induced voltage in a single bunch for beam displacement.

<table>
<thead>
<tr>
<th>Displacement (cm)</th>
<th>Loss factor* (V)***</th>
<th>Induced voltage** (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ = 1 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>-17.4</td>
<td>112.0</td>
</tr>
<tr>
<td>1.0</td>
<td>-61.02</td>
<td>10.0</td>
</tr>
<tr>
<td>2.0</td>
<td>-243.8</td>
<td>420.0</td>
</tr>
<tr>
<td>3.0</td>
<td>-548.4</td>
<td>630.0</td>
</tr>
<tr>
<td>σ = 0.3 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>-56.8</td>
<td>89.9</td>
</tr>
<tr>
<td>1.0</td>
<td>-199.9</td>
<td>168.8</td>
</tr>
<tr>
<td>2.0</td>
<td>-798.0</td>
<td>338.9</td>
</tr>
<tr>
<td>3.0</td>
<td>-1792.5</td>
<td>511.0</td>
</tr>
</tbody>
</table>

* Longitudinal.
** Transverse.
*** Normalized to a single bunch current.

Case of Accelerator structure for PNC

The examples of wake potentials and the impedances are pictured in Fig. 2 for the longitudinal and transverse wake field resulted from changing the cell displacement. The effect is totally capacitive because of actual bunch length and the speed of an electron beam. The patterns of the potential change very little in different cell numbers. This is caused by that Fourier component of the wake field has stronger fundamental than high harmonics, which can be travel inside the accelerator guide. This seems plausible because the impedance spectrum has a strong peak around 1.25 GHz which mode is 2π/3. The dependence of Fourier component for the bunch length between 0.3 - 1.0 cm is nearly constant. The strength of the longitudinal wake potential is basically smaller than the gradient from RF in monopole case. In the dipole case, it gets larger, but still is coherent with bunching effect as mentioned in single cavity case. It is notable from general analysis that in the case of 3.3 - 10 cm bunch length in which the bunch length is nearly equal to the depth of the cavity, there is strong resonance which is chanced by the accelerator structure. It is seen in the impedance calculation that the resonance of wake field is build by 1.9 GHz RF in the transverse wake potential.

From a numerical evaluation, the transverse spike amounts to ~270 V/pC, which correspond to ~2.2 kV per bunch. This value is smaller than 100 kV order which appears in modern colliders. Qualitatively, just like a theory of a electron synchrotron, the tune shift by space charge is also applicable to a linac. In the scaling the space charge parameter ε in the envelope equation from the value of modern colliders to one for PNC linac, the wake transverse voltage is 100 times higher than the voltage from 0.1 A beam. However, the space charge parameter for the wake voltage for 1 cm radius beam is 10^{-15} and still 10^{-2} smaller than beam defocusing value emerged in
colliders. The margin from 0.1 A is order of one hundred. Therefore, from above comparison, BBU starting current is
assumed around 5 A for PNC linac.

Fig. 2 Wake potential from PNC accelerator structure.

**Summary and Conclusion**

The longitudinal wake field has one down swing followed by many smaller oscillation in the beam condition of PNC linac. It may assist phase stability if the attractive force and repulsive wake can be controlled so as to synchronize with RF bucket. Transverse wake field is 100 times higher than the space charge force but still considerably lower than the wake field of present linear colliders. The wake field in the accelerator guide for PNC linac is formed from the coherent sum of single cells. The longitudinal wake has the same period as RF frequency. The dipole component has ~2.2 KV, which is the highest potential of all transverse field. The transverse wake potential in PNC structure is essentially not so high that BBU by the transverse component is expected not to start up to 5 A.

There is a possibility that the longitudinal instability comes first because of phase instability. It is important to observe the bunch lengthening which is common phenomena called microwave instability known circular accelerators. The accumulation of wake field should be estimated for more accurate estimates for the BBU for TWRR. It is important to analyze an overlap integral of higher frequency from the dispersion relation in TWRR which may have a resonance.

**References**

RELATIVISTIC KLYSTRON TWO-BEAM ACCELERATOR STUDIES AT THE RTA TEST FACILITY*

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Abstract

A prototype rf power source based on the Relativistic Klystron Two-Beam Accelerator (RK-TBA) concept is being constructed at the Lawrence Berkeley National Laboratory to study physics, engineering, and costing issues. The prototype, called the RTA, is described and compared to a full scale design appropriate for driving the Next Linear Collider (NLC). Specific details of the induction core test and pulsed power system are presented. Details of the 1-MeV, 1.2-kA induction gun currently under construction are described.

Introduction

For several years a Lawrence Berkeley National Laboratory (LBNL) and Lawrence Livermore National Laboratory (LLNL) collaboration has studied rf power sources based on the RK-TBA concept [1]. This effort has included both experiments [2] and theoretical studies. A preliminary design study for a rf power source using the RK-TBA concept suitable for an rf power source upgrade of the NLC collider design (TBNLC) has been published [3]. The design specifically addressed issues related to cost, efficiency, and technical issues. For a 1.5-TeV center-of-mass energy design, the rf power source is comprised of 76 subunits, each about 340 m in length with 150 extraction structures generating 360 MW per structure. Estimated conversion efficiency of wall plug energy to rf energy for this source could be greater than 40%. Theory and simulations showed acceptable drive beam stability through the relativistic klystron, and no insurmountable technological issues were uncovered.

We have established the RTA test facility [4] at LBNL to verify the analysis used in the design study. The principle effort is constructing a rf power source prototype where all major components of the TBNLC rf power source will be tested. The different sections of the RTA are described in Table 1. Due to fiscal constraints, the RTA will have only 8 rf extraction structures. Table 2 is a comparison between the pertinent parameters for TBNLC and the RTA. The pulsed power system and induction cells in the extraction section will be similar for both machines, allowing a demonstration of the wall-plug power to drive beam power conversion efficiency and establishing a basis for costing of the components.

*The work was performed under the auspices of the U.S. Department of Energy by LLNL under contract W-7405-ENG-48, by LBNL under contract AC03-76SF00098, and by FAR under SBIR grant FG03-96ER82179.

Table 1

<table>
<thead>
<tr>
<th>Section</th>
<th>Beam energy (MeV)</th>
<th>Current (kA)</th>
<th>RF current (kA)</th>
<th>Section length (m)</th>
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<tr>
<td>Electron gun</td>
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<td>3</td>
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<tr>
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<td>1.2</td>
<td>0</td>
<td>8</td>
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<td>1</td>
</tr>
<tr>
<td>Adiabatic compressor</td>
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<td>0.6</td>
<td>1.1</td>
<td>4</td>
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<tr>
<td>Diagnostic section</td>
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<td>-</td>
<td>-</td>
<td>2</td>
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</table>

† Beam parameters at the end of the section.

Table 2

<table>
<thead>
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<th>Parameter</th>
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<th>TBNLC</th>
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<tbody>
<tr>
<td>Pulse duration</td>
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<td>200 ns</td>
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<tr>
<td>Flat-top rise time</td>
<td>100 ns</td>
<td>100 ns</td>
</tr>
<tr>
<td>Current</td>
<td></td>
<td></td>
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<tr>
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<td>1.2 kA</td>
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<td>Extr. section (dc)</td>
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<tr>
<td>Extr. section (rf)</td>
<td>1.1 kA</td>
<td>1.1 kA</td>
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<tr>
<td>Beam energy</td>
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<td></td>
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<tr>
<td>Injector</td>
<td>1 MeV</td>
<td>1 MeV</td>
</tr>
<tr>
<td>Chopper</td>
<td>2.8 MeV</td>
<td>2.5 MeV</td>
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<tr>
<td>Extraction</td>
<td>4.0 MeV</td>
<td>10.0 MeV</td>
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<tr>
<td>Bunch compression</td>
<td>240° to 110°</td>
<td>240° to 70°</td>
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<tr>
<td>Beam transport in extraction section</td>
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<td></td>
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<tr>
<td>Betatron period</td>
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<td>2 m</td>
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<tr>
<td>Lattice period</td>
<td>20 cm</td>
<td>33.3 cm</td>
</tr>
<tr>
<td>Phase advance</td>
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<tr>
<td>Pole tip field</td>
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<td>Beam diameter</td>
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<tr>
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<tr>
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<tr>
<td>Output spacing</td>
<td>1 m</td>
<td>2 m</td>
</tr>
</tbody>
</table>

Pulsed Power System

Conversion of wall plug power into induction drive beam power is a significant factor in the rf power source efficiency. The efficiency of a TBA induction accelerator depends on several factors. Beam transport dynamics will determine the size of the beam pipe. The rf power requirement determines the pulse duration, beam current, accelerating gradient, and repetition rate. Once these factors are established, the outer radius and material of the
core can be calculated from: $\Delta V \Delta t = \Delta B A F_p$, where $\Delta V$ is cell voltage swing, $\Delta t$ is pulse duration, $\Delta B$ is core flux swing, $A$ is core cross section, and $F_p$ is core material packing factor. The core volume increases nearly as the radius squared, so smaller, more efficient and lower cost induction cells can normally be obtained by using higher $\Delta B$ materials and minimizing the inner radius.

Fig. 1. A proposed RK-TBA induction cell design illustrating longitudinal core segmentation.

Several core materials have been tested at the RTA Test Facility [5]. Two METGLAS® alloys, 2605SC and 2714AS, have been selected for use in the RTA. The alloy 2605SC has a $\Delta B$ of $\sim 2.5$ T with a core loss of $\sim 2$ kJ/m$^3$ for a 400 ns pulse and 22 $\mu$m thick ribbon. The alloy 2714AS has a lower $\Delta B$, $\sim 1.1$ T, but a much lower core loss of $\sim 150$ J/m$^3$ with 18 $\mu$m ribbon. The core tests are performed with the expected pulse shape and duration for accurate loss measurements. For our TBNLC geometry, the low core loss 2714AS can achieve a conversion efficiency of wall plug power to drive beam power of 59%, a substantial improvement over 2605SC.

Fig. 2 Core loss for different rates of magnetic flux change.

The modest repetition rate (120 Hz) and current rise time (100 ns) envisioned for the NLC permit the use of a simple, and cost effective thyatron driven modulator. The total induction cell core is segmented longitudinally into smaller cores each individually driven at 20 kV or less. Driving at this voltage level avoids a separate step-up transformer and allows for switching with fast inexpensive single-gap tubes. Length of the induction cell, thus number of cores per cell, is set by geometrical constraints due to extraction structures, magnet positions, etc. The TBNLC design in Fig. 1 has five cores per cell while the RTA has three cores.

Beam energy flatness is an important issue affecting beam transport and rf phase variation. The current required to drive the cores is nonlinear for a constant amplitude voltage pulse since the inductance of the core decreases as saturation of the material is approached. The effect is more pronounced for high aspect ratio ($\Delta t/\Delta z$) cores due to non-uniform saturation starting at the inner radius propagating outward. This effect is shown in Fig. 3 where the voltage pulse has $\sim 200$ ns of flat top during which the drive current increases non-linearly. The generated voltage amplitude can be kept constant, within bounds, as the material approaches saturation by tapering the impedance of the PFN stages. Our PFN will consist of many coupled L-C stages.

We have been testing pulsed power prototypes using a 3-core injector cells. In the prototype we have used EEV CX1538 and TRITON F-232 thyatron tubes. The injector cell design calls for 14 kV/core or 40 kV/cell. Early test performed using a CX1538 tube yielded a rise time (10% to 90%) of about 150 ns with a voltage flat top of 120 ns (see the $V_{\text{single}}$ trace in Fig. 3), however a pretrigger applied to an additional grid on the tube gave performance close to the design (100 ns rise time, 200 ns flat-top). With the pretrigger to an additional grid on the tube we were able to get the rise time to down to 100 ns and obtain a voltage flat top of 180 ns (shown in the $V_{\text{dual}}$ trace in Fig. 3). The $I_{\text{dual}}$ trace in Fig. 3 shows the drive current for the cell with a 40$\Omega$ simulated beam load. The F-232 tube has lower internal inductance as well as a higher dI/dt rating. It also gave performance close to the design criteria.

Fig. 3. Cell voltage and drive current for a prototype injector cell.

**Injector**

The injector consists of two sections, a 1-MV, 12-kA induction electron source, referred to as the gun, followed by several induction accelerator cells to boost the energy
to 2.8 MeV. Two goals of the design are minimizing electrical field stresses in the gun and realizing the lowest possible emittance growth. Gun induction cores are segmented radially to reduce the individual aspect ratios with each driven separately at about 14 kV. Components of the induction cells for the gun are in fabrication.

Beam Dynamics and RF Power Extraction Issues

Beam dynamics issues related to longitudinal and transverse stability, modulation, and transport have been presented in detail elsewhere [3, 8]. A brief description of these issues is given here. Initial beam modulation is accomplished with a transverse chopping technique. After this modulator section, an adiabatic compressor, a system of idler cavities and induction accelerator modules, is used to bunch the beam and further accelerate it to an average energy of 4 MeV. The lower frequency component of the transverse beam breakup instability is controlled by Landau damping. Control of the higher frequency component, excited in the rf cavities, is accomplished with the focusing system in a technique that we refer to as the "Betatron Node" scheme. The rf extraction structures are appropriately detuned to compensate for space charge and energy spread effects so that the longitudinal current distribution is stable.

After the adiabatic compressor, the beam enters the extraction section, where beam energy is periodically converted into rf energy (via extraction cavities) and restored to its initial value (via induction modules). Both traveling wave (TW) and standing wave (SW) structures are being considered for the extraction section of the RTA. The TBNLc design [9] uses TW structures to reduce the surface fields associated with generating 360 MW per structure. RTA is designed to generate 180 MW per structure. Thus, inductively detuned SW cavities are a practical alternative.

References

SCALING THE TBNLC COLLIDER DESIGN TO HIGHER FREQUENCIES*

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Abstract

The TBNLC collider design uses Relativistic Klystron Two-Beam Accelerator (RK-TBA) units as the rf power source for a NLC-type linac at 11.4 GHz. In this paper we report on a simple analysis of using RK-TBA units as a rf power source for a CLIC-type linac at 30 GHz. The desired rf macropulse duration is less than 50 ns with a repetition rate of 600 Hz. We propose to use magnetic pulse-compression units driving ferrite-core induction cells for this system. Many elements of the TBNLC remain the same for a collider design at this higher frequency.

Introduction

In this paper we described a short-pulse rf source that could be used to drive an electron-positron collider. We refer to this design as RK-CLIC. The high-gradient structures being considered are about 1.5 times longer, with a longer fill time, than those that CLIC proposes for their 10-bunch collider design [1]. Each main linac accelerating structure requires 95 MW to produce an average loaded accelerating gradient of 80 MV/m. The structures are 42 cm long and 8 cm are allowed for pumping ports, flanges, etc., resulting in a 0.5 m spacing. Thus, the average gradient is 67 MV/m for a total main linac length of 15 km to produce a 1-TeV center-of-mass energy. The high-gradient linac beam profile is a 50 bunch train with 20 cm spacing. The linac will operate at 600 Hz to achieve a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. The rf pulse shape has a 17-ns linear ramp with a 33.7-ns flat top to produce a constant energy for all the bunches at the interaction region.

In analogy to the TBNLC [2], we propose that the high-gradient linac be powered by 50 RK-CLIC units. Each unit provides rf power for 300 meters of main linac. Similar to the TBNLC, each unit consists of the following major components: a 1.2-kA, 2.5-MeV induction injector, a beam modulation unit, an adiabatic capture section to accelerate and bunch the beam, the main rf power extraction unit, and an afterburner where power is extracted from the decelerating beam prior to the beam dump. At the entrance to the rf power extraction unit, the beam has an average energy of 10 MeV and 1,120 A of rf current. A one meter section of the rf power extraction unit is shown in Fig. 1. Each rf power extraction unit is comprised of about 300 of these sections, and each section drives two high-gradient linac accelerating structures.

Drive Beam Dynamics Issues

The drive beam dynamics issues of concern are beam transport, longitudinal bunch stability, and transverse beam instabilities.

Drive Beam Transport

We use permanent magnet quadrupoles in a FODO lattice for beam transport. The lattice period is 33.3 cm with a 60° phase advance per period to produce a 2-m betatron period. The ferrite magnets have a 800 G pole strength, 2.5 cm radius bore, and a 0.48 occupancy factor.

For a 500 π-mm normalized edge emittance, the drive beam edge diameter should be about 3 mm. The aperture of the 30 GHz rf output structures is 6 mm. This places a high emphasis on the production and preservation of low emittance beams. The emittance requirement could be relaxed by increasing the drive beam energy.

Longitudinal Bunch Stability

We use a transverse chopper to initially modulate the drive beam as in the TBNLC design. However, other modulation schemes can be envisioned. The beam exits the chopper occupying a longitudinal phase of 240° and is compressed to 70° reaching an rf current of 1,120 A and an average current of 630 A.

In the rf power extraction unit, average beam energy is maintained at 10 MeV by 3 100-kV induction cells per 1-m section that restore the 190 MW of power extracted in the rf output structure. The synchrotron period (particle rotation in the rf bucket) in the extraction unit is approximately 30 m. The rf output structures are detuned to compensate for bunch lengthening effects. However, the shorter synchrotron wavelength and closer spacing of rf output structures should improve longitudinal stability relative to the TBNLC design.

Transverse Beam Instabilities

The beam dynamics for the low frequency, 2-4 GHz, transverse instability due to beam interaction with the induction acceleration gaps, should be the same as in the TBNLC. Landau damping from energy spread will suppress this instability. However, the lower emittance required for

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*The work was performed under the auspices of the U.S. Department of Energy by LLNL under contract W-7405-ENG-48 and by LBNL under contract AC03-76SF00098.
the RK-CLIC drive beam may require reducing the transverse impedance of the induction gap.

The high frequency, ~40 GHz, transverse instability due to higher order modes in the rf output structure, is a more difficult problem. There are twice the structures, and their transverse impedance is expected to be greater with respect to the TBNLC design. For the TBNLC, it was necessary to use the Betatron Node Scheme [3]. This scheme will remain valid for RK-CLIC where the structures are spaced at half Betatron wavelengths. The total effect should lead to an instability growth similar to that for the TBNLC, but perhaps requiring a higher tolerance on focusing field errors.

**RF Output Structure Design**

An illustration of the proposed RK-CLIC rf output structure is shown in Fig. 2. Direct scaling, i.e. geometrical dimensions are varied directly with wavelength, of the TBNLC three-cell travelling-wave output structure was used. The longitudinal impedance is invariant while the transverse impedance increases as ~ω with this scaling [4].

The maximum surface field of the TBNLC rf output structure is predicted to be 75 MV/m for 360 MW output. At 190 MW, the surface field should reduce to 55 MV/m. Assuming the surface fields scale inversely with the aperture, we predict surface fields of 145 MV/m for the RK-CLIC structure generating 190 MW. Experiments on relativistic klystrons, with similar pulse lengths to the RK-CLIC, indicate that the rf output structures can be safely operated with 100 MV/m surface fields at 11.4 GHz [5]. Assuming the breakdown limit for a copper structure scales as the square root of the frequency, we can expect to safely operate up to 160 MV/m fields at 30 GHz.

**Induction Cell Design**

The induction cell voltage is 100 kV/cell as in the TBNLC. The pulse length at the FWHM of the voltage waveform is taken as 50 ns. The Ceramic Magnetics CMD-5005 ferrite is used for the accelerator cores. The core consists of a 25 cm long tube of ferrite with an 8 cm inner diameter. Assuming a ΔB of 0.65 T, the outer diameter of the ferrite is about 14.2 cm.

The energy loss per volume at our parameters for the ferrite is estimated to be 600 J/m³. Thus, ~1.6 J is lost in the ferrite per pulse. The energy required for the beam is 1/3 (3 induction cells per rf output) of 190 MW · 50 ns or 3.17 J. The losses associated with capacitance and stray induction for these short pulses can limit efficiency. If we assume a capacitance, C, of 20 pf, then the energy loss is C · V²/2 = 0.1 J. Thus, the efficiency for the cell is:

\[ \eta_e = \frac{3.17}{(3.17 + 1.6 + 0.1)} = 65\% \]  \hspace{1cm} (1)

A smaller inner radius would reduce core losses, but increase the transverse impedance of the induction cell gaps. New core materials could lead to better efficiency and lower costs. Within the limitations of materials that we have tested, the easiest way to improve efficiency is to increase the pulse length. In Fig. 3 the efficiency of the induction cell for three different core materials are plotted as functions of pulse length. The voltage, inner radius, and length of the core were fixed at the RK-CLIC design values given above. For pulses shorter than 50 ns, the

![Fig. 2. Proposed rf output structure for the RK-CLIC. The interaction mode is TM₁₀ with phase velocity of 1.3 c.](image)

CMD-5005 ferrite is the preferred material of those examined. Over 50 ns, the Allied-Signal METGLAS® alloy 2714AS shows improved efficiency. Doubling the pulse length increases the core efficiency by about 8%.

**Pulsed Power System**

We cannot reduce the rise time of thyatron switching, used in the TBNLC design, sufficiently to obtain a 17-ns rise time. Also, the pulsed power system proposed in the TBNLC design is not suitable for a 600 Hz repetition rate.

We are proposing magnetic pulse compression and switching [6]. This technique has been demonstrated at high repetition rates and with fast rise times in other applications [7]. Ability to cool the ferrite cores in the switches/compressors and the pulse power units will need design effort, but multiple kHz operation is possible.

A preliminary design for a three stage magnetic pulse compressor was performed to assist in estimating cost and efficiency. The magnetic compressor/switch parameters used in this design are listed in Table 1. Energy storage for
the third stage consists of a 0.84-m long, water-filled Blumlein line. The first two stages use Strontium-Titanate capacitors. The long charge time of the first stage allows the use of a solid state system for the initial triggering.

The advantage of this magnetic compressor system is that it is totally solid state. It should have high-reliability, long lifetime, good efficiency, and be capable of kHz operation. A drawback of the system is that it is difficult to adjust the voltage wave shapes to obtain different accelerating gradients. Fast correction circuits interspersed in the system could be used to correct for errors.

**System Efficiency**

Where possible, comparable efficiencies for similar components with conventional klystrons or the TBNLC are used. We have based estimates on current technology.

(1) **DC Power Supplies** — Conventional 60 Hz 3 phase full wave rectifier with filter supplies will be used. Estimated efficiency is 93%.

(2) **Command Resonant Charging (CRC) System** — A solid state CRC system with estimated efficiency of 96%.

(3) **Pulsed Power Modulator** — Magnetic compression power losses are due primarily to three components, core losses, ohmic losses in the Blumlein water, and capacitors. Losses due to the cooling system are included under auxiliary power. Table 1 lists core efficiencies. Assuming the same ratio between the outer and middle conductors radii as between the middle and inner, the energy loss in the water can be expressed as:

$$ U_L = \frac{240 \pi L V_o L_0 \Delta t}{\rho \varepsilon_r} $$  

where

- \( L \) is the length (cm) of the Blumlein,
- \( V_o / L_0 \) is the applied voltage (V)/current (A) to the load,
- \( \rho \) is water resistivity (\( \Omega \cdot \text{cm} \)),
- \( \varepsilon_r \) is relative permittivity, and
- \( \Delta t \) is charging time. In our design, \( L = 84 \text{ cm} \), \( V_o = 25 \text{ kV} \), \( L_0 = 17 \text{ kA} \), \( \varepsilon_r \) is 80, \( \rho = 8 \text{ M\Omega} \cdot \text{cm} \) and \( \Delta t = 250 \text{ ns} \) for an energy loss of 0.094 J. The efficiency of the capacitors is estimated at 98%. Total estimated efficiency is 92%.

(4) **Induction Cells** — As described above, the cell efficiency should be about 65% for 50 ns pulses.

(5) **Drive beam (pulse fall time)** — As in the TBNLC, we plan to utilize the rise time of the current pulse. As an estimate of the energy to drive the core during the fall time, we allowed 300 A core current (average core current used for induction cell losses) times 20 ns fall time times one half of 100 kV or 0.3 J. This amount also includes the 0.1 J stored in the gap capacitance. Thus, actual losses during the fall time cannot previously accounted for are only 0.2 J giving an efficiency of 94%.

(6) **Drive beam to rf** — The conversion losses of drive beam to rf power are due to losses at the front of the relativistic klystron, primarily in the chopper, and residual beam power lost in the dump. This will be the same as for the TBNLC design, about 90%.

(7) **Auxiliary power** — This miscellaneous category accounts for losses in systems such as cooling fluids, vacuum, etc. These losses are estimated to be 80 kW. At 600 Hz this represents an efficiency of 0.96.

To summarize, the estimated efficiencies are:

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
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<td>Power supplies</td>
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<td>CRC</td>
<td>0.96</td>
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<tr>
<td>Modulator</td>
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<tr>
<td>Induction cells</td>
<td>0.65</td>
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<tr>
<td>Drive beam (fall time)</td>
<td>0.94</td>
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<tr>
<td>Drive beam to rf</td>
<td>0.90</td>
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<tr>
<td>Auxiliary power</td>
<td>0.96</td>
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<tr>
<td>Total wall plug to rf efficiency</td>
<td>0.43</td>
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</table>

**Summary**

A preliminary study for a 30 GHz linear collider using the CLIC high-gradient linac and scaling of the relativistic klystron (RK) used in the TBNLC design was performed. The result was positive with an estimated wall plug to rf power efficiency of 43%. The rf to beam efficiency for the CLIC parameters used is 67% for a total efficiency of 29%. No attempt was made to optimize parameters for the combined rf power source/CLIC, e.g. gradient, and pulse length. However, increasing the pulse length could substantially improve the efficiency of the (RK) while also improving the efficiency of rf to beam conversion.

A very approximate costing study was performed. The cost of the 30 GHz RK-CLIC is practically the same as for the 11.4 GHz TBNLC. Savings due to the shorter pulse length and reduced energy per pulse are balanced by the additional cost of doubling the number of output structures.

**Acknowledgments**

We thank S. Chattopadhyay and A. Sessler for their support and guidance. We thank J-P Delahaye, C. Johnson, L. Thorndahl, and I. Wilson for their assistance in determining the performance and rf requirements for the CLIC architecture.

**References**


ISAC: RADIOACTIVE ION BEAMS FACILITY AT TRIUMF

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Abstract

A radioactive ion beam (RIB) facility is being built at TRIUMF. A novel design for the target/ion source station will
allow us to bombard a thick target with TRIUMF's 100 μA, 500 MeV proton beam, producing a variety of very intense
beams of nuclei far from stability. After mass separation the
beams can be sent to two different experimental areas. One
uses the 60 keV energy beam and the second one will use the
0.15 to 1.50 MeV/u post-accelerated beam. Singly charged ion
beams, with A ≤ 30 delivered from the on line mass separator,
with an energy of 2 keV/u, will be accelerated in a two stage
linac consisting of an RFQ and a post-stripper drift-tube linac
up to 1.5 MeV/u. CW operation mode is required to preserve
beam intensity. As a consequence of the low q/A ions a low
operating frequency for the RFQ is required to achieve adequate
transverse focusing. The main features of this accelerator are:
35 MHz RFQ, stripping at 150 keV/u, beam energy
continuously variable from 0.15 to 1.50 MeV/u and CW
operation.

Introduction

A radioactive ion beam facility with a post-accelerator
was first proposed at TRIUMF in 1984[1]. Although the full
project was not funded at that time, an on-line target/ion
source and mass separator test facility was installed on one of
TRIUMF's proton beam lines, and has been used since 1987
to provide low energy radioactive beams and to develop the
target-ion source system. The primary motivation at the time
was to determine reaction rates involving short-lived nuclei in
various nucleosynthesis processes. Furthermore, the
possibility of producing intense radioactive nuclear beams with
N/Z ratios largely different from those of natural isotopes opens a new area of research.

The high energy (500 MeV) and high intensity (>100
μA) of the H cyclotron beam make TRIUMF a cost effective
choice for a RIB facility in North America. A new beam line
will transport TRIUMF's proton beam from the cyclotron
vault to two target stations in a new building of approximately
5000 m². This is divided into two parts, namely the heavily
shielded and sealed target hall, and the post-
accelerator/experimental hall, shown in Fig. 1.

Target/Ion Source System

The target stations are to be housed in the new
heavily shielded target hall. All highly activated
and potentially contaminated components such as production
targets, beam dump, ion sources and initial focusing devices
will be located at the target station within the target hall along
with the primary radiation shield and services required to
operate the target station components. Hot cell, assembly area
and decontamination and storage facility will be included.
The target is located in a canyon surrounded by the required
steel and concrete shielding, and consists of a large vacuum
tank with 5 separate modules, entrance, target, beam dump and
RIB optic components. The target module is made up of a 2 m
long shielding plug on the bottom of which is mounted the
target, ion source and the extraction system. The steel plug
will be at ground potential and the target/ion-source assembly
will be biased to give extraction voltages in the range 12 kV
to 60 kV in order to match the 2 keV/nucleon required for
injection into the RFQ. The target station modules are all
designed to be handled remotely.

Fig. 1 Views of the target/ion source module showing the
shielding plug and the services.

Mass Separator

There is no universal ion source for the production of
all the elements required for the physics program. Beam
properties will depend on the type of ion source used. The
extraction system will be optimized for each individual ion
source to give the highest brightness.

In our present design, the mass separator consists of a
two stage system each with a total bend angle of 135°. It will
have a source-defining entrance aperture. Aberrations will be
corrected by surface coils in each dipole. This separator will
have a dispersion at the focal plane of 6 cm/% in ΔM/M and a
mass resolving power of 10,000 for a beam emittance of
5 π mm mrad. A movable slit system will be placed on the
focal plane to select the mass to be transmitted.

Accelerator

General Description

Most of the astrophysics and applied program can be
performed within an energy range between 0.2 and 1.5
MeV/nucleon. Higher energies (≤ 10 MeV/u) would be
desirable for nuclear structure studies, fusion reactions, etc.
This could be viewed as a possible upgrade in the future. At
present, for the ISAC accelerator, we limit ourselves to the specifications list in Table 1.

The layout in Fig. 2 illustrates the two-stage linac that would satisfy the ISAC specifications.

Initial acceleration of the singly charged ion beam delivered by the mass separator is accomplished in a RFQ. To accommodate the fixed ion velocity requirement at the RFQ input it is necessary to adjust the extraction voltage of the ion source so that the ion input energy will be 2 keV/nucleon in all cases. After acceleration to 150 keV/nucleon in the RFQ, the beam passes through the matching and stripper section where its charge to mass ratio is increased to \( \geq 1/6 \). After the stripping and charge state selection the beam is injected into a drift-tube linac operating at 105 MHz, which is divided into several accelerating structures in order to provide continuous energy variation from 0.15 to 1.5 MeV/nucleon.

Given that the radioactive ion beam intensity will be small, space-charge can be neglected and a truncated Yamada-style recipe used for the vane profiles. The vane modulation index ramps quickly from 1.12 to 2.5, while the bore shrinks from 0.70 to 0.38 cm. Due to a requirement from the experimenters for 86 ns time structure, beam bunching is achieved in an external, quasi-sawtooth prebuncher; and so the shaper and gentle buncher portions of the RFQ are omitted, leading to substantial shortening. The prebuncher is located in the LEBT section.

From a structural point of view, the low frequency of the RFQ dictates that a semi-lumped resonant structure be used to generate the required RF voltage between the electrodes. The structure proposed for the ISAC accelerator is a variant of the 4-rod structure developed at the University of Frankfurt[3]. A 4-rod split-ring RFQ structure has been chosen because of its relatively high specific shunt impedance, its mechanical stability, and the absence of voltage asymmetries in the end regions [4].

To confirm the manufacturability of the design and to verify the mechanical stability a prototype section consisting of three 40 cm long modules is being built. One module has been tested at full CW power (85 kV inter-electrode voltage). The thermal and dynamic stability has been measured and they are well within tolerances [5].

**Table 1 - Basic specifications for ISAC-1.**

| Input beam | Sieve energy | 2 keV/nucleon |
| Beam mass | \( A \times 30 \) |
| Beam charge | 1 |
| Beam current | \(< 1 \mu A DC\) |
| Beam emittance (100%) | \(< 0.5 \times 10^{-4} \text{ mm mrad}\) |
| Accelerated beam | \(0.15 \leq E \leq 1.5 \text{ MeV/nucleon}\) |
| Resolution \( \Delta E/E \) | \(\leq 0.1\%\) |
| Duty factor | 100 % |

**LEBT**

The ion beam from the mass separator is to be switchable between the Low Energy (LE) experimental area and the accelerator. At the same time, it is desirable to have an off-line source which is switchable between the same two areas, although its primary purpose is for commissioning the accelerators. A switch-yard has been designed which meets all these goals. At the heart is a cross-over switch which allows the off-line source to supply beam to either the RFQ or the LE, while simultaneously, the mass separator can supply beam to the LE or the RFQ, respectively. All the optics in the LEBT is electrostatic: quadrupoles are typically 50 mm long by 25 mm bore radius, bends are each 45°, with spherical electrodes, 250 mm in radius.

The RFQ, having no bunching section, accepts bunches \( \pm 30° \) in length. A buncher located 5 m upstream of the RFQ, operates at 11.67 MHz, the third sub-harmonic of the RFQ frequency. This is to meet the requirement of bunch separation in the range of 100 ns. In order to place at least 80% of the beam within the RFQ longitudinal acceptance, the buncher waveform will be pseudo-sawtooth, with 4 harmonics.

**RFQ**

A radio-frequency quadrupole provides the initial acceleration of the ion beam delivered by the ISOL. Taking singly charged mass 30 as the reference particle and an operating frequency of 35 MHz, to give a reasonable structure size, we are led to an inter electrode voltage of 73 kV, a characteristic radius to pole tip \( r_p = 0.74 \) cm, focusing strength \( B=3.5 \) and r.f. defocusing \( \Delta = 0.0408 \). The total length of the vanes is 7.60 m.

Drift-Tube Linac

Several accelerating structures were investigated. The first proposed structure was based on the RILAC accelerator[6]. The major problem was the power requirement of 1 MW for only 1 MeV/nucleon. A second study was devoted to investigate the suitability of superconducting accelerating structures[7]. Finally, we decided on a room temperature structure to avoid the high cost of cryogenic equipment and the relatively long period to acquire this technology.
The drift tube linac is required to accelerate, in CW mode, ions with a charge to mass ratio of 1/6 from 0.15 MeV/nucleon to a final energy variable from 0.15 to 1.5 MeV/nucleon. An IH structure [8] is chosen for the drift-tube linear accelerator because of its very high shunt impedance.

A separated function DTL concept has been adopted [9]. Five independently phased IH tanks operating at $\phi_k = 0^\circ$ provide the main acceleration. Longitudinal focusing is provided by independently phased double gap spiral resonator structures positioned before the second, third and fourth IH tanks. A schematic drawing of the DTL is shown in Fig. 2. When operating at full voltage the beam dynamics resembles that of a so called ‘Combined 0° Synchronous Particle Structure’ [8]. To achieve a reduced final energy the IH tanks may be turned off while the voltage and phase of the last powered tank is varied. The spiral resonators are all designed for $\beta = 0.023$ and are effective over the whole DTL velocity range. They also permit the beam to be kept well bunched over the entire energy range. The total effective gradient is 1.5 MeV/m with an estimated power consumption of 91 kW.

HEBT

The HEBT provides three dimensional beam transport using 10 m long periodic sections comprised of 2 quad doublets and a rebuncher. A first triplet matches the beam while the periodic sections and achromatic bend deliver the beam to the high energy experimental stations. Simulations show that the longitudinal beam emittance $\leq 50 \pi$ keV nm will be available for the full energy range.

Reference

9. R. Laxdal and P. G. Bricault, Design of a Drift Tube Linac for the ISAC project at TRIUMF, this conference.

Fig. 2 Schematic drawing of the new target/experimental hall. The mass separator target and the new beam line are at 264° elevation. At the final focal point of the mass separator the beam is bent up 90° and sent to the RFQ or to the Low Energy experiment stations.
Beam Dynamics of the TRIUMF ISAC RFQ

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Abstract

We describe the beam dynamics design and report the anticipated performance, including a sensitivity analysis with respect to beam injection errors or vane displacements, of the proposed TRIUMF ISAC Radio Frequency Quadrupole (RFQ) accelerator. The 35 MHz RFQ is intended for the acceleration of ions with a charge-to-mass ratio greater than 1/30 from 2 keV/u to 150 keV/u. Novel features of the design include the use of an external quasi-sawtooth buncher, the use of only ‘booster’ and ‘accelerator’ sections, and a single constant phase angle of $-25^\circ$. The vane design has large modulations and a constant transverse radius of curvature, and has been corrected to give the two term potential function coefficients. An important design objective is achieving small emittances.

1 INTRODUCTION

The ISAC project conceptual design was presented in [7] and more recently in [8]. ISAC consists of an ISOL and two c.w. linear accelerators: a 35 MHz RFQ and a 105 MHz drift tube linac. The RFQ design can be separated into two parts: RF, electrical and beam-dynamic.

1.1 RF-theoretical design

RF/mechanical engineering aspects of the design, including results of power tests on a prototype, are reported in [9], while RF-theoretical considerations are given in [10, 11, 12, 15, 16], and RF cold model studies reported in [17, 18].

An important part of the electrical design is to produce symmetrical vane voltages such that the orthogonal mid-planes between the electrodes are at ground potential; and so the split coaxial type resonator[1], which leads to inherent asymmetry, was avoided. Instead, the Frankfurt 4-rod split-ring type resonator[5] was adopted. Unlike the Frankfurt design, which compromises voltage symmetry in favour of higher shunt resistance, the TRIUMF design has the inductively loading stems placed in close-pairs rather than equidistant; and this eliminates the unwanted even-type transmission line mode in favour of the desired odd-mode. Detailed 3D design work with the MAFIA code and extensive measurements on cold models resulted in a design that has a specific shunt resistance of $\approx 400$ kOhm.m.

2 BEAM DYNAMICS DESIGN

The history and progress of the beam dynamics design may be followed in [7, 13, 19], etc. The present accelerator design has an external multi-harmonic buncher (composed of an RF gap and 5.3 m drift space) followed by an 8.0 m long RFQ which contains 7.6 m long modulated vanes and ancillary space for vacuum flanges and RF tank end walls. The ISOL transmits a reference beam of 100% emittance $= 0.1\pi \text{ mm.mrad}$ (normalized), and based on tracking with the 2-term-potential the RFQ acceptance is almost $0.5\pi \text{ mm.mrad}$.

2.1 Choice of parameters

Let $V$ be inter-vane voltage and $r_0$ be characteristic radius from beam axis to pole tip. For a constant Kiplpatrick factor, and average electric field $E = V/r_0$, it is found that the focusing strength $B$, the transverse acceptance $A$ (in $x$-$\phi$ space), and the kinetic energy gain per cell $\Delta T$ are respectively given by

$$B = qE\lambda^2/(m_0c^2r_0) \quad , \quad A = qEr_0\lambda/(m_0c^2 \times 8.88) \quad , \quad (1)$$

$$\Delta T = qEr_0 \cos \phi_x \times 0.7854(1-a^2/r_0^2) / [1+(\pi \alpha \beta \lambda)^2] \quad . \quad (2)$$

From these equations, it is clear that increasing $B$ by reducing bore radius will lengthen the RFQ and reduce the acceptance. For this reason, we have taken $B$ rather lower than is conventional. Contrarily, too small a value of $B$ results in inadequate transverse focusing. A compromise was reached with $B = 3.5$. Increasing $B$ by using long wavelength $\lambda$ leads to prohibitively large RF-electrical structures.

Because a pre-bunched beam is injected into the RFQ and because space-charge effects are negligible, the RFQ vane profiles are shortened to comprise only ‘booster’ and ‘accelerator’ sections. Though a Yamada-type recipe is used for the vane profiles, the shaper and gentle buncher portions of the RFQ are omitted leading to substantial shortening. Further, the synchronous phase is large and constant, which maximises the acceleration. Two candidate reference designs were studied in detail, and the main parameters are presented below.

<table>
<thead>
<tr>
<th>#</th>
<th>L (m)</th>
<th>kV</th>
<th>$r_0$</th>
<th>B</th>
<th>$\Delta_T$</th>
<th>$\bar{m}$</th>
<th>$\bar{a}$</th>
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<tbody>
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<td>(1)</td>
<td>6.25</td>
<td>85.4</td>
<td>.8645</td>
<td>3.0</td>
<td>-.0400</td>
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<td>3.5</td>
<td>-.0408</td>
<td>2.599</td>
<td>.3846</td>
</tr>
</tbody>
</table>

Both designs have a gap-dependent Kiplpatrick factor of $E/E_{Kipl} = 1.15$. Design (1), though very attractive, has the transverse and longitudinal tunes cross. To avoid the possibility of a 2nd order synchro-betatron parametric resonance[3], the focusing strength was raised from $B = 3.0$ to $B = 3.5$ resulting in design (2). Larger $B$ also reduces the sensitivity w.r.t. transverse injection errors. To compensate the lower intervane voltage of design (2) the RF-defocusing parameter was raised so as to shorten the ‘booster’ section, and the minimum bore radius, $\bar{a}$, was reduced from 0.45 to 0.38 cm to shorten the ‘accelerator’ section. The chosen RFQ reference is design (2). In the booster section the modulation index, $\bar{m}$, is rapidly ramped from 1.124 to 2.6 The beam radius is typically 2.5 mm.

J. Staples, of LBL, advised to consider the scenario of inadequate vane voltage and its impact on the longitudinal acceptance; and after study (see figure 1) it was concluded to move the synchronous phase angle further from the crest of the RF wave-form; from $-20$ (design 1) to $-25$ degrees (design 2).
2.2 External buncher

The use of an external, independent buncher had been considered academically for some time [13, 14, 20] but the request from experimentalists to do ‘time of flight’ work and discriminate against background made this essential. Pulse spacings of 86 nsec. are obtained by placing a quasi-sawtooth waveform klystron-type buncher operating at the 3rd sub-harmonic 5.3 m upstream of the RFQ. The buncher is excited with 11.667 MHz fundamental and its first three harmonics. The choice to bunch rather than chop the beam maximizes the beam transmission by phase-concentration into the RFQ’s acceptance. This approach also shortens the RFQ (by eliminating the internal bunching sections) and improves longitudinal emittance at the RFQ exit.

The buncher-to-RFQ separation is a compromise: close proximity makes bunching less sensitive to energy spread and/or offset of the incident beam but increases the required voltages. Kinetic energy errors arise from imperfect regulation of the ion-source voltage and from the inherent energy spread produced within ion source itself; and are anticipated to be several eV. With a separation of 5.3 m, the system can accommodate beams with a Gaussian distributed random energy variation of $1\sigma = 10$ eV without any significant degradation in performance.

The proposed buncher hardware consists of two parallel plates, with apertures of radius 0.7 cm, separated by 0.8 cm and enclosed in a grounded box. The dimensions are large compared to $\beta\lambda$ so that the acceleration is confined to the region between the plates. The peak inter-plate voltage will be less than 400 V for each of the Fourier components. A broad-band solid-state amplifier in conjunction with a ferrite core step-up transformer will be used to drive the plates in push-pull mode.

The beam dynamics of the buncher have been modelled numerically[25] by integrating 5000 particles through calculated 3D fields. Because the buncher dimensions are much less than $\lambda$, the static field approximation was used to determine the spatial dependence of the fields using the RELAX3D[6] code. The subsequent buncher-to-RFQ beam line was assumed to be composed of a periodic section of quadrupole doublets. The transverse emittance growth due to the buncher is less than 1%.

Figure 2 shows the longitudinal distribution of the bunched beam at the RFQ entrance extends over three periods of the 35 MHz RF. Calculations with PARMTEQ[2] indicate that approximately 80% of this beam can be successfully transported to the exit of the RFQ. About 20% of the particles are lost longitudinally, because the tails of the bunched beam fall outside of the RFQ’s acceptance and will be eliminated with a chopper.

2.3 Radial matching section

The designs of Yamada and Crandall for the vane profiles in the radial matching section (RMS) have been improved[24] and used as a basis for 3D particle tracking through the fringe fields in the region between the tank wall and the RFQ periodic focusing channel. The fields were computed with RELAX3D and input to the tracking program TRACK[27]. A detailed study[26] was deemed necessary, because of the very low rigidity of 2keV/u ions and consequent sensitivity to disturbances. The RMS profile was optimised (by stretching from 8 to 10 cells) to reduce the required beam convergence at the RFQ input.

3 VANE PROFILES AND FIELD CORRECTION

If one uses the ideal pole-tip geometry of the two-term potential function, then constant focusing parameter, $B$, leads to a constant characteristic radius $r_0$. However, we have adopted vanes with constant transverse radius of curvature (i.e. semi-circular pole tips), in which case constant $B$ implies a varying $r_0$. The simpler geometry gives rise to high order multipoles, but the choice of low tunes, makes the beam dynamics inherently insensitive to them. This electrode geometry is inexpensive to manufacture, but has the disadvantage that the local bore radius, $a$, and modulation index, $m$, of each cell must be adjusted to obtain the same electric fields as for the ideal geometry. A method to do this and its implementation is described in [12, 13]. The algorithm leaves the cell length, $l$, invariant, and recently advantage was taken of this property to improve the accuracy by replacing...
3D interpolation from an array of coefficients indexed by \( m, a, l \) with a set of 2D interpolations, one for each cell. The vane profiles are sketched in figure 3.

4 SENSITIVITY ANALYSIS

The goal of the most recent RFQ beam dynamics simulations was to perform a sensitivity analysis of the RFQ performance (transmission and emittance) with respect to injection errors of the beam and displacement errors of the vanes.

4.1 Beam injection errors

To facilitate automation, interactive shells for the RFQ simulation programs were devised using the LISP-like scripting and GUI builder language ‘tcl/tk’ with ‘expect’. The PARMEQ program was modified so that the description of a field-corrected RFQ could be read from file. Particle tracking with the 8-term potential shows[23] substantial halo formation and emittance growth even for the on-axis beam: 1% of particles constitute 40% of the occupied phase-space area.

Based upon tracking an ensemble of 4400 particles with various initial injection errors it is concluded that beam position, angle, phase and energy offsets, respectively, \( \Delta r < 0.5 \text{ mm} \), \( \Delta \phi < 0.02 \text{ rad} \), \( \Delta T < 0.5 \text{ keV} \) will cause less than 10% growth of the 95% emittance contours; and often much less. Growth of the 99% contours is usually much less than 25%. Within the stated injection error tolerances, the transmission through the RFQ is always 91.5% except for the case of \( \Delta = -0.5 \text{ keV} \) where it drops to 90%.

4.2 Vane position errors

The vane displacement study is being performed with the package ‘RFQCODE’[4] in conjunction with PARMEQ. Extensive modifications and improvements have been made to these codes at TRIUMF, particularly to the algorithms for the effect on the meshing of displacing the vanes. The mesh generator now accepts the RFQ description after field correction, and this entails using a different \( r_0 \) for each cell. When vanes are moved, the 8-term potential is supplemented with dipole and sextupole components to give a 10-term potential; normalization discrepancies between RFQCODE and PARMEQ of the 10-term coefficients have been corrected.

Let us number the vanes counter-clockwise. Based upon the mechanical support and connections we consider two types of vane displacement: (i) where vanes 1 & 3 and/or 2 & 4 move as pairs with radial errors (likely vibrational modes); and (ii) where all vanes twist (likely thermal deformation). We have considered both constant and ramped vane position errors.

For combinations of vane movements of norm less than .2 mm, there is no detectable change in the transmission, and the growth of the 95% emittance contours is typically less than 5%. For movements of less than .5 mm, the emittance growth is less than 40%. But for larger displacements the emittance grows very quickly and the transmission drops dramatically; e.g. with a 0.1-0.9 mm ramp the transmission falls to 77% and the 95% emittance increases more than 5-fold. Analytic estimates of the dipole coefficients and emittance growth are given in[28].

5 REFERENCES

[17] P. Bricault: Simulation of the TRIUMF split ring 4 rod RFQ with MAFIA; Proc. PAC 95, Dallas, Texas.
[18] P. Bricault: RFQ cold model studies; Proc. PAC 95, Dallas, Texas.
THE RFQ PROTOTYPE FOR THE RADIOACTIVE ION BEAMS FACILITY AT TRIUMF


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Abstract

The ISAC radioactive ion beams facility being built at TRIUMF requires cw operation of a low frequency RFQ structure. This implies a large structure with adequate cooling while still maintaining mechanical alignment and stability. Our goal is to achieve a thermal stability alignment of +/-0.08 mm along the entire length of the RFQ structure and a dynamic stability of the operating assembled RFQ structure, taking into account deformation due to thermal drifts and vibrations induced by cooling and vacuum pumps, to within +/- 0.025 mm. Cold model studies [1] have been carried out to confirm the RF characteristics of the RFQ design. To confirm the manufacturability of the design to maintain the above tolerances, a prototype section consisting of three RFQ rings is being fabricated and will be tested to full cw power (85 kV between electrodes). The basic design of the structure is different from other RFQ structures in that the RF surfaces have been de-coupled from the mechanical support structure for improved stability. The features of this mechanical design will be discussed and the first results of the RFQ prototype tests will be presented.

Introduction

The accelerating system of the ISAC radioactive ion beams facility consists of an RFQ and a post-stripper DTL. Singly charged ion beams with A < 30, delivered from the on line mass separator with an energy of 2 keV/amu, will be accelerated to 150 keV/amu through the RFQ and then to a maximum energy of 1.5 MeV/amu through the DTL structure. The low charge-to-mass ratio of the ions dictate a low operating frequency to achieve adequate transverse focusing, and cw operation is required to preserve beam intensity. The reference design [2] for the RFQ is a four rod split ring structure operating cw at 35 MHz with 85 kV potential between the electrodes. The RFQ accelerator section is 8 meters long and is designed in 40 cm long modules. To confirm the manufacturability of the design to maintain the tight tolerances, an RFQ prototype section consisting of three such modules is being fabricated but initial measurements are made on a single module.

RFQ Components

Figure 1 is a sketch of one module with the major components identified. The basic design of the structure is different from other RFQ structures in that the water cooled RF skin has been de-coupled from the mechanical support structure (strongback) for improved mechanical stability. This design feature introduces an additional joint across the RF current path at the interface of the electrode supports and the RF skin in which special care must be taken to provide a good RF contact. The first module uses an indium gasket and a groove is provided for fingerstock contacts.

Electrodes

The electrodes (Fig. 1a) are machined from Tellurium copper which has an electrical conductivity of 93%. The electrodes are 40 cm long with a tip radius of 8.61 mm. The cross section of the electrode is shaped to provide the proper tip capacity and sufficient room for cooling channels. Two additional sample electrodes were successfully machined with the injection and extraction modulations incorporated into the tip radius.

![Figure 1. Sketch of one RFQ module. (a) electrodes, (b) electrode supports, (c) shims (d) strongback, (e) inner RF skin, (f) outer RF skin (g) stem, (h) adjustable base plate (i) RF shield (j) vacuum tank wall](image)

Electrode Supports

Tellurium copper was not readily available in the size required for the electrode supports (Fig. 1b) and were therefore NC machined from chromium copper which has an electrical conductivity of 80%. The electrode supports were complicated by a non-uniform tapered shape to maintain the
optimum structure design for maximum shunt impedance and
the desire to have three separate cooling circuits (electrodes,
electrode supports, RF skin) in the prototype to measure the
power distribution in the RFQ module. Provision has been
made for shimming (Fig. 1c) the electrodes with respect to the
electrode supports.

**Strongback**

The purpose of the strongback (Fig. 1d) is to provide the
mechanical stability of the RFQ structure. For the prototype it
was more expedient to fabricate it from aluminum but for the
accelerator system it could be fabricated from carbon steel to
provide added mechanical stability if necessary. The cross-
section is 7.0 cm wide and a radial thickness of 4.5 cm. The
outer radius of the strongback ring is 22 cm.

**RF Skin**

The RF skin is fabricated from standard copper sheet. The
inner RF skin (Fig. 1e) includes the side surfaces of the ring,
giving it a U shaped cross-section 15 cm wide and 8 cm deep
with an outer radius of 26 cm. An initial attempt to spin it from
one piece of copper failed and was subsequently fabricated
from three separate pieces of copper with welded joints at a
radius of 19 cm on each side surface. Since the joint is in the
direction of the current flow, the effect should be minimal on
the losses. To ease the fabrication process the wall thickness
was increased from 2.5 mm to 5 mm with the consequence of
producing a much stiffer RF skin structure than initially
planned. In the meantime we were successful in finding a
manufacturer who was successful in spinning the RF skin from
one piece of 1.75 mm thick copper sheet and the second RFQ
module will incorporate this RF skin and enable us to compare
the two designs. The inside surface of the RF skin is water
cooled. The outer RF skin (Fig. 1f) is a simple flat copper strip
15 cm wide shaped to the outer radius of the inner RF skin
with an extension at the bottom to cover the stem.

**Stem and Base Plate Assembly**

The stem (Fig. 1g) is fabricated from mild steel in two
sections and is nickel plated to prevent any rusting. Its main
purpose is to support the weight of the RFQ structure in its
proper position and provide access for the water cooling
circuits.

The base plate assembly (Fig. 1h) for the RFQ prototype
allows for 6 degrees of adjustment in order to have better
control of the alignment for measuring misalignment effects on
the RF field. The base plate assembly for the accelerator
system will be greatly simplified.

**RF Skirt**

The RF skirt (Fig. 1i) shields the base plate assembly and
linear bearings from the RF fields. It is fabricated from
standard copper sheet with finger contact at the stem and the
vacuum tank wall.

**Vacuum Tank**

The vacuum tank (Fig. 1j) is fabricated from copper plated
mild steel with an inner diameter of 104 cm. Unfortunately a
30 cm wide strip at the top of the tank did not get copper
plated and the quality of the copper plating on the rest of the
tank was very poor. Also the RFQ design was based on a tank
diameter of 120 cm. Both these errors will increase the RF
losses in the tank wall for the prototype system.

**RFQ Measurements**

Figure 2 is a photograph of the first ring installed in the
vacuum tank. In order to obtain preliminary measurements the
electrodes were aligned to only +/- 0.250 mm but the average
alignment (i.e., electrode tip capacitance) was within the +/-
0.08 mm tolerance.

[Image of Figure 2: Photograph of first RFQ module installed in the tank.]

**Signal Level Measurements**

The frequency was measured to be 35.186 MHz compared
to the design value of a nominal 35 MHz. Although MAFIA
predicted a Q as high as 14000 for the single ring the
maximum Q measured was 7200. Improving the RF contacts at
the interface of the electrode/electrode support or the
electrode support/RF skin did not improve the Q. Mafia
predicted an R/Q of 71 ohms compared to a measured R/Q of
60.4 ohms A shunt impedance of 435 kilohms was derived
from the measured values of Q and R/Q which gives a power
requirement of 8.3 kW for 85 kV at the electrodes.
Power Level Measurements

Without the RFQ module installed, the tank vacuum was 4 x 10-7 torr. With the RFQ module installed, following several days of pumping, leak checking and bakeout, a vacuum of 1.2 x 10-6 torr was reached. By the end of two weeks of power level measurements the base vacuum was 6 x 10-7 torr and 9.5 x 10-7 torr with RF on. Full voltage was reached in 8 hours with only two minor problems; heating on the top of the vacuum tank where the copper plating was missing and production of x-rays from the walls of the ports where the material is thinner than the tank wall. A water cooling saddle was installed on the top of the tank and the port walls were wrapped with lead shielding to attenuate the x-ray radiation to acceptable working levels. A graph of the X-ray production near the window port as a function of electrode voltage is shown in Figure 3 for both cw and 20% duty cycle operation.

![Figure 3. X-ray production near the window port.](image)

The voltage at the gap was determined by measuring the energy of the x-rays produced and gave a power requirement of 8.0 kW for 85 kV at the electrodes, which is in very good agreement with the signal level measurement and calculation of 8.3 kW.

Thermocouples and water flow meters were installed on the return lines of the cooling circuit for the electrodes, electrode supports and RF skin. The remaining power was assumed to be dissipated in the vacuum tank wall. With proper copper plating and increased tank diameter for the actual RFQ accelerator system, the tank wall losses are expected to be much less. Table 1 is a summary of the RF power distribution.

<table>
<thead>
<tr>
<th>Skin</th>
<th>Kilowatts</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode Support</td>
<td>1.8</td>
<td>22.5%</td>
</tr>
<tr>
<td>Electrode</td>
<td>1.2</td>
<td>15.0%</td>
</tr>
<tr>
<td>Tank wall</td>
<td>1.4</td>
<td>17.5%</td>
</tr>
<tr>
<td>Total</td>
<td>8.0</td>
<td>100%</td>
</tr>
</tbody>
</table>

The frequency of the RFQ decreases by 36 kHz from signal level to full power (see figure 4). The thermal movement of the electrodes from signal level to full power was measured by observing the position of the electrodes with a theodolite. A movement of less than +/- 0.050 mm was observed when the voltage was slowly increased to 85 kV and no dynamic movement (< +/- 0.25 mm) was observed due to cooling water or vacuum pumps. When the voltage was instantaneously applied a movement of approximately 0.200 mm was observed by each pair of the same polarity electrodes in the direction away from the beam centre, but returned to its aligned position within three minutes.

![Figure 4. Frequency change as a function of electrode voltage.](image)

The effect of slowly shutting off the water cooling to the electrodes was a decrease in frequency of 18 kHz with no observable movement of the electrodes.

Conclusion

Despite the design changes which had to be incorporated for manufacturability, the design feature of de-coupling the water cooled RF skin of the ring from the mechanical strongback structure was successfully fabricated and a stable RFQ module was produced. Our thermal and dynamic stability tolerances of +/- 0.08 mm and +/- 0.0250 were achieved. The RF specifications of 85 kV between electrodes at 35 MHz was also achieved.

Plans are already in progress to simplify the RFQ design to reduce the cost.

Acknowledgment

There are many people who helped to achieve the above results. A special thanks to Bill Uzat who designed and built the RF amplifier, Bhalwinder Warach, Peter Harmer and John Tanguay who did a tremendous job with the mechanical assembly and Vijay Verma who was a tremendous help in scheduling, planning and expediting.

References:

EXPERIMENTS ON RESISTIVE-WALL INSTABILITY IN SPACE-CHARGE DOMINATED ELECTRON BEAMS WITH LOCALIZED SPACE-CHARGE WAVES

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Abstract

We present the experimental results on the interaction between a resistive wall and the localized space-charge waves in space-charge dominated beams. The experiments have clearly demonstrated the growth of slow waves due to the resistive-wall instability and the decay of fast waves. The spatial growth/decay rates are measured and compared with theoretical analysis.

Introduction

The longitudinal instability of charged particle beams is an important issue in particle accelerators. The theoretical investigation of longitudinal velocity instability began long time ago in connection with the development of microwave tubes [1-2]. The amplification of longitudinal density fluctuations was first observed in an electron stream surrounded by a resistive wall by Birdsall et al. [3]. The first theoretical work on the longitudinal resistive instability for intense coaxing beams in particle accelerators was performed by Neil and Sessler [4]. Following these early studies, considerable theoretical work has been done mainly for circular high-energy particle accelerators [5].

In recent years, the problem of longitudinal instabilities has received new attention in connection with induction linear accelerators as drivers for heavy ion inertial fusion. When the heavy ions are accelerated by induction gaps, the beam sees dissipative impedances. The interaction between the intense beam and the gap impedances causes the longitudinal instability which may be detrimental to the beam. Though there have been extensive theoretical and computational investigations on the instability [6-11], an experimental study of the instability with heavy ion machines would be too difficult and too costly since a large-scale facility would be required. This is evidenced by the conventional spatial growth rate formula

$$k_i = R_w^* \sqrt{\frac{\pi e_0 q \Lambda_0}{g m \gamma}}, \quad (1)$$

where $R_w^*$ is the wall resistance per unit length, $\Lambda_0$ is the beam line-charge density, $q/m$ is the ratio of charge to mass of the particles, $\gamma$ is the relativistic Lorentz factor, $e_0$ is the permittivity of free space, and $g$ is a geometry factor of the order of unity. With heavy ions in induction linear accelerators an e-fold growth rate would require a machine of hundreds of meters in length, according to Eq. (1).

We have designed an experiment to study the longitudinal instability with space-charge dominated electron beams [12]. By taking advantage of the small mass $m$ of electrons, the large line-charge density $\Lambda_0$ in space-charge dominated beams, and using a rather large wall resistance $R_w^*$, we are able to measure the instability growth rate in a small-scale facility. A novel feature in our experiments is the fact that we employ localized space-charge waves. Conventionally, the longitudinal instability has been studied with sinusoidal waves. This approach does not usually lead to a complete solution of the problem. In practice, perturbations to beams in accelerators are often in the form of localized short pulses. Thus, a time-domain approach based on localized perturbations in the experiment provides a better picture and a more realistic and complete analysis of the instability.

Experiments

The experimental setup, as shown in Fig. 1, consists of a short-pulse electron beam injector, a resistive-wall channel, and diagnostics. The injector contains a gridded electron gun, which can produce desired beam parameters with localized perturbations. The key component of the resistive-wall channel is a glass tube of about 1 m in length and 3.81 cm in inner diameter. The inner surface of the glass tube is coated with Indium-Tin-Oxide. The total resistances of two tubes employed in the experiments are 5.44 kΩ and 10.1 kΩ, respectively. The beam is focused by a 1.4-m long uniform solenoid. The diagnostics includes two fast wall-current monitors at the entrance and the exit of the resistive tube to measure beam current signals with perturbations. Typical beam parameters are 3-8 keV in energy, 25-140 mA in current, and about 100 ns in duration.

![Fig. 1 Setup of resistive-wall instability experiment.](image-url)

In the experiment, electron beams with localized perturbations are generated in the gridded electron gun and transported through the resistive-wall channel. By employing the technique described in a previous paper [13], single slow or fast waves can be developed on these beam pulses. The interaction between the space-charge waves and the resistive wall leads to the instability. Figure 2 shows the growth of a single slow wave where (a) depicts the beam current signals with a slow wave at the entrance and exit of the channel, (b) is the zoom-in view of the slow wave before and after the resistive channel. It is clear that the amplitude of the slow wave is increased as expected. A similar picture is obtained for the decay of a localized fast wave after passing through the resistive-wall channel.
Fig. 2 Growth of a single slow wave.

For localized perturbations, the spectrum of space-charge waves covers a wide frequency range. In general, the spatial growth/decay rate \( k_s \) of the longitudinal instability under the long-wavelength limit is given by [14]

\[
k_s = \pm \frac{\pi k_0}{Z_0 c} \left( \sqrt{R_w^2 + X_s^2} - X_s^* \right)^{1/2}.
\]

Here \( K \) is the generalized perveance, \( Z_0 = 1/(c_0 c) = 377 \, \Omega \), \( \omega \) is the perturbation frequency, and \( X_s^* \) is the space-charge wave impedance per unit length given by

\[
X_s^* = \frac{gZ_0 c}{4\pi \beta c^2}.
\]

It is obvious that both the growth rate and the space-charge wave impedance are frequency-dependent. If the space-charge wave impedance dominates over the wall resistance, the spatial growth rate formula, Eq. (2), reduces to Eq. (1).

In the experiments various perturbation waveforms from a Gaussian-like or triangular shape to a "trapezoidal" one with a flat top have been employed for the instability study. The trapezoidal-like perturbation waveform contains a wide frequency spectrum. The long-wavelength limit condition is still satisfied for most frequency components of this spectrum in the experiments, so that Eq. (2) does apply. For the low frequency components, the space-charge wave impedance is comparable to or even smaller than the wall resistances. Hence Eq. (1) is not valid any more. The growth/decay rate for these frequency components would be smaller than that determined by Eq. (1). Overall, the amplitude increase/decrease of localized slow/fast waves are smaller than what is usually expected according to Eq. (1).

**Analysis**

In the analysis, we first find the frequency spectrum density of the measured input perturbation signal \( h(t) \) at the entrance of the resistive channel by the Fourier transformation

\[
H_i(\omega) = \frac{1}{\sqrt{2\pi}} \int h_i(t) e^{-j\omega t} dt.
\]

The calculated output signal \( h_o(t) \) at the exit of the channel is obtained by the inverse Fourier transformation

\[
h_o(t) = \frac{1}{\sqrt{2\pi}} \int H_i(\omega) e^{jk_s(t)} e^{j[k_r(\omega)t]} d\omega,
\]

where \( L \) is the length of the resistive tubes, and \( k_r(\omega) \) is the perturbed wave number given by

\[
k_r = \frac{\omega}{\beta c} \left[ \frac{\pi k_0}{Z_0 c} \left( \sqrt{R_w^2 + X_s^2} + X_s^* \right) \right]^{1/2}.
\]

The function \( h_o(t) \) is compared with the measured output signal.

In Fig. 3 we compare the experimental data for a slow wave of the trapezoidal-like perturbation with the analysis. Here (a) depicts the experimental perturbation at the entrance (input) and the exit (output) of the channel. In Fig. 3(b) the "input" denotes the digitized input signal in (a), while the "output" represents the slow space-charge wave at the exit of the channel, calculated from Eqs. (4)-(6). A similar comparison between the experiment and analysis for a fast wave can also be made. In both cases (slow and fast waves), there is good agreement between the experiment and the analysis in terms of the average wave amplitude. The rather significant difference on the edges of the perturbation waveform is due to the effect of high frequency components beyond the long wavelength limit in the perturbation signal, the effect of distributive capacitance along the resistive wall, and some reflections in the measured signal from mismatch. These are a subject of future study.
Fig. 3 Comparison between experiment and analysis for a slow wave.

Figure 4 shows the amplitude growth rates of the slow waves with the trapezoidal waveforms for different beam parameters and wall resistances, where the dots with error bars represent the experimental results, the stars are from the Fourier analysis, and the triangles are from Eq. (1). The data points 1-5 are from the 5.44 kΩ tube, while the data points 6-10 are from the 10.1 kΩ tube. Note that for each data point at a certain beam energy, the beam current as well as the geometry factor g, differ. A similar plot for the decay of fast waves with the same perturbation waveforms is shown in Fig. 5. These figures show that the amplitude changes of localized space-charge waves passing through a resistive channel are smaller than the theoretical values calculated from Eq. (1).

Fig. 4 Amplitude growth rate of slow waves.

Fig. 5 Amplitude decay rate of fast waves.

Summary

The resistive-wall instability experiment has demonstrated the growth of slow waves and the decay of fast waves. The theoretical analysis of the evolution of the pulse shape in the resistive channel based on Fourier transforms shows good agreement with the measurement except for edge effects where the distributive capacitance plays a role and the long wavelength assumption breaks down. We have found that the amplitude change of localized space-charge waves due to the instability is smaller than that calculated from the conventional growth rate formula of Eq. (1).

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References

PROTOTYPE OF THE RFD LINAC STRUCTURE*

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Abstract

A 2.5-MeV prototype of a “Compact 12-MeV Proton Linac for PET Isotope Production” is under construction at Linac Systems. This unit will serve as the “proof of principle” for the revolutionary new Rf Focused Drift tube (RFD) linac structure. Both the prototype and the production unit will operate at 600 MHz. The prototype comprises a 25-keV proton source, a short LEBT, a 0.65-m-long RFQ linac to 0.8 MeV, and a 0.35-m-long RFD linac to 2.5 MeV. Because of the similarity of the accelerating and focusing properties of the RFQ and RFD linac structures, no matching section is required between them. The two linac structures will be resonantly coupled together and powered by a collection of planar triodes. The prototype is scheduled for completion in the fall of 1997.

Introduction

The RFD Linac Structure[1-3] resembles a drift tube linac (DTL) with radio frequency quadrupole (RFQ) focusing incorporated into each “drift tube”. As in conventional DTLs, these drift tubes are supported on single stems along the axis of cylindrical cavities excited in the TM_{010} rf cavity mode. The RFD drift tubes comprise two separate electrodes, operating at different electrical potentials as determined by the rf fields in the cavity, each supporting two fingers pointing inwards towards the opposite end of the drift tube forming a four-finger geometry that produces an rf quadrupole field distribution along the axis. The fundamental periodicity of this structure is equal to the "particle wavelength", βλ. The particles, traveling along the axis, traverse two distinct regions, namely gaps between drift tubes where the acceleration takes place, and regions inside the drift tubes where the rf quadrupole focusing takes place.

Most proton and light-ion linac systems start with an RFQ linac section to capture the beam from the ion source and to bunch it for acceleration in more efficient linac structures. The RFD linac structure provides a graceful way to accelerate the small diameter, tightly bunched beams that come from RFQ linacs to higher energies. Because of its rf electric focusing, the RFD linac structure operates well at much lower energies than the conventional magnetically focused DTL linac. Consequently, the transition energy between the RFQ linac, required to capture the unbunched beam from the injector, and the RFD linac can in the range of 0.5 to 1 MeV, significantly lower than for conventional RFQ/DTL combinations.

The Prototype

The “Proof-of-Principle” prototype, under construction at Linac Systems, involves acceleration of a 25-keV proton beam from the ion source to 0.8 MeV in a 0.65-m-long RFQ linac and on to 2.5 MeV in a 0.35-m-long RFD linac structure. The experimental setup, made possible by an SBIR Grant from the National Institute of Mental Health, is shown in Fig. 1. At this relatively low transition energy, the acceleration and focal properties of the RFQ are very close to that of the RFD. Consequently, little or no matching is required between the structures. The RFQ structure can be bolted directly to the RFD structure and resonantly coupled to it. The extreme simplicity of the interface between the two structures contributes to the practicality of this operational test on a limited budget. The entire length of the two linacs, including their interface, is only one meter. We believe that this new structure will become the structure of choice to follow RFQ linacs in many applications.

The ion source and LEBT system can be of conventional design. The ion source will be a simple duoplasmatron of the type used in the PIGMI program at Los Alamos in the late 70s. This design is readily available in the public domain. The LEBT will consist of a drift space to let the beam expand followed by one or two einzel lenses for focusing the beam into the aperture of the RFQ linac. A current toroid at the entrance to the RFQ will provide a measure of the beam current at that point. An ultra-thin vacuum valve will provide vacuum isolation between the LEBT and RFQ regions.

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* Work supported by the National Institute of Mental Health, (NIMH).
Because of the exceptional low-energy capabilities of the RFD structure, the RFQ linac need only go to 0.8 MeV. The cross section of this 0.65-m-long RFQ structure is shown in Fig. 2. The width of the assembly is only 0.16 meters. It will be built out of tellurium copper in four pieces as shown in the figure. The cooling channels will be gun drilled. The vane tips will be contoured by a "V-shaped" die in a die-sinker type of EDM machine. The four pieces will be pinned and bolted together (copper bolts), and hydrogen furnace brazed together, using the wire alloy technique tested recently by LANL. It will also be brazed to its stainless steel mounting flange at the same time. As the RFQ is surrounded by an aluminum vacuum jacket, these brazes and penetrations (monitor loops, coupling slots, etc.) need not be vacuum tight.

The average rf power dissipation in the structure is 3 kW, approximately 2 kW of which are dissipated in the tank wall. The cooling channels are gun drilled in the tank wall. Provisions are made at the ends of the tank to put some of these channels in series. All water connections to the tank will be near the bottom of the structure.

The tank will be oriented with the welded bar at the bottom. The purpose of the welded bar is to provide a thicker wall on which to mount the drift tubes. After all the tank welds are finished and it has been heat treated, the mounting holes for the drift tubes will be precision bored through the thickened tank wall. These holes represent "hard sockets" for the drift-tube stems. No provision will be made for further alignment of the drift tubes. This of course, requires that the drift tubes be built with adequate precision to achieve the required alignment.

To achieve the required precision in the drift-tube fabrication, the drift tubes will be built in two stages, each ending with a hydrogen furnace braze. In the first stage, the stainless steel stem base will be joined to the stainless steel tubing of the inductive stem, a stem-stiffening frame, and a copper annulus that forms the central portion of the drift-tube body.

Fig. 2. Components of the RFQ Assembly.

Enclosing the RFQ structure inside of a vacuum jacket simplifies some facets of the design and complicates others. Special provisions have to be made for electrical and cooling services and their connections. The cooling water will come in and out through the bottom edge of the RFQ mounting flange and be routed to supply and return manifolds running the length of the RFQ inside the vacuum jacket. The electrical connections (monitor loops, thermal couples, etc.) will terminate on a panel that seals to a window frame in the vacuum jacket that is on the back side of the RFQ.

The RFQ/RFD interface is extremely simple. The RFQ structure will be bolted directly to the RFD structure. There will be no provision for beam manipulation (steering), beam diagnostics, or vacuum isolation at this interface.

A resonant coupler, designed to couple the excitation of the two linac structures together by locking their fields in phase and amplitude, will be employed. This resonant coupler will extract precisely the right amount of rf power from the RFD structure to excite the RFQ structure. Such couplers operate in the r/2 rf cavity mode and are well understood. They have been employed in many standing-wave linac applications since the discovery of their potential by researchers at Los Alamos in the mid '60s.

The RFQ/RFD interface region with resonant coupler.
After this assembly is furnace brazed, the stainless steel parts are copper plated and the stem base is precision ground to its final length and diameter. In the second stage, the precision-ground portion of the stem base is held in a precision jig, coolant is circulated through the drift tube body, and a precision seat is machined into the copper annulus by the die-sinker EDM process. Then precision end caps (different for each drift tube) are positioned in these precision seats and the final assembly is furnace brazed together.

The finished drift tube assemblies are inserted into their hard sockets from the inside of the tank. This requires that the completed drift tube assembly be somewhat shorter than the inner tank diameter. We insist on being able to remove and reinstall any drift tube without disturbing its neighbors. The principal drift-tube-stem vacuum seal is a proprietary copper seal. A secondary elastomer seal on each stem provides for vacuum-checking convenience and a backup vacuum capability.

Approximately 1 kW of rf power is dissipated in the 12 drift tubes of the structure, implying an average of 80 W/drift tube. They will all be cooled, in parallel, from supply and return headers running along the top of the support cabinet below the linac.

The 600-MHz rf power system for the proof-of-principle test must have a peak rf power output of 250 kW with an average value of 3 kW. This kind of power can be obtained from a collection of 6-to-8 Einac Planar Triodes (YU-141). One of the authors (JMP) has extensive experience in this field and has conceived of a new geometrical configuration to facilitate this combination. We expect JP Accelerator Works, Inc. to supply the rf power system for this test.

The vacuum system for the proof-of-principle test will consist of one turbo pump on the ion source/LEBT, one turbo pump on the RFQ linac structure, one ion pump on the RFD linac structure, and one roughing pump shared by all systems through a set of valves. We will strive for metal seals where they are convenient or where they involve critical components that are hard to replace (drift tubes, for example). We will accept elastomer seals on some of the large joints between tank sections and end plates.

The cooling system for the proof-of-principle test will be a recirculating system, based on a single commercial unit with a temperature control capability of ±1°C and a capacity of 3 kW. Some deionized cooling capacity will be needed for the high voltage parts of the rf power system. An additional 5 kW of cooling, without sophisticated temperature control, will suffice for the rest of the system.

The control system for the proof-of-principle prototype will be PC-based. It will utilize commercially available control and equipment oriented software. Its principle function will be to support important personnel safety and equipment protection functions, some beam diagnostic measurements, and some data-logging functions to assist in accident reconstruction. The control of most accelerator parameters will be accomplished manually in the course of developing the required controls procedures.

The beam diagnostics for the proof-of-principle test will be based on beam transmission measurements (current monitors), beam profile measurements (wire scanners), beam loading measurements (rf power monitor), and energy discrimination measurements (absorber foil).

Potential RFD Applications

We expect the RFD linac structure to form the basis of a new family of compact, economical, and reliable linac systems serving a whole host of scientific, medical, and industrial applications. The principal medical applications include the production of short-lived radio-isotopes for the positron-based diagnostic procedures (PET and SPECT), the production of epithermal neutron beams for BNCT, and accelerated proton beams for injection into proton synchrotrons to produce the energies required for proton therapy. S-Band versions of the structure might prove economical enough to serve as 70-MeV injectors to 250-MeV coupled cavity linacs (CCL) for the proton therapy application.

The principal industrial and military applications include the production of intense thermal neutron beams for Thermal Neutron Analysis (TNA), Thermal Neutron Radiography (TNR), and Nondestructive Testing (NDT). High duty factor RFD linac systems could produce nanosecond bursts of fast neutrons to support Pulsed Fast Neutron Analysis (PFNA).

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http://www.linac.com/
COUPLING SLOTS WITHOUT SHUNT IMPEDANCE DROP

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Abstract

It is well known that coupling slots between adjacent cells in a π-mode structure reduce shunt impedance per unit length with respect to single cell cavities. To design optimized coupling slots, one has to answer the following question: for a given coupling factor, what shape, dimension, position and number of slots lead to the lowest shunt impedance drop? A numerical study using the 3D code MAFIA has been carried out. The aim was to design the 352 MHz cavities for the high intensity proton accelerator of the TRISPAL project. The result is an unexpected set of four "petal" slots. Such slots should lead to a quasi-negligible drop in shunt impedance: about -1% on average, for particle velocity from 0.4 c to 0.8 c.

1. Introduction

The TRISPAL[1] linac is designed for producing a 40 mA beam of 600 MeV protons. The aim is tritium production from spallation neutrons. The main part of the linac (from 100 to 600 MeV) is made of coupled cells cavities at 352 MHz. This rather low frequency has been chosen for klystron availability, and because SUPERFISH simulations showed that for a given beam tube diameter \( \Theta = 50\,\text{mm} \), the shunt impedance was almost the same for 352 and 704 MHz cavities. Moreover, this choice leads to a small number of cell per cavity which permits to use the simple and efficient π-mode structure.

First of all, the 2D geometry has been optimized with the code SUPERFISH [2]. The resulting cell is shown in fig.1.

![Fig. 1 Optimized 2D cell (β_0=0.7)](image)

2. Optimized slots

In a multi-cell cavity [3], slots have to be performed between adjacent cells in order to spread the RF power within the whole cavity. They must be big enough to insure a flat π-mode, but usually, this reduces the shunt impedance.

A systematic optimization of the slots has been carried out with the code MAFIA. We chose a fixed velocity value \( \beta_0=0.7 \) and started with slots inspired from the LEP cavities [4]. We computed the coupling factor, defined from the frequency difference between 0 and π modes:

\[
\gamma = \frac{f_0 - f_n}{f_n},
\]

(1)

and the shunt impedance drop defined from the difference of shunt impedance between π-mode and a single cell cavities:

\[
\delta R = \frac{R_{\pi} - R_1}{R_1},
\]

(2)

Fig. 2. Slots optimization: starting and final cases. (*: variations with respect to a single cell cavity)

![Fig. 2 Slots optimization](image)

![Fig. 3 1/8 of a cell with "4-petals" slots as computed by MAFIA (colours represent surface power dissipation).](image)

Fig. 3 1/8 of a cell with "4-petals" slots as computed by MAFIA (colours represent surface power dissipation).

in which indices π, 0 and 1 represent values of π-mode, 0-mode and single-cell modes, respectively. As these differential values are rather small, the three cases are always
computed with an identical mesh, in order to get rid of the bias due to the meshing approximation.

In order to distinguish between volume energy and surface dissipation effects, we split the shunt impedance into two factors: quality factor $Q$ and geometrical impedance:

$$ g = \frac{R}{Q} = \frac{1}{2PQ} \int E_z \times \exp(i\omega z / \beta c) \, dz. $$  \hspace{1cm} (3)

Analogously to $\delta R$, relative variations of $Q$ and $g$ (between $\pi$-mode and single cell) are noted $\delta Q$ and $\delta g$, respectively.

Then, we changed step by step the size, the number and the shape of the slots. At each step, we watched how the coupling factor and the shunt impedance drop would vary. Our goal was to keep the same coupling factor and to minimize the shunt impedance drop. We will not give here the winding path we followed during the optimization process, but fig. 2 shows the starting and ending points. Fig. 3 is a 3D view of the MAFIA computation.

3. Variations

We will consider here variations from the 4-petals geometry to show that it is optimized. All the results about $Q$, $g$ or $R$ are given with respect to a single cell cavity.

Number of slots. First of all, the number of slots per disk has been reduced to two instead of four.

<table>
<thead>
<tr>
<th>slots</th>
<th>$\gamma$</th>
<th>$\delta Q$</th>
<th>$\delta g$</th>
<th>$\delta R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-petals</td>
<td>0.66%</td>
<td>-2.8%</td>
<td>+2.6%</td>
<td>-0.4%</td>
</tr>
<tr>
<td>4-petals</td>
<td>1.38%</td>
<td>-5.6%</td>
<td>+5.2%</td>
<td>-1.0%</td>
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Roughly, all effects are proportional to the number of slots. The "price" for coupling is approximately: $\delta R \approx 0.7 \times \gamma$.

Slot width. It has been varied from 80 to 200 mm. As shown in fig. 4, the coupling coefficient is approximately proportional to the cube of the slot width. On the other hand, the shunt impedance drop increases linearly from a slot width of 100 mm. From this value, the price to pay for increasing the coupling is: $d(\delta R)/dy \approx 3$. This is much more "expensive" than increasing the number of slots. This would suggest a slot width of 100 mm with six slots per disk. But, compared to the optimized solution, the shunt impedance improvement would be rather small and the cooling circuit would be much more complicated.

Slot height. Upper and lower limits measured from the axis have been varied independently. Fig. 5a shows that the lowest shunt impedance drop is reached by the highest upper limit, while the coupling coefficient remains constant in this area. We just kept a 5 mm margin from the highest possible value of the upper limit (i.e. the cell radius), in a way to simplify the mechanical design. Fig. 5b shows that the lower limit is as small as possible: the coupling increases and the shunt impedance drop gets smaller. The limitation is given by the cooling circuit.

### Fig. 5. Influence of slot height.

Limits are from the z-axis. The optimized case is circled.

4. Other particle speeds

As proton energy varies along the linac, the cell length varies according to the velocity, and the gap length has to be adjusted. Simulations showed that the goal frequency could be reached by varying the gap length according to:

$$ gap = 234 \text{ mm} \times (\beta - 0.15). $$

Figure 6 gives the characteristics of the coupling slots for different speed values. According to MAFIA results, $\gamma$ varies approximately in $1/\beta$. The frequency detuning factor due to the slots volume ($\alpha$, defined as the relative difference between the $\pi$-mode and a purely 2D cell) is almost constant ($\approx 1.4\%$). In all cases, the slots actually improve the
geometrical impedance (δg<0), but this effect is more important for low speeds. On the other hand, the slots always reduce the quality factor. This effect does not seem to depend on β: (6Q>7), but the result suffers from numerical noise probably due to the mesh approximation. The net result in shunt impedance is null for β=0.6.

5. Higher order modes

Influence of slots has been investigated on the first higher order modes. We computed the bandwidth of these modes in the "2-beans" and "4-petals" cases. As far as we investigated monopole and dipole modes under 1 GHz, we did not see any evidence of dangerous modes emerging. Table 1 gives the data of the TM110 mode (generally considered as the most dangerous one).

<table>
<thead>
<tr>
<th>Table 1. TM110 mode coupling characteristics.</th>
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<tr>
<td>g&lt;sub&gt;z&lt;/sub&gt;, Ω/m</td>
</tr>
<tr>
<td>ω, MHz</td>
</tr>
<tr>
<td>Δt</td>
</tr>
</tbody>
</table>

6. Computations with other codes

The 4-petals geometry has been computed with two other 3D electromagnetic codes: ANTIGONE [5] (which can use two solving methods: E or H), and SORPRANO [6]. The aim is not to compare absolute code performances, but rather to get more confidence in the results. As a matter of fact, the codes raw results are juxtaposed here without any consideration about meshing and solving methods, number of points, symmetry used, computation time, etc.

**Single cell results.** These may be compared with the ones of the well known 2D code SUPERFISH (Table 2). Numerical values are very close from each other, except for Q-value which seems underestimated by MAFIA.

<table>
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<tr>
<th>Tab. 2. Single-cell and 0-mode results with 3D codes (Superfish for single-cell)</th>
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<tr>
<td>Superfish</td>
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<td>Soprano</td>
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**Effects of coupling slots.** According to results of Table 3 (γ,δQ,δg), the slots effects are rather coherent. The only strong difference comes from the Q drop which is much more important according to ANTIGONE-H.

7. Interpretation and conclusion

The quality factor drop may be interpreted as follows: the surface current lines, which are radial in the iris of a non coupled cell, have to deviate because of the coupling slot. This induces a current concentration on the slot edge in the π-mode. In the 0-mode, the current lines do not deviate but cross through the slot to the next cell (See fig. 7).

Until now, we have no explanation on geometrical impedance improvement due to slots. Actually, a small part of this effect (about one fifth of it) can be explained with transit time factor variation. As real cavity must be tuned anyway at the right frequency, this effect should be deduced by using the goal frequency (π=2π×352 MHz) instead of the one of each mode in the impedance formula (eq. 3). This would lead to a conclusion a little less optimistic for δg (about -1%), but as this correction should also be applied to the "2-beans" shape, the conclusion is unchanged.

A cold model experimentation is planned to settle the point of Q-factor drop, as code results do not totally agree.

![Fig. 7. Slots influence on current lines and Q value.](image)

**Acknowledgments**

The author thanks G. Le Meur from LAL (Orsay) who developed ANTIGONE and carried out the computations presented here. The author is debtsful to C.Riley from Vector Fields Ltd (Oxford) for his processing with SORPRANO.

**References**

APPLICATION OF RF CROSSED LENSES FOR BEAM FOCUSING IN LINAC

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Abstract

A method of beam focusing by two-electrode RF crossed lenses with decelerating fields is proposed. The lenses are arranged in accelerating gaps of a drift tube linac. The crossed lens is a set of plane electrodes with rectangular apertures such that the apertures in the neighbouring electrodes are rotated 90° each other. Different variants of the focusing period structure are considered. The βλ FD period is shown to be used for low energy part of the linac. The transverse phase advance for the FD period is independent on the particle phase when the synchronous harmonics of the accelerating field is absent and the structure is analogous to RFO with unmodulated vases in the case. In the main part of the linac it is worth to change to the 2βλ FODO period to obtain essentially higher acceleration rate.

Introduction

At present two basic methods of RF focusing of ions are used in linacs: the quadrupole focusing (with spatial-uniform and spatial-periodic structures) and alternating-phase focusing (APF) [1]. The spatial-uniform quadrupole (RFQ) focusing [2] and focusing in spatial-periodic systems of RF quadrupoles with "horned" electrodes [3] enable to obtain large phase length of radial stability region and high current limit. A common disadvantage of these methods is rather low acceleration rate. Besides a serious problem of maintenance of necessary electrical strength in accelerating system arises at realization of gaps with put forward electrodes ("horns"). The beam focusing in spatial-periodic system of RF rectangular aperture quadrupoles [4] and also alternating-phase focusing provide high acceleration rate, however, herewith a region of radial-stable phase capture is significantly reduced. The focusing strength in the structures decreases with enhancement of particle energy a fact that results in increase of transit time of the focusing period with a distance along the linac. Since an equality of instantaneous transverse frequencies at joints of periods with different transit time is difficulty satisfied, there is the growth of the effective emittance in the linac due to the beam mismatching with the channel.

Below a method of ion focusing in linac by decelerating fields of RF crossed lenses [7] is considered which permits to obtain phase length of radial stability region up to 360° and energy-independent focusing strength, as well as high values of current limit at low injection energy and acceleration rate.

Variants of focusing period structure

The considered method of beam focusing [7] is based on use of system of crossed lenses, to electrodes of which RF voltage is applied. Note, that the lenses with electrostatic fields are widely used in ion and electron optical systems [5]. The crossed lens is a set of plane electrodes with rectangular apertures such that the apertures in the neighbouring electrodes are rotated 90° each other (see Fig. 1).

![Fig. 1. Two-electrode crossed lens.](image)

We choose a ratio of sides for the rectangular apertures from a condition a/b<1 (see Fig. 1), then an electrical field component, directed along the slit, is negligible as compared with a component across the slit.

Within the considered method the two-electrode RF crossed lenses with decelerating fields are arranged in accelerating gaps of drift tubes linac. FODO structure of focusing period with arrangement of the crossed lenses through a gap of accelerating system, formed by drift tubes with round apertures, is shown in Fig. 2.

![Fig. 2. FODO focusing period with RF crossed lenses (a) and focusing gradients (b): 1, round aperture drift tubes; 2, two-electrode RF crossed lenses.](image)

The lenses are identically aligned within the limits of the focusing half-period and rotated 90° in the subsequent one. The drift tubes and lenses are supplied in RF resonant system operating in π-mode.
A spatial distribution of focusing gradients in the FODO period is displayed in Fig. 2b. The radial particle motion is determined by transverse components of the accelerating fields and quadrupole fields of the crossed lenses. The accelerating field causes RF beam defocusing for autophasing ($\varphi_u < 0$) mode. Owing to accepted orientation of the lenses and application to them appropriate RF voltage a particle moving along the axis undergoes action of the quadrupole fields with sign-alternating gradients (see Fig. 2b). It results in the effect of strong focusing in the channel.

Advantage of the method of beam focusing by the RF crossed lenses is opportunity in the best way to combine RF focusing and acceleration of the beam in the linac.

To see this we take the following into consideration. Firstly, use of the decelerating areas allows considerably to increase the focusing gradients, because directions of transverse field components inside the crossed lenses and between them coincide (see Fig. 2b). Secondly, since the quadrupole field gradients are not decreased with reduction of sizes of the decelerating areas, it is possible by choice of number of the crossed lenses in accelerating gaps to get energy-independent focusing strength and also expand the radial stability region. The expansion of radial stability region occurs due to increase of time of beam interaction with the quadrupole fields. Thirdly, decrease of acceleration rate caused by the decelerating areas is insignificant, since the ones are chosen rather narrow and arranged in that part of the accelerating gap, where energy gain of particle is small.

Advantage of the method of focusing by the RF crossed lenses is also a fact, that the method is easily combined with other ways of RF focusing, for example, focusing by the RF rectangular aperture quadrupoles (see Fig. 3) or/and alternating-phase focusing ($\varphi_u(z)$ is a sign-alternating function in Fig. 2). In this case it is possible to achieve reduction of number of the crossed lenses and, consequently, increase of the acceleration rate, keeping all advantages of the proposed method.

Analysis of stability of particle motion

We consider a focusing by the RF crossed lenses in accelerating system with rectangular aperture drift tubes.

Fig. 3. FD focusing period with RF crossed lenses (a) and focusing gradients (b): 1, rectangular aperture drift tubes; 2, two-electrode RF crossed lenses.

FD focusing period of length $S=\beta\lambda$ formed by two RF rectangular aperture drift tubes and pair of the crossed lenses is presented in Fig. 3. A feature of the given period is absence of spatial variation of focusing gradient sign along the structure axis (see Fig. 3). Obviously, that this property is kept for any number of the lens pairs. The strong focusing effect in this period, as well as in RFQ, is reached only by time variation of the field.

Let $\varphi_u$ (negative for autophasing mode) is the synchronous phase in centre of gap between the drift tubes, $d$ is the thickness of drift tubes and electrodes of crossed lenses, $G$ and $g$ are the lengths of accelerating and decelerating gaps respectively (see Fig. 3). Then according to results of Ref. [6], the expression for transverse phase advance per period $S$ at $dS / e < 1$ has the form

$$\cos \mu = 1 - 4p_0 \left( \frac{1}{2} - \sin \frac{\pi g}{S} \right) \sin \varphi_u - 8p_0^2 \times$$

$$\times \left[ \frac{G + g}{S} \left( \frac{3G + g}{S} \right) \sin \frac{\pi g}{S} \sin^2 \varphi_u \right. +$$

$$+ \left. \frac{1}{2} \frac{2G}{S} \left( 1 - \frac{2G}{S} \right) \left( \cos 2\varphi_u + \cos \frac{2\pi g}{S} \right) \right],$$

where constant within the limits of period parameter $p_0$ is defined by a relation

$$p_0 = \frac{eZe_G\lambda}{2AW_0\beta\gamma} k_F = \frac{eZe_G\lambda}{2AW_0\beta\gamma} k_F,$$

$E_G$ and $E_q$ are the field amplitudes in accelerating and decelerating gaps; $e$ and $W_0$ are the charge and rest energy of proton; $Z$ and $A$ are the charge and mass numbers of ion; $\beta$ and $\gamma$ are the average reduced velocity and energy of ion; $\lambda$ is the wavelength of accelerating field; $k_F = \lambda / \beta \lambda$.

At $G = g$ a synchronous harmonic of the field is absent and particles are not accelerated, then formula (1) is reduced to equality

$$\cos \mu = 1 - 4p_0^2 \frac{3}{3}.$$

As it follows from (3), the average transverse tune does not depend on a particle phase. Therefore it is possible to consider the FD period structure at $E_G = E_q$ and $G = g$ as analogue of unmodulated RFQ channel. Decrease of field amplitudes in lenses ($E_q < E_G$) or reduction of lengths of decelerating gaps ($g < G$) results in effect of resonant particle acceleration and is equivalent to introduction of vane modulation in RFQ.

It is advantageous to use the FD periodic structure (see Fig. 3) as an initial part of the linac because this structure provides high current limit, due to large phase width of radial stability region and small length of the focusing period $S = \beta\lambda$, and allows low injection energy, since the drift tubes and lens electrodes can be rather thin. The initial part of the RF crossed lens linac can be designed according to the procedure accepted for RFQ and contain 6D-matching, adiabatic bunching, and regular acceleration sections. In this case it is possible to get the linac parameters similar to the RFQ ones.

In the main part of the linac, where the bunches are already shaped and efficiency is the principal parameter of the accelerating system, it is worth to change to FODO period of length $S = 2\beta\lambda$ (see Fig. 2) to obtain much higher acceleration rate as compared with the FD period (see Fig. 3).
We consider stability of proton motion in the FODO focusing period (see Fig. 2) at the following parameters: the field amplitudes in accelerating and decelerating gaps $E_a = E_d = 160$ kV/cm, the transverse phase advance $\mu = 60^\circ$, and the synchronous phase in centre of gap between drift tubes $\phi_{s} = 30^\circ$ (see Fig. 2). For the FODO period a dependence of the minimum number of crossed lenses providing stable radial motion of particles within the limits of separatrix on proton energy is presented in Fig. 4a (curve 2). The appropriate acceleration rate for given energy is shown in Fig. 4b (curve 2).

Fig. 4. Number of RF crossed lenses in focusing period (a) and acceleration rate (b) vs proton energy for FODO (1, rectangular aperture drift tubes and sign-alternating phasing; 2, rectangular aperture drift tubes and autophasing; 3, round aperture drift tubes and autophasing) and FFDD structures (4, rectangular aperture drift tubes and autophasing).

The FODO accelerating system is rather effective. In autophasing mode for FFDD structure [7] with the same parameters lenses are required almost 40% more than in the FODO system (cf. curves 4 and 2 in Fig. 4). Herewith distinction in the acceleration rate is about 20% (cf. curves 4 and 2 in Fig. 4b). The decrease of necessary number of crossed lenses in the FODO system is caused by the well known effect of lens focusing strengthening by a drift space.

Note, that the focusing properties of the FODO period weakly depend on a configuration of the drift tubes and are mainly determined by fields of the crossed lenses. Under other conditions being equal, for the FODO period with round aperture drift tubes the crossed lenses are required only 10% more than for the similar period with rectangular aperture ones (cf. curves 2 and 3 in Fig. 4). Besides manufacture of the round apertures in drift tubes is easier than the rectangular ones.

It is possible to reduce a number of the crossed lenses in the focusing period and, consequently, to increase acceleration rate in main part of the linac through decrease of RF defocusing by change from autophasing to sign-alternating phasing. For the FODO system with sign-alternating phasing $\mu = 60^\circ$ and length of radial-phase stability region $90^\circ$ are reached at number of the lenses in the focusing period $N = 2-18$ and the field in them 160 kV/cm in a wide energy range from 2 up to 100 MeV (see Fig. 4a, curve 1). Herewith the acceleration rate is 6-8 MeV/m (see Fig. 4b, curve 1). By the last parameter the considered system is on a par with the APF linac. For the similar structure with autophasing $N = 6-20$ crossed lenses are required, a fact that results in decrease of the acceleration rate down to 5-7 MeV/m (see Fig. 4a, curve 2).

References

SOME NEW ITEP APPROACHES TO DESIGN OF HIGH INTENSITY PROTON LINAC FOR TRANS MUTATION

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Abstract

The basic problems for construction of high intensity linear accelerator are providing of high efficiency, reliability and reduction of induced radioactivity in its parts. In the framework of ITEP feasibility study of linac for nuclear transmutation on energy about 1 GeV with a current up to 100 mA some new version of the accelerator is considered. It is shown that the rigidity of the focusing has to be increased to prevent large particle losses. For the given value of beam current it can be achieved by the using as short lengths of focusing periods as possible. Main part of the linac consists of a large number of single-gap independent accelerating cavities. It is supposed, that the basic constructional material for these resonators will be graphite.

It is shown, that such approach to design of main part of the linac allows to increase reliability of the accelerator, to reduce the requirements for mechanical tolerances of resonators and to improve parameters of a longitudinal movement of particles. It is also shown, that the replacement in large extent such conventional for linac design materials as steel, aluminium and copper on materials with small residual activation and low neutron production rate allows to increase the upper limit of permissible level of particle losses in linac. Graphite as main material of resonators will allow to build the linac with relatively low induced activation. It will provide handle maintainability at an achieved up to that time particle losses level.

Introduction

The projects of the high power proton linacs (≈100 MW) have been offered in various laboratories for nuclear power installations. They are designed practically under the same block scheme with very similar parameters of the beam. They are conventional CW RF linacs based on several types of accelerating structures, which are working in the existing low power linacs. These structures are RFQ as an initial part of the linac, some versions of DTL for intermediate part with beam up to ≈ 100 MeV, DAW and CCL structures for acceleration of the beam up to target energy [1]. The parameters of these linacs are chosen from the spallation neutron production efficiency and the linac electrical efficiency. The value of the beam current 100 mA and output beam energy ≈ 1000 MeV, at the moment indicated in the most of the projects, are chosen to satisfy these requirements. The proposed projects are the realistic solution of a high power accelerator design. However there is not only the problem of efficiency. To build the linac with high average beam power of it is necessary to solve a critical problem of the accelerator parts activation. The permissible value of particle losses under conditions of hand-operated service of installation is equal 0.1 - 1.0 nA/m and depends on energy of the beam [1,2]. It means, that in the powerful linac constructed in accordance with the proposed schemes and with the parameters mentioned above, the level of relative losses should be reduced in two order of the magnitude in comparison with achieved in LAMPF linac level.

The processes, leading to the beam halo formation, are now under investigation very widely both analytically and with simulations of beam dynamics [3,4]. As result it was essential progress in the understanding of that fact, that particle motion nonlinearity at the presence of space charge is the main factor of the particle losses. Due to results of these investigations have been already changed some basic parameters of the proposed linacs in comparison with the projects, considered earlier: a current of the beam is reduced, a focusing strength and an aperture factor are increased, the better beam matching with the linac channels is provided etc. Nevertheless the existing methods for studies of beam halo formation give mainly qualitative results, not allowing to obtain exact value of particle losses in different parts of the linac. Therefore, problem of the minimization of particle losses in the linac is still actual.

The low activation of the powerful linac can be achieved not only by reduction of the level of losses, but also by using the materials with low induced activity for construction of linac accelerating structures and transport channels.

Opportunity of maintenance of low activation level of the accelerator both by an optimum choice of parameters of linac focusing channels and by use of the appropriate materials in the linac design is discussed below.

Numerical simulation

In spite of the facts that in a recent beam dynamics simulations are used very large number (1-2 · 10⁹) macro particles and the special codes for beam halo formation investigation were developed, there is no reliable method to predict the particles losses in the high power linacs [4,5]. It is due to extreme low allowable level of relative particle losses. The analysis of a beam motion nonlinearity degree and determination of its allowable level can be more convenient. According to the general nonlinear mechanics theorems the small nonlinearity should result in limited perturbation of the particle trajectories in phase space. The increasing of the nonlinearity degree leads to the particles motion in the phase space with mixing and, correspondingly, to the appearance of motion chaoticization. The beginning of this process corresponds to a beam emittance growth.

The consideration of some specific spectral properties of dynamical system in the transition region from order to
chaos is given in [6]. It is based on the study of the spectral density of the correlation function \( R_N(\omega_m) \) calculated for sequence of particle coordinates \( x_k \) stored in certain crosssection in every cell during the simulation. The correlation function is:

\[
R_N(\omega_m) = \frac{1}{N} \sum_{-N/2}^{N/2} R_N(k)e^{-i\omega_m k}
\]

\[
R_N(k) = \frac{1}{N} \sum_{-N/2}^{N/2} x_j x_{k+j}
\]

\( \omega_m = 2\pi \frac{m}{N} \)

In this expression \( N \) determines the number of stored points for every particle trajectory.

It follows from given in [7] spectrum correlation function qualitative analysis that it is determined by structure of the phase space. In the presence of space charge it can see inside phase space the stability islands which correspond to the resonances of different orders [4]. The spectrum becomes wider and more uniform. There is one more universal spectral property. Well marked peak appears for zero frequency (so called “central peak”). It is due to some trajectories pass the vicinity of hyperbolic points of the separatrix for a very long time or pass near the border of stability region.

This method was used to analyze the ITEP beam dynamics simulation results for the different structures of the high power linac. The spectra were calculated for 30 particle trajectories in dependence of space charge parameter \( h \):

\[
h = \frac{n\lambda}{\sigma_0 \beta \gamma^2 I_0} e
\]

Where \( n \) - length of focusing period in \( \beta \) unit; \( \beta \) - particle relative velocity; \( \gamma \) - relativistic factor; \( \lambda \) - RF field wavelength; \( \sigma_0 \) - transverse oscillation phase advance at zero current; \( I_0 \) - characteristic current equal for protons \( 3.13 \times 10^7 \) A; \( I \) - average beam current; \( e \) - normalized beam emittance.

This combination can be a fruitful for estimation of nonlinearity degree of particle motion in focusing channel.

The results of ITEP simulations analysis are shown in fig. 1. In this figure are presented data for DTL section (intermediate part of an accelerator) with the parameters of the beam and channel given in Table 1.

The curves in figure represent dependences of average frequency \( \sigma \) in the spectrum of corresponding correlation functions, and also the lower \( \sigma_l \) and upper \( \sigma_u \) borders of the spectra on space charge parameter \( h \).

It follows from the figure that for \( h \geq h_i \) the particles with zero frequency appear in the beam. The presence of zero frequency in a spectrum of correlation function (central peak) testifies that some particles change their amplitudes under influence local instabilities. In the simulation results displayed in Fig. 1, the lower border of a spectrum reached zero at \( h = 0.2 \), and the emittance growth began be considerable starting from the same point. It is possible to assume, that the value \( h_i \) of space charge parameter \( h \) at which the lower spectrum border of the correlation function reaches zero, can serve as the upper limit of a beam current for the given channel, at which the particles motion has laminar character.

![Graph showing dependence of average transverse particle oscillations frequency and border frequencies of spectra on space charge parameter. 1 - \( \sigma_l \), 2 - \( \sigma_s \), 3 - \( \sigma_u \).](image)

**Table 1**

<table>
<thead>
<tr>
<th>Operating frequency</th>
<th>350 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial average frequency of transverse oscillations</td>
<td>60 MeV</td>
</tr>
<tr>
<td>Length of focusing period</td>
<td>( 2\beta \lambda )</td>
</tr>
<tr>
<td>Type of focusing period</td>
<td>FODO</td>
</tr>
<tr>
<td>Beam emittance</td>
<td>0.2 cm.mrad</td>
</tr>
<tr>
<td>Beam energy</td>
<td>100 MeV</td>
</tr>
</tbody>
</table>

The space charge parameter, calculated for the schemes without beams funneling proposed in [1] (LANL) and [8] (ITEP) for an average beam current 100 mA are shown in fig. 2. As it can be seen, in ITEP project of accelerator the space charge parameter slightly exceeds the specified above limit in the accelerator intermediate part, and in LANL linac this parameter exceeds the limit in several times. It is due to using in the last case the focusing period lengths with \( n = 10 \), beginning with rather low beam energy. Our results show that in this case it will lead to fast halo formation in this part of the accelerator. To decrease this effect it is necessary to use shorter focusing period in the linac at least at beam energy lower 200 - 300 MeV.

**Activation of high power linac**

The radiating problems can be solved not only by reduction of the particle losses in comparison with achieved level, but also by application of materials, having consid-
Fig. 2 Space charge parameter along linac for LANL (curve 1) and ITEP (curve 2) projects.

If to reduce the use of copper and steel as constructional materials in the linac as much as possible and to replace them by graphite (in which lost particles will be mainly absorbed), the level of radioactivity will be considerably lowered. The accelerator becomes practically clean from the radioactivity point of view up to energy of 25 MeV at any level of beam losses. In this energy range residual radiation is caused by $^{13}$N and $^{11}$C radionuclides with half-life time of 10 and 20 minutes accordingly, and, hence, radiation near to accelerator is quickly reduced up to allowable level.

Because neutron yield of carbon is less than 10% of copper, the beam focusing can be provided in DTL by permanent magnets.

The allowable level of induced radioactivity of the accelerator with use of graphite corresponds to essentially more high level of the particle losses. At proton energy above 500 MeV of the dose power during 2 hours after switch off the beam becomes 100 times less, than in the case of using of traditional materials for the same beam losses.

The principal possibility of application of graphite in accelerating channel constructions results from physical process features of particles losses in linac. As the accelerated beam has small phase volume, lost particles fall on internal wall with angle less than 10 mrad and, hence, their trajectories pass in thin surface layer. The depth of proton penetration is increased due to repeated Coulomb dissipation of protons on atoms of the wall. The given dependence is obtained in assumption of a uniform distribution of particles losses along the channel and taking into account the fact, that capture of the lost particles takes place in the inner wall substance due to nuclear interactions. The penetration depth is smaller than aperture radius at energies $\leq$ 100 MeV while at the energy range 100 - 1000 MeV the penetration depth is comparable to the accelerating structure sizes.

Our calculations show that in the case of the "graphite" accelerator with 100 mA average beam current relative beam losses should be only slightly lower than those are in LAMPF now to have suitable activation level at high power linac. The permissible level of the relative particle losses may be in our case $10^{-3} - 10^{-4}$. The progress of the accelerator science and engineering during last period allows to hope that this value is achievable goal.

### Conclusion

The permissible level of activation is one of the most important parameters for of high power linac design. It can be possible to achieve required level by decreasing of particle losses and appropriate choice materials of accelerating structures and transport channels. In this report the introducing of the upper limit of space charge parameter is discussed. The limit is based on the study of the spectral properties of the transverse particle oscillations. It is shown that space charge parameters should not exceed value corresponding only 15% phase advance depression. For average beam current 100 mA it leads to shorter focusing period lengths along the linac then in earlier proposed projects of the high power linac.

The introducing into construction of the linac materials with low residual activity and low neutron yield improves considerably the radiation situation at the high power linac. To have hand-on maintenance of the linac the relative beam losses may be only slightly less than those in LAMPF now.

The results of the beam dynamics analysis and study of interaction lost particles with linac materials led to development in ITEP of the new conception of high power proton linac design [9]

Further development of the proposed version of the accelerator design requires thorough numerical calculations. The understanding of the picture of the transport of particles being lost, which undergo multiple reflection prior to their absorption, will help the development of methods for smoothing out the distribution of losses.

It is also necessary to solve technical problems of graphite use in deep vacuum and strong electric fields.

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CONCEPTUAL DESIGN OF LINAC FOR POWER HIF DRIVER

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Abstract

Linac for singly-charged (positive and negative) ions of the four various Pt isotopes has been proposed. Eight beams of different charges and masses of ions are accelerated in parallel RFQ channels to an energy of 100 MeV. The beams are then brought together by a system of alternating gradient magnet for a 180° bending and matching of the beams. The main channel which accelerates all beams together consists of three stages. The first one (till 600 MeV) is a Wideroe structure followed by two consecutive Alvarez channels (2.5 GeV and 10 GeV) having different radio frequencies. Characteristics of the output beam for each kind of ions are: average pulse current 45 mA, horizontal emittance 0.6π cm · mrad, vertical emittance 0.4π cm · mrad, momentum spread ±0.07%, bunch length 3.6 cm, and spacing between bunches of each kind is 15.3 μm.

Introduction

In this work we describe the scheme of a special linac (see Fig. 1) for simultaneous acceleration of eight platinum ions (four isotopes) till maximum energy of 10 GeV. The total average pulse current is 8 × 45 mA. The linac is a beam generator for the power HIF driver with total stored energy 9.6 MJ and total power ≃ 1000 TW [1].

![Figure 1: The total scheme of linac: IS - ion sources; RFQ1,2,3 - injector channels; TMD - transverse matching device; W - Wideroe channel; A1 and A2 - Alvarez channels; all lengths are measured in meters.](image)

Ion source

For ITEP Heavy Ion Fusion Project (IHIFP) it is necessary to have the beams of negative and positive heavy ions with current about 50 mA. The existing now Negativ Heavy Ion Sources (NIS) provide the output current two order of magnitude less. Nevertheless, the simple theoretical consideration show the increase opportunity of NIS current up to requirement level to be realistic.

We are planning to organize our NIS investigation at the injector of the heavy ion RFQ linac (TIPr-1). We suppose to develop this investigation in two directions.

The first - a new version of NIS. As the prototype of this version we have chosen the MEVVA ion source version ITEP-90 [2].

The second, as a reserve variant, Plasma - Shutter NIS, has taken into account. For the effective surface 140 cm² as sputtering target, we hope to receive the heavy negative ion current about 100 mA. It is according to scaling law for plasma ion sources (H.V. Smith, Jr. Paul Allison, and J.D. Sherman - Los Alamos NL).

For IHIFP we plan to use eight ion sources of eight kinds of platinum ions (Pt⁺₁₉₂, Pt⁺₁₉₄, Pt⁺₁₉₆, Pt⁺₁₉₈) are divided into two symmetrical arrays according to the mass and charge sign of ion: four sources of positive ions and four sources of negative ions [1].

All sources produce identical parallel beams: ion energy of 0.15 MeV, beam radius of 0.2 cm, transverse emittance of 24 π cm · mrad in each direction. Each source must provide the entrance separatrix bucket of injector (momentum spread ±10% and phase length 300°) with an average pulse current of 130 mA. The distance between beams in each array is 15 cm. The distance between arrays (measured from the middle axes) is 36 m. The sources of each array are positioned symmetrically with respect to the common axis of symmetry. The higher mass isotope the source is further from the common axis.

Injector

Each ion source is followed by its RFQ injector. All parallel channels are located in one horizontal plane. Four injector channels of each array may share the same vacuum system. The total length of RFQ injector is about 760 m, output energy is 100 MeV. The injector consists of four stages: RFQ buncher (RFQb) and three consequent RFQ accelerating channels (RFQ1, RFQ2, RFQ3) with different radio frequencies (RF). RFQb is essentially the initial part of RFQ1, but the electrodes in RFQb are modulated so that the separatrix length is constant and equal to 3.1 cm. Characteristics of RFQ channels are presented in Table 1 where b is bunch length and a is beam radius. Mismatching of transverse and longitudinal oscillations due to "jumps" of RF is minimized by choice of channel char-
Table 1: The stages of injector and main channel

<table>
<thead>
<tr>
<th></th>
<th>T</th>
<th>L</th>
<th>V</th>
<th>RF</th>
<th>( \varphi_s )</th>
<th>b</th>
<th>( \Delta p/p )</th>
<th>a</th>
<th>( \varepsilon/\pi )</th>
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<td>RFQb</td>
<td>1.1</td>
<td>12.2</td>
<td>190</td>
<td>6.25</td>
<td>37</td>
<td>5.0</td>
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<td>0.29</td>
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<td>7.8</td>
<td>0.14</td>
<td>0.9</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Transverse matching device

The bending magnet arrangement is followed by a transverse matching device to reduce the oscillation amplitudes in the main accelerating channel. The device consists of 6 quadrupole lenses with permanent magnets (for example, \( S = 0.7 \)). A sequence of elements in horizontal plane is L1, L2, D1, D2, L3, L4, D3, L5, D4, L6, D5, L7. All drift lengths \( L \) are 50 cm, the last drift length \( L7 \) is 17 cm, thickness of each lens is 50 cm. Gradients are: in F1 and D1 - 2 kGs/cm, in D2 and F2 - 1.5 kGs/cm, in F3 - 1.3 kGs/cm, in D3 - 0.5 kGs/cm. The total length is 617 cm. At the exit of the matching device, the beam parameters are: horizontal size is 0.8 cm, vertical size is 0.4 cm, length of bunch is 27 cm, momentum spread is ±0.1%.

The main channel

The main channel consists of 3 stages. The first one is a Wideroe accelerating structure, the second and the third ones are Alvarez accelerators with different RF. The design parameters are shown in Table 1. The initial part of each stage is a quarter-wave device for matching the longitudinal oscillation; its parameters are presented in Table 2. The total length of main channel is 4585 m. The focusing is realized by quadrupole lenses with permanent magnets too. The gradient of magnetic field in the lenses is ranged from 0.7 to 3.3 kGs/cm. The three stages of main channel require RF power of \((0.18 + 0.684 + 2.7)\) GW accordingly. The exit beam has an energy of 10 GeV, bunch length is 3.6 cm, momentum spread is ±0.07%, horizontal emittance is 0.6 \( \pi \cdot \text{cm} \cdot \text{mrad} \), vertical emittance is 0.4 \( \pi \cdot \text{cm} \cdot \text{mrad} \), radius is less than 1.1 cm. The distance between identical ion bunches is 15.3 m. The total growth of the longitudinal phase space along
the linac is about 40%. The horizontal phase space increases by about 5 times, the vertical one by about 3.5 times. The calculations were made for ideal channels without misalignments and errors.

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References
TWO-FREQUENCY KLYSTRON AMPLIFIER

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Abstract

The necessity to create the RF sources operating in two frequency mode is supported by the proposals concerning the suppression of the emittance growth generated inside the RF gun [1] and the possibility to increase the limited accelerated charge [2] by involving into the interaction with the beam, in addition to the fundamental harmonic, the highest harmonics of a RF field with the power ratio up to 10:1 and the absolute synchronism of changing phase and amplitude ratios of signals. In this paper we present the preliminary results on studying the possibilities of multiple-frequency RF power generation by a single klystron through installation of a supplementary high harmonic cavity into the exit one after the main output cavity along the beam direction. The physical motivation of the proposal consists in the effect of lengthy bunch rearrangement due to the interaction with the high-strength RF fields. The computer simulation results and experimental data are given.

Introduction

One of the fundamental problems of the physics of accelerators is the one of increasing the accelerated beam current. As is known, the main limits for the permissible accelerated charge values are caused, first of all, by the beam emittance blow up in the injector systems and by the increase of radiated fields amplitude, including that of HEM-type in the accelerating structures. The apparent method to enhance the limited accelerated charge consists in the decrease of the charge density in bunches by increasing their phase length. In this case the emittance growth suppression in the RF injectors can be provided by the multi-frequency operation mode of the RF gun cavity [1] or with a single-mode RF gun, including the correcting cavity in the injector setup. The identical condition for acceleration of all the particles in the lengthy bunch, when the level of radiation fields is considerably decreasing with the form-factor value decrease, can be obtained in the multi-mode acceleration regime in the resulting RF field of a “rectangular” form [2]. In particular, the same is performed in the accelerating interval of proton synchrotrons for widening the region of phase stability and lowering the space charge effect [3]. In both cases one of the most important problem of a practical realization is the generation of absolutely synphase RF fields of sufficiently high levels at multiple frequencies.

In this paper are presented the preliminary results on studying the possibilities of multiple-frequency RF power generation by a single klystron through installation of the supplementary high-harmonic cavity into the exit one after the main output cavity along the beam direction. The physical motivation of the proposal consists in the effect of lengthy bunch rearrangement due to the interaction with the high-strength RF fields.

The Previous Design

It is obvious that during interaction of the bunches of a large phase length with the field of the output cavity, when the total time of interaction is more than a half of RF oscillation period, one part of particles in the bunch is accelerating. In the further passing of the drift space the possibility exists of outflying the main braked part of bunch (“flipping” effect). As a result, the beam may be rearranged so that instead of one bunch formed by the field of a fundamental frequency there will be two flying away bunches in the flow.

It is clear that changing the length of the drift tube one can attain the multiplicity to the wave length in the location of these bunches, i.e. to provide the beam modulation at the multiple frequencies.

Previously, we observed this effect investigating the beam parameters at the bunching system exit of the klystron (“Aurora”-type: 2.797 GHz; 20 MW; 35 % efficiency) [4]. The investigations were performed by a well-known method of reconstruction of the modulated flow structure on a level of spectral components of the output RF power with changing the length of the drift tube. The general view of the installation is shown in Fig.1.

Fig.1. The general view of experimental klystrons with the variable length of the end drift tube (left) and with the additional output cavity (right).

The effect of resonance excitation of the second harmonic signal depending on the space length was discovered (Fig.2).
The increase of the negative gradient of the focusing field in this space region has resulted in decreasing the amplitude of the excited signal at the second harmonic frequency (Fig.3) and simultaneously the small increasing the power level at the fundamental frequency mode. The effect of the power increase at the fundamental mode was observed for the magnetic field gradient values within the limits of the situation where the low energy component of the beam is removed onto the drift space wall and the main bunch is passed into the output cavity [5].

Investigation of the characteristics of a RF field excited by the beam in the supplementary output cavity, identical to the main one and installed after it (see Fig.1), has shown besides the other effects, the considerable increase of the second harmonic level signal as compared to the base model of klystron.

Fig.2. The pulse output power at the frequency of second harmonic as a function of the length of the latter drift space for various anode voltage (a); the output power at the frequency of fundamental harmonic as a function of the drift space for the anode voltage 200 kV (b).

\[
\gamma = \lg(P_2/P_1), \text{ dB}
\]

Fig.4. The relative level of the second harmonic power as a function of the anode voltage in the supplementary output cavity (curve 1) and at the exit of a standard klystron (curve 2).

In our opinion the presented data indicate conclusively on the existence of the effect of an electron bunch rearrangement in the high power amplifiers and confirm the possibility of creating the two-mode operation RF sources.

**Computer Simulation**

In order to check the second beam current harmonic Laval after the output cavity, the 2.5D Particle-In-Cell ARSENAL-MSU code [7] has been applied to B-Factory Linac 50-MW pulse klystron PV3050, which has been developed at KEK [8]. Because of the mass production, the tube performances were carefully studied, and detailed information is available on this tube. Therefore this tube is a good example for theoretical study of high harmonic energy extraction from spent electron beam in klystron. This tube produces 51 MW.
The magnetic field distribution (upper), fundamental and the second harmonic beam current distribution and electronic efficiency (middle) and momentary photo of electrons (lower) downstream the klystron (z/Le - the normalized distance, Le - the electron wave length).

at a 310 kV beam voltage with efficiency 47% at saturation. But theoretical investigations had shown that significant second harmonic beam current Laval can be reached not for optimal regime. So calculations were made for input power 100W, which is below saturation.

(Bz/Bo) distribution is presented. The fundamental and the second harmonic beam current distribution and electronic efficiency (middle slide) and momentary photo of electrons (lower slide) downstream the klystron are shown. Two bunches on the one electron wavelength with different density after the output cavity can be seen on this slide.

The electron beam bunching in normalized (over 2π) phase diagram from the longitudinal coordinate z/Le is presented on Fig. 6. Obtained efficiency 33% corresponds to output power 37 MW. Second beam current harmonic Laval 0.7 from fundamental current is quite high for receiving high RF power on the second harmonic. This value allowed to extract from spent beam second harmonic power near 5 - 10 MW.

Conclusion

The foregoing experimental data and numerical simulation results indicate on the real possibility of creating the high-power klystron amplifier with simultaneous generation of the signal at fundamental and multiple frequency. In turn, the existence of such a RF source can provide a certain progress in the field of accelerators development.

Acknowledgment

The authors would like to express their gratitude to Dr. S. Fukuda for the data on the PV3030 klystron parameters to be used as a base model in the numerical simulation.

References

SUPERCONDUCTIVE STABILIZATION SYSTEMS FOR CHARGED PARTICLE ACCELERATORS

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Abstract

For the development of accelerators the key problem is the maintenance of radial and phase stability of the flow. Wide opportunities in this direction are opened by the application of superconducting systems with using the effects of magnetic potential well. Without restricting the generality of the problem, as a particular case, we have considered the stability and stationary motion conditions for charged particles in the electromagnetic fields of ideally conductive rings. Results of theoretical analysis, based on Lyapunov's stability theory, of the radial and longitudinal particle motion in the superconductive magnetic system are presented. The estimation of criterion and conditions of beam stability is given.

Introduction

It is generally recognized that simultaneous attainment of the intense beam stability along all the coordinates is not possible without involving into interaction the external stabilizing magnetic fields. On our opinion the new principal method of approach to decision of the question of stabilization and concentration of the charged particle beams consists in the development of superconducting (SC) control system based on the use of the effect of the magnetic potential well (MPW) [1].

Model, Formulas and Results

As a particular case, let us study the possibility to use this effect for formation of the electron ring in the collective ion accelerator. Consider the dynamics and stability conditions for particles of the electron ring in the field of the SC magnetic contour (see Fig. 1).

For the case of the movement of S charge particles in the electromagnetic field of the ideally electroconductive ring the Lagrange function to members of the \( \frac{v^2}{c^2} \) order has the form [2]:

\[
L = \sum_{i=1}^{S} \frac{m_i \cdot v_i^2}{2} + \sum_{i=1}^{S} \frac{m_i \cdot v_i^2}{2 \cdot c^2} + \sum_{i=3}^{S} \frac{1}{2} \cdot \Psi_{q_i} + L_{11} \cdot \frac{l^2}{2}
\]

\[
- \frac{1}{4 \cdot \pi \cdot \varepsilon_0} \sum_{i=1}^{S} \frac{q_i \cdot q_j}{R_{ij}} \left[ 1 - \left( v_i \cdot v_j + (v_i \cdot n_{ij}) \left( v_i \cdot n_{ij} \right) \right) \right],
\]

(1)

where \( m_i, v_i, q_i \) - mass, velocity and charge of the i-particle, \( \Psi_{q_i} \) - flow, created by i-charge through contour, \( I \) - current in SC ring, \( R_{ij} \) - distance between two charges, \( \varepsilon_0 \) - physical constant, \( n_{ij} \) - normal vector in the direction between \( q_i \) and \( q_j \) charges.

The stationary movement on circular orbit imposes the necessary conditions of stability on the system:

\[
\frac{\partial L}{\partial p_{j0}} = 0; \quad \frac{\partial L}{\partial z_{j0}} = 0.
\]

The given conditions should be executed for any orbit. Assuming that the particles move slowly \( \left( \frac{v}{c} \ll 1 \right) \) we receive the Lagrange function in the form:

\[
L = \sum_{i=1}^{S} \frac{m_i \cdot v_i^2}{2} + \sum_{i=1}^{S} \frac{1}{2} \cdot \Psi_{q_i} + L_{11} \cdot \frac{l^2}{2} \cdot \frac{1}{4 \cdot \pi \cdot \varepsilon_0} \sum_{i=1}^{S} \frac{q_i \cdot q_j}{R_{ij}}
\]

(3)

For analysis of the stationary movement we enter the dimensionless parameters of the system:

\[
x_j = \frac{r_j}{r_1}, \quad \text{the dimensionless radius of the j-particle orbit;}
\]

\[
x_{2j} = \varphi_j, \quad \text{the dimensionless angular coordinate of the j-particle;}
\]

\[
x_{3j} = \frac{z_j}{r_1}, \quad \text{the dimensionless deviation from the plane of orbit at stationary movement;}
\]

\[
x_{ij} = \frac{\partial x_{ij}}{\partial \alpha}; \quad r_1 \text{ - radius is SC contour.}
\]

Expressions:

\[
\chi_i = \frac{1}{S} \sum_{j=1}^{S} \varphi_j
\]

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\( \chi_j = \frac{1}{S} (\varphi_{j} - \varphi_{j}) \); \( \varphi_{j} = \sum_{i=1}^{s} \chi_j \); \( \varphi_{j} = \varphi_{j} - S \cdot \chi_j \); 

represent the speeds of the appropriate dimensionless coordinates, \( \tau = \omega \cdot t \), where \( \omega \) has the dimension \( 1/c \), and \( t \) represents the time coordinate.

We enter new parameters:

\( \gamma_0 = \frac{\beta}{\Psi} \cdot \frac{L_{11} \cdot 1}{m \cdot r_1}, \ D_j = \frac{\chi_{ij}}{k_j} \cdot \left( (2 - k_j^2) \cdot K_j - 2 \cdot E_j \right) \)

\( \gamma_1 = \frac{1}{4 \pi \cdot \varepsilon_0 \cdot c \cdot \varepsilon_0} \cdot \frac{S \cdot q^2 \cdot L_{11}}{r_1 \cdot \Psi^2}, \ \gamma_2 = \frac{\sqrt{S} \cdot q \cdot \mu}{2 \pi \cdot \sqrt{L_{11} \cdot m}} \),

where \( \Psi \) is the magnetic flux frozen in the SC ring; \( K, E \) - are the elliptic integrals of the first and second kinds of the modulus \( k_1 \).

The new constant of the particle interaction (Coulomb) \( \gamma_1 \) and the dimensionless constants \( \gamma_0 \) and \( \gamma_2 \) as well as the dimensionless current and speed of the particles determine the final version of equations.

These cyclic coordinates are connected with two first integrals of the motion which are the law of conservation of momentum and the law of conservation of magnetic flow:

\[
\frac{\partial L}{\partial \chi_i} = m_i \cdot \rho_i^2 \cdot \sum_{j=1}^{s} \chi_j + \sum_{j=1}^{s} m_i \cdot \rho_j^2 \cdot \left( \frac{\chi_i - S \cdot \chi_j}{\sum_{b=1}^{s} \chi_{b}} \right) + \\
+ \frac{I \cdot \sum_{j=1}^{s} \chi_j}{m_i} \cdot \chi_i = \beta_i \\
\frac{\partial L}{\partial I} = f_i \cdot \sum_{j=1}^{s} \chi_j + \sum_{j=1}^{s} f_j \cdot \left( \frac{\chi_i - S \cdot \chi_j}{\sum_{b=1}^{s} \chi_{b}} \right) + L_{11} \cdot I = \Psi, \]

or after corresponding transformations:

\[
\begin{align*}
\dot{x}_{i} \cdot a_{11} + I \cdot a_{12} = & \left[ \beta - \sum_{b=1}^{N} \left( a_{11} - N \cdot m_i \cdot \rho_j^2 \right) \right] ; \\
\dot{x}_{i} \cdot a_{12} + I \cdot a_{22} = & \left[ \Psi - \sum_{b=1}^{N} \left( a_{11} - N \cdot f_j \right) \right].
\end{align*}
\]

\( \beta \) - is the moment of momentum of system;

\( f_i = \frac{\Psi_i \cdot F_i}{q_i}, \quad L_i = \frac{1}{2 \pi \varepsilon_0 \cdot c}, \quad \sum_{i=1}^{s} \sum_{j=1}^{s} R_{ij} \cdot c \)."
\[ \frac{\partial^2 W}{\partial x_{1j}^2} \bigg|_0 > 0; \left[ \left( \frac{\partial^2 W}{\partial x_{1j}^2} \right) \bigg|_0 \right] \left[ \frac{\partial^2 W}{\partial x_{1l}^2} \bigg|_0 \right] - \left[ \frac{\partial^2 W}{\partial x_{1l} \partial x_{1j}} \bigg|_0 \right] > 0 \]  

(12)

concerning to the radial stability;

\[ \frac{\partial^3 W}{\partial x_{1j}^3} \bigg|_0 > 0 \]  

(13)

concerning to the longitudinal stability.

The numerical experiments show, that the inequalities (12,13) are fulfilled in a wide range of magnetic and geometrical parameters of the system, that is seen from the results of numerical analysis submitted on Fig. 3,4,5.

![Graph showing stability conditions](image)

**Fig. 3. Sufficiently stability condition by \( x_1 \) when \( \gamma_2 = \text{const}, \frac{\partial^3 W}{\partial x_1^3} = f(x_1) \).**

![Graph showing stability conditions](image)

**Fig. 4. Sufficiently stability condition by \( x_1 \), when \( x_1 = \text{const}, \frac{\partial^3 W}{\partial x_1^3} = f(\gamma_2) \).**

![Graph showing stability conditions](image)

**Fig. 5. Space of stability as a function \( \frac{\partial^3 W}{\partial x_1^3} = f(x_1, \gamma_2) \).**

**Conclusion**

So, the above analysis shows that the system for formation and accompaniment of electron bunches of toroidal geometry with included SC elements guarantees the stable process run in the parameter range sufficient for the practical achievement.

**References**


A DIGITAL SIGNAL PROCESSOR BASED RF CONTROL SYSTEM FOR THE TRIUMF ISAC RFQ PROTOTYPE

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Abstract

A stand alone digital signal processor is used to control the RFQ prototype in the TRIUMF ISAC development program. The advantage of a digital control system over the traditional analogue system is that it offers the higher degree of flexibility necessary for a development system. For this application the system is designed to have the outward appearance of an analogue system, and uses dials, knobs, and switches as the operator interface. The digital signal processor is used as a feedback controller during CW rf operation, with the feedback gain parameters continually adjustable. It is also able to perform the same regulation during pulsed operation, with additional feedforward compensation for initial pulse on duration. Using a low cost analogue-to-digital converter with a sample rate of 100 kHz, a regulation bandwidth of 10 kHz is achieved.

Introduction

The development of new, low cost, high speed digital signal processors, analogue-to-digital converters, and digital-to-analogue converters has given rise to important changes in regulation system design, at TRIUMF [1] and elsewhere. The ISAC RFQ prototype control system is built around such a low cost, medium performance, flexible control system using a DSP as the compensator and user interface. It uses a DSP56022 by Motorola. This is a 40 MHz, 24 bit integer DSP. The analogue voltage from the rf detector is sampled by a 100 kHz, 12 bit ADC made by Linear Technology. The digital value from the DSP is converted back to analogue form by a 400 kHz full power bandwidth, 14 bit DAC from Analog Devices. This is used to modulate the rf going into the cavity. The useable signal bandwidth is better than 10 kHz.

To minimize cost and maximize ease of use, the control unit is self-contained with a conventional user interface that includes switches and knobs for control, and warning lights and meter readbacks for status. With the DSP controlling both the duty cycle and the regulation of the rf, amplitude regulation is possible both in CW mode and in pulse mode. Advances in digital control theory have developed many new control algorithms. However, for a single-input/output system with a dominant pole (i.e., a rf cavity), the optimum controller in terms of performance and simplicity is still a proportional-integral(-derivative) controller. In our system a PID algorithm is used in feedback regulation, and in pulsing mode there is the additional possibility of adaptive feedback/feedforward control.

Digital Controller

A digital controller offers a number of advantages over its analog counterpart. The absence of resistors and capacitors in the compensator eliminates component drift associated with analog components. The use of a 24 bit DSP also gives a larger dynamic range when compared with an analog system, although now the dynamic range is determined by the ADC in the input and the DAC in the output. For the RFQ prototype control system, the dynamic range as well as the resolution of the feedback signal is enhanced by extracting the error signal in analog form as a voltage using a difference amplifier.

This error signal is then converted to digital information with 12 bits resolution. We use a 14 bits bipolar DAC in the output. Since only unipolar voltages are used to modulate the rf drive we effectively only use 13 bits, which gives a 0.01% error in regulation.

Since the controller is controlled by software, another major advantage is that of flexibility in the control algorithm. Different operating modes can be programmed into the controller and activated under operator control. In this system, there are 5 operating modes:

- CW open-loop
- CW closed-loop
- Pulsed open-loop
- Pulsed closed-loop
- Pulsed closed-loop with adaptive feedforward/feedback.

Normally the last 2 modes would be very difficult if not impossible to achieve using an analog system, due the presence of an integrator in the feedback loop. The integrator must be disabled during the pulse-off interval. The switching transients from the integrating capacitor can cause problems, since input offset currents must be taken into account. With a digital system, the integrator can easily be stopped during the pulse off interval. Changing controller gain and time constants are also easier in a digital system than in an analog system, where the gain can only be adjusted by switching in different resistance values. Also, the amount of reserve processing power and intelligence available to a digital system can make adaptive feedback and feedforward possible. This is implemented in the pulsed closed-loop mode to reduce the turn-on transient.
PID Controller for a Digital Control System

In time domain, the equation for a PID controller is given by

\[ m(t) = K \left[ e(t) + \frac{1}{T_i} \int e(t) dt + T_d \frac{d}{dt} e(t) \right] \]  

Equation (1)

where \( e(t) \) is the error signal and \( m(t) \) is the control signal, and \( T_i \) is the integral time constant, \( T_d \) is the derivative time constant and \( K \) is the proportional gain.

Using a bilinear transform, the PID controller z-transform is

\[ Y(z) = X(z) \cdot k \left( 1 + \frac{k_i}{1 + z^{-1}} + k_d (1 - z^{-1}) \right) \]  

Equation (2)

![Figure 1. Direct implementation of a PID controller](image)

where \( k_i \) is the integral gain, \( k_d \) is the derivative gain and \( k \) is the proportional gain. There are many different ways of implementing the above z-transform in a digital controller. These different implementations result in the same \( Y(z) \), but differ in memory requirements, processing speed, requirements of coefficient resolution, internal variable magnitude gain and, as a result, stability over the entire numerical range. For a feedback controller, the most important factor is the stability of the system, when the system is operating normally as well as when saturation occurs. Particular attention should be paid to internal variables, as these may be saturated even though the input and output appear to be within the allowable numerical range. The proportional term will always be within the number range, since fractional arithmetic is used. The integral term, however, will overflow, if the input does not average to zero due to some anomaly condition in the feedback loop. For a high voltage rf cavity, sparks occur frequently. At the instant when a spark is fully developed, the voltage across the cavity is temporarily reduced. The feedback system must be allowed to go into saturation to prevent overdriving the high power rf components such as the final amplifier, the transmission line, and the cavity. When the spark dissipates, the system should recover without becoming unstable. We found the direct form (see Fig.1) realization the most stable with respect to saturation. The Motorola DSP has internal hardware to implement this realization very effectively. In particular, it has 2 indexed cyclic buffers to access the coefficients and the variables. These data moves can occur in parallel with the multiply and accumulate instructions that are used to calculate \( y(kT) \). Thus a PID algorithm takes only 3 instructions. The DSP also has hardware test logic that detects overflows in its accumulators and substitutes into their contents a limited data value. By adding a base value to \( y(kT) \) before the saturation arithmetic and removing the base value afterward, a variable saturation level is achieved. The PID algorithm takes 3 instructions with this added feature. This restricts the output to less than an adjustable value, and is useful to limit the rf power going into the RFQ. An additional 8 instructions are needed for determination and indication of various operating modes, so the total computational delay is 550ns, which is 5.5% of the sampling period.

Adaptive Feedforward Controller

In the ISAC RFQ prototype system, we would like to measure and study the cavity parameters. Adaptive feedback control would compensate and mask variations in the cavity parameters. It was decided that the control system would only use adaptive feedforward control for regulated pulse mode operation. The goal was to provide, for vacuum conditioning purposes, a fast rise-time rf envelope with minimum overshoot. To this end, feedforward control of gain scheduling is employed. This is a form of adaptive control in which the system gain is varied according to a schedule based on a known model of the system. No estimation of system parameters is required, and the controller parameters can be changed very quickly in response to changes in system operating conditions. The trade-off for the quick response is that it is open-loop compensation, and the adaptive performance is only as good as the schedule derived from the model of the system. In the ISAC RFQ prototype system, the feedforward parameter is the timing of the pulse. The system gain during the leading edge of the pulse is reduced to allow for the rise time of the cavity. Equation 3 is used to modify the input \( x'(kT) \) to the PID algorithm to achieve this gain reduction:

\[ x'(kT) = x(kT) - \Psi(kT) \cdot \langle x(kT) \rangle \]  

Equation (3)

where \( \tau_{cav} \) is the time constant of the cavity, \( \langle x(kT) \rangle \) is the average error from previous pulses and \( \Psi(kT) \) is a scaling function chosen to best represent the rising edge of the voltage pulse.

Sources of Error in Digital Control

There are several sources of error in digital control, such as quantization errors of either data or coefficients, round off errors, and overflow error. Quantization error arises due to finite word length in either the data or the coefficients. With 24-bits of resolution, coefficient quantization errors are not significant in a PID feedback loop. Their only effect is to shift the locations of the zero's slightly, which has a negligible effect on the performance and stability of the loop. The
precision and resolution of the ADC and DAC used also affect the data quantization error. With a 24 bit DSP and a 12 bit ADC, the ADC is a major contributor to quantization error. The noise variance \( \sigma^2 \) due to quantization is given by
\[
\sigma^2 = \frac{Q^2}{12} \quad \text{equ (4)}
\]
where \( Q \) is the value of the least significant bit. For a 12 bit ADC, this gives \( \sigma = 7 \times 10^{-5} \) of full scale of ADC input. In the prototype, the feedback signal is first subtracted from the reference, and then the resultant error signal is amplified by a factor of 10. Quantizing of this error signal results in the quantization noise being \( 7 \times 10^{-6} \) of the full scale feedback signal. The second major error source is the 14 bit bipolar DAC. Because of unipolar operation, only 13 bits are actually used. This gives a quantization noise of \( \sigma = 3 \times 10^{-5} \).

Overflow can occur in both analog and digital systems. For a digital system, overflow can result in numerical wrap around, a highly undesirable situation. In the Motorola DSP there is built-in hardware to prevent numerical wrap around, and overflow results only in saturation.

**Operator Interface**

The use of a high speed DSP provides enough CPU power to implement an operator interface, as well as the PID feedforward algorithm, on a single processor. The reference setpoint and the maximum output drive are controlled by the operator via front panel dials. These are potentiometers with digital readout whose analogue voltages are digitized and read by the DSP. Three toggle switches control rf on/off, CW/pulse, and feedforward on/off respectively. There is no switch for open/closed-loop control and the PID algorithm runs full time. Open-loop operation is achieved by setting the maximum output drive lower than the reference setpoint. This lets the saturation arithmetic take over, and limits the output drive to the value set by the maximum output drive potentiometer. By raising the maximum output drive, the system goes smoothly into closed-loop operation when the drive required is less than the set maximum. A separate microcontroller with internal ADC's samples the actual readback voltage and the output drive and displays them on a fluorescent display. This gives independent confirmation that the system is operating.

**Measurement**

The entire rf system is first operated in pulsed mode without adaptive compensation. The transient voltage response at the cavity exhibits either underdamped (Fig.2) or overdamped behavior, depending on the initial setting of the PID parameters. Figure 3 shows the cavity voltage when adaptive feedforward is enabled. It shows that the underdamped ringing is effectively eliminated. Since the adaptive algorithm prevents overdriving the cavity at the rising edge of the pulse, the rise time is equal to the natural decay time of the cavity. To set the control system up for CW operation, the system is first operated in pulse mode with the adaptive control disabled. PID parameters are then changed to give a critically damped response on the rf cavity voltage. This gives rise to optimum closed-loop operation in CW mode. The total time required to tune the feedback loop for optimum performance using this method is less than 5 minutes.

![Figure 2. Pulse mode underdamped response](image)

![Figure 3. Pulse mode with feedforward compensation](image)

**Summary**

A control system with 10 kHz of control bandwidth was built using a 100 kHz ADC and a 40 MHz DSP. Its performance in CW operation is similar to analogue control systems using conventional operational amplifiers. One of the advantages it has over an analogue system is its flexibility in changing feedback parameters. The major performance advantage lies in pulsed operation. It is able to regulate in pulse mode, and adaptive feedforward is implemented to minimize pulse-on rise time and ringing.

**References**

DESIGN OF A DRIFT TUBE LINAC FOR THE ISAC PROJECT AT TRIUMF

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Abstract

The ISAC radioactive ion beam facility under construction at TRIUMF combines an isotope-separator-on-line with a post accelerator. Required in the accelerator chain is a drift tube linac capable of accelerating unstable nuclei with a post stripper charge to mass ratio of $\geq 1/6$ from $E = 0.15$ MeV/u to a final energy fully variable up to 1.5 MeV/u. Due to the relatively low intensities of some of the ion species continuous ($cw$) operation of the accelerator is required. A five tank interdigital H-type structure, operating at 105 MHz, has been chosen. The beam dynamics conceptual design and the results of various particle simulations are presented. Computer modelling of the rf structure and model measurements have been completed and are reported.

Introduction

A radioactive ion beam facility is being built at TRIUMF. [1] In brief, the facility includes a proton beam ($I \leq 100 \mu A$) from the TRIUMF cyclotron impinging on a thick target, an on-line source to ionize the radioactive products, a mass-separator for mass selection, an accelerator complex and experimental areas. The accelerator chain comprises an RFQ [2] to accelerate beams of $q/A \geq 1/30$ from 2 keV/u to 150 keV/u and a post stripper, variable energy drift tube linac (DTL) to accelerate ions of $q/A \geq 1/6$ to a final energy between 0.15 MeV/u to 1.5 MeV/u. Both linacs are required to operate $cw$ to preserve beam intensity.

Both a Wideroe structure and a super-conducting structure have been considered [4] for the post stripper linac in the ISAC project. The former idea was abandoned due to the high power consumption and the latter was abandoned because of the required technological development. Instead, the IH structure has been chosen for its high shunt impedance. The structure has been configured as a separated function DTL. Five independently phased IH tanks operating at $\phi_e = 0^0$ provide the main acceleration. Longitudinal focussing is provided by independently phased, double gap, spiral resonator structures positioned before the second, third and fourth IH tanks. Quadrupole triplets placed after each IH tank maintain transverse focussing. A schematic drawing of the DTL is shown in Fig. 1.

When operating at full voltage, the beam dynamics resemble that of a so called ‘Combined 0° Synchronous Particle Structure’[5]. To achieve a reduced final energy, the higher energy IH tanks are turned off sequentially and the voltage and phase in the last operating tank is varied. The spiral resonator cavities are adjusted to maintain longitudinal bunching. In this way, the whole energy range can be covered with minimal longitudinal emittance growth.

Figure 1: Schematic drawing of the ISAC variable energy 105 MHz DTL (upper figure) and corresponding beam envelopes (lower figures). Five IH tanks (A) provide acceleration at $0^0$ synchronous phase, three double gap spiral resonators (B) provide longitudinal focus ($\phi_e \sim -50^0$) and quadrupole triplets (C) provide transverse focus. The beam envelopes define the $x$ and $y$ maximum half sizes of the beam and the maximum energy spread and phase spread in the beam as a function of linac length. The calculations are for a beam of $q/A = 1/6$ with matched elliptical emittances of $0.25\pi \mu m$ (normalized) transversely and $48\pi \mathrm { keV } \cdot \mathrm { ns }$ longitudinally.

Specifications

The physical specifications of the DTL have been determined and the beam dynamics studied using the code LANA[6]. MAFIA has been used to model the rf characteristics of the IH tanks. Due to the relatively small longitudinal and transverse emittances of the beam injected into the DTL ($\leq 50\pi \mathrm { keV } \cdot \mathrm { ns }$ and $\leq 0.16\pi \mu m$ (normalized)) an rf frequency of 105 MHz was chosen, three times the RFQ frequency. Each IH tank has a diameter of 94 cm with the resonant frequency tuned by optimization of the ridge geometry. The gross specifications of the five IH tanks and the three spiral resonators for the design particle of $q/A = 1/6$ are given in Table 1. The Q and shunt impedance values of the IH structure are calculated with MAFIA.

The chief design considerations for the DTL are the $cw$ operation, and the variable energy requirement. To achieve efficient acceleration and to distribute power losses uniformly, a constant gradient IH structure is adopted. The gap length to cell length ratio $q/\ell$ is tuned to flatten the field distribution[5]. Maximum accelerating gradients are determined by restricting the
Table 1: Summary of parameter specifications for each IH tank and spiral resonator cavity (B1-B3) for the design particle of $q/A = 1/6$. All cavities operate at 105 MHz. Here $L$ is the length, $a$ is the aperture, $\ell$ is the average cell length, $E_0 \cdot \ell$ is the effective field gradient and $P_i$ is the power per unit length. Other parameters have their normal designations. The quoted IH shunt impedance values are from $\kappa = 3\lambda$. The power/length and power calculations for the IH structure assume a shunt impedance 75% of the value quoted. In the case of the buncher cavities, the shunt impedance is quoted from reference [7].

<table>
<thead>
<tr>
<th>Tank</th>
<th>No. Cells</th>
<th>$L$ (cm)</th>
<th>$a$ (mm)</th>
<th>$\ell$ (mm)</th>
<th>$\beta_m = 1.8$</th>
<th>$E_0 \cdot \ell$ (MV/m)</th>
<th>$V_{eff}$ (MV)</th>
<th>$Q$ ($\times 10^9$)</th>
<th>$Z$ (MS/m)</th>
<th>$P_i$ (kW/m)</th>
<th>$P$ (kW)</th>
<th>$E_{out}$ (MeV/u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>26</td>
<td>10</td>
<td>28</td>
<td>2.2</td>
<td>2.1</td>
<td>0.5</td>
<td>11</td>
<td>374</td>
<td>16</td>
<td>4</td>
<td>0.23</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>50</td>
<td>14</td>
<td>38</td>
<td>3.1</td>
<td>2.4</td>
<td>1.2</td>
<td>13</td>
<td>410</td>
<td>18</td>
<td>9</td>
<td>0.44</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>77</td>
<td>16</td>
<td>51</td>
<td>4.1</td>
<td>2.5</td>
<td>2.0</td>
<td>19</td>
<td>471</td>
<td>18</td>
<td>14</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>90</td>
<td>16</td>
<td>65</td>
<td>5.0</td>
<td>2.2</td>
<td>2.2</td>
<td>23</td>
<td>421</td>
<td>18</td>
<td>16</td>
<td>1.14</td>
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<tr>
<td>5</td>
<td>13</td>
<td>98</td>
<td>18</td>
<td>76</td>
<td>5.6</td>
<td>2.3</td>
<td>2.2</td>
<td>25</td>
<td>376</td>
<td>18</td>
<td>18</td>
<td>1.50</td>
</tr>
<tr>
<td>B1</td>
<td>2</td>
<td>8</td>
<td>14</td>
<td>33</td>
<td>2.2</td>
<td>3.2</td>
<td>0.22</td>
<td>60</td>
<td>10</td>
<td>0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>2</td>
<td>8</td>
<td>14</td>
<td>33</td>
<td>3.1</td>
<td>3.2</td>
<td>0.22</td>
<td>60</td>
<td>10</td>
<td>0.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>2</td>
<td>8</td>
<td>14</td>
<td>33</td>
<td>4.1</td>
<td>3.2</td>
<td>0.22</td>
<td>60</td>
<td>10</td>
<td>0.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>70</td>
<td>543</td>
<td></td>
<td></td>
<td></td>
<td>8.1</td>
<td></td>
<td>91</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The variable energy requirement sets restrictions on the tank and quadrupole lengths, and on the specifications of the bunching cavities. Any tank and triplet combination is required to be short enough to limit the phase spread entering the next section to $\Delta \phi \leq 90^\circ$ so that the beam can be bunched without longitudinal emittance growth. This requirement forces a short first tank of 9 cells and 27 cm with corresponding reduction in shunt impedance. The quadrupole triplets are designed to be very compact. Each triplet unit has an effective length of 32 cm, with a bore aperture of 28 mm and a maximum gradient of 63 T/m. They will occupy a 40 cm space between tanks.

The two gap spiral resonator structure is chosen for its large velocity acceptance and large multipactor-free voltage range. The three bunchers must operate over $\beta$ regimes given by 1.8%→2.2%, 1.8%→3.1%, 1.8%→4.1% respectively and over voltage ranges varying by a factor of ten or more. For ease of manufacture, three resonators with a constant $\beta = 2.3\%$ have been specified yielding a gap crossing time constant of at least 75% over the whole velocity range. The properties of the device have been studied extensively elsewhere [7] and the quoted shunt impedance value is taken from the literature. We are presently modelling the device with MATIA.

Beam Dynamics

Beam dynamics calculations have been done using the code LANA with $^{25}$Na$^{+5}$ as the reference particle. All transverse emittances quoted below are normalized values. The calculated envelopes for the full energy case are shown in Fig.1 for matched elliptical emittances of 0.25$\mu$m and 48$\pi$ keV-nsec. The longitudinal optics is typical for a $0^\circ$ structure. The beam is injected into each accelerating structure with an energy higher than that of the synchronous particle. The longitudinal phase space position rotates $\sim \pi/2$ in each tank and remains primarily in the second quadrant providing a stable transport. The strong periodic longitudinal and transverse focusing yield small beam sizes and increased acceptance. The true useable region of the longitudinal acceptance corresponds to $144\pi$ keV-nsec and the transverse acceptance is $1.3\pi \mu$m.

An 11.7 MHz time structure is imposed on the beam from the separator ($\epsilon_{x,y} \leq 0.1\pi \mu$m) by a pre-buncher upstream of the RFQ (35MHz)[3]. Particle simulations through the RFQ, stripping foil and pre-DTL matching section produce realistic particles that are subsequently run through the DTL. A summary of before and after emittances for two MEBT conditions (Case A and Case B) are given in Table 2. Case A includes a bunch rotator before the stripping foil while Case B has none. The transmission is 100% in both cases for an ensemble of 4000 particles.

Table 2: Beam quality before and after DTL for two MEBT set-ups.

<table>
<thead>
<tr>
<th>% enclosed</th>
<th>$\epsilon_{x,y}$ ($\pi \mu$m)</th>
<th>$\epsilon_{z}$ ($\pi$ keV-nsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>0.11</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>0.21</td>
</tr>
<tr>
<td>Case B</td>
<td>0.11</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Variable energy operation

A plot of the tank voltage and phase required for a given final energy are shown in Fig.2. For a reduced voltage the particle bunch is phased negatively with respect to the synchronous phase so that as the particles lose step with the synchronous particle and drift to more positive phases they gain the maximum possible energy. This phase setting also coincides with the minimum phase spread at the exit of the following triplet section. The buncher following this tank is then used to capture the diverging beam. The following bunchers provide longitudinal transport. Simulations show that in this way the longitudinal emittance growth for typical beams can be kept below 15% for the whole energy range.

The final phase spread of the beam exiting the DTL for either none, one, two, or three bunching cavities is shown in Fig. 3. The
aim is to achieve a phase spread no larger than can be bunched with a 35 MHz buncher in the HEBT. The plot shows that the first and second bunchers are essential and that the third would improve the beam quality in the energy range from 0.5–0.7 MeV/u.

Figure 2: Tank voltage and phase required for a certain final energy. Full energy case corresponds to tank voltages of 1.0 and phases of 0°.

NC machined copper model of a stem and tube was made to test the mechanical rigidity of the structure under various heat and water loads. The tests show that a water flow of 3 l/min is sufficient to cool the drift tube. The water flow does not produce any measurable mechanical vibrations.

Figure 4: Field distribution measured on an 11 gap model (b) and associated g/ℓ values for each gap (a).

Conclusions

The separated function DTL concept provides a low power solution to achieve variable energy heavy ion acceleration in the low β regime without significant increase in the longitudinal emittance. A mechanical concept for the DTL is being discussed. The first module consisting of Tank 1, a quadrupole triplet and a double-gap buncher is scheduled to be completed by the end of 1997. The DTL is scheduled to be fully installed by the middle of 1999.

Acknowledgements

The authors would like to thank U. Ratiznger for pleasant and informative discussions concerning IH structures, and P. Ostrov and D. Gorelov for their assistance with the LANA code. Thanks go also to summer researchers N. Sy and T. Duncan for their patient computations with MAFIA and LANA.

References

UPDATE PLAN OF SPRING-8 LINAC

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Abstract

The SPRING-8 linac was completed and the first beam was observed in August 1996. This Linac is used for injection of the SPRING-8 storage ring and New SUBARU ring (VUV-soft X-ray ring, under construction), and also used for some experiments like the slow positron facility and the parametric X-ray source. For the next stage, we are planning the reconstruction aimed at the single pass FEL (SASE : Self Amplified Spontaneous Emission). In the 1-D simulation, we get the 20 nm wavelength coherent light with 10-20 m length undulator. The gun system will be replaced from the thermonic HV cathode to the photocathode RF gun. And the magnetic bunch compressor section will be installed in several areas.

Introduction

The SPRING-8 linac was completed and the first beam was observed in August 1996 [1]. The layout of SPRING-8 site is shown in Fig.1. And the present linac characteristic is shown in Table 1.

![Fig.1 SPRING-8 site layout](image)

Table 1: Characteristic of present linac

<table>
<thead>
<tr>
<th>Energy</th>
<th>1.15 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized Emittance</td>
<td>100 πmm•mrad</td>
</tr>
<tr>
<td>Bunch length</td>
<td>10–20 ps</td>
</tr>
<tr>
<td>Energy Dispersion</td>
<td>1%</td>
</tr>
<tr>
<td>Charge</td>
<td>3 nC/bunch</td>
</tr>
<tr>
<td>Electron Gun type</td>
<td>HV+, Thermal Cathode</td>
</tr>
<tr>
<td>Cathode</td>
<td>Disposed BaO (Y796)</td>
</tr>
<tr>
<td>Bunching</td>
<td>Pre Buncher + Buncher</td>
</tr>
</tbody>
</table>

The linac will be operated twice a day as the injector in the future and utilized for various applications in the rest of the time. For example, an inverse Compton scattering for nuclear excitation, a parametric X-ray and channeling X-ray generation, a slow positron generation are proposed. Especially a single pass FEL operating in the SASE mode is proposed as a VUV-soft X-ray coherent light source that is the most important and interesting application.

Future plan of SPRING-8 Linac

This Linac is used to injection the SPRING-8 storage ring and New SUBARU ring. And we have some plan to use some experiments like the slow positron facility, the parametric X-ray source and the single pass FEL. We report the study of the parametric X-ray and the single pass FEL.

Parametric X-ray

With the crystal is bombarded by the electron beam, the X-ray of the energy which satisfies the Bragg condition at a Bragg angle is generated for the crystal plane is emitted. We call this electromagnetic radiated emission phenomena parametrics X-ray radiation (PXR). By choosing the crystal incidence angle of the electron beam, it is possible to take out the X-ray of hoping wavelength. Though the flux of coming out X-ray is also dependent on the electron energy a little, if we use the electron beam over 300 MeV, in the X-ray region of 14.4 keV, the conversion efficiency is about 10⁻⁹ photon/electron. At present, in the energy region under several hundred keV on the average flux, it is by far abounding of the synchrotron radiation of the storage ring. Recently, though we also examine that the strength is made to be the several score time by the technique with addition matching of X-ray and parametrics X-ray radiation by resonance transition radiation (RTR). It is very low flux than a synchrotron radiation of the storage ring yet. However, the electron of about 10¹⁰ is contained in the 1 bunch when the linac was operated at a single bunch. It is useful for the necessary experiment on the time resolution, because electron beam is bunched as 10 ps. This utilization is under preparation for the experiment, because it is corresponding by present linear accelerator.

Single pass FEL

The high brightness high-intense electron beam is bent by the undulator, and synchrotron spontaneous radiation light which arose that time is exponentially rapidly amplified by the interaction with the electron beam, and SASE is to generate the laser beam of high brightness and narrow spectral band width. Since the optical resonator which limits the wavelength shortening of the conventional free electron laser oscillation is
not used, we notice the SASE radiation source as a high luminosity high brightness small wavelength coherent radiation light source. The photon flux at the peak surpasses by far the synchrotron radiation of the SPRing-8 storage ring. In addition, we have the characteristic of that it is the light in the coherent pulse and that output itself is semi-monochromatic, and the burden for the spectroscopy is also little.

The FEL characteristics and the electron beam parameters are shown in Table 2. And calculation result is shown in Fig. 2. At the first phase, for proof of principle, the 20 nm FEL will be challenged. However the linac was optimized only for the injector to the booster synchrotron, its beam characteristics are not adequate for the FEL without improvement.

At first we determine the undulator parameters. the period of 3.2 cm and K=1.62, so as to minimize the field gain length. The beam energy of 0.69 GeV is realized without any improvement of the linac. However 1.55 GeV will be achieved by addition of extra accelerator tubes or energy doubler (SLED) system.

We will realize this value by means of attaching the focusing element with the undulator. We are now developing the 3-D calculation code which includes the element of external quadrupole field.

R&D status of the single pass FEL

Some R&D studies were started already for SASE. We introduce R&D of the electron gun for low emittance beam and beam transport simulation.

Photocathode RF gun

In order to obtain a small emittance beam an RF photocathode system is required. In the SPRing-8 single cell RF photocathode gun is developed. In case of 2cell or multicell, it is possible to raise achievement energy in the cavity exit. However, in that structure for suppressing the effect of adjustment mechanism and 0 modes of the resonant frequency, the coupler structure is required. Therefore, we raise that it may become a factor of the break down in the high field generation and that the field intensity of the disk tip rises further than the field intensity of the cathode surface as a defect. And, in usual accelerating cavity, by doing the association of one combination hole, the RF power from the waveguide supplies the cavity. However, the center of the electromagnetic-field distribution is displaced from the central axis of the cavity, since the electromagnetic field in the cavity is distorted by the combination hole. Therefore, the coupler structure suppresses the increase in the emittance by the higher mode component as a double feed coupler structure. The layout of test stand of photocathode RF gun is shown Fig.3.

Table 2: FEL characteristics and beam parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength [nm]</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>Beam energy (GeV)</td>
<td>0.69</td>
<td>1.55</td>
</tr>
<tr>
<td>Undulator period [cm]</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Undulator parameter K</td>
<td>1.62</td>
<td>1.62</td>
</tr>
<tr>
<td>Peak current [kA]</td>
<td>1-10</td>
<td>1-10</td>
</tr>
<tr>
<td>Normalized Emittance</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>[mm mrad]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Betatron wavelength [m]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>FEL parameter r</td>
<td>2.7-5.7x10^4</td>
<td>1.6-3.4x10^7</td>
</tr>
<tr>
<td>Field gain length [m]</td>
<td>0.55-0.26</td>
<td>0.94-0.44</td>
</tr>
<tr>
<td>Saturation length [m]</td>
<td>10-4.5-2</td>
<td>16.8-8.5</td>
</tr>
<tr>
<td>Undulator length [m]</td>
<td>20-10</td>
<td>30-15</td>
</tr>
<tr>
<td>Peak power (GW)</td>
<td>1.9-40</td>
<td>2.4-52</td>
</tr>
<tr>
<td>Peak brilliance [phs/sec./mm^2/mrad^2/0.1%B.W.]</td>
<td>5.2-5.4x10^27</td>
<td>2.5-2.6x10^28</td>
</tr>
</tbody>
</table>

Fig 3. Layout of test stand of photocathode RF gun
PM : profile monitor. FC : faraday cup
From this fact, we manufacture the test equipment of the simple cavity by the double feed coupler structure, and we do the emission testing of the photocathode RF gun. It will be made to be metal cathode which is more integrated than the viewpoint of the break down prevention with the cavity in the cathode.

There are one CW seed laser and two different laser amplifier systems for photocathode. The seed laser is the Lightwave 131 whose frequency is 178.5 MHz. This frequency corresponds to 1/16 of acceleration frequency. The amplifier system is switched by retractable mirror.

The high power "Regenerative" amplifier which generates a single pulse (bunch) will be used at the proof of principle mode. In this case metal cathode, for example Cu or Al, is used. The electron charge will be expected as 10 nC/bunch. The other is 6 pass "Cascade" amplifier which generates multiple pulse (bunch) train is used for higher average power FEL. In this case the alkali cathode will be used, for example Ce2Te. The electron charge will be expected as 1 nC/bunch.

**Beam transport**

The schematic drawing of layout for SASE is shown in Fig. 4. The electron beam from the RF photocathode gun, whose pulse width is expected as that of laser system 10 ps, is accelerated to 100–150 MeV. Then the beam is compressed to 1 ps. After compression the beam is accelerated to final energy. The building for general purpose use is now under construction. This building is located at the left side where the linac beam can be introduced. To transport the beam the isochronous 90 degree bending system will be installed. It is easily expect if the high current beam passes through the large dispersive section the emittance growth occurs. In order to preserve the emittance the energy compression system is installed in front of the bending section. After the bending section the beam is re-compressed to the pulse width of 0.1-1 ps by means of two compressors.

**Conclusion**

The construction of SPring-8 linac will be completed soon. We reported some plan of the linac next stage. Various technological development is necessary for the SASE. These are important for the activity of the linac members.

**Acknowledgment**

Special thanks for supporting of SASE simulation code to Y. Kishimoto at Naka establishment of JAERI.

**References**


INJECTOR LINAC OF SPRING-8

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Abstract
The linac that is SPring-8 injector was completed and started operation from August 1. A beam was able to be transported to the final beam dumping at a tail end on August 8. From now on this linac carries out beam adjustment and be scheduled to do a beam injection to a synchrotron in October. The construction and fundamental performance of the linac are described.

Introduction
SPring-8 is the synchrotron radiation facility of 8GeV in Japan. The storage ring operation will begin next February in 1997, and common use of the light is scheduled from the autumn of the year. The number of beam lines begin from 10, and 60 beam lines will be constructed finally. The buildings of this facility is already completed (fig.1). This linac is built as the injector for the booster synchrotron which accelerates the beam from 1 to 8 GeV[1].

Fig.1 Birds view of the site.

Configuration
This injector linac is 140m long, and maximum energy of electron beam is 1.15GeV. Positron beam can be generated optionally and used properly the demands of the storage ring to reduce ion trapping and stretch the life time.
The electron gun has three types of grid pulser. One is called single pulser for 1 nano-second width[2], short pulser can generate 10 to 40 nano-seconds pulse, and long pulser of 1 micro-second for beam commissioning and full-fill operation of the storage ring. The cathode assembly is used Y-796 of IMAC. Beam current of 20 amps is derived by 200 kV in the emission stability of 1.5%.
Bunching section has two single cell prebunchers and a 13 cells buncher of standing wave type. Transport efficiency of 64% corresponding to a simulation is established without sub-harmonic bunchers. Specifications of bunching section was searched in Tokai establishment of JAERI before moving to the site two years ago. According to the result of the search, the bunching section rearranged and drift space between the electron gun and first prebuncher was cut short to adapt a high current mode operation by removing the profile monitor just behind the gun.
Main region consists of 26 accelerator sections and 13 klystron of 80MW. Accelerator sections are 3m long of 81 cells, constant gradient type of 2856MHz. Accurate phase deviations of the accelerator sections are shown in Fig.2. Auto squeeze machine of MHI and detailed comparison of measurement with calculations established this accuracy in spite of low cost.

Fig.2 Phase deviations of accelerator section

13 klystrons of 80MW type are used. Flatness of modulators is less than 0.5% in 2 micro-seconds ( modulator pulse width is 5 micro-seconds). Drive power for the klystrons are distributed by a ladder consists of a phasing device and WF-H-50 coaxial cables[3]. Phase of microwave for each accelerator sections are controlled by comparison of phase of beam wake field with the phase of a reference line of high stability coaxial cable.
QT magnets are regularly placed each two accelerator sections. Bending magnets are placed at 60 MeV point, 250 MeV point and 1 GeV point for energy analyzing and latter two bending magnets can be used for beam extractors.
Profile monitors, which are placed with each QT in regular sections, are mainly used for alignment of beam transport. Ordinary CT for long pulse and tuned fast CT for single pulse are set at eight points. The fast CT can observe the modulation of 2856MHz. Wire grid monitors are set for emittance measurement, and the lines of cherenkov monitors are prepared for measurement of micro-structure on time base.

Construction
Set up of this linac at the site began in August 1995, and finished in March 1996 including test of each devices and alignment. Factory fabrication excepting a gun and bunching section takes about two years over rapped setting up.
Devices are aligned by the laser referenced position pointer. Under the very quiet condition of stopping air conditioner in midnight, the position of center of QT, flange of accelerator sections and profile monitors are measured 5 minutes intervals from downstream. Temperature fluctuations is under 0.1 degree during the measurement due to the insulating effect of shield 3m thickness. Three times measurement a night and the average of data uses for positioning the next day. It takes two weeks for first alignment in December 1995, and we measured the positions again just before starting beam operation for confirmation of alignment and estimation of deformation of the building in July 1996. At last displacement of these positions are suppressed in 0.1 mm (Fig.3) without using a vacuum chamber for the laser beam.

**Operation**

Before the beam commissioning, aging of microwave components was done. It was expected that aging of whole system takes long time caused of experience in factory conditioning of the one unit of klystron and waveguide. We prepared automatic aging system by computers. Aging process is explained in qualitative analysis and experience, but actual parameters like a vacuum threshold are depends on the configuration of each system, microwave power and surface history. In this condition, we consider fuzzy logic is suitable for aging process. For the definition of membership functions, standard PD control process using temporary thresholds are made (Fig.4). Consequence of the trial of this PD control process, it is observed that the temporary thresholds suit for this system, and the initial aging of all sections were done by this process. We expected it might taken 1500 hours but it took only 500 hours for the aging of all sections. Then each klystron generates 80MW, 2 micro-seconds, 60 pps. And each accelerator section is supplied 34MW maximum. At the ordinary operation, klystrons are drove in 60MW.

In the aging term, the relation of out gas ratio versus input microwave power of this system is observed. Lower power than 5MW activates surface molecules of impurities, and around 25MW power derives sinking impurities in copper material (Fig.5). In this region, out gas volume balances with pumping ability of this system and vacuum response becomes dull without break down. Gradual long aging in this region is effective for the shortening the time of conditioning after machine intervals.

After the term of summer maintenance, Two aging processes of a PD control and a Fuzzy logic control are compared. Necessary microwave power can be fed to the wave guides and accelerator sections, but copper surface is not enough clean and a rapid aging process needs when the operation restarts.
Fig.5 Out gas vs micro wave power at typical section

First beam of this linac was successfully established on August 1 just after raw admission is given. The gun operated in 2 amps, 10 nano-seconds, 5 pps under the radiation survey. Beam transport efficiency from the bunching section to the beam dump is over 95%. But we are not allowed to send a beam to the synchrotron area yet. The bending magnet at 1GeV can not actuate and energy specter could not measured. At the point of just after the buncher, H/V/F/M of energy spectrum is 2%, and normalized emittance is 130 mm-mrad. Before starting injection to the synchrotron in October, accurate phase control will be done in long pulse mode.

Modification Plan
This linac will be operate full time as a injector until the end of commissioning of the storage ring. And another beam transport line adds for the use of other purpose. We design a RF photo-cathode electron gun[6]. Low power model of cavities are tested now, and single cell type is the first candidate. Cathode material is copper, and titanium is coated to suppress secondary emission with controlling thickness. The first target is 1nC and 1ps, and a isochronous transport line is designed for Self Amplitude Spontaneous Emission[6]. As a first R&D, we prepare 3 or 5 m undulator to prove the gain and the assumptions of initial spontaneous emission. For this SASE, modification of alignment system of active feedback is required, and several methods are estimated. We have an extraction line at 250 MeV point. At this place, we plan several experiments under the collaborations with other sections. One is to generate gamma lay for the excitation of nucleus by the interaction with high power lasers. The design of laser system of the photo-cathode electron gun and this high power laser are combined to minimize a timing jitters. Another plan is high flux slow positron generation. A bending magnet at 250 MeV is used for 45 degree transport line. From the summer in 1997, local government of Hyogo prefecture start the construction of New-SUBARU which is 1 GeV storage ring for synchrotron radiation. This ring is used for special industrial purpose and ring physics itself. SPring-8 linac is used as the injector of New-SUBARU too. Higher reliability, higher rate of operation and flexibility are required to this linac.

Conclusion
SPring-8 injector linac started operation. First beam was observed at 11:10 the day of official admission as a radiation device was given. Detailed tuning up and machine study will be done in this year, and routine operation for injection starts from next February. After commissioning of the storage ring, modification for many other purpose of SASE, gamma source and injection to medium energy ring of New SUBARU project.

References
A CONTRABAND DETECTION SYSTEM PROOF-OF-PRINCIPLE DEVICE USING
ELECTROSTATIC ACCELERATION *

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Abstract

A new Contraband Detection System (CDS) Proof-of-Principle (POP) device is nearing completion at Northrop Grumman's Advanced Technology and Development Center. We employ gamma resonance absorption (GRA) to detect nitrogen or chlorine in explosives and certain forms of illegal drugs. Using tomography, 3-D images of the total density and selected element density are generated. These characteristics together may be utilized with considerable confidence in determining if contraband is present in baggage or cargo.

The CDS employs a high current (10 mA) DC electrostatic accelerator that provides a beam of protons at either 1.75 or 1.89 MeV. These high energy particles impinge upon a target coated with $^{13}$C or $^{34}$S. The resultant resonant gamma rays are preferentially absorbed in either $^{14}$N or $^{35}$Cl. Because of the penetrating power of the gamma rays, this approach can be utilized for inspection of fully loaded aircraft containers such as the LD3.

Our current program calls for testing of the POP CDS by late 1996. This paper presents the overall design and characteristics of the CDS POP.

Introduction

The interrogation of man-portable containers through the GRA process has been found from previous work [1] [2] [3] to be a potential candidate for determining the presence of explosives. As a result of the work in this project, we have further developed the GRA approach into a system design that offers the potential for detecting a significant portion of illegal drugs. The contracted CDS POP mission is to examine the range of available parameter space for the GRA technique and for drug and explosives detection applications, provide a technical data base sufficient to assess the practicality for use with man-portable luggage. We have found during the conduct of this effort that the CDS approach may also be effective for the interrogation of medium sized containers such as the LD3. In addition, the development of a high current electrostatic accelerator for the CDS breaks new ground using state-of-the-art technology that will be beneficial to other applications such as radiography or medical therapies.

Technical Approach

There are two primary characteristics that can be used to identify explosives and illegal drugs among common materials; they are material total density, and individual selected element density [4]. Due to the overlap in total density of many materials, X-rays alone, which can determine total density if used with tomography, may not be sufficient to separate contraband from common materials or materials deliberately used for concealment. If nitrogen density imaging is employed in addition to total density imaging, the detection of contraband can be significantly improved, resulting in lower false alarms with a higher probability of detection. Separation between contraband and common materials is performed using the available multi-dimensional density space (nitrogen and total densities). The addition of chlorine density imaging can provide a valuable means of detecting chlorine based explosives.

After surveying all of the possible reactions for generation of resonant gamma rays from energetic protons, we selected the best reaction, $^{13}$C(p,$\gamma$)$^{14}$N, for nitrogen. This resonance occurs at a proton energy of 1.75 MeV. Of the next best resonant reactions there are two for chlorine ($^{34}$S(p,$\gamma$)$^{35}$Cl) that occur at proton beam energies of 1.89 MeV and 2.79 MeV. We selected the lower proton energy to minimize the accelerator requirements for the POP. The performance figure of merit for this reaction is about 5% of that for nitrogen which results in longer inspection times. If the POP shows the chlorine reaction is usable, then the higher proton beam energy would improve CDS performance by a factor of 2 for chlorine detection.

The cross section for generation of resonant gammas gives rise to a proton beam requirement on target having small energy spread (12 keV). This in turn leads to the selection of an electrostatic accelerator. The need for fast inspection time drives the accelerator current upward toward the survival limits of the gamma generating target. We have found that proton currents of 10 mA or more are required. For the CDS POP a tandem configuration is chosen which requires an electron stripper at the high voltage terminal. The development of such an accelerator pushes the state of the art and opens the possibility for use in other applications such as neutron radiography or medical therapies.
The proton beam target for the GRA technique is identified as the highest risk in the system. There is limited experience about the lifetime of the target coating from constant bombardment by energetic protons; however, a parallel test program has been underway for some time at Northrop Grumman which addresses this issue. A rotating target design is employed to maximize lifetime by spreading the effects of beam sputtering and heating.

Another risk area for the CDS POP is in the performance of a suitable electron stripper. At the beam current densities of interest, a conventional foil stripper would burn up quickly. Simulations for a gas stripper channel indicate that the required performance should be achievable; however, the issue of proper gas confinement in the stripper region to mitigate HV accelerator breakdowns is being addressed with an off-line test program at TRIUMF.

Discrimination between resonant and non-resonant gamma rays is achieved by exploiting the fact that the resonant gammas are emitted at a specific angle. The detection system is required to be position sensitive (see Fig. 1). This is accomplished using segmented Bismuth Germanate (BGO) detectors much like, but improved over PET systems, which provide good spatial resolution and high detection efficiency. A detector development program is in place and demonstrating positive results.

![Fig. 1. Position Sensitive Detection](image)

Camouflage techniques to hide contraband among other materials leads to the conclusion that a tomographic imaging approach should be used. Furthermore, this approach is necessitated by use of density for discrimination. By rotating and elevating a volume to be inspected, the attenuation factor of the gamma rays are recorded at all positions and angles (see Fig. 2). A 3-D image of resonant and normal gamma rays' attenuation factor per unit volume are used to reconstruct 3-D images of both total and elemental densities. An algorithm based upon the multi-dimensional density data of substances is used to signal the presence and position of contraband.

### Description of the POP Device

An isometric view of the CDS POP device is shown in Figure 3. This machine is not optimized for field use. Instead it is designed for maximum flexibility and ease of access for quick changes and/or modifications. The centerline of the tandem accelerator is 108 inches above the floor.

![Fig. 2. Tomographic Inspection Technique](image)

![Fig. 3. View of CDS POP at Northrop Grumman](image)

This configuration provides adequate length in the high energy beam transport section which must be bent at an angle of 80.7 degrees for proper position of the proton beam with the target surface to result in a horizontal gamma ray fan at the area of container inspection. Another choice to have the accelerator at a lower level would require that the target, the detector and container handling equipment be at elevation. We selected the former based upon the anticipation that most of the hands-on time with the POP device will be with the target, detectors and container handling. The POP shown in the figure employs a double decked array of 88 BGO segmented detectors spanning a field of view of 53°. Due to funding constraints on the present program, the initial POP demonstration scheduled to take place in December 1996 will use a scaled down set of detectors (single layer of 7 BGO detectors) and a smaller baggage handler than as shown in the figure. The proton accelerator will demonstrate full CW output, but the gamma production target will be a low-cost/low-duty factor interim design. The POP will demonstrate key principles that are scaleable to a fieldable CDS including; (1)high current DC tandem accelerator operation and long term stability at the required beam conditions for resonant gamma production, (2)image resolution and resonant/non resonant gamma ray sorting, and
(3) Basic 3-D tomographic imaging. Successful operation of the CDS POP accelerator will lay the ground work for higher output tandem accelerators that might be used for BNCT or Neutron Radiography.

An accelerator of this type offers lower capital and operating cost than RF driven linear accelerators of the same output. The cross section view in Figure 4 shows the two accelerating columns extending from the high voltage center terminal. The center terminal contains two sets of triplet magnets, a vapor stripper subsystem, a series of collimators and associated diagnostics. The whole assembly fits within a corona cage and sits on top of a 1 MV power supply. The external containment vessel provides an enclosure for SF₆ (dielectric) at 60 psi.

![Side View of Tandem Accelerator](image)

**Performance**

The counter-drug mission differs significantly from explosives detection in that the volumes of contraband involved are usually larger when compared to high explosives, relaxing the need for high resolution. The larger volume of contraband associated with drug trafficking permits integration of the 3-D scan information over larger slices, thereby enhancing the signal to noise and allowing separation and detection of the relatively low nitrogen densities. On the other hand the amount of nitrogen in most high explosives makes detection less difficult. The ability to detect thin sheet forms of high explosives is actually easier than bulk drugs in similar quantities.

The key parameters for a fieldable CDS device which are being used as goals for the CDS POP are presented in Table 1. To provide the capability for dual element detection, the energy of the accelerator must be variable. The proton current is a compromise between technical capability and production yield per proton. A 10 mA proton beam is adequate for detection of nitrogen in high explosives while proton current between 10-20 mA is required for chlorine imaging because of the lower gamma yield. For small or loose baggage, the carousel can be sized for an optimum volume to maximize throughput and still maintain sufficient transmission of gamma rays for high probability of detection. For suitcase size containers it is estimated that the CDS could process 430 bags/hr with a detection probability of 90% for a 1 pound quantity of thin sheet high explosive. We have also performed simulations of fully loaded containers as large as the LD3 that indicate inspection times on the order of 10 to 15 minutes per container are possible.

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
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</tr>
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<tr>
<td>Element Detected</td>
<td>Nitrogen, Chlorine</td>
</tr>
<tr>
<td>Nuclear Reaction</td>
<td>$^{13}\text{C} (p,\gamma)^{14}\text{N}$, $^{34}\text{S} (p,\gamma)^{35}\text{Cl}$</td>
</tr>
<tr>
<td>Target Type</td>
<td>segmented surface</td>
</tr>
<tr>
<td>Beam Current (mA)</td>
<td>≥10, 10/20</td>
</tr>
<tr>
<td>Beam Energy (MeV)</td>
<td>1.75, 1.89</td>
</tr>
<tr>
<td>Energy Spread (keV)</td>
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</tr>
<tr>
<td>Detector FOV (degrees)</td>
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<tr>
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<tr>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Est. Q (bags/hr)</td>
<td>430, 25/50</td>
</tr>
<tr>
<td>Sensitivity (kg)</td>
<td>0.5, 4.0</td>
</tr>
<tr>
<td>Detection Probability</td>
<td>0.9, 0.7</td>
</tr>
</tbody>
</table>

**Conclusion**

The requirements for a GRA based detection system have been defined and a device to demonstrate the achievability of the required performance is nearing completion. Although there are some areas of the device that may not be completed to the full potential due to limited funding at this time, the planned demonstration will suffice to show whether the GRA approach is practical for either or both drug and explosives detection. The POP device will benchmark our models and facilitate accurate prediction of fieldable CDS performance. Development of the high current tandem accelerator may have other applications.

**References**


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THERMO-MECHANICAL DESIGN OF A CW SWEEP PLATE EMITTANCE SCANNER

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Abstract

A sweep plate emittance scanner for use with high power, continuous wave (CW) beams has been designed, fabricated and commissioned at Northrop Grumman. The design is capable of scanning beams of up to 20 kW beam power with a spot diameter as small as 2 cm. The scanner pod is mounted on a ball screw driven linear bearing table that is driven through the beam by a stepper motor at velocities up to 30 cm/sec.

This paper presents the thermo-mechanical analysis of the pod moving through a gaussian beam and the details of the mechanical design of the pod and motion system. Analyses to determine scanner cooling schemes and structural materials are presented.

Design Description

The emittance scanner system was designed at Northrop Grumman in 1994 as a tool for CW ion source development. The first scanner pod (see Fig. 1) was designed for beams up to 100 keV and 200 ma. The complete system consists of the pod, the pod drive system, a vacuum enclosure, vacuum system, beam dump, and data acquisition and control system.

Fig. 2. Complete Installation at Northrop Grumman
(see Fig. 2). The scanner is an Allison type sweep plate scanner [1] with defining slits at the entrance and the exit of the sweep plate region (see Fig. 3).

Fig. 3 - Section Through Scanner Pod

This pod incorporates a dual slit at the exit of the sweep region to facilitate energy resolution. Each slit is formed by a pair of knife edges (blades) adjusted to achieve a gap of .025 mm with a tolerance of +/- .0025 mm. The slits facing the incoming beam pose the biggest problem in the design because they scrape a large amount of beam at high power density. The transient deflection of these knife edges under thermal load must not change the gap during the scan time by

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more than .0025 mm. To protect the bulk of the upstream blades from the beam, an armor plate that is both mechanically and thermally isolated from the scanner body is used. The function of this plate is simply to absorb the beam power without exceeding the thermal stress limits of the material. On the opposite end of the scanner are the dual slits. Since the thermal load at this point is negligible, these blades are made from 7075 aluminum. Once through this set of slits the beam enters the collector assembly. This consists of a suppressor electrode followed by a pair of Faraday cups, one behind each slit. Figure 4 shows a view of the dis-assembled pod looking from the collector end.

![Fig. 4 - Dis-assembled scanner pod - collector end view](image)

The scanner is operated by driving the pod through the beam using a stepper motor drive system that correlates position with time. As the scanner traverses the beam, thin ribbons of beam are admitted through the .0025 mm front slit. At the same time the voltage applied between the deflection plates is rapidly swept, causing the beam to sweep across the rear apertures. The current measured in the Faraday cups is then correlated with the deflection voltage and the position to determine the phase space of the beam. The CW scanner system is unique in that the voltage on the deflection plates is varied at high frequency allowing the pod to move at up to 30 cm/sec while gathering the complete data set for phase space reconstruction [2].

**Engineering Analysis**

The primary areas for concern in the design of the scanner pod were the stability of the .025 mm aperture at the entrance to the pod, and the survivability of the armor plate which takes the bulk of the thermal loading. Several 2-D and 3-D FEA models of the armor and knife edge were constructed using ANSYS to address these concerns. The beam was modeled as a three dimensional gaussian beam with a total power of 20 kW and a 2σ diameter of 2 cm. The analysis was run using only the core 2σ (17.4 kW total power) but the remaining 2.6 kW in the outer edges of the beam should have negligible effect on the results shown here. Figure 5 shows a 2-D plot through the center of the power density profile for the 2 cm diameter beam which peaks at 12.7 kW/cm². This 3-D loading was applied in an ANSYS finite element transient analysis. An external program generated the ANSYS load step commands based on the pod speed.

The first area of analysis was to evaluate candidate materials and cooling schemes through a series of 2-D scoring runs. Figure 6 shows the results of a 2-D run for a copper armor plate and knife edge with an elaborate array of cooling passages. Figure 7 shows results for a 3-D analysis done on solid components (no cooling) with the same materials, the same pod speed of 20 cm/sec, and the same time step. Comparing the results it can be seen that the peak temperatures are lower for the case with no cooling than for the case with cooling. This is explained by the time scale of the transient. At a speed of 20 cm/sec, the pod is exposed to

![Fig. 5 - Power density profile](image)

![Fig. 6 - 2-D Results for Cooled Configuration](image)

![Fig. 7 - 3-D Results for Un-cooled Configuration](image)
the beam for a total of 0.86 seconds and no point is exposed for more than 0.10 seconds. On this time scale, the coolant film represents a lower conductivity boundary when compared to solid copper. To further lower the peak temperatures, the translation velocity was increased to 30 cm/sec. Figure 8 shows the corresponding output. As a result of this analysis, the design incorporates water-cooled chill blocks that are mechanically attached to the pod housing and to the back side of the armor plate to remove the heat between scans.

Glidcop® Al-15 was chosen for the armor plate. The peak stress of 10200 psi at 877°C is well below the yield stress of 45000 psi for Glidcop® but too high for pure copper. We do, however, expect that mud cracking may take place over many hours of operation at peak beam power and therefore have made replacement of the armor very straightforward.

The second area of analysis focused on the blade deflection during a scan. Both Glidcop® Al-15 and the molybdenum alloy TZM were considered in the analysis. The results show that although the TZM blade reaches the considerably higher temperature of 284°C versus 163°C for the Glidcop®, the much lower thermal expansion coefficient and reduced thermal conductivity of TZM make it superior to the Glidcop®. Figure 9 shows the Glidcop® and TZM deflection data. The time step corresponds to the point when

Fig. 9 - Blade Deflections for Glidcop® and TZM

the beam has just cleared the aperture and the last moment when the requirement for a gap of .025 +/- .0025 mm exists. The Glidcop® gap has changed by +/- .006 mm in the area of interest (1 cm radius) while the TZM blade gap has changed by less than +/- .001 mm. In both cases the character of the deflection reflects rapid thermal expansion in the area of the beam core. This causes closing of the gap in that region and associated high compressive stress that leads to bending of the blade and opening of the gap away from the beam core (see fig. 10). In both cases the maximum deflection of the blades occurs well after the scan is complete and the heat soaks into the bulk material.

TZM was chosen in favor of pure molybdenum because of its somewhat better ductility and improved machining characteristics that are important when manufacturing the long straight knife edges.

Conclusion

The CW emittance scanner has been commissioned and utilized in applications with CW beam power up to 1 kW. Most recently, the scanner has been used to commission a 40 keV, 10 mA H⁺ injector [3]. A second scanner pod of the same design but for beam energies up to 2 MeV is in fabrication at Northrop Grumman. The new pod will be used to commission a 2 MeV, 10 mA CW tandem accelerator in late 1996 [4] that will require the pod to perform to the full design levels.

References


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A SWEEP PLATE EMMITTANCE SCANNER FOR HIGH-POWER CW ION BEAMS

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Abstract

Sweep plate scanners are preferred for emittance measurement due to their versatility, simplicity, and precision. At the Advanced Technology and Development Center of Northrop Grumman, we have routinely used these devices for characterization of injector beams with less than 20 W/cm² average power density. To characterize higher power beams, like those required for production of tritium or for radioactive waste transmutation, the scanner pod and data collection algorithm must be redesigned due to the possibility of melting the scanner’s protective front face or distorting the precision entrance knife edges. Among the methods we have used to mitigate these effects, one consists of drastically reducing the amount of time required for data collection. In this method, the emittance scanner pod traverses the beam in two passes, each requiring less than 0.5 second. In the first pass, the phase space limits of the beam are determined. In the second pass, data is collected primarily within the phase space region limits determined in the first pass. In this way, enough points are collected to assure that the precision of the measurement is high, even though the data collection time for each scan is less than 0.5 second. This paper will describe the layout of the scanner components, the data collection electronics and algorithm, and the data analysis.

Introduction

To measure the emittance of a particle beam, the angular distribution of the beam particles must be determined as a function of spatial position in the beam. The data are usually displayed in a phase-space graph similar to that shown in Fig. 1.

![Phase space graph of a particle beam showing the contours corresponding to various beam fractions.](image)

One measure of the beam emittance is the magnitude of the area of the pseudoeptitpeal space enclosed by the contours shown in Fig. 1. It is usually reported as a function of beam fraction. Using a sweep plate scanner, the angular distribution of the beam particles is determined by noting the electric field at which particles enter a thin aperture at the front of the scanner and exit a thin aperture at the rear of the scanner. The electric field under these conditions is proportional to the beam entrance angle. Knowing the geometry of the scanner and the energy of the beam particles, the angle of the beam particles is easily calculated.

To assure that the whole angular range of the beam is sampled at all positions, the electric field must be swept to cover the lowest to the highest expected angular limit. The most straightforward method (which is most commonly used) is to sweep through these limits from the beginning position to the final position of data collection. In effect, this means that the total rectangular area of the phase space region in Fig. 1 is sampled in the process of a measurement. This is defined as a “gross scan” in this paper.

The disadvantage of a gross scan is that, for a highly diverging or converging beam, most of the data collection occurs outside of the beam phase space region. Therefore, a large amount of storage is required for a small amount of useful data. This can be mitigated by using a mass storage device during data collection; however, this increases the minimum time necessary to obtain a scan, since these devices are slower than RAM storage. If faster internal RAM memory is used for storage, the maximum amount of data that can be collected in a single scan is limited to the total amount of RAM memory available. Ideally, one would like to use RAM storage to collect data that lies only within the phase space of the beam. This maximizes the data collection efficiency and minimizes the amount of time that the pod is in the beam.

This paper will describe a technique that accomplishes this objective in two steps. In the first step, a gross scan is obtained and stored in RAM memory. The approximate angular limits, position limits, and maximum spread in the angular distribution at a constant position are obtained from the scan. The two extreme angular and position limit coordinates define a straight line that connects the two ends of the phase space. The maximum angular spread of any scan defines the deflection plate voltage change that must be applied at any single position. This defines a parallelogram that encloses the beam phase space. In the second step, data is collected only within this parallelogram. The mean deflection plate voltage is changed in steps as the scan progresses from the beginning position to the end position.
while the deflection plate voltage spread within a sweep is held constant. In this paper, this is defined as a "detailed scan". A detailed scan maximizes the data collection efficiency, producing the highest point sampling density for the amount of RAM memory available for storage.

The sweep plate scanner is designed to be used for emittance measurement of beams with a power density up to 12.7 kW/cm². According to the thermal analysis[1], this will require that the scanner traverse the particle beam in a time period of 0.5 second or less. Therefore, the commonly used technique of stepping the scanner through the beam and collecting data during each step will take far too much time. The scanner must move through the beam continuously and quickly. The deflection plate voltage must be applied in a continuous triangle waveform and data collection must be continuous during the scan. This is accomplished by using two waveform generators. The first defines a DC voltage that is applied in steps. The second defines a triangle waveform that is not changed during a scan. Adding these waveforms produces a triangle waveform with an offset that changes in steps from position to position. When this waveform is synchronized with the movement of the pod, continuous data collection, primarily within the limits of the phase space, is accomplished in a time period of 0.5 second or less.

Scanner Pod Geometry

A functional diagram of the emittance scanner pod and electronics is shown in Fig. 2.

Two emittance scanner pods have been constructed, one for a beam energy up to 100 keV and another for a beam energy up to 2 MeV. The primary difference in the two pods is the deflection plate separation. The lower energy scanner has a deflection plate gap of 1.4 cm while the higher energy scanner has a gap of 0.35 cm. Table 1 shows a comparison of the critical scanner properties in each configuration.

<table>
<thead>
<tr>
<th>gap (cm)</th>
<th>θ max (mrad)</th>
<th>V max (Volts)</th>
<th>V/θ (V/mrad)</th>
<th>Δθ (mrad)</th>
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<tbody>
<tr>
<td>100 keV</td>
<td>1.4</td>
<td>±170</td>
<td>±3065</td>
<td>18.1</td>
</tr>
<tr>
<td>2 MeV</td>
<td>0.35</td>
<td>±42</td>
<td>±3832</td>
<td>90.3</td>
</tr>
</tbody>
</table>

Data Collection

A rack-mounted computer chassis houses the two waveform generators (D/A) used to produce the composite deflection plate voltage, the three A/D modules, a trigger (not shown), a DC bias voltage supply for the Faraday cup (not shown), and a stepper motor controller. An in-house built current to voltage converter (I/V) translates the Faraday cup current into a voltage that is digitized in one of the three A/D's. The voltage summer is another in-house built electronic module. The input to the summer comes from the two waveform generators. The summer has two outputs: the first is the sum of the two input voltages and the second is the inverse sum. They are independently amplified and applied to the two deflection plates. Using this scheme assures that the region of zero potential is near the entrance slit and exit slit of the scanner pod to assure that the two "field-free" regions have minimum electric field. The two amplifiers have separate outputs that are fed into the remaining two A/D's for monitoring and recording. The movement of the pod across the beam is controlled by the stepper-motor drive controller. The speed can be as high as 30 cm/sec after acceleration. The position of the pod is inferred from the A/D data stream. The A/D data collection speed can be as high as 125,000 conversions/second. This is combined with the known speed of the pod to obtain the position of the pod at any point in the scan. Absolute position resolution is estimated to be 1 mm; however, relative position resolution at 125,000 conversions per second and 30 cm/sec is 2.4 μm.

Results and Analysis

Sample Faraday cup signals and deflection plate voltages from a partial gross scan and from a partial detailed scan are shown in Figs. 4a and 4b.
Fig. 4. Faraday cup and corresponding composite deflection plate signals from a portion of a gross scan (a) and from a detailed scan (b).

Table 2 shows the data collection statistics corresponding to these two partial scans.

<table>
<thead>
<tr>
<th></th>
<th>mrad/sec</th>
<th>% of points in phase space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Scan</td>
<td>28,000</td>
<td>6.9%</td>
</tr>
<tr>
<td>Detailed Scan</td>
<td>4,000</td>
<td>58%</td>
</tr>
</tbody>
</table>

The improvement in the fraction of useful data points in a detailed scan is clearly seen.

The results of an analysis to obtain the emittance for the detailed scan are shown in Fig. 5. (See Ref. [2].)

Fig. 5. (a) Position profile, and (b) extrapolation of rms emittance to 100% beam fraction (f)

plate scanner by taking data continuously as the pod moves through the beam at speeds up to 30 cm/sec. The data collection efficiency was optimized by first obtaining the parallelogram that encloses the phase space, and then collecting data primarily within that parallelogram. For a typical partial scan, 221 total useful points were obtained out of 384 total points, with the number of angular points per position ranging from 7 to 48.

References

STATUS OF THE 1.76 MEV PULSED LIGHT ION BEAMLINE AT THE NORTHROP GRUMMAN ADVANCED TECHNOLOGY AND DEVELOPMENT CENTER

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Abstract

The Northrop Grumman Corporation (NGC) Advanced Technology and Development Center (ATDC) beamline has recently been upgraded to provide a 1.76 MeV beam for use in the testing of various types of targets for gamma ray production. The beam is produced by an RF Driven multiscup volume ion source. After transport through a dual solenoid LEBT, the beam is captured and accelerated to 1.013 MeV by an electroformed monolithic RFQ. The DTL boosts the 1.013 MeV output of the RFQ up to 1.76 MeV. A bunching cavity and three permanent magnet quadrupoles match the RFQ output to the DTL. Downstream of the DTL an electromagnetic quadrupole HEBT transports the beam to a diagnostic station housing target testing hardware.

Automatic startup and control algorithms have been developed to simplify beamline operations. A new sequenced autostart has been developed to start up all three RF cavities and initiate amplitude, phase, and frequency control subsystems. The frequency-control system, which uses a sliding-short tuner and an I&Q tune sensor, is currently integrated into the main control system.

This paper will discuss the status of the beamline with emphasis on the energy upgrade, automatic startup and control systems, and the frequency-control subsystem.

Current Beamline Configuration

The current beamline configuration is shown in Fig. 1. The beam is produced in a Berkeley type multiscup volume ion source. The source is 7 cm in diameter and the plasma is driven by up to 20 kW of 2 MHz RF. The amplifier is located at ground and is isolated from the HV at the source body and antenna by an integrated RF matching circuit and isolation transformer. Beam is extracted at 36.5 keV using a triode extraction electrode geometry for a final source beam energy of 32 keV.

The LEBT consists of a pair of water cooled pancake coil solenoids and a pair of x-y steering magnets. The solenoids are capable of peak fields of about 5000 Gauss in the center (limited by the power supplies), and the steers of 160 Gauss at 10 Amps. In the middle of the LEBT is a diagnostic station. A variety of diagnostics can be housed in the station including a Faraday cup, quartz plate viewscreen, emittance scanner and others.

After the LEBT, an RFQ accelerates the beam to 1.013 MeV in about 1 meter. The RFQ is a twin to the BEAR (Beam Experiment Aboard Rocket) RFQ built for and flown

Fig. 1 NGC ATDC Beamline

Beam Direction

MicroStrilines

High Energy Diagnostics Station

EM Quadrupole Focusing Magnets

DTL Cavity

Matching Section Cavity

RFQ Cavity

Solenoid Focusing Magnets

X-Y Steering Magnets

Cryopump

Ion Source
in space by LANL\textsuperscript{1}. It consists of four copper plated aluminum vanes/wall sections which are electroformed together to form a monolithic structure The RFQ was originally designed to operate at 0.1% duty factor. We are currently running it up to 0.7% duty factor. To prevent overheating, cooling bars have been mounted at the vane roots outside the cavity.

The beam is matched to the DTL by a matching section consisting of 3 permanent magnet quadrupoles and a single gap RF cavity. The permanent magnet quadrupoles maintain and adjust the x-y focus of the beam, and the cavity matches the longitudinal focus.

The DTL accelerates the beam to 1.76 MeV. It is a 9 gap structure with a $2\beta_0$ FO-DO focusing lattice. The DTL and its installation will be discussed at greater length in the next section.

Following the DTL is a HEBT with three water cooled electromagnetic quadrupoles. They transport the beam to the second diagnostic station. This station currently holds our target testing equipment. Targets are being tested which will be used to produce $\gamma$ rays for a gamma-ray absorption contraband detection system\textsuperscript{2}. The thermal response and lifetime of the targets are being evaluated under different beam conditions\textsuperscript{3}.

Energy Upgrade with the 1.76 MeV DTL

The DTL cavity is a room temperature, constant gradient, Alvarez DTL designed for a proton or H beam. The focusing lattice is a $2\beta_0$ FO-DO. Important cavity characteristics are outlined in Table 1. The DTL cavity is shown in Fig. 2. It has eight drift tubes (nine cells), four post couplers, two tuning slugs, and one tuning bar. There are two large coupling loops, one for the input drive and one for a sliding short tuner. Vacuum windows in the coaxial waveguide are made of Rexolite and are located as close as possible to the cavity (approximately two inches). There are provisions for two RF pickup loops; although, as of this writing, only one is installed. Several vacuum ports penetrate the cavity wall which is also the vacuum wall. Two of these look directly at the high and low energy DT gap and are meant for X-ray end-point measurement of the gap voltage.

The DTL cavity is fabricated from copper plated carbon steel with SS ports. This provides a strong, ridged, inexpensive structure which provides good shielding properties. The endwalls with half drift tubes are made from OFHC copper. The drift tubes and stems are also made from OFHC copper.

After installation of the drift tubes, the DTL was tuned. The cavity was first tuned for flat fields using the bead pull technique. A small dielectric bead is pulled through the cavity, causing the resonant frequency of the cavity to shift. The magnitude of the shift depends on the magnitude of the field at the bead. As the bead is moved, the shift in the resonant frequency of the cavity is measured thus giving a measure of the cavity field. Post couplers are then used to tune the fields to the desired configuration.

The final configuration of the fields after the post couplers have been adjusted and brazed was measured and the field tilt found to be 0.26%. The scatter of about 0.5% is a little larger than we would like but is as good as we can get, given the location of our post couplers.

The installation of the DTL began with the mounting of the matching section cavity, magnets, and vacuum vessel on to the DTL low energy end wall. An interface plate to mate the high energy end wall to the HEBT was then installed and the entire assembly transported to the beamline. The matching section and DTL were aligned with precision.

Table 1 DTL Characteristics and Specifications

<table>
<thead>
<tr>
<th>Frequency (measured)</th>
<th>424.893 MHz</th>
<th>Input Energy</th>
<th>1.013 MeV</th>
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<tr>
<td>Q₀ (measured)</td>
<td>17,280</td>
<td>Output Energy</td>
<td>1.760 MeV</td>
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<tr>
<td>Coupling (measured)</td>
<td>0.77</td>
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<td></td>
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<tr>
<td>Q₀ (Superfish inc. 15% on power in non-ends)</td>
<td>31,301</td>
<td>Cavity Power (Superfish uncorrected)</td>
<td>38.88 kW</td>
</tr>
<tr>
<td>Q₀ (Superfish inc. 15% on power in non-ends)</td>
<td>31,301</td>
<td>Cavity Power (Superfish + 15% on non-ends + correction for meas'd Q)</td>
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<tr>
<td>Q₀ (Superfish uncorrected)</td>
<td>34,975</td>
<td>Beam Power @ 30 mA</td>
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<td>Stored Energy</td>
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<tr>
<td>Accelerating Field</td>
<td>1.890</td>
<td>Total Power (CP+BP+15%)</td>
<td>76.03 kW</td>
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<tr>
<td>Peak Field (on input end wall DT)</td>
<td>19.293</td>
<td>MV/m</td>
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<tr>
<td>Gap Voltage (last gap)</td>
<td>94.800</td>
<td>kV</td>
<td></td>
</tr>
</tbody>
</table>
Automated Startup for RF Systems

We have implemented an automatic startup algorithm which brings the cavity system up with a single keystroke. The automatic startup consists of the following three steps:

Step 1: Set initial amplifier controls. Most of the system control variables for the RFQ, MS, and DTL are set in order as soon as the autostart command is given. Control setpoints are stored in a protected file. These initial setpoints generally cannot be changed from inside the control system program. During this step the automatic control loops imbedded in the cavity amplifiers are activated.

Step 2: Tuner initializations. Initialize tuners for MS and DTL, then set tuners to the center of their range.

Step 3: Activate RF. Turn on RFQ RF, wait one minute then turn on MS and DTL RF. The frequency tuning routine is then activated.

The use of this auto startup routine has greatly simplified day to day operation of the system. It reduces the 30 commands required to start the system to one and eliminates the need to have a list of setpoint numbers available at all times. It is especially useful when the system is being operated by personnel who are not experts on the system.

Active tuning using a sliding short.

Tuning for the DTL and MS cavities is performed with a sliding short tuner, an I&Q tune sensor, and a computer control system. The RFQ, which does not employ active tuning, is used as the system reference.

The sliding short tuner is simply a length of coaxial line coupled to the cavity with an inductive loop. The line is shorted at the end. The frequency shift of the cavity, the VSWR looking into the cavity at the drive, and the cavity field linear magnitude are all shown as a function of the position of the tuner in Fig. 3. One can see that only a portion of the tuner position range can be used. As the length of the tuner becomes close to \( \lambda/4 \), it begins to interact strongly with the cavity. At \( \lambda/4 \) it behaves like a second coupled cavity, splitting the mode. We use this tuner to provide approximately \( \pm 200 \) kHz of tuning range.

The I&Q tune sensor consists of a dual directional coupler, a pair of IQ demodulators, and a reference master oscillator (MO) signal. The forward and reflected signals are fed into the demodulators along with the MO reference signal. They produce four DC signals: Forward In-Phase (I, real), Forward In-Quadrature (Q, Complex), and Reflected In-Phase (I, real), a Reflected In-Quadrature (Q, complex). The DC signals are fed back to a computer which then calculates the amplitude and phases of the original signals. For active tuning, the only signal analyzed is the reflected phase. The computer system moves the tuner to drive this signal to setpoint, bringing the cavity to the correct frequency.

Conclusion

The beamline is serving as a usefull testbed for the development of accelerator systems technology as well as a tool for generating beam. It will be used primarily to generate beams for target evaluation for near future. It’s operation and maintenance provide constant opportunities for the evaluation of accelerator systems. Future applications and upgrades are under consideration.

4. M. Curtin, Private Communication
PARAMETRIC STUDY OF EMERGING HIGH POWER ACCELERATOR APPLICATIONS USING ACCELERATOR SYSTEMS MODEL (ASM)


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Abstract

Emerging applications for high power rf linacs include fusion materials testing, generation of intense spallation neutrons for neutron physics and materials studies, production of nuclear materials and destruction of nuclear waste. Each requires the selection of an optimal configuration and operating parameters for its accelerator, rf power system and other supporting subsystems. Because of the high cost associated with these facilities, economic considerations become paramount, dictating a full evaluation of the electrical and rf performance, system reliability/availability, and capital, operating, and life cycle costs.

The Accelerator Systems Model (ASM), expanded and modified by Northrop Grumman during 1993-96, provides a unique capability for detailed layout and evaluation of a wide variety of normal and superconducting accelerator and rf power configurations. This paper will discuss the current capabilities of ASM, including the available models and data base, and types of trade studies that can be performed for the above applications.

Introduction And Background

High power rf-driven ion linacs are currently being considered for a variety of applications including, but not limited to:

- Spallation neutron production for scientific and materials studies (e.g., European Spallation Source [ESS], US National Spallation Neutron Source [NSNS])
- ~14 MeV neutron production for fusion materials testing (e.g., International Fusion Materials Irradiation Facility [IFMIF])
- Production of nuclear materials (e.g., Accelerator Production Of Tritium [APT])
- Destruction of high-level nuclear waste (e.g., Accelerator Transmutation of Waste [ATW])

The Accelerator Systems Model (ASM), expanded and modified by Northrop Grumman since 1993, provides a unique capability for detailed layout and evaluation of the wide variety of rf linac and rf power configurations. This capability, recently used to support the IFMIF accelerator design effort (as well as internally funded efforts involving higher energy linacs), provides the following features:

- Ability to model ion linac configurations based upon a large number of existing and recently proposed normal and superconducting linac structures, operating over a wide range of rf frequencies
- Detailed tracking of the linac's cell-by-cell configuration and the electrical and rf power system performance
- Generation of detailed component inventory that includes all accelerator systems and dedicated facilities
- System reliability, availability, maintainability (RAM) modeling for estimation of operational availability and the cost of component replacement and/or refurbishment
- Cost analysis capability which encompasses capital, construction, and annual operating costs, resulting in a single net present value life cycle cost estimate.

ASM allows the user to consider many linac configurations and technology trades, in a limited time, using a complete set of data and a consistent set of modeling algorithms.

The on-going physics and engineering modeling effort of ASM is now concentrating on improvement of existing models (e.g., diagnostics, instrumentation and control and cryogenics), implementation of an automated capability for parameter trades, and adaptation of the code for pulsed ion linacs. Future ASM variants dedicated to applications involving electron beam accelerators, free electron lasers, ion cyclotrons and ion storage rings are envisaged.

ASM Calculational Flow

The ASM code is driven by a Macintosh™ Graphic User Interface (GUI) that provides a user interactive, on-screen format for data input. In addition, the code reads several formatted files that convey engineering, cost and RAM data.

As shown in Fig. 1, the first series of Fortran routines use the input data to establish a cell-by-cell layout of the accelerator, starting at the ion injector and proceeding through all of the major rf structures, completing each at a specified energy breakpoint. A generalized set of algorithms is used to match the synchronous phase and the longitudinal and transverse phase advances from structure to structure.
The electric field is linearly ramped within an rf tank according to any of several criteria (e.g., proportional to particle velocity, $\beta$, up to a limiting value). Tank sizing may be specified according to the available rf power, energy break points or other user inputs. When the layout is completed, the rf power requirements and an inventory of linac components (see Fig. 2) is passed to the subsequent routines.

The next set of ASM routines are used to size and configure the rf power system, which is critical to the overall evaluation because it represents the largest cost component of the accelerator, dominates the electric power requirement and plays a major role in the system availability. As a first step, ASM reviews the required sizes and frequencies of rf sources and compares them with its rf amplifier data base, illustrated in Figure 3. The code selects the tube with the best operational efficiency, then lays out the remainder of the rf system including the driver tube(s), peripheral equipment, high voltage equipment and rf transport components. Based upon the inventory of rf components and their various rf and electrical
efficiencies, the electrical power requirement of the rf system is estimated.

A third set of ASM routines is used to estimate the overall operational availability of the accelerator (during scheduled operation). Starting with a RAM library containing the failure rates (mean time before failure, or MTBF) and repair times (mean time to repair, or MTTR) of the constituent equipment, the ASM RAM routines process the configuration and parts inventory data to develop estimates of the RAM performance of individual subsystems. These are combined (with consideration of spares and redundancies) to develop an overall estimate of the system reliability and availability. The results are also used to predict the rates of replacement of major components.

The next set of ASM routines provide estimates of the capital, operating, and life cycle costs for the major subsystems of the accelerator. Using the parts inventory, these routines develop engineering, fabrication labor and materials cost estimates. The engineering estimates are comprised of both non-recurring design and development activities for the first unit and recurring engineering for subsequent units. Where large quantities of parts or components are required, learning curve techniques are used to model the decreasing cost of unit production or acquisition.

Annual operating cost estimates are developed from the electric usage, component refurbishment/replacement requirements and facility staffing estimates. A life cycle cost estimate that combines the capital costs, with projections of the facility construction costs and the annual operating costs is also developed. Standard net present value analysis is used to represent the life cycle cost as a single value.

**Trades That Can Be Performed Using ASM**

The types and applicabilities of trades currently supported by ASM are indicated in Table 1. In the table, a "✓" indicates that the code has already been used to perform the indicated type of trade, a "✗" indicates that the trade should be considered for the indicated application, and "N/A" indicates that the trade is not applicable.

An example of a recent trade involves the selection of the preferred accelerating gradient for a drift tube linac (DTL). As shown in Figure 4, the capital and operating costs increase at high gradient due to the increased rf power consumed in the rf structure, which leads to larger rf power requirements and larger electricity requirements. As the gradient is decreased the rf power requirement also decreases, but the DTL length and the number of rf tanks increase, decreasing the rf power per tank and ultimately increasing the overall life cycle cost. The best balance between these trends results at a gradient of 1.8 MV/m, where the life cycle cost is minimized.

![Figure 4: Example Of Use Of ASM To Determine Optimal Accelerating Gradient For A Drift Tube Linac](image)

**Table 1. Current ASM Trade Study Capabilities**

<table>
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<th>Candidate Trade Study</th>
<th>IFMIF</th>
<th>ATW</th>
<th>NSNS</th>
</tr>
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<tbody>
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<td>Beam Pulse Length</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>Alternative Accelerating Structures</td>
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<td>✓</td>
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<td>Normal vs. Superconducting</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>Transition Energies &amp; Matching</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>Beam Energy vs. Current</td>
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<td>Accelerating Gradient</td>
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<td>N/A</td>
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<td>N/A</td>
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<td>Design Optimization vs. Plant Life</td>
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**Acknowledgments**

The Northrop Grumman Version of ASM is a product of G. H. Gillespie Associates, Inc.

Figure 2 was provided courtesy of Los Alamos National Laboratory.
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Tuesday, August 27, 1996
IFEL FIRST EXPERIMENTAL RESULTS OF THE BNL INVERSE FREE ELECTRON LASER ACCELERATOR

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3Department of Applied Physics, Columbia U., New York NY 10027
4Physics Department, State University of New York, Stony Brook, New York 11794

Abstract

A 40 MeV electron beam, using the inverse free-electron laser interaction, has been accelerated by $\Delta E/E = 2.5\%$ over a distance of 0.47 m. The electrons interact with a 1-2 GW CO$_2$ laser beam bounded by a 2.8 mm ID sapphire circular waveguide in the presence of a tapered wiggler with $B_{max} = 1$ T and a period 2.89 cm $\leq \lambda_w \leq 3.14$ cm. The experimental results of $\Delta E/E$ as a function of electron energy $E$, peak magnetic field $B_w$ and laser power $W_l$, compare well with analytical and 1-D numerical simulations and permit scaling to higher laser power and electron energy.

Introduction

The study of the Inverse-Free Electron-Laser (IFEL) as a potential mode of electron acceleration has been pursued at Brookhaven National Laboratory (BNL) for a number of years [1–4]. Recent studies have focused on the development of a low energy, high gradient, IFEL accelerator [5] as a first step toward a multi-module electron accelerator of maximum operating energy of a few GeV. Experimental verification of the IFEL accelerator concept was obtained in 1992 [6], using a radiation wave length of $\lambda = 1.65$ mm, and more recently [7] using a wavelength of 10.6 $\mu$m. In this report further experimental evidence of the IFEL interaction ($\lambda = 10.6$ $\mu$m) is presented. The experiment used a 50 MeV electron beam, a 1–5 GW CO$_2$ laser beam provided by BNL's Accelerator Test Facility (ATF) and a uniquely designed period length tapered wiggler.

The wiggler is a fast excitation electromagnet with stackable, geometrically and magnetically alternating substacks of Vanadium Permendur (VaP) ferromagnetic laminations, periodically interspersed with conductive (Cu), nonmagnetic laminations, which act as eddy current induced field reflectors [8,9]. Four current conducting rods, parallel to the wiggler axis, are connected at the ends of the assembly, constituting the excitation loop that drives the wiggler. The overall wiggler stack is easily assembled, is compressed by simple tie rods, and readily permits wiggler period ($\lambda_w$) variation. Configured as a constant period wiggler, $\lambda_w = 3.75$ cm and $B_{max} = 1$ T, the system has shown [10] an rms pole-to-pole field variation of approximately 0.2%.

The CO$_2$ laser beam is brought into the IFEL interaction region by a low loss dielectric (Al$_2$O$_3$, sapphire) circular waveguide which evidenced very good transmission properties [11] of the high power CO$_2$ laser beam. Extensive studies were carried out to establish optimum coupling into the guide and to measure the transmission loss of the long (1.0 m) extruded single crystal sapphire guides. Also, because of the overmoded guide configuration (ID = 2.8 mm), attempts were made to determine the transverse mode spectrum. To this end various wave guide configurations were tested at low laser beam power with the beam focused to a Gaussian waist with adjustable radius at the entrance of the waveguide. The beam profile was measured using a pyroelectric vidicon TV camera combined with digital frame grabber. For the 2.8 mm, ID sapphire dielectric guide a laser power attenuation factor of 0.2 dB/m was measured. The laser beam profile within the guide was inferred by measuring the beam diameter at the guide exit for various guide lengths. The results show that, commensurate with the near constant beam profile within the guide, the mode structure is dominated by the guide fundamental mode only. This is in accord with the absence of mode mixing reported in Ref. [11] for filamentary sapphire guides for CO$_2$ laser radiation transport.

In the IFEL accelerator, the electron beam is accelerated by the interaction with the laser radiation wave in the medium of a periodic wiggler field. The theoretical description of the interaction has been given by a number of authors [3,12]. Approximate analytical expressions derived in Ref. [3] were used to parameterize a single acceleration stage. Subsequently, 1-D and 3-D simulation programs were written solving the self-consistent system of Lorentz equations for the electrons and the wave equations for the input laser field as discussed in Ref. [12]. The 1-D program has been used to determine the self-consistent wiggler period length and its taper for given values of electron beam energy and laser power and to calculate the bucket acceptance and bucket leakage for a single or multi module accelerator. The 3-D code has been used to study beam walk-off, transverse phase space distributions and emittance growth.

Experimental Arrangement and Result

Extensive IFEL simulation studies were carried out both for a single IFEL accelerator module and for a sequence of IFEL modules. The objective of the present experiment was a proof of principle performance of a single IFEL unit incorporated in beam line II of the ATF [13,14]. A schematic layout, specific to the IFEL experiment only, is shown in Fig. 1. Beam transport downstream from the nominal 50 MeV Linac is so dimensioned as to yield a dispersion free IFEL interaction region. The electron beam, at the IFEL location, is matched vertically to the natural wiggler betatron amplitude $\beta_\gamma = 0.17$ m, $\alpha_\gamma = 0.0$ and to a horizontal amplitude $\beta_x =$
0.3 m, \(\alpha = 0.0\). Downstream of the IFEL interaction region the optical system is configured as a momentum spectrometer with adjustable dispersion magnitude (0.0 < \(n_p < 3.0\) m) at a diagnostic endstation; there the beam momentum dispersion is measured by means of a phosphor screen-vidicon TV camera-Spiricon frame grabber. Also shown schematically in Fig. 1 is the CO\(_2\) laser beam entry into the interaction region vacuum envelope through a ZnSe window, and its propagation as a free-space mode, to the sapphire dielectric waveguide entry. With deliberation, the dielectric guide was taken to be 0.6 m in length, whereas the accelerator module length (wigglers length) was set at 0.47 m. This was done to approximate a mode matching section, enhancing thereby the mode purity in the IFEL module proper.

![Schematic of the Experimental Configuration](image)

Fig. 1 Schematic of the Experimental Configuration.

The design parameters used in this IFEL accelerator experiment are listed in Table 1. With optimized overlap of the electron and CO\(_2\) laser beams, both spatially and temporally, and the interleaving of the lower repetition rate CO\(_2\) laser pulses with the higher repetition rate electron beam pulses, the IFEL electron beam acceleration could readily be established. Electron acceleration was measured with the spectrometer at the diagnostic screen. An example of the momentum spectrum of the unaccelerated and accelerated electrons is given in Fig. 2, where the beam intensity distribution is shown versus \(\sqrt{\beta_e e_p + \eta_p \Delta \beta_e / p}\), with the spectrometer optics adjusted so that \(\eta_p \Delta \beta_e / p >> \sqrt{\beta_e e_p}\). Optimization of the IFEL effect and exploration of parameter space, with variation of the electron beam injection energy, CO\(_2\) laser power and wiggler maximum magnetic field magnitude was carried out in several consecutive runs, the results of which established the unambiguous signature of the IFEL acceleration. This is illustrated in Figs. 3 and 4, where \((\Delta E/E)_{IFEL}\) is shown both as given by the 1-D model simulations and as obtained experimentally. Figure 3 shows the relative energy gain for \(E_a\) and \(W_i\) constant; in Fig. 4 the plot \((\Delta E/E)_{IFEL}\) vs. \(B_a\) is given.

The approximate IFEL design equations [3] are:

\[
\frac{d\psi}{dz} = A(K/\gamma^2)f(K)\sin\psi \quad \psi = (k + k_0)z - kc
\]

where the normalized laser electric field is \(A = (e/mc^2)(1/R_0)(\pi W Z_0/2)\), \(K = (eB_0 Z_0)/(2\pi mc) = 2.7\) is the wiggler parameter, \(f(K) = 0.38\) is a correction factor due to the linear polarization of the wiggler, \(Z_0 = 377\), \(L_0\) is the waveguide radius and \(k, k_0\) are the radiation and wiggler wavevectors, respectively. The resonance condition leads to:

\[
\lambda = 0.5 \lambda_{we} / \gamma^2 (1 + K^2/2)
\]

### Table 1

<table>
<thead>
<tr>
<th>e(^-) beam</th>
<th>Injection Energy</th>
<th>40.0</th>
<th>MeV</th>
</tr>
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<tr>
<td>Exit Energy</td>
<td>42.3</td>
<td>MeV</td>
<td></td>
</tr>
<tr>
<td>&lt;Accel. Field&gt;</td>
<td>4.9</td>
<td>MV/m</td>
<td></td>
</tr>
<tr>
<td>Current, nominal</td>
<td>5</td>
<td>mA</td>
<td></td>
</tr>
<tr>
<td>N(bunch)</td>
<td>10(^{10})</td>
<td>e(^-)</td>
<td></td>
</tr>
<tr>
<td>I(max.)</td>
<td>30</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>(\Delta E/E) (one (\sigma))</td>
<td>5 \times 10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission (one (\sigma))</td>
<td>10(^{-8})</td>
<td>m.rad</td>
<td></td>
</tr>
<tr>
<td>Beam radius</td>
<td>0.2</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Wiggler Length</td>
<td>0.47</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Section Length</td>
<td>0.6</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Period Length, (\lambda)</td>
<td>2.9–3.1 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wiggler Gap</td>
<td>4</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Field max.</td>
<td>10</td>
<td>kG</td>
<td></td>
</tr>
<tr>
<td>Beam oscil., (a_{osc})</td>
<td>0.16–0.2 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power, (W_{(Laser)})</td>
<td>10(^{3})</td>
<td>Watts</td>
<td></td>
</tr>
<tr>
<td>Wave Length, (\lambda)</td>
<td>10.6</td>
<td>\mu m</td>
<td></td>
</tr>
<tr>
<td>Max. Field, (E_a)</td>
<td>0.78 \times 10(^{3})</td>
<td>MV/m</td>
<td></td>
</tr>
<tr>
<td>Guide Loss, (\alpha)</td>
<td>0.05</td>
<td>m(^{-1})</td>
<td></td>
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<tr>
<td>Field Attenuation</td>
<td>0.26</td>
<td>dB/Sect.</td>
<td></td>
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<tr>
<td>Pulse, (fwhm)</td>
<td>220</td>
<td>ps</td>
<td></td>
</tr>
<tr>
<td>(\Lambda_0)</td>
<td>1.53 \times 10(^3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\tau_L/(L_0/2))</td>
<td>1.0</td>
<td>mm</td>
<td></td>
</tr>
</tbody>
</table>

The relative energy gain of the electron beam in a wiggler of length \(L_w\) is:

\[
\Delta \gamma / \gamma = (\Delta p/p)_{IFEL} = A(K/\gamma^2)f(K)\sin\psi L_w, \quad \psi = \text{resonance phase} (45° \text{ for optimum bucket size}).
\]

![Momentum Spectrum of the unaccelerated and IFEL accelerated electron Beam](image)

Fig. 2 Momentum Spectrum of the unaccelerated and IFEL accelerated electron Beam

\(E_i = 40\) MeV, \(B_a = 10\) kG, \(\lambda_a = 2.9–3.1\) cm, \(W_i = 1\) GW.

In Fig. 3 the solid line shows the results of the numerical simulations with laser power \(W_i = 1\) GW and \(B_a = 10\) kG normalized to the maximum experimental value. The
agreement of the simulations with the experimental results are good. Similarly, in Fig. 4 experimental results are compared with the simulations for 35 MeV and 40 MeV, in both cases the agreement is good. The maximum $(\Delta p/p)_{IFEL}$ for initial electron energy of 35 MeV leads to a value of the magnetic field $B_w = 8.35$ kG, to be compared with the experimental value of 8.44 kG, and for $E = 40$ MeV, the calculated $B_w$ is 9.98 kG and the experimental value was $B_w = 9.96$ kG.

![Simulation, norm. [B_w=10 kG] Experimental Data [B_w=9.5 kG]

Fig. 3 Relative Energy Gain $\Delta E/E$ vs $E$, with $B_w$, $W_i$ constant.

![Simulation, norm. Experimental Data]

$E(e')=35[MeV]$ $E(e')=40[MeV]$

Fig. 4 Relative Energy Gain vs $B_w$ with $E$ and $W_i$ constant.


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References

LIAR - A NEW PROGRAM FOR THE MODELLING AND SIMULATION OF LINEAR ACCELERATORS WITH HIGH GRADIENTS AND SMALL EMITTANCES*

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Abstract
Linear accelerators are the central components of the proposed next generation of linear colliders. They need to provide acceleration of up to 750 GeV per beam while maintaining very small normalized emittances. Standard simulation programs, mainly developed for storage rings, do not meet the specific requirements for high energy linear accelerators. We present a new program LIAR ("Linear Accelerator Research code") that includes wakefield effects, a 4D coupled beam description, specific optimization algorithms and other advanced features. Its modular structure allows to use and to extend it easily for different purposes. We present examples of simulations for SLC and NLC.

Internal data structures
The internal data structures are designed in such a way that easy data access is guaranteed. An INCLUDE statement like

INCLUDE 'lattice.inc'

will give access to all beamline information, including names, s-locations, magnetic fields, RF phases, gradients, misalignments, Twiss parameters, beam offsets, emittances and many more quantities.

Let's consider an easy example. The beamline is defined in a structure ELEMENT that has pointers to the BPM structure. The following loop would print the vertical emittance at the BPM's for the whole beam and the first bunch:

DO I = 1, NUM ELEMENT
   IF (ELEMENT(i).IS_BPM) THEN
      ibpm = ELEMENT(i).POINTER
      WRITE(outlun,*)
5          BPM(ibpm).YEMITALL,
      2          BPM(ibpm).YEMIT(1)
   ENDF I
EN DO

The emittance information at the BPM's is updated automatically during each tracking. Another hypothetical example is to misalign all quadrupoles vertically by 1% of the vertical beta function:

DO I = 1, NUM ELEMENT
   IF (ELEMENT(i).IS_QUAD) THEN
      iquad = ELEMENT(i).POINTER
      QUAD(iquad).DY =
5          1
          0.01 * TWISS(i).BETAY
   ENDF I
EN DO

During the next tracking the new quadrupole misalignments will be used. Those examples illustrate how easy it is to access and manipulate the internal beamline information without a detailed understanding of other parts of the program. Complete reference information about the internal data structure can be found in [1].

The LIAR command language
The goal to make LIAR easily extendable required a modular structure of the different parts of the program. It should be possible to add subroutines (commands in the LIAR language) without major modification to other parts of the program. Subroutine parameters are therefore passed through a command language. The main program knows only the name of a subroutine and passes the control with whatever parameters have been defined. It is the task of the subroutine to process and use the parameters

---

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properly. When the LIAR program is started without command line parameters then it enters an interactive mode:

```
LIAR>
```

and commands can be entered. Alternatively LIAR can be run in batch mode, reading its input from a file. Let’s consider the example of a simple SLC simulation. We go through it in steps, explaining the purpose of every part. For most commands many more parameters than shown are available. However, if parameters are not specified explicitly, then they are set to their default values. Command lines are automatically continued if an input line is ended with a comma.

In the first two commands we initialize all internal data structures to zero, we switch off the debug level and we set the output unit to the standard output:

```
RESET, all
SET_CONTROL, debug = 0,
               outlun = 6
```

Then we read the lattice from a transport input deck and define the injection energy:

```
READ_TRNS, infile = ‘input/slc.trns’,
energy = 1.19
```

In the next step the RF-phases for BNS damping are defined and the lattice is rescaled accordingly. Note that two different RF-phases are specified along the linac with the switch at 800 m:

```
SET_RF, energy = 50.,
scale = .t.,
phase1 = 22.,
lswitch1 = 800.,
phase2 = -16.5
```

Next we calculate the Twiss parameters, specifying the initial values:

```
CALC_TWISS, betax = 3.40,
betay = 3.08,
alphax = 0.156,
alphy = 0.066
```

After that we need to define the initial conditions for the beam setup. We define an initial beam offset y, the injection energy and energy spread, the normalized emittances and the Twiss values:

```
SET_INITIAL, y = 200.d-6,
energy = 1.19,
espread = 0.014,
nemity = 0.3d-5,
betax = 3.40,
betay = 3.08,
alphax = 0.156d0,
alphy = 0.066d0
```

Everything is prepared now to set-up the beam. We specify the bunch population, the bunch length, the number of bunches, the number of slices per bunch, the number of mono-energetic beam ellipses per slice and the bunch spacing:

```
SET_BEAM, current = 4.d10,
blength = 1100.d-6,
nb = 1,
ns = 20,
nm = 3,
bspace = 0.
```

Next we have to define the wakefields. They are read in from design specific input files. We only define short-range wakefields:

```
SET_SR_WF, file = ‘input/srwf_slc.dat’
```

Before we track the beam through the lattice, we misalign all quadrupoles vertically by 200 µm rms:

```
ERROR_GAUSS_QUAD, name = ’’,
y_sigma = 200.e-6
```

Now we can finally track the beam through the lattice:

```
TRACK
```

and measure the normalized beam offsets at the BPM’s:

```
MEAS_BPM, file = ‘output.data’,
norm = .t.
```

The output is saved into a file. As already mentioned many more parameters and commands are available in LIAR. For example the command TRACKKC would have tracked the beam through the lattice while applying a 1-to-1 trajectory correction. The complete reference information is available in the LIAR manual [1].

During the execution of the commands LIAR provides extensive information. For example the progress of the tracking is indicated by a “trackometer”:

```
TRACKOMETER:
----------------------------------------
0 10 20 30 40 50 60 70 80 90 100 %
----------------------------------------
```

At the end of the tracking, summary information is printed to the standard output:

```
End of tracking  ANALYSIS:
----------------------------------------
```

Beam energy
- acceleration: E_0 = 1.190 GVeV --> E_0 = 45.998 GVeV
- spread: E_s10 = .916 GVeV --> E_s10 = .126 GVeV
- rel. spread SIGMA_E/SIGMA_E = .132 % --> SIGMA_E/SIGMA_E = .274 %
Beam blow-up
- Delttance (bl): q_x = 41.680 % --> q_x = 295.158 %
- trans: q_x = 41.680 % --> q_y = 295.158 %
- Limi. factor: n_x = 91.1 --> n_y = 86.3
- RMS mismatch: RMS_X = 1.016 RMS_Y = 1.355
Initial beam size:
- Horizontal: s_x = 275.6 um s_x' = 45.2 used
- Vertical: s_y = 87.5 um s_y' = 24.2 used
Final beam size:
- Horizontal: s_x = 135.91 um s_x' = 3.56 used
- Vertical: s_y = 55.695 um s_y' = 1.439 used
Jitter offsets w.r.t reference 1 for bunch 0:
- Horizontal: s_x = .43 um s_x' = .67 used
----------------------------------------

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Limitations

The LIAR program is presently limited to linear accelerators without bending magnets. It is assumed that the longitudinal charge distribution remains unchanged. This is perfectly valid for linear accelerators. However, bunch compressors cannot be simulated. For example, LIAR is now also used for the modeling and simulation of the SLAC Linac Coherent Light Source (LCLS) [5]. Bunch compressors are an important part of this proposal. Further we have not yet implemented sextupoles or any matching abilities into LIAR.

Future plans

The correct treatment of bending magnets will be implemented into LIAR in the near future. This will allow to include bunch compressors into the simulation. We further plan to implement automated dispersion-free steering algorithms into the program. However, those are just two examples of future additions. There are many more useful extensions of LIAR. We invite all interested accelerator physicists to join the LIAR project and to contribute their experience and knowledge.

References

EMITTANCE DILUTION DUE TO SLOW ALIGNMENT DRIFTS IN THE MAIN LINACS OF THE NLC

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Abstract
The tight tolerances in the main linacs of the Next Linear Collider (NLC) result in a large sensitivity of the beam emittance to slow alignment drifts. Once the accelerator is tuned, the optimized emittances must be maintained. Slow alignment drifts will make re-steering and re-optimization necessary. The frequency of these linac re-optimizations is an important parameter that determines how well the linear collider can be operated. We present simulation results that address this question for the main linacs of the NLC. We will show that the effects of alignment drifts can indeed be handled.

Introduction
The alignment stability in the main linacs of NLC determines how often the alignment and correction algorithms need to be applied. It has been shown that static imperfections in NLC can be corrected down to the required levels [1]. Linac stability effects are dominated by quadrupole alignment drifts; the quadrupoles generally have the tightest alignment tolerances. Here, we do not discuss the BPM stability. However, the requirements are tight. For the alignment algorithm we require a $2 \mu$m static rms offset between the BPM and quadrupole centers [1]. This tolerance can be achieved with a time consuming beam-based alignment procedure and it must be stable over significant periods of times (days). The question of BPM stability is discussed in [2]. Since quadrupoles and BPM’s are mechanically mounted together, the BPM stability that can be achieved is mainly determined by the BPM electronics, cables and similar factors. Results from beam-based alignment experiments at HERA and LEP show that the BPM to quadrupole alignment presently is being done with an absolute accuracy of better than 10 $\mu$m [3, 4]. The results in HERA are found to be remarkably stable over years.

Simulation parameters
The simulations were done with the computer program LIAR [5] using the 500 GeV version of NLC-II as defined in [2]. We consider a single bunch with with a population of $1.1 \times 10^{10}$ particles. The injection energy is 10 GeV, the bunch length is 150 $\mu$m, and we include an initial uncorrelated energy spread of 1.5%. The initial horizontal and vertical beam emittances are $\gamma_{\epsilon_x} = 3.6 \times 10^{-6}$ $\text{m-rad}$ and $\gamma_{\epsilon_y} = 4.0 \times 10^{-6}$ $\text{m-rad}$. We assume that the chicanes in the diagnostics stations are switched off. The simulations were done for the vertical plane where the small initial emittance makes it much harder to avoid emittance dilutions. A realistic BNS damping setup is included [2].

![Graph](image)

Figure 1: Example of ATL-like alignment drifts. The upper plot shows the displacements of quadrupoles, RF-structures and BPM’s after 30 minutes with an A-coefficient of $5 \times 10^{-7}$ $\mu$m$^2$/sec/m. The alignment was flat initially. The lower plot shows the corresponding trajectory offsets $y_{BPM}$ at the BPM’s. The dotted lines indicate the locations of trajectory feedbacks where $y$ and $y'$ are corrected back to zero. Thus the size of coherent betatron oscillations is constrained.

ATL-like alignment drifts
In order to model alignment drifts, we use the ATL-model [6]. This predicts that the rms vertical misalignment $\sigma_{\Delta y}$ (in $\mu$m) deteriorates with time $T$ (in seconds) and over the length $L$ (in m) as follows:

$$\sigma_{\Delta y}^2 = A \cdot T \cdot L$$

Recent studies [7] show that a constant $A$ of better than $5 \times 10^{-7}$ $\mu$m$^2$/sec/m can be measured on the SLAC site. We use $A = 5 \times 10^{-7}$ $\mu$m$^2$/sec/m.

Figure 1 illustrates ATL-like alignment drifts. It shows the displacements $\Delta y$ and corresponding trajectory offsets $y_{BPM}$ at the
BPM's after 30 minutes. The offsets of quadrupoles, BPM's, and RF-structures are overlaid in the plot and are essentially indistinguishable. The trajectory offsets at the BPM's show the coherent betatron oscillations that build up. The dotted lines indicate the locations of seven trajectory feedbacks that constrain \( y \) and \( y' \) to zero. The coherent betatron oscillations are thus broken up into eight smaller oscillations. The oscillation amplitude is a few \( \mu m \) and is large enough to be detected easily with the NLC single shot BPM resolution of 1 \( \mu m \).

![Graph showing the number of entries vs. distance](image)

**Figure 2:** Histogram of vertical emittance growth \( \Delta \varepsilon_y / \varepsilon_{y,0} \) for 1000 different error distributions. ATL-like alignment drifts over 30 minutes with an \( A \) of \( 5 \times 10^{-7} \mu m^2/sec/m \) are assumed. The average emittance growth is 29.0% ± 0.8%. The solid curve shows an exponential fit for large emittance dilutions.

A histogram of the vertical single-bunch emittance growth from alignment drifts after 30 minutes is shown in Figure 2. The average emittance growth is found to be 29.0% ± 0.8%. Note, however, the exponential distribution for large emittance dilutions. The most probable emittance growth is only about 10%.

The average emittance growth along the linac is shown in Figure 3. The locations of the trajectory feedbacks are clearly seen. As a coherent betatron oscillation builds up the emittance starts to grow rapidly. The feedbacks stop the fast growth. More effective feedbacks can be imagined if the rms \( y \) trajectory is minimized up to the next feedback instead of correcting \( y \) and \( y' \) to zero locally.

![Graph showing the average vertical emittance growth](image)

**Figure 3:** Average vertical emittance growth \( \Delta \varepsilon_y / \varepsilon_{y,0} \) along the linac for ATL-like drifts after 30 minutes. We assume an \( A \) coefficient of \( 5 \times 10^{-7} \mu m^2/sec/m \). The dashed curves specify the errorbars around the average (solid curve).

Figure 4 shows the average vertical single-bunch emittance growth for different BNS configurations. All previous results were obtained using the standard NLC BNS configuration which requires an energy overhead of 1.3%. The standard BNS is optimized for the beam-based alignment algorithm and uses three different RF phases along the linac. Figure 4 shows that BNS configurations using higher energy overheads reduce the emittance growth from 29% to about 16%. One can therefore imagine to trade alignment performance against better stability.

Let us relate the ATL-like alignment drifts to the other results. Since the emittance growth is linear in time we would get an additional average emittance growth of about 15% when we assume a beam-based alignment every 30 minutes. This is about a factor of six smaller than the emittance growth expected after beam-based alignment of quadrupoles and RF-structures. It is small enough not to be an important limitation of the NLC linac performance as long as the linacs are corrected on a half-hourly to hourly basis. Since the alignment and correction algorithm does not interfere with the standard operation, its frequent application should be no major obstacle.

**Conclusion**

The dominant stability problem in the NLC main linacs is caused by drifts of the quadrupole alignment. We simulated this effect by using the ATL-model with a coefficient \( A = 5 \times 10^{-7} \mu m^2/sec/m \) as measured at SLAC. We showed that the alignment drifts drive coherent betatron oscillations that lead to rapid emittance growth. The addition of seven trajectory feed-
backs breaks the coherent betatron oscillation into eight smaller oscillations. Assuming a beam-based quadrupole alignment every 30 minutes, we would expect an additional average emittance growth contribution of 15%. Since the emittances roughly add up in quadrature, this is small compared to the 110% average emittance growth after beam-based alignment. The alignment algorithm does not interfere with the normal linac operations, so that it can be applied very frequently. We conclude that slow alignment drifts can be handled safely for the NLC linacs, if we assume a beam line stability similar to or better than the one observed in the Final Focus Test Beam (FFTB) experiment at SLAC.

References

[1] R. Assmann et al., "Emittance and Trajectory Control in the Main Linacs of the NLC", these proceedings.


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EMITTANCE AND TRAJECTORY CONTROL IN THE MAIN LINACS OF THE NLC

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Abstract
The main linacs of the next generation of linear colliders need to accelerate the particle beams to energies of up to 750 GeV while maintaining very small emittances. This paper describes the main mechanisms of static emittance growth in the main linacs of the Next Linear Collider (NLC). We present detailed simulations of the trajectory and emittance control algorithms that are foreseen for the NLC. We show that the emittance growth in the main linacs can be corrected down to about 110%. That number is significantly better than required for the NLC design luminosity.

Introduction
Emittance preservation in the main linacs of a future linear collider like the NLC is demanding [1]. Strong wakefields and small emittances make the beams very sensitive to beamline imperfections. The achievable final beam emittance and luminosity depend strongly on the ability to avoid and to correct imperfections, especially quadrupole and structure misalignments. Initial alignment errors are limited by the available accuracy of mechanical survey and alignment methods and are much larger than the required tolerances. Instead, beam-based alignment will reduce the initial errors to a level that meets the linac tolerances. This is a crucial step in the operation of a next linear collider and it must be verified that the procedure is understood and that the necessary precision can indeed be achieved.

We describe numerical calculations with the computer program LIAR [2] that were performed to study the NLC main linacs emittance transport. By assuming realistic errors in all major accelerator components, we can study the complex interactions between different mechanisms of emittance growth and the proposed correction algorithms.

Simulation parameters
The simulations were done for the 500 GeV version of NLC-II as defined in [1]. The beam consists of 90 bunches with $1.1 \times 10^{10}$ particles per bunch. A bunch is 150 $\mu$m long and has an initial uncorrelated energy spread of 1.5% at an injection energy of 10 GeV. The initial horizontal and vertical beam emittances are $\gamma \epsilon_x = 3.6 \times 10^{-6}$m-rad and $\gamma \epsilon_y = 4.0 \times 10^{-6}$m-rad. We assume that the chicanes in the diagnostics stations are switched off and that multibunch beam loading is perfectly compensated. Finally, BNS damping as described in [1] is included.

The beam-based alignment algorithm
The emittance growth in the NLC linacs is driven by transverse offsets between the beam and the centers of quadrupoles and structures. These offsets must be minimized in order to maintain the normalized emittances. We studied an algorithm that minimizes the quadrupole and structure BPM readings by first moving the quadrupoles, thereby steering the trajectory, and then moving the accelerator structures to align them along the beam trajectory. Because of imperfections in the accelerator model, a long linac is typically divided into many shorter regions of 50 to 100 quadrupoles and the algorithm is applied to each region individually. To obtain full correction, one usually has to iterate the correction multiple times. The simulations include the effect of finite BPM resolution (reading-to-reading jitter) and accelerator component misalignments.

The algorithm determines the quadrupole movements in an attempt to align the magnets in a straight line between the first and last quadrupoles of the region being considered; the first and last quadrupoles of the region are not moved by the algorithm. The beam is then launched along the beamline by adjusting either the initial conditions, for the first region of the linac, or by adjusting a single dipole corrector located at the first quadrupole for all subsequent regions; only a single dipole corrector is needed to join regions because the beam trajectory should be centered at the first quadrupole which is the last quadrupole of the preceding region. Finally, weights can be added for the bpm resolution and the quadrupole movements; the nominal values are the expected,bpm resolution and the expected quadrupole misalignments with respect to adjacent magnets. These weights will limit the magnitude of the moves, constraining the trajectory to lie along the pre-determined axis which can be assumed to be set by the initial mechanical alignment.

In specific, the quadrupole alignment algorithm finds the least squares solution to the problem:

$$
\begin{pmatrix}
m_1 \\
\vdots \\
m_N \\
0
\end{pmatrix}
= R_1
\begin{pmatrix}
q_2 \\
\vdots \\
q_{N-1} \\
x_1 \\
x_1
\end{pmatrix}
\quad \text{or} \quad
R_i
\begin{pmatrix}
q_2 \\
\vdots \\
q_{N-1} \\
\theta_1
\end{pmatrix}
$$

(1)

with a weighting vector given by

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\[
\begin{pmatrix}
1/\sigma_{bpm\,1} \\
\vdots \\
1/\sigma_{bpm\,N} \\
1/\sigma_{quad\,2} \\
\vdots \\
1/\sigma_{quad\,N-1} \\
1/\sigma_{init} \\
\beta/\sigma_{init}
\end{pmatrix}
\] (2)

The measurement vector consists of \( N \) BPM measurements \( \pi_i \) followed by \( N \) zeros which are used to limit the quadrupole movements. The solution vector consists of \( N - 2 \) quadrupole movements followed by \( x_1 \) and \( x_1' \) which are the initial conditions of \( \dot{\eta}_1 \) which is a corrector located at the first quadrupole of the region. Next, the weighting vector consists of \( \sigma_{bpm}, \sigma_{quad}\), and \( \sigma_{init} \), which are the estimated BPM resolution, quadrupole misalignments and initial error which nominally would be equal to the quadrupole misalignments. Finally, the matrix \( R \) is given by:

\[
R_1 = 
\begin{pmatrix}
0 & 0 & \cdots & 0 & R_{11} & R_{21} \\
-1 & 0 & \cdots & 0 & R_{11} & R_{21} \\
K_2 R_{12} & -1 & \cdots & 0 & R_{11} & R_{21} \\
K_2 R_{12} & K_2 R_{12} & \cdots & 0 & R_{11} & R_{21} \\
\vdots & \vdots & \cdots & \vdots & \vdots & \vdots \\
K_2 R_{12} & K_2 R_{12} & \cdots & K_{N-2} R_{12} & R_{11} & R_{21}
\end{pmatrix}
\] (3)

where \( K_i \) is the integrated quadrupole strength, \( R_{12} \) is the \((1,2)\) transport matrix element from the \( i^{th} \) quadrupole to the BPM, \( R_{11} \) and \( R_{21} \) are the \((1,1)\) and \((2,1)\) matrix elements from the initial point to the BPM.

After applying the quadrupole solution, the motions on the accelerator structures are adjusted such that the average RF-BPM reading on a girder is minimized. An RF girder supports two accelerator structures which each has two RF-BPM’s at either end [3]. The RF-structure alignment is performed after each iteration of quadrupole beam-based alignment.

We assume that the step resolution of the magnet and girder movers is infinitely small. The typical step size of 0.25 \( \mu m \) is indeed small compared to the accuracy of the RF-BPM’s of about 15 \( \mu m \) rms and can therefore be neglected for the RF-structures. The step size problem is avoided for quadrupoles by having dipole correctors at each quadrupole that shift its effective magnetic center. Small quadrupole misalignments are therefore corrected with dipole correctors. If the dipole strengths get large enough they are ‘exchanged’ into a step of the quadrupole mover.

**Simulation results**

We first consider a simple case where we start with a random quadrupole misalignment of 100 \( \mu m \) rms. Both types of BPM’s are perfectly aligned to the quadrupole and structure centers and have zero resolution. The quadrupole alignment is done in 14 regions to allow for good convergence. Each region contains about 52 quadrupoles and is iterated 15 times. The number of iterations is chosen higher than necessary in order to explore the optimal solution. The simulated misalignment of quadrupoles, BPM’s and RF structures, after the application of the interleaved alignment procedure, is shown in the upper part of Figure 1. The dipole kicks at the boundaries between correction regions are shown in the lower part of the same figure.

![Figure 1: Example of the beam-based alignment algorithm with perfect BPM’s and RF-BPM’s. The initial random quadrupole misalignment was 100 \( \mu m \) rms. The alignment is done in 14 sections and 15 iterations. At the end of each section a dipole corrector is used to launch the beam into the next section. The upper plot shows the misalignment \( \Delta y \) of quadrupoles, RF-structures and BPM’s after alignment. The lower plot shows the integrated fields of the dipole correctors.](image)

A very smooth alignment between the endpoints of each section is indeed achieved. At the endpoints the beam is deflected into the next section, causing sharp kinks. The endpoints are not moved and reflect the initial random quadrupole misalignment of 100 \( \mu m \). Between the endpoints, the alignment is bowed towards zero. This absolute zero line is known to the system only because the initial misalignment was random about it. Constraints on the rms size of magnet movements bias the solution towards the initial average misalignment between endpoints.

The solution shown in Figure 1 is largely determined by the choice of \( \sigma_{bpm}, \sigma_{quad} \) and \( \sigma_{init} \). Changes in the relative weights will result in solutions that are not equivalent in terms of emittance growth. We have chosen to constrain the rms magnet movements and the rms of the BPM readings relatively strongly while allowing for large dipole kicks.

For a complete simulation run, we put the most important imperfections together, apply the correction algorithms and observe the emittance growth. In order to illustrate the importance of the several effects, we proceed in steps. For each case we quote the emittance growth \( \Delta e_y/e_{y,0} \) at the end of the linac and the rms beam offset \( \sigma_y \) at the BPM’s.

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1. Initial random quadrupole misalignment of 100 μm rms. RF structures are aligned to the beam.

\[
\frac{\Delta \varepsilon_y}{\varepsilon_{y,0}} = (24.4 \pm 2.3)\% \\
\sigma_y = (0.35 \pm 0.01)\mu m
\]

2. Add: BPM resolution of 1 μm rms. Static BPM-to-quadrupole offsets of 2 μm rms.

\[
\frac{\Delta \varepsilon_y}{\varepsilon_{y,0}} = (41.1 \pm 2.4)\% \\
\sigma_y = (1.08 \pm 0.01)\mu m
\]

3. Add: RF-BPM accuracy of 15 μm rms.

\[
\frac{\Delta \varepsilon_y}{\varepsilon_{y,0}} = (90.2 \pm 6.0)\% \\
\sigma_y = (1.21 \pm 0.01)\mu m
\]

4. Add: RF-phase errors of 1° rms. RF amplitude errors of 0.2% rms. Quadrupole roll errors of 300 μrad rms. Quadrupole gradient errors of 0.3% rms.

\[
\frac{\Delta \varepsilon_y}{\varepsilon_{y,0}} = (97.8 \pm 3.6)\% \\
\sigma_y = (1.22 \pm 0.01)\mu m
\]

5. Add: Multibunch long-range wakefield effects.

\[
\frac{\Delta \varepsilon_y}{\varepsilon_{y,0}} = (106.6 \pm 3.9)\% \\
\sigma_y = (1.23 \pm 0.01)\mu m
\]

All emittance growth numbers, apart from the last one, refer to the single-bunch emittance growth. The total multibunch emittance growth of about 110% is well below the allowed emittance dilution of 175% for NLC-IIB [1]. Internal structure misalignments, special multibunch imperfections and the effects of missing BPM's will be added to the simulations in future studies.

The most important imperfections are BPM and RF-BPM errors. They determine the quality of the correction and the residual emittance growth. In all cases, the correction and alignment is done on the first bunch, assuming that all other bunches behave similarly. The small additional multibunch emittance growth shows that this is a valid assumption, although we have not yet fully included the effects of internal structure misalignments. The distribution of emittance growth for different error distributions is shown in Figure 2 for the full simulation (last case). The exponential tail for large emittance dilutions tends to bias the average emittance growth towards larger values. It results from error distributions that have a large component at the betatron frequency. Fortunately, these errors are easily corrected using bump (global) correction methods.

**Figure 2:** Histogram of vertical emittance growth \(\Delta \varepsilon_y/\varepsilon_{y,0}\) for 200 different error distributions. The average emittance growth is 106.6% ± 3.9%. Note the exponential distribution for large emittance dilutions.

**Conclusion**

A beam-based alignment algorithm for quadrupoles and RF-structures was simulated with a realistic BNS configuration. It was shown that the large initial misalignments from conventional alignment procedures can be corrected to acceptable levels. The emittance growth that finally can be achieved depends on the initial misalignment and most importantly on the performance of the BPM's and RF-BPM's. Assuming realistic imperfections in many subsystems we find a multibunch emittance growth of 106.6% ± 3.9%. This emittance growth is smaller than the allowed total emittance growth of 175% for the NLC-IIB parameter set. As the emittances roughly add in quadrature the impact of additional imperfections gets smaller with larger emittances. It is anticipated that the alignment algorithm can be further optimized by smoothing the transitions between alignment sections. Future simulation studies will include internal structure misalignments, multibunch imperfections (bunch-to-bunch charge, energy, etc. variations) and the effects of missing BPM's. In addition, we further want to apply emittance bumps in order to compensate the emittance growth below what has already been achieved. Finally, we need to study the impact of different bunch shapes on the linac emittance transport.

**References**


POSSIBLE SOURCES OF PULSE-TO-PULSE ORBIT VARIATION IN THE SLAC LINAC

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Abstract
Pulse-to-pulse variation of the transverse beam orbit, frequently referred to as 'jitter', has long been a major problem in SLC operation. It impairs the SLC luminosity both by reducing the average beam overlap at the IP and by hampering precision tuning of the final focus. The origin of the fast orbit variation is not fully understood. Measurements during the 1994/95 SLC run showed that it is random from pulse to pulse, increases strongly with current and grows steadily along the SLAC linac, with a typical final rms amplitude of about half the beam size. In this paper, we investigate possible sources of the vertical orbit jitter.

Introduction
In the Stanford Linear Collider (SLC), electron and positron beams, which are extracted from two damping rings, are accelerated in the 3 km long SLAC linac to about 50 GeV, then separated and transported through 1.2 km long arc sections, before they are collidated at the interaction point (IP). It is a long-standing problem of SLC operation, that the vertical IP orbit position of either beam varies markedly from pulse to pulse, by about 0.4–0.5 \( \sigma_y \). The orbit 'jitter' at the IP is highly correlated to the orbit variation measured at the end of the SLAC linac and of about the same size. The jitter at injection into the linac is much smaller (\( \leq 0.1 \sigma_y \)) and only poorly correlated to the IP orbit. The orbit variation has been a main concern and the subject of intense studies during the 1994/95 SLC run [1, 2, 3], in which the orbit jitter was observed to be random from pulse to pulse and to grow steadily along the linac [1]. The jitter also appeared to be strongly current-dependent (see Fig. 2). The orbit jitter is a concern primarily for three reasons: first, it reduces the overlap of the two colliding beams at the IP and, thus, decreases the luminosity, by about 10%; second and more importantly, it makes measurements of the beam size with beambeam deflections or wire scans more difficult. Sophisticated techniques using orbit information from strategic sets of upstream beam-position monitors had to be developed [4] to correct for the orbit jitter during a scan; third, as long as its origin has not been uncovered, the jitter adds an uncertainty to the design of future linear colliders.

In this report, we evaluate and compare the importance of several possible jitter sources in the linac, namely: ground motion, uncorrelated quadrupole vibration, accelerator-structure vibration, quadrupole field ripple, bunch length variation and bunch intensity fluctuation. Throughout the text we specify the jitter as a percentage of the beam size, assuming a normalized vertical emittance of 0.5 \( \times 10^{-5} \) m-rad at the end of the linac.

Ground Motion
The response of the linac to a harmonic vertical displacement of quadrupoles at a certain wavelength can be characterized by a lattice response function \( G \), which is defined as the average squared ratio of the final orbit variation and the perturbation amplitude. For low current, wakefields are not important and \( G \) can be written as [5]

\[
G(k) = \sum_{j_{1,2}} \mu_{j_{1,2}} \cos(k(s_{j_{1}} - s_{j_{2}}))
\]

where \( k = 2\pi/\lambda \) denotes the wavenumber, \( s_{j} \) is the position of the \( j \)-th quadrupole, \( \mu_{j} \) is equal to \( \sqrt{\zeta_{j}/\gamma_{j}} k_{j} R_{54 j}^{-1} R_{33}^{-1} \) for \( j \neq 1 \) and \( \mu_{1} \) equals \( -\sqrt{\zeta_{6}/\gamma_{6}} R_{53}^{-1} R_{33}^{-1} \) and \( R_{33}^{-1} \) are the (3,4) and (3,3) transport-matrix coefficients, respectively, from quadrupole \( j \) or from the entrance to the end of the linac; \( k_{j} \) is the integrated strength of quadrupole \( j \); \( \zeta_{6} \) and \( \gamma_{6} \) denote the initial and final beam energy, and \( \gamma_{j} \) the energy at position \( j \), all three in units of the rest mass. We assumed that the vertical betatron-phase advance across the linac is a multiple of \( \pi \), but this is not essential.

Using the dispersion relation between ground-motion wavelength and frequency that was measured in the SLAC linac tunnel [6], it is possible to convert the response function \( G(k) \), Eq. (1), into frequency space. The function \( G(f) \) thus obtained is represented by the solid line in Fig. 1, which shows that, at low frequencies, or large wavelengths, the response is strongly suppressed. Also displayed in the figure is the measured ground-motion power spectrum \( P(f) \). The spikes of \( P(f) \) around 10 Hz and 30 Hz are caused by vibration resonances of the accelerator supports. As a third (dotted) curve, the measured orbit-feedback response for the SLAC linac [7], \( F_{f}(f) \), is also depicted.

The integral over the product of \( P(f) \), \( G(f) \) and \( F(f) \) yields the rms orbit jitter caused by the ground motion [5],

\[
\Delta y_{f,\text{rms}}^{2} = \int_{0}^{\infty} df \ G(f) P(f) F(f),
\]

assuming that all quadrupoles move exactly as the ground beneath them. Integration over the frequency range from 0.008 to 64 Hz predicts an rms orbit variation of about 40 nm with feedback on, and 32 nm without feedback. (The main contribution to the integral (2) comes from the resonance-spikes at frequencies where the feedback amplifies.) The nominal beam size for our reference point at the end of the linac is 52 \( \mu \text{m} \) (\( \delta_{y,f} \approx 50 \mu \text{m} \)), \( \epsilon_{y} \approx 54 \mu \text{m} \mu \text{rad} \); hence, the expected jitter arising from ground motion is less than 0.001 \( \sigma_{y} \).
To confirm these rough estimates, we have performed a computer simulation using the program LIAR [11]. The simulation includes the transverse and longitudinal wakefields in the accelerator structures as well as the energy profile due to BNS damping, i.e., the correlated energy spread introduced for wakefield compensation. Specifically, the rf phase with respect to the rf crest in the first third (last two thirds) of the linac is chosen as 22° (−16.5°) for bunch populations larger than 2.0 × 10^{10}, and as 12° (−3°) for 1.0 × 10^{10}. There is no BNS phase change for the zero-current case. Simulation results are shown in Fig. 2. The simulated beam jitter grows from zero at the beginning of the linac to the final value shown. It increases linearly with the rms vibration amplitude.

The simulation confirms that quadrupole vibration can explain a substantial part of the observed SLC beam jitter.

Structure Vibration

The 12-m long girders which support the accelerator structures vibrate at rms amplitudes Y_s of about 1 μm [9, 10]. Because an off-center beam induces a transverse wakefield, also structure vibration can cause an orbit variation. For a driving point charge transversely offset by y, the linear slope of the dipole wakefield is given by [12] W_y = 0.33 V/(ps pC) y/a_cell, where a denotes the disk iris radius (a = 1.16 cm). A Gaussian bunch of rms length σ_y experiences a centroid kick of Δ(εy) = W_y e^{2σ_y^2} N/(c√π). Here, N is the number of particles in the bunch. A kick Δy received at position s causes an orbit change Δy = β_y(Δy')/√2/√γ(s) γ' at the end of the linac, where we have averaged over the betatron phase, γ(s) is the beam energy at position s and γ' the final beam energy, both in units of the rest mass, and β_y ≈ 30 m denotes the average beta function.

The SLAC linac consists of about 200 girders. Each girder carries four 80-cell structures. Let us assume that the 4 structures on each girder and all cells which compound these structures vibrate at about the same amplitude and in phase, and ignore possible correlations between different girders. By approximating the number of cells per girder by n_{cell}, the number of girders by n_y, the final beam energy by E_f, and averaging over the linac, one finds

$$\Delta y_{f,\text{rms}} \approx \beta_y \frac{W_y e^{2σ_y^2} \sqrt{n_y}}{2cE_f \sqrt{2π}} Y_s σ_y σ_y N$$

or Δy_{f,\text{rms}} = 10 nm σ_y [m] N Y_s. For a vibration amplitude Y_s of 1 μm, a bunch length of 1 mm and N ≈ 4 × 10^{10}, we obtain Δy_{f,\text{rms}} ≈ 400 nm (0.008 σ_y), which is insignificant. In order to contribute sensibly to the observed orbit jitter, the vibration amplitudes must be a factor of 5 larger (5 μm rms); this seems rather unlikely.

Quadrupole Field Ripple

Quadrupole field ripple induces an orbit jitter of about

$$\Delta y_{f,\text{rms}} \approx \left( \frac{\gamma_e γ_f R_{33}^{p_e-f}}{k} - 1 \right) \frac{(Δk_k)}{k}_{\text{rms}} y_{\text{rms}}$$

where y_{\text{rms}} and (Δk_k)_{\text{rms}} denote the rms beam offset and ripple, respectively. We have used the relation [5] $\sqrt{γ_e γ_f R_{33}^{p_e-f}}$ —
1 = \sum_i R_i^{33-f} k_i \sqrt{\gamma_i / \gamma_{ij}} (k_i$ is the strength of the $i$th quadrapole), which can be derived by considering a constant vertical displacement of the entire beam line. Assuming an rms orbit offset $Y_{rms}$ of 0.5 mm and using $(\sqrt{\gamma_i / \gamma_{ij}} R_i^{33-f} - 1) \approx 0.5$, we find that an unrealistically large field ripple $(\Delta k_i/k)_{rms}$ of 10% is required to explain an orbit jitter of 0.5 $\sigma_y$.

**Bunch Length and Charge**

There is some evidence that the longitudinal 'sawtooth' instability which occurs at high current in the two SLC damping rings [13] contributes a sizable part of the jitter [14, 15]. Streak-camera and rf-monitor measurements show a pulse-to-pulse bunch-length variation of about 10%, both in the damping rings and in the linac [15, 14].

To study how a bunch-length change affects the orbit in the presence of wakefields and with proper klystron phasing for BNS damping, we have again performed simulations with LIAR [11]. We assumed realistic misalignments and correction methods, and included orbit bumps for emittance control. A number of different random seeds were considered for the misalignments. The simulation results, depicted in Fig. 2, suggest that a bunch-length variation of 10% causes a beam jitter of 0.35 $\sigma_y$. Figure 3 displays the simulated vertical beam jitter as a function of position.

![Vertical jitter as a function of position](image)

**Figure 3:** Vertical beam jitter in percentage of the expected beam size along the linac. The simulation assumes a random bunch length jitter of 10% and a bunch population of $3.5 \times 10^{19}$. The oscillations reflect a beta mismatch between the simulation and the design lattice.

Figure 4 demonstrates that the orbit changes observed when varying the bunch length are mainly effected by the transverse wakefields. These introduce a dependence of the betatron phase advance on the bunch length, $d\psi_B/ds \approx \beta W_L \sigma_x e^2 N n_{cell}/(2\sqrt{\pi mc^2} \gamma(z) L_g)$, where $L_g$ denotes the girder length, and, thereby, convert bunch-length changes into orbit jitter. In the SLAC linac, the effect of a betatron phase shift is aggravated by the large orbit bumps over a few hundred meters, which are introduced for emittance reduction. Phase advance variations result in an imperfect termination of these bumps, so that part of the induced oscillation leaks out and manifests itself as jitter downstream.

![Bunch length vs. $\sigma_y$](image)

**Figure 4:** The rms trajectory change as a function of bunch length. A nominal bunch length of 1.1 mm is used as a reference for the other points. For this study we excited a 200 $\mu$m rms trajectory oscillation in the SLAC linac. The solid line presents the full simulation, while transverse wakefields were switched off for the dashed curve.

**Conclusion and Thanks**

We have studied several possible sources of the vertical-orbit jitter in the SLAC linac. The most prominent source that we identified is the bunch-length variation of about 10%. Quadrupole vibration, with measured rms amplitudes of 250 nm, may account for much of the rest. Both these sources would lead to a monotonic jitter growth along the linac, consistent with observation. The effects of field-ripple, ground motion, structure vibration and intensity jitter all appear to be insignificant. We thank C. Adolphsen, F.J. Decker and T. Raubenheimer for helpful discussions.

**References**

Beam Emittance, Transmission, and Intensity Distribution Measurements of the Northrop Grumman Corporation 1.76 MeV Pulsed Beamline and Contraband Detection System Target Test Facility

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Abstract

The Northrop Grumman Advanced Technology and Development Center beamline consists of an RF driven ion source and double solenoid LEBT, a 1.013 MeV electroformed RFQ, a matching section (MS) bunching cavity, a 1.76 MeV DTL, and a HEBT designed to deliver a 10 mA H+ beam to a prototype contraband detection system (CDS) target. We have characterized the beam phase space in the LEBT, at the RFQ output, MS output, and DTL/HEBT output as a function of ion source, LEBT, RF cavity and HEBT parameters with a pair of electrostatic sweep emittance scanners. The beamline transmission was measured with Faraday cups and toroids. The beam intensity distribution incident on a CDS test target was obtained from radiometric surface temperature measurements of the target with a scanning HgCdTe infrared detector. In this paper we will discuss the performance and operational characteristics of this beamline and present data on beam characteristics for nominal and off nominal RF cavity operation.

Introduction

The Northrop Grumman 1.76 MeV beamline was designed as a test bed for H and H+ beam transport measurements, RF accelerating cavity characterization and development of beam diagnostics and computer controls. The key features of the beamline are a 7 cm RF driven multicusp ion source, a double solenoid LEBT, a four-vane RFQ, a matching section (MS) cavity, a 9 gap DTL, a HEBT consisting of three emq’s, and a target station and diagnostic box. The details of the beamline layout are shown in ref. [1].

An output energy of 1.76 MeV was chosen to complement our target development program for a contraband detection system (CDS) machine employing gamma resonance absorption, and utilizing a 1.76 MeV electrostatic tandem accelerator [2].

Optimum beamline performance is obtained by appropriate LEBT and rf cavity design. In order to optimize and understand the system performance a thorough experimental characterization is necessary. Many of the beamline parameters cannot be set a priori to the design values. Variation in the rf input power and the cavity phasing as well as the focusing lenses, can be used to optimize the beam transport.

In this paper we will present measurements of the beamline transmission as a function of the beam current and RF cavity parameters, measurements of the beam emittance at several points in the accelerator, and beam intensity distributions obtained by fast radiometric measurements from a prototype CDS target.

1. Beam Transmission and Emittance Measurements

The dependence of the transported current through the LEBT, RFQ and MS combination, and DTL, on the ion source output current is shown in figure 1. Current toroids are located at the ion source output, rfq input, DTL input, and after the emq HEBT. For these measurements all of the LEBT parameters, rf cavity parameters (input power and rf phase), and HEBT emq settings were held constant. Only the ion source input power was varied. Also shown in this figure is the H+ emittance measured after the first solenoid in the LEBT.

Over the range of source output currents the H+ beam fraction varies from 60% to 80%. The double solenoid LEBT is designed to focus only the H+ beam into the rfq entrance while the H2 and H3 beams remain divergent. Since the rfq input current is measured with a toroid located at the rfq entrance flange there is a small contribution to this current from the on axis H2 and H3 components.

![Figure 1. Transported Current and LEBT Emittance vs. Ion Source Output Current. Transported Current (left axis): (●) RFQ input; (■) MS input; (▲) Target current. LEBT Emittance (right axis): (◆) Solenoid 1 = 3.96 kG.](image-url)

The LEBT emittance is a function of the total ion source output current via the pervenance match to the extraction optics, and it is also a function of the LEBT...
solenoid settings. Independent measurements of the rfq transmission show that transmission remains constant at approximately 65% for rfq powers between 70 kW and 90 kW and output currents from 0 to 25 mA. The data in fig. 1 shows that the combined MS and RFQ transmission slowly decreases from 0.65 to 0.5 indicating that the MS transmission varies from approximately 100% to 85% as the output current is increased. The combined DTL and HEBT transmission rises in the LEBT emittance and the inability to properly match the ion source output beam to the RFQ acceptance. Variation of the rfq input power has a significant effect on the transported current and beam emittance. These results are shown in fig. 2. The rfq nominal design power is 67 kW with a vane tip voltage of 44 kV. At the design value the rfq transmission is approximately 47%, and increases to 64% at 100 kW corresponding to a 22% increase in the vane tip voltage. The knee in the curves shown in fig. 2 corresponds with the minimum rfq output emittance.

Horizontal emittances were measured at the rfq output, and the MS output as a function of the output current. These results are shown in figure 3. Initially emittance measurements at the MS output were made with no rf power applied to the cavity. This results in no longitudinal bunching, and only transverse focusing via the three pmd’s located in the cavity.

From fig. 1 we see that the input beam emittance is approximately 0.08 π mm mrad at 10 mA rfq output and increases rapidly to greater than 0.18 π mm mrad for output currents greater than 17 mA. The rfq output emittance however varies from 0.068 π mm mrad to 0.095 π mm mrad over this same range and shows that the rfq filters the output emittance via transmission losses of high emittance particles. The matching section data shows a strong dependence on the output current and some emittance growth of the rfq output beam at currents below 20 mA.

For optimum DTL performance both the MS and DTL must be correctly phased. The MS phase must be set to bunch the beam longitudinally without acceleration, and the DTL must be phased to correspond with the 34 deg synchronous phase of the rfq output beam. Since we are not set up to perform any longitudinal beam characterization we must rely only on transverse emittance and transmission measurements to optimize the beamline performance and use the cavity phase as an adjustable parameter.

Figure 2. Transported Current and RFQ Output Emittance vs. RFQ Input Power. (●) RFQ input current; (■) DTL input, (▲) Target current. (▼) Horizontal RFQ output emittance; (♦) Vertical RFQ output emittance at 25 mA.

remains constant at approximately 98% over the measurement range. The data shown in fig. 1 were optimized for a 15 mA rfq output current. By re-optimizing the LEBT we have transported 25 mA through the rfq.

We believe that the decrease in RFQ transmission at higher source output currents is primarily due to the rapid rise in the LEBT emittance and the inability to properly match the ion source output beam to the RFQ acceptance. Variation of the rfq input power has a significant effect on the transported current and beam emittance. These results are shown in fig. 2. The rfq nominal design power is 67 kW with a vane tip voltage of 44 kV. At the design value the rfq transmission is approximately 47%, and increases to 64% at 100 kW corresponding to a 22% increase in the vane tip voltage. The knee in the curves shown in fig. 2 corresponds with the minimum rfq output emittance.

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From fig. 1 we see that the input beam emittance is approximately 0.08 π mm mrad at 10 mA rfq output and increases rapidly to greater than 0.18 π mm mrad for output currents greater than 17 mA. The rfq output emittance however varies from 0.068 π mm mrad to 0.095 π mm mrad over this same range and shows that the rfq filters the output emittance via transmission losses of high emittance particles. The matching section data shows a strong dependence on the output current and some emittance growth of the rfq output beam at currents below 20 mA.

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Figure 3. RFQ and MS output emittance vs Output Current. RFQ output at 77 kW (●). MS output with no RF power in the MS cavity: (♦) 90 kW rfq; (▲) 80 kW rfq; (■) 70 kW rfq.

Figure 4. DTL transmission and MS output emittance vs. MS phase. (●) Transmission; (♦) ε_x; (▲) ε_y.
When power was applied to the MS cavity the MS output emittance was measured as a function of the relative rf phase between the MS and the rfq. After the DTL was installed the DTL transmission was also measured as a function of the MS cavity phase. This data is shown in fig. 4. The MS emittance was measured at 10 mA, and the DTL transmission was measured at 6.10 and 16 mA and was found to be independent of current. The results show clearly that the maximum DTL transmission is obtained at the minimum MS output emittance. Furthermore both measurements show a sinusoidal like variation with phase with some evidence of 360 degree periodicity. Based on this data we have chosen a MS operating point at -20 deg.

A similar transmission measurement was performed with variation of the DTL relative phase. These results are shown in fig. 5. The solid line shows the least squares fit of the 16 mA data to a cosine function. Based on these results we have chosen $\varphi_{\text{ms}} = +90$ deg as the DTL operating point.

Beam emittance measurements at 10 mA in the downstream diagnostic box with $\varphi_{\text{ms}} = -20$ deg, and $\varphi_{\text{dtl}} = +90$ deg show that $\varepsilon_x = 0.100$ $\pi$ mm mrad, and $\varepsilon_y = 0.155$ $\pi$ mm mrad.

![Figure 5. HEBT Transmission vs. DTL Relative RF Phase.](image)

The results of TOPKARK [3] simulations of the DTL output beam indicate that the x emittance increases by 29%, and the y emittance increases by 125% at the DTL output. If we take our effective MS output emittance as $\varepsilon_{\text{ms}} = \sqrt{\varepsilon_x \varepsilon_y} = 0.076$ $\pi$ mm mrad then our data shows a 39% increase in the x emittance and a 122% increase in the y emittance. These results are in good agreement with the TOPKARK simulations.

2. Radiometric Temperature Measurements

After completion of the initial beamline characterization we replaced the emittance scanner diagnostic in the downstream diagnostic box with a water cooled target holder for CDS prototype target testing. The generic structure of the CDS targets consists of a 1 $\mu$m thick layer of C deposited on approximately 15 to 20 $\mu$m of Au which is deposited on a suitable substrate material, such as Cu to provide structural rigidity. Theses targets must withstand peak power densities of approximately 40 kW/cm$^2$ for up to 600 us.

In order to investigate the target survivability we have designed a radiometric surface temperature measurement device for probing the surface temperature rise during the beam pulse. The surface temperature measurement is made by measurement of the surface radiance emission at a known or characterized surface emissivity through application of the Planck law relating object temperature to its optical emission characteristics.

The radiometric measurement spot size is defined by a series of variable apertures installed in the device. With a 0.33 mm aperture the device resolution is 0.5 mm. The radiometric surface temperature profile measured at 10 mA beam on target at 1.76 MeV is shown in fig. 6. The beam distribution has $x_{\text{rms}} = 1.95$ mm, and $y_{\text{rms}} = 3.1$ mm. The spot size can be adjusted by varying the emq's in the HEBT. For a gaussian beam the peak power density for the beam in fig. 6 is 46.4 kW/cm$^2$, and the average power density at a 95% beam threshold is 14.8 kW/cm$^2$.

![Figure 6. Beam intensity profile on a C/Hf/Au/Be target.](image)

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Commissioning of the 40 keV Injector for a Contraband Detection System Proof-of-Principle Device
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Abstract
The contraband detection system proof-of-principle device being developed at the Northrop Grumman Advanced Technology and Development Center employs a high current (10 mA) DC tandem accelerator designed to provide a beam of protons at either 1.75 or 1.89 MeV. In this paper we will describe the commissioning of the 40 keV ion injector to the tandem accelerator. The injector to the tandem consists of a filament-driven multicusps H- ion source with a virtual filter field and a triode extraction assembly, a pair of steering magnets, a solenoid lens, a pair of beam collimation slits, and a fast kicker magnet for commissioning the accelerator with a low duty-factor beam. The diagnostics in the LEBT for commissioning include a Faraday cup, a DC current toroid, isolated collimation slits, and a CW electrostatic sweep emittance scanner. We will describe the injector design, and present data on the source and LEBT operating characteristics. Results of beam phase-space measurements at the match plane of the tandem as a function of the source and LEBT parameters will be presented.

Beamline Layout
The CDS ion source, LEBT, and diagnostic station are shown in figure 1. The full system layout is discussed in more detail in ref [1], and end to end particle simulations are presented in ref [2]. The key features of the beamline are: a filament driven volume ion source; a triode extraction system; a differentially pumped extraction region; a solenoid focusing magnet with an integrated strength of 0.0482 T m at a peak axial field of 0.3042 T and 160 A drive current; a pair of dipole steering coils; a magnetic beam kicker for fast beam shutdown and low duty factor commissioning; and a variable aperture beam collimator and beam position monitor. Beam currents are measured with a dc current toroid, and a faraday cup, and phase space measurements are made with an electrostatic sweep emittance scanner. This scanner is described in detail in refs. [3,4].

The ion source is a dc filament driven cusp H- source with a virtual filter field. The source chamber was designed and fabricated by TRIUMF and is described in detail in ref. [5].

The three grid extraction system with the relevant aperture and gap dimensions is shown in fig. 2. This geometry was modeled with IGNU with a 0.25 eV ion temperature, first gap voltage V1=5 kV, and a second gap voltage V2=35kV. The beam current at the plasma boundary was chosen to be 14 mA to allow for stripping of 20% due to e- current and 10% scraping on the third lens electrode. The simulated rms normalized emittance was 0.093 pi mm mrad with a divergence of 7.75 mrad.

The first extraction lens flange houses the electron separation magnets which form a pair of opposing dipoles. The first extraction lens flange is designed to dissipate approximately 700 W without damage to the magnets.

In the current configuration the diagnostic station is mounted at the tandem accelerator interface. When the tandem is installed the diagnostic station will be removed.

Figure 1. CDS injector and diagnostic station.

A 20 mm diameter water cooled aperture is mounted on the downstream face of the solenoid in order to shield a small diameter beam tube required for the kicker magnet. This fixed aperture and the independently variable four slit collimating aperture are the major limiting aperture in the LEBT.

Normally the source is operated at a constant arc voltage of 120 V, and the gas pressure in the source is controlled by adjusting the gas flow. At 35 A arc current typical gas flow rates range from 13 to 19 sccm. The gas flow, plasma grid bias, and first gap extraction voltage are set to maximize the H- current at each arc current. The second gap voltage has only a small effect on the H- output current and is used to control the final beam energy.
Figure 2. Extraction geometry. Plasma aperture diameter = 13 mm, first accelerating gap = 5.5 mm, extraction lens upstream aperture diameter = 9.5 mm, second accelerating gap = 19.35 mm, extraction lens upstream aperture diameter = ground electrode aperture diameter = 14.0 mm

Results

We have measured the e- and H- output currents directly into a large diameter faraday cup located approximately 70 cm downstream from the extraction aperture with no focusing elements in the beamline and no restrictive apertures, and we measured the transported LEBT current with all of the beamline components in place as shown in fig. 1. These results are shown in fig. 3.

![Graph](image)

Figure 3. Ion and electron current vs. Arc current. (●) Extraction directly into faraday cup. Transported LEBT current with: (▲) residual H2; (●) Xe gas added to LEBT. Solenoid current = 160 A. Beam energy = 40 kV.

The maximum measured H- current was 11.8 mA at 36 A arc current with an electron to ion ratio of 3.6. In the full LEBT configuration 10.9 mA, with an electron to ion ratio of 4.7, was transported with residual H2 gas only in the LEBT.

The details of the beam transport were found to be quite sensitive to the gas pressure in the transport channel. Measurement of the beam current entering a faraday cup, and the current striking an isolated beam scraper diagnostic located immediately upstream of the faraday cup showed that the faraday cup and scraper signal were oscillating 180 degrees out of phase and were synchronized with the LEBT cryopump cold head displacer motion (approximately 1 Hz). Since the sum of the scraper and faraday cup current remained constant and equal to the total beam current this shows that the beam phase space (i.e. size and divergence) was changing. Closing the LEBT cryopump gate valve reduced the oscillation amplitude below the detection limit on the fixed scraper aperture, and addition of Xe gas into the transport channel reduced the oscillation amplitude significantly. We are in the process of setting up a measurement to correlate the phase space oscillation frequency with measured variations in the cryopump cold head temperature. We believe that the observed phenomenon is due to a variation in the degree of space charge neutralization of the transported beam due to variation in the background pressure in the transport channel. Measurement of the transported LEBT current with Xe gas added to the transport channel resulted in 11.4 mA transported.

![Graph](image)

Figure 4. Beam parameters vs. Solenoid current. (●) Ion current; (■) rms beam size; (▲) rms divergence; (●) normalized rms emittance. Variable aperture = 40 x 40 mm².

Figures 4 and 5 show the dependence of the transported beam current, rms size, divergence, and emittance at 40 kV beam energy, on the solenoid current and the variable collimator opening dimensions. For these measurements the emittance scanner was located 132 cm from the center of the solenoid, and the variable slit collimator center to solenoid center distance was 73.5 cm. The steering dipoles were optimized.
with the solenoid set to 160 A, and the variable aperture set for a 20 x 20 mm² opening. No steering adjustments were made during solenoid or slit variation.

Figure 5. Beam parameters vs. Variable aperture opening. (●) Ion current; (■) rms beam size; (▲) rms divergence; (◆) normalized rms emittance. Solenoid current = 160 A.

For all the points shown in figs. 4 and 5 the beam was divergent at the scanner location. The variation in beam current with solenoid strength is due to scrape off on the 20 mm diameter fixed aperture on the downstream face of the solenoid. This is also the primary reason why the emittance drops with decreasing solenoid field.

The original CDS LEBT design was intended to produce a waist at the plane of the variable slits in order to scrape off beam halo. Experimentally we have determined that the solenoid strength is too weak to achieve this, and the beam is divergent downstream of the solenoid.

The measured beam characteristics were used in a TRACE LEBT model and matched to the expected ion source output beam with the transport channel space charge as the variable parameter. A good match was obtained for the case where the beam was fully neutralized in the region from the ion source to the downstream face of the solenoid, and 0.75 mA of space charge was turned on downstream of this point. This fitting procedure matched the measured beam phase space with the expected ion source output beam, and correctly predicted correct rms beam size measured at the variable aperture.

This is a physically reasonable picture since the location where space charge was introduced into the beam corresponds to the location of the 20 mm fixed scraper aperture and the small diameter kicker magnet beam tube which limits the source gas flow downstream from the restrictive aperture. The space charge in the transport channel then effectively counteracts the focusing strength of the solenoid. Experiments are in progress to determine the effect of supplemental neutralizing gas injection into the LEBT while maintaining the 10⁻⁶ torr requirement at the tandem entrance region.

Phase space measurement made with the 20 mm limiting aperture removed, and a 10 cm inner diameter beam tube used in place of the existing 4.75 cm tube showed that a parallel beam could be obtained at 120 A of solenoid current. This suggests that these changes to the beamline geometry altered the gas pressure profile enough to significantly decrease the space charge current. More experiments in this area are planned.

Beam dynamics simulations using the Northrop Grumman developed TOPKARK code show that the best match to the tandem accelerator resulting in highest transmission is obtained at the highest solenoid setting. The measured emittance at this value is 0.109 π mm mrad.

A phase space measured with the variable aperture fully open to 40 x 40 mm² is shown in fig. 6. The ellipses drawn correspond to the best fit ellipse for a fixed intensity threshold. The outermost ellipse shown is for a 100% beam fraction.

Figure 6. H- phase space at the tandem accelerator entrance plane. I(H-) = 10.5 mA, Normalized rms emittance = 0.10 π mm mrad.

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BEAMLINE STABILITY MEASUREMENTS WITH A STRETCHED WIRE SYSTEM IN THE FFTB\textsuperscript{*}

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Abstract

Beamline stability is of great importance for future linear colliders where tolerances generally are in the micron to sub-micron range. A stretched wire system in the sealed FFBT tunnel at SLAC was used to monitor beamline motion with a sub-micron resolution. In future linear colliders low frequency changes of the beamline alignment (< 0.1 Hz) lead to intolerable quasi-statical misalignments and betatron oscillations. Since it requires time to correct those errors, it is very important to determine how often corrections are needed. We present our measurements, discuss the systematics of the stretched wire system and compare the observations with the ATL-model for ground motion.

Introduction

Linear collider designs like the NLC \cite{1} require stability tolerances in the micron or even sub-micron range. It is particularly important to show that “natural” ground vibrations and drifts do not exceed the tolerances. Fast ground motion was studied extensively in the frequency range down to about 0.1 Hz with accelerometers, geophones and seismographs \cite{1, 2}. The frequency range below 0.1 Hz is not accessible to those measurement devices. We call magnet motions in this range “slow alignment drifts”. Slow alignment drifts of the quadrupoles limit the stability of beam linac trajectories in the time range of a few minutes to many hours. The amplitude of drifts determine how often correction algorithms must be applied and how well an emittance-optimized beam trajectory can be maintained.

In this paper we present beamline stability studies in the Final Focus Test Beam (FFTB) tunnel at SLAC. The measurements have a sub-micron resolution and were taken over 140 hours with a measurement point every 6 seconds. The data covers the time range that is of interest for the day-to-day operation of an accelerator.

The FFBT stretched wire system

The FFBT experiment at SLAC features a sophisticated stretched wire alignment system along its beamline. The system was developed and installed by DESY as a part of the international FFBT collaboration \cite{4}. The beamline is divided into four sections with two parallel stretched wires in each section (“left” and “right” wire). The wire lengths vary from 30 m to about 45 m in the different wire sections. An illustration of the wire in section 2 is shown in Fig. 1.

A harmonic Rf-signal of 100 MHz is coupled to the wire. High resolution pick-up monitors in the quadrupoles and sextupoles are used to detect the Rf-signal with three antennas. The three

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![Diagram of FFBT section 2 with stretched wire elements and a weight indicator.]

Figure 1: Illustration of the wire in section 2. The wire is stretched with a weight of about 35 kg at its upstream end. The beamline elements are distributed along the wire, sometimes grouped in doublets or triplets. Each element has three wire position monitors attached to it.

signals are processed online into a horizontal and vertical “wire offset”. The expected resolution of the wire monitors is about 100 nm \cite{5}.

The original purpose of the stretched wire alignment system is to monitor and eventually adjust the absolute quadrupole and sextupole alignment in the FFBT \cite{5}. For our study we decoupled the data acquisition from the SLC control system and improved it. Using 100 data samples for every measurement we got an alignment measurement of the whole beamline about every 6 seconds. The statistics and the time resolution of the data acquisition was enhanced by about a factor of 50. The improved time resolution allowed to study time dependent systematic effects that were inaccessible before.

Systematic errors

The stretched wire system is easily perturbed by systematic errors. It is especially affected by temperature variations in the FFBT tunnel. A temperature change of 1°K causes the wire sag to change by approximately 200 nm. The alignment data would show apparent alignment drifts that are indeed changes in the thermal wire expansion. Extreme care was taken to minimize temperature variations in the tunnel. The magnets were switched on and the FFBT tunnel was closed about one week before the start of the measurements, that were taken during the Californian rainy season. Rain kept variations of the outside temperature small. The measurements were taken in sections 1 and 2 in the underground part of the tunnel during a time without beam.
Figure 2: Vertical wire position measured in section 2. The average of the two parallel wires is shown at different locations along the wire (the wire length is 39.5 m). Note that an almost periodic perturbation affects the data.

Both wires in section 2 were affected by a significant systematic perturbation. This is illustrated in Fig. 2. Every few minutes the measured vertical wire position shows a short variation of up to ± 5 μm. The size of the effect is largest in the middle of the wire and approaches zero at either end. It is seen for both wires but only the vertical plane. From its signature it can be concluded that it is neither a thermal nor an electronic effect. Possible but unlikely explanations are a periodic pull on the weight or a device that lifts up the wire every few minutes. The source of the perturbation is not yet identified. The absolute calibration of the wire position monitors was checked by controlled changes of the magnet offsets using magnet movers.

Measurements

Measurements with the stretched wire system were done in March 1996. We now discuss the results. In order to remove the effects of overall wire movements we consider the motion Δy (or Δx) of a magnet i in the center of the wire with respect to the two magnets 1 and 2 at either of its ends:

\[ Δy = y_i - \frac{y_1 + y_2}{2} \]  

(1)

Here we assume that the magnet i is located exactly in the middle. If magnets are located very close to each other in doublets or triplets the averages of their readings are used. The analysis was done individually for the two parallel wires. It was confirmed that the results that are in good agreement. We therefore combine the data into an average. The motion of the middle magnet in section 1 is shown in Fig. 3 as a function of time for both planes. It is seen that the alignment is remarkably stable. At about 180 hours the weight was touched, explaining the sharp rise in the vertical plane. The large alignment change in the middle of the experiment (100-120 hours) corresponds to a Monday morning when the FFTB was accessed. The observed change is likely explained by this.

The ATL rule [3] states that the Rms alignment change \( σ_y \) after a time ΔT and a over a distance \( L \) is

\[ σ_y^2 = A \cdot ΔT \cdot L \]  

(2)

Figure 3: The measured motion Δx, Δy of the middle magnet with respect to the end magnets in section 1.

where \( A \) is usually specified in units of \( μm^2/(m\cdot s) \). A simple approach to calculate \( A \) from our measurements is to divide our measurement period of 140 hours into many shorter intervals, each covering a time ΔT. We then calculate the Rms alignment change \( σ_y^2 \) over those time intervals ΔT. If the distance between the two end magnets is \( L \) then the observable \( σ_y^2 \) at the middle magnet includes contributions from the two magnets each \( L/2 \) away. We can therefore use the full distance \( L \) between the end magnets in order to calculate the constant \( A \).

Figure 4: Calculated A constant as a function of the time interval ΔT in the ATL rule. The three different curves refer to the horizontal (solid) and vertical (dotted) data of section 1 and the horizontal data of section 2 (dashed). The upper results include all data. In the lower case the data between 100 and 120 hours (see Fig. 3), was excluded. The perturbing effect of an FFTB access was such eliminated. The A constant was determined over a distance of approximately twice 15 m.

The results are shown in Fig. 4 for two data sets. The up-
per case represents the complete set of data. We find an $A$ of smaller than $1 \times 10^{-8} \mu m^2/(m \cdot s)$ for the horizontal data. The $A$ from the vertical data reaches $9 \times 10^{-8} \mu m^2/(m \cdot s)$. The calculated $A$ grows linearly with the chosen time interval, indicating that systematic effects are dominating the data. The ATL rule does not apply. However, from the horizontal data we already obtain $A$'s that are well below published results of $1 \times 10^{-5} \mu m^2/(m \cdot s)$ [3].

It was mentioned that on Monday morning the FFTB was accessed, probably leading to systematic instrumental drifts. If the period from 100 to 120 hours (see Fig. 3) is excluded from the data analysis then the results in the lower part of Fig. 4 are obtained. The calculated $A$'s are significantly reduced for both planes and both sections. This is another hint that a common systematic perturbation affected the data during the excluded time period. $A$ is now almost constant for different time intervals $\Delta T$, as expected from the ATL rule. In addition the horizontal and vertical data sets give similar results. The calculated $A$'s behave largely as expected from the ATL-rule and indicate the dominance of diffusive alignment drifts. The numerical value of $A$ is below $5 \times 10^{-7} \mu m^2/(m \cdot s)$. The horizontal data from section 2 indicates an $A$ as low as $2 \times 10^{-7} \mu m^2/(m \cdot s)$.

Spectral analysis

Two magnets in section 2 were studied further: QT1 and QT3. The two quadrupoles are about 10 m apart (compare Fig. 1). The wire data was analyzed with a method that extracts the power spectral density (PSD) of the uncorrelated magnet motion [6]. The spectrum of the uncorrelated part of the vertical motion is shown in Fig. 5. Due to the systematic error shown before the data was filtered digitally with a time constant of 300 seconds. The experimental power spectrum is compared with the spectrum expected from a constant $A = 2 \times 10^{-8} \mu m^2/(m \cdot s)$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{spectral_analysis.png}
\caption{Spectrum of uncorrelated vertical magnet motion obtained in section 2 of the Final Focus Test Beam at SLAC. The straight line corresponds to an ATL spectrum with a proportionality constant $A = 2 \cdot 10^{-8} \mu m/(m \cdot s)$ and distance $L = 10$ m.}
\end{figure}

CONCLUSIONS

The stretched wire system of the FFTB was used to measure slow alignment drifts. Systematic instrumental effects could largely be minimized by isolating the FFTB tunnel from environmental changes. The $A$ constant of the so-called ATL-rule was found to be at or below $A = 5 \times 10^{-7} \mu m^2/(m \cdot s)$ for time intervals $\Delta T$ smaller than about five hours. It was shown that $1/7$ of the data is likely be affected by an FFTB access. If this data is excluded from the data analysis we find an $A$ of about $3 \times 10^{-7} \mu m^2/(m \cdot s)$. A spectral analysis indicates even smaller results for $A$.

The values for $A$ that we found are below the requirements for next linear colliders like NLC. Trajectory corrections will have to be applied on an hourly time-scale. We should stress that our measurements were done in a real beamline environment including many perturbing effects. The $A$ constant is site specific and can vary largely from site to site. However, our results clearly demonstrate that suitable sites, e.g. for NLC, can be found. Cultural noise and technical problems, like the not understood, systematic vertical wire changes in the FFTB section 2, will likely remain the major worries for the operation of future linear colliders.

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References

ANALYSIS, CHOICE AND DESIGN OF MONITORS FOR BEAM DIAGNOSTICS

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Abstract.

This paper treats the problem of use of artificial intelligence methods, in particular expert systems, for beam diagnostics because beam diagnostics is a complex process of obtaining, transforming and representing various information about different beam parameters with using theoretical, technical and program tools. Such expert systems help to solve the problems of analysis, choice and design of beam monitors for accelerator's control system according to their purposes, technical demands, working conditions and choice criteria. In this paper there are basic results and the structural scheme of such integrated expert system.

Introduction.

Beam diagnostics is a complex process of obtaining, transforming and representing various information about beam parameters with using theoretical, technical and program tools. A successful decision of these problems is necessary for effective management of accelerators; not only during the exploitation process, but also during arrangement and tuning; for development of control systems, for increase of exploitation reliability, improvement of metrologic characteristics etc.

Theory.

It is necessary to note the significance of theoretical tools. They are following:
I. A definition of beam parameters and their common interpretation.
II. A classification of monitors according to different classification signs.
III. A definition and standardization of metrologic, exploitation-reliability and constructive-technological characteristics of beam monitors, change ranges of beam parameters, technical demands, work conditions and choice criteria.

Analysis of modern trends in the development and the realization of monitors for beam diagnostics has revealed some problems. It is necessary to use the methods and ideology of artificial intelligence for arriving at decisions for these problems. For instance, strong integration in the field of development, projection and exploitation of control systems for accelerators displayed evident contradiction with numerous existing commercial and industrial systems. These systems having been created by different organizations and scientific centers are incompatible with each other. The clients who wish to use and apply concrete expert systems may encounter some difficulties which are just part of the initial problem. Due to a large amount of heterogeneous developments, diversity of characteristics, parameters and demands and as well as a lack of competent independent experts, bring together significant elements of undefined risk, when investment of essential financial means can lead to great economic waste and unpredictable consequences.

The next problem is associated with an exponential growth of information in specialized, technical magazines, books, reports etc. This abundance of information makes it difficult for developers, managers and scientific workers who are specializing in this field, to follow.

Analysis.

Taking into account all these elements, it is obvious that there is necessity to create an integrated expert system (ES) for analysis and for choosing monitors to analyze charged particles beam according to their purpose; technical demands and abilities; working conditions and the choosing of the setting criteria during projection process of accelerator's control systems.

It is known, that the development of ES is not always well founded, in this case, the principal factors which aided in the development of expert systems are as follows:
1) Problems are extremely specialized. They serve definite purposes and require large amounts of criteria in choice of solutions.
2) Problems require a great deal of experience in field of diagnostics of charged particles beams.
3) Formalization of facts and heuristics of the knowledge field.

The development of such ES is well founded economically because similar systems can satisfy demands on experts and consultant services and save human experience. Lastly, the characteristics of problems under consideration does not allow them to be solved with methods of traditional programming, i.e. the application of non-algorithmic heuristics is essential because it is necessary to manipulate numerical data, as well as symbolic information. There is a great problem complexity, and multitude of problem variants and problem connections.

Integrated ES.

This report considers a project of integrated ES which examines the use of expert knowledge, as well as, algorithms, procedures and models resulting
from previous investigations regarding the nature of problems, data base monitors and principal elements of measuring schemes [1].

The basic stages of choosing monitors and the parameters definition realized in current ES are:
1) Evaluation of limited abilities of monitors according to their time characteristics and sensibility;
2) Choice of monitors, which satisfy given technical demands and working conditions;
3) Choice of monitors according to their level of influence on beam particles, taking into account required metrologic, exploitation, reliability characteristics and given constraints;
4) Comparison of selected types of monitors according to the information they examine and choice of monitor type with constructive and technological characteristics;
5) Calculation and definition of parameters of selected monitor type with the possibility of technical realization of measuring scheme of charged particles beam parameters.

Integrated ES consist of ES, knowledge base about type and parameters of beam monitors and packet of calculation programs of beam monitor parameters. Integrated system GURU is selected as most convenient and powerful tool of ES design automatization. It unites: ES design means, relational data base, spreadsheets, text editors, business graphics, communications means with other computers.

Integrated ES realization is carried out with IBM-compatible computer of IBM PC/AT type. Knowledge base volume of current integrated ES version is formed by about 200 rules. Integrated ES provides intelligent support of all stages of analysis, choice and design of monitors for beam diagnostics.

At present, integrated expert system's knowledge base holds information about different types of beam parameter monitors (BPM) such as electromagnetic, electrostatic (pick-up electrodes), magnetic monitors, current transformers, Faraday's cups, secondary emission monitors and so on and their main parameters. This information includes basic descriptions and main parameters of known and described BPMs, such as sensitivity, bandwidth, resolution, precision, dimensions, mass and so on. In order to obtain this data as much as 400 papers, reports, lectures describing results of investigations of different BPMs were processed. This knowledge base is being continually appended and extending while receiving new information (conference's proceedings, publications in different journals and so on). Also packet of calculation programs is extending. The possibilities of integrated expert system is continually broadening and this system is used in designing control and measuring systems not only when choosing BPM and calculating its parameters but also to choose the structure and the modules of the systems (analog-to-digital converters, different amplifiers, integrators, the means of processing, registration and displaying the information about beam parameters), concerning their conditions of work, technical requirements, choice and computation criteria. As an example of rule in the expert system the following one can be presented:

RULE : R1
IF : 0.1 <= sm <= 10 &
1 <= pl <= 10 &
50 <= pf <= 1000 &
pc >= 1 &
nopcf = "yes"
THEN : type = "current transformer"
run "ct.exe"

There the following variables are used:
sm - sensitivity of monitor (V/A);
pl - pulse length (ms);
pf - pulse frequency (Hz);
pc - pulse current (mA);
nopcf - necessary of obtaining of pulse current form;
type - type of beam monitors;
"ct.exe" - calculation program of current transformer.

In conclusion it is necessary to note that demonstration prototype of integrated expert system illustrating basic principles of system work was developed by means of instrumental system GURU for PC 386/486. At present, the elaboration of research real-time prototype is started. This project is based on instrumental system G2 by Genym for Alpha AXP workstations.

References.

UNDULATOR AND RF-SYSTEM FOR ION LINEAR ACCELERATORS

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Abstract

The paper continues the study of an undulator linear accelerator (UNDULAC). The various versions of UNDULAC with transverse and longitudinal RF fields are investigated. The suggested method of beam focusing and acceleration can be considered as the special case of those by means of two nonsynchronized waves. The comparison with two wave approximation method, where the accelerating wave synchronizes and the focusing wave doesn't synchronize with beam, is described. This comparison is suitable for demonstration of the capabilities of the new method.

Introduction

It is known, that one wave can not simultaneously accelerate and focusing the particles of beam. In a normal drift tube linac (DTL) where one synchronous wave is present, longitudinal beam stability is provided, but then transverse beam defocusing occurs inevitably. The transverse beam stability can be ensured by quadruple magnets, installed in the drift tubes, or by a focusing wave which has a phase velocity different from the equilibrium particle velocity (RF-focusing). In a conventional low energy ion DTL, it is difficult to install focusing magnets of sufficient strength in the very short drift tubes. That is why RF-focusing is used. The simplest RF-focusing principle for periodical structure was suggested by Good [1] and Faynberg [2] and was named an alternating phase focusing (APF). Such focusing can be realized by changing the drift tube lengths and applying some gaps to one period. The beam dynamics theories for APF have been proposed in many papers [3-5]. The main idea consists of the study of space harmonics influence on beam dynamics. The accelerating harmonic synchronizes with beam, whereas the focusing harmonics have phase velocities different from equilibrium particle velocity. In the paper [4] it was shown that the two travelling waves approach can be applied to three main types of APF. In contrast to the two wave approximation, standing wave approach for many harmonics was used in the theory discussed in [5].

The other way to create three-dimensional potential well by means of two nonsynchronous waves was mentioned in the paper [6]. Summary field \( E = \text{Re}\{E_1 e^{i k_1 z - \omega_1 t} + E_2 e^{i k_2 z - \omega_2 t}\} \) can accelerate particles efficiently with simultaneous achievement of longitudinal and transverse beam stability, if \( k_1, k_2 \) and \( \omega_1, \omega_2 \) are linked by a relation \( \omega_1 + \omega_2 = \nu_z (k_1 + k_2) \). In the low energy ion accelerator it is difficult to create resonator system for the two varied frequencies. However in the case, when one of frequencies \( \nu_z = 0 \) (a static field of undulator), the problems with RF-system tuning do not arise. The idea to apply a combination of undulator field and RF field for acceleration and focusing of ion beams was discussed in [7] for magnetostatic undulator (UNDULAC-M) and electrostatic undulator (UNDULAC-E).

Longitudinal beam dynamics

At first, we discuss the motion equation for a particle in the UNDULAC-M. The coordinates and the kinetic momentums of the particles can be expressed by the summation of two different type of motion: the slowly varying \( R_c, p \) and the rapidly oscillating \( \tilde{R}, \tilde{p} \). By averaging over rapid oscillations, we obtain the equation, that describes the slow evolution of \( R_c \)

\[
\frac{d^2 R_c}{dt^2} = -\frac{e^2}{2m^2} \nabla < A_z^2 >, \quad (1)
\]

where \( A_z = A_v + A_0 \) is the total vector potential of RF field and periodical field of undulator. Taking into account only the main space harmonics of the magnetostatic undulator \( a_0 = \frac{eA_0}{mc} = a_{0z} e^{i k_0 z} \) and electromagnetic field in RF structure \( a_v = \frac{eA_v}{mc} = a_v e^{i k_0 z + i \omega t} \) with \( k << k_0 \), the equation (1) can be rewritten in the form

\[
\frac{d^2 r}{d t^2} = \frac{1}{4} \nabla_r U_M, \quad (2)
\]

where \( r = \frac{2\pi}{\lambda} R_c \), \( \lambda = \frac{2\pi}{k} \) - the RF-field wavelength,

\( \lambda_0 = \frac{2\pi}{k_0} \) - the undulator period, \( \tau = \omega t \) - the potential function \( U_M = U_{1,M}(r^1) + U_{2,M}(r^2, \psi) \)

\( U_{1,M} = |a_{0z}|^2 + |a_v|^2 \); \( U_{2,M} = 2 \text{Re}(a_{0z}^* a_v e^{i\psi}) \) \( (3) \)

\( \psi = z/\beta_z - \tau + \psi_0 \) is the particle phase in the composite wave field, \( \psi_0 \) - the initial phase, \( \beta_z = \lambda_0 / \lambda \) - the normalized velocity of the synchronous particle.

The same equation can be obtained for the UNDULAC-E, where the potential function

\( U_e = U_{1,E}(r^1) + U_{2,E}(r^1, \psi) \)

\( U_{1,E} = |e_{0z}|^2 + |e_v|^2 \); \( U_{2,E} = 2 \text{Re}(e_{0z}^* e_v e^{i\psi}) \) \( (4) \)

Here \( e_{0z} = e E_{vz,0} / 2mc^2 \) are the dimensionless amplitudes of the basic RF-field harmonic and the first electrostatic field harmonic.

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The acceleration rate is proportional to the amplitudes of the RF and the undulator fields. The energy increase is maximum, when \( \mathbf{B}_\perp \parallel \mathbf{B}_0 \) or \( \mathbf{E}_\perp \parallel \mathbf{E}_0 \). Therefore the choice of the magnetic (electrostatic) undulator type and field orientation depend on the RF-structure type \([7]\).

In order to achieve effective beam bunching and capture the function and undulator period \( \lambda_0 \) have to grow and the synchronous phase has to decrease from \( \pi / 2 \). For example, if the synchronous phase \( \psi_s = \pi / 2 - \mu \zeta \), where \( \mu \) is the factor of sliding, the undulator period is growing and can be calculated by the formula

\[
\lambda_0(z) = \left[ \lambda_0(0) + \frac{3}{2} \zeta \int_0^z \left( r^+ + \mu \zeta \right) d \zeta \right]^{1/3}. \tag{5}
\]

The acceleration gradient of the synchronous particle
\[
d\dot{W}_s / dz = e T_{mE} E_s \cos \psi_s,
\]
where \( E_s \) is basic nonsynchronous harmonic amplitude, \( T_{mE} \) - an acceleration efficient factor for UNDULAC-M and for UNDULAC-E

\[
T_m = \frac{e B_0 \lambda_s}{2 \pi n c^2}, \quad T_E = \frac{e E_s \lambda_s^2}{2 \pi n c^3 \lambda_0}. \tag{6}
\]

It is interesting to compare this acceleration method with APF linac for resonant periodical structure, where RF field has one synchronous harmonic \( E_s \) and a number of nonsynchronous harmonics \( E_n \). The equation of motion for APF linac can be received in the smooth approximation as above

\[
d^2 r / d \tau^2 = \text{Re} \left( e_s e^{i \psi_s} \right) - \frac{1}{4} \nabla \cdot \nabla_{\perp} \overline{U}_E, \tag{7}
\]

where \( e_s \) is the amplitude of synchronous harmonic. The potential function \( \overline{U}_E \) is analogous to (4) and consists of two parts:

\[
\overline{U}_E = \overline{U}_{1,E} (\mathbf{r}^+) + \overline{U}_{2,E} (\mathbf{r}^+ + 2 \mathbf{v}) \tag{8}
\]

\[
\overline{U}_{1,E} = \frac{1}{4} |e_s|^2 + \sum_{n \neq s} \alpha_{n,s} |e_n|^2,
\]

\[
\overline{U}_{2,E} = \frac{1}{2} \left( \overline{e}_s e_{n,s} e^{2i \psi_s} + 2 \sum_{n \neq s} \alpha_{n,s} e_n e_{n+2s} e^{2i \psi_s} \right),
\]

\( e_n \) is the nonsynchronous harmonic amplitudes of RF-field, \( \alpha_{n,s} = s^2 / (n - s)^2 \).

For two travelling waves \( E_s \cos(k_s z - \omega t) \) and \( E_n \cos(k_n z - \omega t) \), \( \overline{U}_{2,E} = 0 \). In this approach the acceleration gradient is proportional \( e_s \cos \psi_s \) and is independent of the nonsynchronous harmonic \( e_{s,n} \). For the resonant structure only a standing wave approach must be used. In this case the all back waves are considered. The conditions of longitudinal beam stability are changed because of \( \overline{U}_{2,E} \neq 0 \). If the amplitude of the nonsynchronous harmonics are large, additional maxima and minima in the longitudinal potential well occur. The phase trajectories are deformed and new separatrix appear on the phase plane. In the APF linac the velocities of the nonsynchronous harmonics are approaching to equilibrium velocity, when the injection beam energy is low. In this case the resonant capture of particles with \( \nu \neq \nu_s \) is possible and overlap of a synchronous resonance with another one on the phase plane takes place. As a result longitudinal stochastic instability occurs \([8]\). The magnitudes of the nonsynchronous harmonic amplitudes must be chosen to retain large longitudinal acceptance. But the most important circumstance, which limiting the amplitudes of harmonics in APF linac, is the realization of transverse beam focusing.

**Transverse focusing of the beam**

Let us consider first the transverse beam focusing in UNDULAC. The choice of the RF-field harmonic amplitude and the undulator field harmonic amplitude is not arbitrary because it is necessary to keep up the focusing of the beam simultaneously with acceleration. The total effect can be found only from the analysis of equation

\[
\nabla \cdot \nabla_{\perp} U_{1,mE} = 0. \tag{9}
\]

Equilibrium trajectories may exist for all particle phase, if two conditions are valid

\[
\nabla \cdot U_{1,mE} = 0, \quad \nabla \cdot U_{2,mE} = 0. \tag{10}
\]

In a simple case the potential functions \( U_{mE} \) can be found without considering higher harmonics of the RF-field and undulator field \((3), (4)\). The motion around an equilibrium trajectory is stable if the potential has an absolute minimum. The analysis of the transverse stability for undulators of different types shows, that trajectory of the particle with any phase is stable in the transverse movement, if

\[
B_0 = \alpha_{m,E} \frac{\lambda_s}{\lambda_0} B_s, \quad E_0 = \alpha_{m,E} E_s, \quad \text{where} \quad \alpha_{m,E} \equiv 1.
\]

It is possible to express the acceleration efficient factor \( T_{mE} \) in (6) with the amplitude of the main nonsynchronous RF-field harmonic

\[
T_{mE} = \frac{e E_s \lambda_s}{2 \pi n c^3 \lambda_0} \alpha_{m,E}. \tag{11}
\]

The acceleration rate decreases when \( \lambda_0 \) and the beam velocity grow. This fact indicates that UNDULAC is more suitable for the low energy region.

The exact magnitude \( \alpha_{m,E} \) can be found after analysis of decisions of \((9)\) and \((10)\) where the influence of the higher harmonics must be accounted for. It is important also to study non-linear oscillations of the beam particles to investigate the coupling resonances. As a rule the higher harmonic
amplitudes reduce the quality of the bunch and must be minimized.

For APF linac it is necessary to have large amplitudes of the higher harmonics to supply the transverse beam focusing. When only one synchronous $E_s$ and one nonsynchronous $E_n$ harmonics of the travelling wave are taken into account, the condition stability for small oscillations can be derived from equation (7), where $\vec{U}_{1, E} = \vec{U}_{2, E} = 0$,

$$\alpha_{n,S} = \frac{e^2_n g - \beta_s e_s \sin \psi > 0,}$$

$$\alpha_{n,S} = \frac{e^2_n g - \beta_s e_s \sin \psi > 0,}$$

$$\alpha_{n,S} = \frac{e^2_n g - \beta_s e_s \sin \psi > 0,}$$

The amplitude $E_s$ and the acceleration rate can be large when the synchronous phase $\psi_S = 0$ and the longitudinal acceptance is small. The trajectory of the particle with any phase $\psi_S$ is stable in the transverse direction, when

$$E_s < \frac{e E_n^2 \lambda}{2 \pi m c^2 \beta_s} \alpha_{n}\lambda.$$

(13)

To express the acceleration rate with nonsynchronous harmonics amplitude $E_n$, we use

$$\frac{dW}{dz} = T_{RF} E_n \cos \psi_S,$$

(14)

where the factor $T_{RF} = \frac{e E_n^2 \lambda}{2 \pi m c^2 \beta_s}$. This magnitude coincides with (11) for UNDULAC.

For the resonator structure it is necessary to use a standing wave approach and to take into account a number of nonsynchronous harmonics. As it was showed above in this case $\vec{U}_{2, E} = 0$, the acceleration rate and the longitudinal acceptance may be inferior to the two wave approximation.

The analysis of the transverse stability for APF linac may be implemented if the potential function $\vec{U}_E$ is used. As in the UNDULAC the higher nonsynchronous harmonics reduce the longitudinal and transverse acceptances in the APF linac.

### Examples

As it was shown above, the longitudinal or the transverse RF-field can be used for acceleration and focusing of ion beams in the UNDULAC. There is no need for drift tubes. It simplifies the design of RF-system and makes it possible to operate at higher frequency or in a lower-$\beta$ region than usual ion RF-accelerator. Many versions of unconventional design permit the increase of the ion beam intensity in the UNDULAC.

The current may be increased for a ribbon beam with the large cross-section. Study of the ribbon ion beam interaction with the RF-field in the plane electrostatic undulator was carried out in the paper [9].

For UNDULAC-M, it is impossible to obtain the large cross-section area of the beam. However, there is an opportunity to accelerate more then one beam in the magnetic channel because there are no drift tubes. The task is to choose a special symmetry of the transverse RF-field and periodical magnetostatic field. The RF system must have a small transverse dimension to fit inside the undulator. Therefore, it is preferable to use a multielectrode line where transverse electromagnetic waves (TEM or TE) travel [10].

The one more interesting method for increasing of the ion beam intensity in UNDULAC exists. How was shown the potential function $\vec{U}_{E,M}$ depends on the particle charge squared, and the motions of positive and negative charged ions are identical. This fact can be used for compensation of the space charge by acceleration of ions with different signs of the charge in the same bunch. Study of the possibility of simultaneous acceleration of both positive and negative ions with the identical charge-to-mass ratio in UNDULAC is great interest because in all kinds of RF accelerators (DTL, RFQ, APF), this opportunity can not be realized [11].

### Conclusion

A use of the undulator and RF resonator system to accelerate low energy ion beams promises to be a very perspective practice. The conditions to achieve both the transverse focusing and large longitudinal acceptance are found. The acceleration rate for UNDULAC is comparable with the acceleration rate for APF linac, but the definite advantages exist for UNDULAC. For acceleration of ions it possible to use not only longitudinal, but also transverse RF-fields. There is no need to have the drift tubes in the RF-structure, where only one nonsynchronous wave is travelling. It simplifies the design of RF-system and permits to reduce a RF power losses in the walls and to increase the ion beam intensity. Three methods for increasing of the ion beam intensity in UNDULAC are suggested.

### References

THE ON-AXIS COUPLED ACCELERATING STRUCTURE FOR APPLICATION IN PROTON LINACS WITH MODERATE HEAT LOADING

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Abstract
The On-axis Coupled Structure (OCS) has been optimized for applications in proton linacs with moderate heat loading to the accelerating structure. Without interior cooling of the cells the total length of the coupling cell together with webs between cells may be done relatively small. This case the coupling constant for OCS also may be strongly increased. With the numerical 3D optimization of coupling slot dimensions, shape and position it was shown, that coupling constant may be increased up to (15-17)% with tolerable (5-8)% reduction (due to coupling slots) in shunt impedance. For low energy region (≤ 100 MeV) the shunt impedance and accelerating gradient of the OCS may be improved with introduction of additional intermediate drift tube (OCSDTL option), keeping coupling constant up to 10%. The ideas, restrictions and results of the structure optimization are presented. The optimized OCS version has the shunt impedance not less than another Coupled Cells (CC) structures and combines it with increased value of the coupling constant and the simple design.

Introduction
After the Side-Coupled Structure (SCS), the OCS with magnetic coupling (due to coupling slots in the webs between cells) is now at second place in the usage in particle accelerators. This structure was applied for linac in the Advanced Free-Electron Laser Initiative at Los Alamos with high gradients (to 22 MeV/m), high peak-power klystron (20 MW) and up to 50-ms long macro pulses [1]. For cw operation with heavy heat loading this structure is used in Mainz [2] and INP MSU [3] race-track microtrons. The structure also was investigated in details, both theoretically and experimentally [4], for the set of small electron linacs for industrial applications.

The benefit OSC features are very simple design and small transverse dimensions. The optimization of the OCS for applications in proton linacs has been performed, providing good results in the structure parameters.

Structure Optimization
The electron linacs, for which OCS was considered before, usually operate in S-band, with operating wavelength λ ≈ 10 cm. The requirements of mechanical strength and heat conductivity from the central region to outer one (to cooling channels) lead to relatively thick web, limiting the coupling constant k_e to 3% ± 5%. Total distance 2t + 2l_c, where 2l_c is the coupling cell length, t - web thickness, takes essential part of the structure period, leading to smaller, (in comparison with another CC structures) value of the effective shunt impedance Z_e.

The theoretical background for the structure optimization in details is presented in [5], below application to OSC is shortly described. In our optimization of the OCS for proton linacs, with operating wavelength λ ≈ (25±40)cm, we do not do direct scaling of the cells dimensions from "electron OCS" version. First of all, decision has been done to have no cooling channels in webs of "proton OCS". This case we can restrict the web thickness with the value 3 ± 4 mm, limiting only with mechanical constraints. The length 2l_c also should be as small as possible, but one have to take into account two restrictions.

First one is the detuning of coupling cells. It is known well, coupling slots reduce own frequencies both accelerating and coupling cells. One can show that detuning value δf ~ 1/l_c. Reduction in the frequency must be compensated by reduction of the cell radius l_c R_c and for small values l_c R_c becomes less than radius r_sl for optimal position of coupling slots.

Second restriction relates with sparking in coupling cells. Sparking in the structure may take place both in accelerating and in coupling cells [5]. In steady-state regime coupling cells do excite with very low level to provide rf power flux along the structure for compensations of rf losses. Strong excitations of coupling cells takes place during transient, in the initial time period τ_f:

\[ τ_f = \frac{2L}{v_g}, \quad v_g = \frac{c n k_e β_p}{4}, \quad τ_f = \frac{2N}{π k_e f_0}, \]  

where L and N are the length and number of the structure period from the input point to the end, v_g - the group velocity, c - speed of light, f_0 - operating frequency and β_p - relative velocity of protons. During this time period, maximum electric field at the surface of coupling cell E_{semag} may be high enough [5], leading to sparking in coupling cells [6]. E_{semag} depends on shape, dimensions of coupling cell and another parameters of the accelerating structure. Comparing accelerating structures of existing proton accelerators, we have founded, that SCS structure at FNAL Linac Upgrade [6] operates with maximum value E_{semag} during transient, according (2). Referring to FNAL Linac Upgrade successful operation, we have limited E_{semag} for OCS with FNAL SCS E_{semag} value.

In the OCS structure E_{sc} is large at two points - at the lower edge of the coupling slot and near bore hole. To decrease E_{semag} value, coupling slots and coupling cell bore hole must be rounded with radius not less then 1~2.0. Taking into account reasons above we have chosen 2l_c ~ 6 ± 8 mm.
The shape and dimensions of the accelerating cells for OCS were optimized for DESY Linac 3 Upgrade proposal [7] in 2D approximation, by using set of 2D codes [8]. For the same beam hole radius $a = 15$ mm, operating frequency and $E_{omax}/E_k = 1.35$, 2D calculated effective shunt impedance $Z_e$ for OCS is less than 2D $Z_e$ for FNAL SCS at 9% for $\beta_p = 0.4$ and at 6% for $\beta_p = 0.7$. The total thickness $2t + 2l_c = 13$ mm remains larger than web thickness 7.5 mm in SCS FNAL design.

**Coupling Slots**

The coupling slots investigation, optimization and choice was performed using MAFIA code.

There are two coupling slots at each web between accelerating and coupling cells. Mutual orientation of coupling slots is important for $k_c$ value. To increase $k_c$ by canceling mutual influence, slots position is rotated at 90° in webs of coupling cell. The difference between $k_c$ values for rotated and slot-to-slot orientation in short coupling cell is more than 2.5 times. Orientation of coupling slot at opposite webs of accelerating cells practically do not influences for $k_c$. Only frequency of coupling cell changes approximately at 5%, because field of coupling cell significantly penetrates into accelerating one. The mutual orientation of coupling slots in accelerating cell strongly defines quadrupole distortions in the accelerating field distribution. To reduce this distortion, we accept slot-to-slot orientation for accelerating cells.

The radial position of slots is chosen near the half of the accelerating cell radius.

It is known, that rise of $k_c$ by slot length increasing all time assists with reduction in $Z_e$. The coupling slots provide perturbation for rf current distribution in accelerating cell. The maximum value of rf current density $j_{max}$ takes place at the ends of slots, the minimum one $j_{min}$ - in the middle of the slot. To provide the high $k_c$ value with small reduction in $Z_e$ the coupling slots are chosen wide enough. Total set of decisions in the structure optimization leads to the tolerable reduction of $Z_e$ even for significant values of $k_c$ (Fig. 2).

$\beta_p$. To compensate this decreasing one need increase opening, providing larger reduction in in $Z_e$. Maximum values of $k_c$ were found in this research $\approx 19\%$ for $\beta_p = 0.45$ and $\approx 16\%$ for $\beta_p = 0.7$.

Comparing calculated 3D $Z_e$ values for proposed OCS and FNAL SCS, one will have practically the same numbers (differing in units of %) but with $k_c \approx 15\%$ for OCS.

In this OCS proposal coupling cells are heavy loaded with coupling slots (see Fig. 1), but accelerating cells are not. The problem of high coupling is solved by coupling cells, without large perturbations in accelerating ones.

**Cooling Capability**

The temperature distribution in the OCS ($f_0 = 810$ MHz) with one cooling channel per period (see Fig. 1) is shown at Fig. 3. (Special procedure has been developed to calculate temperature distribution due to rf losses with MAFIA code.) For the heat loading $1.5 \text{ kW/m}^2$ maximum temperature difference (between drift tube nose and cooling channel) is $3.4$ °C. This value of the heat loading is comparable with that for existing "meson facility" linacs and do not provide difficulties for existing frequency control systems. Maximum of the temperature gradient and associated thermal stresses take place at radius of slots position and with wide slots are not dangerous for stable longtime operation.

**Figure 1:** The cells of the On-axis Coupled Structure.

As the result of the OCS optimization we have the option with $k_c \approx 15\%$ and $Z_e$ reduction due to coupling slots $\approx 5\%$ for $\beta_p = 0.45$ and $\approx 7\%$ for $\beta_p = 0.7$. Because the distance $2t + 2l_c$ is fixed, with the same slots opening $k_c$ decreases for higher

**Figure 2:** The $k_c$ value and reduction in $Z_e$ in dependence on coupling slot opening, $\beta_p = 0.5$.

**Figure 3:** The temperature distribution in OCS for heat loading $1.5 \text{ kW/m}^2$, $\beta_p = 0.5$. Regions with high temperature are marked with lighter shadowing.
Vacuum Conductivity

The vacuum conductivity may be strongly improved by additional radial slots in webs (Fig. 4). Two of these radial slots cross coupling slots in the middle, two another are placed between coupling slots. So, four additional radial slot in each web provide four channels through the structure from one end to another. With small angle opening (not more than 15°), radial slots are not resonant elements and do not interferer significantly the field distribution in accelerating cells. To keep $E_{semas}$ limited, the cross of the radial slot with lower edge of the coupling one should be rounded.

Figure 4: The OCS cell with additional radial slots.

OCSDTL Option

It is known well that efficiency of all CC structures decreases with decreasing $\beta_p$. Very powerful solution was proposed [9] and tested with the SCS to avoid this disadvantage and to combine the efficiency of the Drift Tube structure with stability properties of CC structures by introducing Intermediate Drift Tubes (IDT). The length of the period $d'$ this case is $d' = (2n + 1) \beta_p/2$, where $n$ is the number of IDT. This solution can be applied to OCS (Fig. 5). Because $d'$ becomes large, coupling cell together with webs take a small relative part and do not lead to significant reduction of 2D $Z_e$. All improvements and problems, related with IDT, are the same as for SCS, except one.

For all CC structures introduction of IDT leads to redistribution of magnetic field for accelerating mode. Maximum of the magnetic field take place near IDT. Together with increasing of the accelerating cells volume, it leads to decreasing of the $k_e$ value. In OCSDTL version we can, by increasing of the slots opening to 79° ± 81°, keep coupling constant at 10% for $\beta_p = 0.35$ value with the same 5% reduction in $Z_e$. Because in estimations [5] of coupling cells excitation $\tau_f$ and $E_{semas}$ should be transformed for CCDTL into $\tau_f = (2n + 1) \tau_f$, $E_{semas} = (2n + 1)E_{semas}$, the OCSDTL option looks to be more strong against possible sparking in coupling cells.

Figure 5: The OCSDTL cells.

Conclusion

The optimization of coupling cells and coupling slots leads to attractive characteristics of the OCS for application in proton linacs. Combining the simple design, improved coupling constant and high shunt impedance, the structure can, after high power test, provide strong competition to another candidates for application in proton linacs with moderate heat loading.

Acknowledgments

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References

THE DATA LIBRARY FOR ACCELERATING STRUCTURES DEVELOPMENT.
RF PARAMETERS OF THE DRIFT TUBE ACCELERATING STRUCTURE

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Abstract
The Drift Tube (DT) accelerating structure is very well known, developed and widely used in existent proton linacs. Nevertheless, in the development of new projects all time arise the problem to estimate rf parameters of the structure for particular case given. This paper is the first report about activity in the creation of the data library for accelerating structures development. Basing on particularities of codes, which were developed early in INR (CPU time to calculate in 2D approximation one variant of the cell is several seconds with modern computer) and later were added with the shell to change automatically cell dimensions and tune to the frequency given, we store one time extremely large number of variants. The ranges of the cell dimensions overlap all known and another reasonably interesting variants of the DT structure application (both with focusing lenses inside drift tubes and without lenses). The main (cells dimensions, quality factor, shunt impedance, transit time factor) and additional results (the distribution of rf losses and so on) are stored in the file and provide the data base for further treatment. Using the data base obtained, we can with scaling and interpolation consider and compare, without additional calculations, rf parameters of the structure at different frequencies and with different limitations, finding either optimal or compromise solution for the structure.

Introduction
All times in design of the accelerating structure there is the problem to find reasonable compromise between different requirements. It may be internal problem in the structure design - how to choose dimensions to have effective shunt impedance \( Z_s \) as high as possible and to keep electrical field at the surface \( E_{\text{max}} \) (usually in parts of the Kilpatrick limit \( E_k \)) in reasonable limits. The increasing of an aperture radius is good for beam dynamic, but leads to the reduction in the \( Z_s \). The manufacturing processes will be simpler if a set of dimensions will be constant through the structure, but it means that will be deviation from optimal parameters.

As a role, dependencies of parameters from dimensions qualitatively are known, but, if the problem arises to have a number (to estimate "the price" of the solution), the designer needs to do estimation or additional calculations.

To simplify the design procedure for the DTL structure, this work has been performed.

The Data Base Storage
Several years ago the set of very powerful 2D codes [1] was developed in INR. With modern "middle power" computers, like DEC ALFA 2000, one run takes of order 3 ÷ 5 sec CPU time from mesh generation to physical postprocessing with high precision of results. Later, this set of codes was added with several simple codes to provide the system, which allows to perform automatically the set of similar calculations.

The idea and realization of the data base are not so complicated. The cell of the accelerating structure may be specified with several independent parameters (for example length, aperture radius, gap ratio and so on) and one dependent - to tune the cell for the operating frequency given \( f_0 \).

Two options of the DTL structure have been considered (Fig. 1). The first one is a conventional DTL with the possibility to place focusing lenses inside drift tubes. The second option has small drift tubes without lenses and is intended for high frequency DTL application - Bridge Coupled DTL (BCDTL) [2].

![Figure 1: The field distribution and drift tube shape for the conventional DTL option and for the BCDTL one.](image)

The cell of the DTL for both options is specified with six independent parameters and the cell radius \( R_c \) as dependent one. The limits of the independent parameters in normalized type (in parts of operating wavelength \( \lambda_0 \)) are listed in Table 1.

Several steps with each parameters were done during the data base storage. As a role, the dependencies of the structure rf parameters vs dimensions are smooth enough and not so many
points are needed to approximate any curve using cubic spline interpolation. It is evident, that accuracy of this interpolation is better for larger number of points. But, if we have \( M \) independent parameters and are going to do \( N \) steps with each parameter, number of variants to be calculated is \( M^N \). As the results of the compromise between accuracy of the interpolation and the total number of variants for calculations, from 4 to 7 steps for each parameter were chosen, depending on influence of the parameter given on the structure rf characteristics.

<table>
<thead>
<tr>
<th>Table 1 The ranges of the DTL cells dimensions.</th>
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<tbody>
<tr>
<td>Conv. DTL</td>
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<tr>
<td>( \beta )</td>
</tr>
<tr>
<td>Aperture rad. ( a/\lambda_0 )</td>
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<tr>
<td>Low. DT rad. ( r_1/\lambda_0 )</td>
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<tr>
<td>Upp. DT rad. ( r_2/\lambda_0 )</td>
</tr>
<tr>
<td>DT radius ( r_1/\lambda_0 )</td>
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<tr>
<td>DT angle ( \phi )</td>
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<tr>
<td>Gap ratio</td>
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</tbody>
</table>

It is not so difficult to develop algorithm for this work and to pass this long routine job to computer, for which it is directly intended. The system takes one variant, tunes it to frequency specified, stores results and goes to next variant automatically.

The results of this job are \( M \)-dimensional arrays in direct access file.

For every variant are stored:

a) the cell dimensions,
b) general parameters of the structure - transit time factor \( T \), quality factor \( Q \), effective shunt impedance \( Z_s \), maximum electric field at the surface - \( E_{s_{\text{max}}}/(E_0T) \) ratio, maximum magnetic field at the surface - \( H_{s_{\text{max}}}/(E_0T) \) ratio.

The surface of the cell is divided in several segments. For each segment are stored:

c) the relative part of rf losses (with respect to losses in total cell),
d) frequency shift due to possible displacement of this segment,
e) maximum electric field at the segment - \( E_{s_{\text{max}}}/(E_0T) \) ratio.

As the particularities of the DTL structure, frequency shift and additional rf losses in the stem together with additional rf losses in the end wall are calculated and stored.

**The Data Treatment and Applications**

The data base stored is the main value of the system.

The procedure of the application is also simple. First of all, the designer should specify DTL option and the operating frequency. The data base will be extracted, scaled to the frequency specified and the available ranges of the cell dimensions will be displayed.

There is a large variety of the data base applications for the DTL design. The simplest one is the comparison of different DTL variants. For this purpose the designer should specify the cells dimensions under interest. After each specification, using standard methods of the cubic spline interpolation, dimensions of data arrays will be reduced at 1. At the end of this procedure the values of rf parameters, corresponding to the cell dimensions specified, will be displayed.

For example, at Fig. 2 and Fig. 3 the plots of \( Z_s \) and \( E_0T \) for different BCDTL operating frequencies, assuming \( a = 15 \text{ mm}, r_1 = 3 \text{ mm}, r_2 = 7.5 \text{ mm}, \phi = 0 \) are shown. If the dimensions of the drift tube are fixed, especially aperture radius, the increasing of the operating frequency do not leads to the increasing in shunt impedance.

![Figure 2: The effective shunt impedance of the BCDTL option for different operating frequencies.](image)

Figure 2: The effective shunt impedance of the BCDTL option for different operating frequencies.

![Figure 3: The accelerating gradient \( E_0T \) of the BCDTL option for different operating frequencies.](image)

Figure 3: The accelerating gradient \( E_0T \) of the BCDTL option for different operating frequencies.

Two dimensional plots are efficient tool to provide general picture for the DTL parameters behavior vs cell dimensions. For example, at Fig. 4 and Fig. 5 the surfaces of \( Z_s \) and \( E_0T \), available for BCDTL option assuming \( a = 15 \text{ mm}, E_{s_{\text{max}}} = 1.5E_k, r_1 = 3 \text{ mm}, r_2 = 7.5 \text{ mm}, f_0 = 700 \text{ MHz} \), are plotted. Compar-
ing these two surfaces, one can see, that conditions to get maximum shunt impedance practically coincide with ones to have a large $E_0 T$ value.

More interesting and important case of application is to find optimal parameters with restrictions. Usually, the aperture radius is restricted from below with the beam dynamic requirements. The maximum electric field at the surface - $E_{\text{max}}$ should be also specified in the beginning of the design. Then, to simplify the manufacturing process, the designer can specify the set of another parameters, for example, cavity radius $R_c$, lower and upper DT radii $r_1, r_2$, and find maximum of $Z_s$, determining simultaneously the deviation from global maximum (without limitation in parameters specified for manufacturing simplification).

It is possible to consider also the segmentation of the structure into accelerating cavities, taking into account additional rf losses. At Fig. 6 the plots of the effective shunt impedance for regular (a) BCDTL cell ($f_0 = 600$ MHz, $E_{\text{max}} = 1.5 E_k, a = 10$ mm), average $Z_s$ for 6 cells BCDTL cavities taking into account rf losses in end walls (b), in end walls and stems with radius $r_s = 9$ mm (c) are shown. Additional rf losses strongly reduce efficiency of the structure, especially for low proton energies.

Because the code source for data base treatment is open, it can be added with any possibility proposed.

Figure 6: The effective shunt impedance for the BCDTL, a) - "ideal" structure, b) - 6 cells tank without stems, c) 6 cells tank with stems $r_s = 9$ mm.

Conclusion
The data base for rf parameters of the DTL structure has been developed. The large number of calculations has been performed one time and stored. The application of this data base allows for the designer to work more creatively, providing him more time to choose the best solution.

Acknowledgments
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THE FIRST PRODUCTION AND TRANSPORT OF RADIOACTIVE $^{17}$F AT ATLAS FOR RESEARCH

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Abstract

A secondary beam of radioactive $^{17}$F was produced at the ATLAS accelerator and delivered to an experimental target station with an intensity of at least $2 \times 10^9$ particles per second for use in the research program. The beam was delivered through the $p(^{16}O,^{17}F)n$ reaction by bombarding a hydrogen gas target with 250 particle nA of 83 MeV $^{16}$O from the ATLAS superconducting linac. The gas target was maintained at a pressure of 300 Torr and a temperature of 257K. Beam quality was dominated by multiple scattering in the gas cell windows and by the reaction kinematics and beamline acceptance for energy spread.

Introduction

Radioactive beams have many applications in modern nuclear physics and astrophysics. This potential has caused several accelerator laboratories around the world to develop techniques to produce radioactive beams with useful intensities and controllable beam properties. The effort to develop a $^{17}$F beam at the superconducting linac ATLAS [1] is primarily aimed at measurements of interest in astrophysics, but is also a demonstration of a technique to produce on-line, short half-life radioactive beams, and deliver these to a secondary target.

The physics goal of the experiment was to measure the cross-section for $^{17}$F(p,$\alpha$)$^{14}$O in the 3 to 4 MeV region in the center of mass system. For this measurement, the inverse reaction $p(^{17}F,^{14}O)\alpha$ is appealing, because a target of $^{17}$F ($T_{1/2} = 65s$) is not possible. For such a short half-life, the batch transfer process, as has been used for radioactive beams $^{18}$F ($T_{1/2} = 109m$) [2,3], is also impractical. Therefore, a primary proton target was used to transform a fraction of an $^{16}$O beam to a $^{17}$F beam. A bending magnet selected the fluorine particles in charge state $9+$, thereby filtering out most of the $^{18}$O isobar nuclei. Finally, the $^{17}$F beam was delivered over a distance of 12 m to a secondary CH$_2$ target. The desired $^{17}$F beam energy for the 3.63 MeV resonance in inverse kinematics is 62 to 63 MeV, producing approximately 45 MeV $^{14}$O and 15 MeV $^6$He. Since $p(^{17}F,^{16}O)\alpha$ is forward peaked in the laboratory system, the ATLAS spectrograph was used as a powerful tool to separate the $^{16}$O nuclei from the background of scattered particles.

Severe challenges had to be overcome in order to carry out a successful measurement with this technique:

- Build a sufficiently robust proton production target
- Transport the $^{17}$F beam of huge energy spread and divergence with maximum efficiency to the target
- Understand and handle beam impurities
- Identify clearly $^{16}$O in the spectrograph in the presence of different backgrounds.

Experimental Configuration

The physical layout showing the relationship of the $^{17}$F production target, the connecting beamline to the secondary target and the ATLAS spectrograph is shown in Fig. 1.

![Fig. 1. Floor plan of the spectrograph area showing the positions of the primary gas target and the secondary target in front of the ATLAS spectrograph.]

Design of the $^{17}$F Production Target

The $^{17}$F production target must be capable of sustaining an $^{17}$F beam current of as much as one particle $\mu$A and have an effective thickness of at least 250 $\mu$g/cm$^2$, in order to obtain
more than $10^5$ particles per second on the secondary target given the $^{17}$F production cross-section [4] in the order of 10 to 100 mb and a transport efficiency of about one percent.

Experience indicates that foil (CH$_2$) targets cannot take the necessary high beam current, even in rapid rotation. Therefore, a gas target with an effective length of 7.5 cm and thin HAVAR [5,6] windows was chosen (see Fig. 2). To keep the temperature of both the windows and the hydrogen gas low, the chamber has double walls to accommodate a constantly flowing cooling liquid in the outer cylinder. Four support pipes supply cooling fluid and H$_2$ gas.

Fig. 2. A simplified cross-section of the cylindrical gas target used. The effective diameter of the windows is 1.27 cm.

The selection of window material and thickness was made as a compromise between the maximum sustainable gas pressure and the deleterious effect of thick windows on angular and energy straggling. The effect on the energy spread is negligible, since usually the reaction kinematics dominates this even near the reaction threshold. On the other hand, the contribution of the small-angle scattering to the beam divergence can dominate the effective beam emittance. The required energy on the secondary target led to reaction energies between 73 to 77 MeV (threshold at 63.8 MeV) resulting in an maximum divergence of $\pm 1.5^\circ$ from kinematics (average of about $\pm 1^\circ$). This relatively small cone is due to the negative Q-value of p($^{17}$O, $^{17}$F)n. A reaction with a positive Q-value would result in a much larger angular spread.

For two 1.9 mg/cm$^2$ HAVAR windows, the small angle scattering is also of the order of $\pm 1^\circ$, which made this type of window a good choice. Glued in a mounting ring with an inner diameter of 1.27 cm, they withstood a 250 pA beam of 83 MeV $^{17}$O at H$_2$ pressures up to of 460 Torr. A higher pressure was not tested.

The divergence and energy width of the $^{17}$F is estimated to be $\pm 1.6^\circ$ and $\pm 4$ MeV from the combined contribution of all effects. Calculations of the beam optics and examination of the windows after the run suggest a beam spot radius of 2 mm on the entrance windows. This makes a spot with a 3 mm radius on the exit windows. From this, we estimate the unnormalized emittance of the secondary $^{17}$F to be 84 $\pi$ mm-mrad.

**Transport of the $^{17}$F beam to the secondary target**

The program TRANSPORT [7] was used to calculate the beam optics of the $^{17}$F and predict a transport efficiency. For such a large emittance beam, a transmission of 3.5% is predicted, assuming a uniform density profile. Using a peaked density profile increases this number by a factor of 2. It is also estimated that 35% [8] of the $^{17}$F beam is in the 9$^1$ charge state, resulting in another attenuation factor of 3. The calculated beam envelope is shown in Fig. 3, and compared to mechanical apertures in the system.

![Diagram showing the transport of the $^{17}$F beam](image)

**Fig. 3.** The calculated envelope of the produced $^{17}$F beam from the production target at 30 m in this calculation to the scattering chamber at 43 m. The quadrupole doublets are in a YX-YX-configuration.

Both energetic and angular distributions of the $^{17}$F beam are strongly affected by the reaction kinematics. Therefore, a correlation between energy and angle of a particle is to be expected. These correlations are not included in the TRANSPORT studies and place significant uncertainties on the predicted transmission. However, this simple model leads to an expected overall efficiency of 1 to 2%.

**Parameters and Results**

At a primary beam of 250 pA $^{17}$O, one expects a $^{17}$F production rate of 2.10$^7$ per second. At the spectrograph, a $^{17}$F current of 1.10$^5$ per second was observed. The upper limit of the vertical spot size on the secondary target is calculated to be 1 cm. The y-magnification of the spectrograph is three, and so the detector [9] in the spectrograph focal plane is unable to intercept all beam particles. We estimate a detection efficiency of only 50% due to this effect, resulting in a transport efficiency of 1%, in reasonable agreement with the estimate in the last paragraph.
The ratio of $^{17}$F particles to other nuclei detected in the focal plane of the spectrograph in the experiment was better than 3:1, in a measurement taken at 0° and therefore with a much weaker primary $^{17}$O beam of only 175ppA on the gas target [See Fig. 4].

![Secondary Radioactive Beam Components at Spectrograph](image)

Fig. 4. The energy spectrum of the secondary beam in the ATLAS spectrograph at 0° without gates.

The goal of the experiment was to detect $^{14}$O nuclei from $^{17}$F(p,o)$^{16}$O in inverse kinematics. To provide easy discrimination between $^{16}$O nuclei and background, the $\alpha$ particle was detected in coincidence in a silicon detector. While the spectrograph covered 2° to 10° on the left side of the beam, the alpha detector measured $\alpha$-particles on the right side between 6° and 20°. In the coincidence spectrum, the $^{16}$O particles are the most prominent group [see Fig. 5]. The $^{17}$F and $^{17}$O particles scattered in the spectrograph are only in random coincidence with uncorrelated particles in the silicon detector.

![α-Coincidence Spectrum](image)

Fig. 5. The spectrum of nuclei in the spectrograph in coincidence with $\alpha$-particles in the silicon detector. The values of Z and M/Q have been linearized.

By slightly changing the field of the 22° switching magnet, a certain energy control of the secondary beam was available without retuning the accelerator. Due to the large energy spread in the $^{17}$F particles, the current of the secondary beam did not change more than 50% when swept over a 2 MeV energy region.

**Summary and outlook**

This first experiment with a radioactive $^{17}$F-beam shows that a gas target can be used to produce a radioactive beam from a stable beam in flight. However, it is difficult to transport the secondary beam, and the accessible energy range is restricted by the cross-section and the reaction kinematics. Nevertheless, the technique works well, producing on the order of a few 10^5 particles per second. With this radioactive beam, it is already possible to measure an astrophysically significant nuclear reaction cross section.

To gain a larger range of accessible energies, to uncouple the production reaction energy from the energy of the secondary beam, and to reduce the energy spread of the secondary beam, the production target has to be moved in front of active elements of the accelerator system. A strong focusing element, directly after the gas target also improves the overall transport efficiency. However, the acceptance of the rest of the beam transport system limits this effect.

Testing different production target locations and the refinement of the gas target itself are the next steps in the development of this in-beam production of radioactive beams at ATLAS.

**Acknowledgments**

This work was supported by the US D.O.E., Nuclear Science Division, under contract No. W-31-109-ENG-38.

Boris Harss is a student of Prof. H.J. Körner at the Institute for Nuclear Physics and Nuclear Solid State Physics E12, Technische Universität München, working on this project in partial fulfillment for a diploma thesis.

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AN ACTIVE MECHANICAL STABILIZATION SYSTEM FOR LINEAR COLLIDER QUADRUPOLES TO COMPENSATE FAST GROUND MOTION

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Abstract

Next generation Linear Colliders require very low emittance beams in order to achieve sufficiently high luminosities. Due to the extremely small beam sizes of some ten nanometers height at the IP, these machines are very sensitive to ground motion leading to uncorrelated quadrupole jitter. As measurements performed at several laboratories indicate, the required vertical jitter tolerances of 30 nm rms for frequencies above \(\approx 2\) Hz cannot be guaranteed in an active accelerator environment. Therefore, an active stabilization system based on geophones and piezo actuators has been developed as part of the DESY S-band Linear Collider Test Facility. This system damp magnetic motion in the frequency band 2 - 30 Hz by up to -14 dB, resulting in remaining jitter rms values of some 25 nm even in a very noisy environment. Recent results of the system’s performance with different sensor types will be presented.

Introduction

To achieve sufficiently high luminosities of some \(10^{36} \text{ cm}^{-2}\text{sec}^{-1}\), future linear colliders make use of extremely tiny beam spot sizes at the interaction point (IP) of some 10 nm height and some 100 nm width. To provide head-on collisions of the two opposing linac beams, beam trajectories have to be controlled by some means in order to fight ground motion induced beam jitter. The required tolerances for uncorrelated vertical quadrupole vibrations can be estimated as [1,2] 85 nm vertically and 380 nm horizontally.

Since ground motion measurements (fig.1) at DESY [3] indicate that vertical ground motion amplitudes have to be expected in the vicinity of the required tolerance limit, an active stabilization system for the linac quadrupoles has been developed to fight beam jitter at its source. This paper describes some considerations leading to the present design of the system as well as some results of active stabilization. Additionally, possible further improvements of the system’s performance using broadband seismometers are presented.

Design considerations

For compensation purposes, the spectrum of ground motion can be divided into two frequency bands, each of them requiring different compensation schemes. While for low frequency distortions beam-based methods are applicable, this method fails in the high frequency region beyond \(f_{\text{rep}}/6\) and leads to reasonable damping only below approximately \(f_{\text{rep}}/25\) [4]. Therefore, high frequency beam jitter has to be compensated independently of the beam.

The simplest possible solution consists of a passive vibration absorber with resonance frequency \(f_r\) well below the lowest frequency to be compensated. Though such a system would be capable of damping high frequency vibrations by a factor \(1/\omega^2\), it would, on the other hand, be very sensitive to any excitation acting on the magnet itself, like cooling water pressure fluctuations etc.

To achieve significant damping of frequencies beyond 2 Hz, a resonance frequency of \(f_r = 1\) Hz is necessary. Together with a magnet mass of 100 kg, this leads to a very small spring constant of the passive absorber being \(D = 4000\, \text{N} \cdot \text{m}^{-1}\). Therefore, even a static force as
small as $4 \cdot 10^{-3}$ N would lead to a magnet displacement of 1 $\mu$m.

These considerations led to the development of an active stabilization system with a vibration sensor on top of each magnet and some means of actuator to move the magnet in order to keep it at rest.

As can be easily shown, application of an active feedback system to a low frequency passive vibration absorber would lead to a modification of the system's spring constant only within the limited bandwidth of the vibration sensor, while for very low as well as very high frequencies the system would show the same behaviour as a purely passive one [5]. Therefore, piezo actuators with high resonance frequencies have been chosen.

At present state, geophone type vibration sensors made by KEBE Scientific Instruments are used to measure magnet motion. The internal noise of these sensors has been determined to $1.1 \pm 0.3$ nm for frequencies higher than 2 Hz [6], which is well below the desired remaining magnet jitter.

For simplicity reasons, the mechanical design was chosen such that the magnet is tilted by a single piezo actuator around its horizontal transverse axis, as schematically shown in figure 2. The complete active stabilization system is shown in figure 3.

![Figure 2: Schematic view of the active stabilization system.](image)

**Experimental results**

The active stabilization system has been set up in DESY hall 2, an experimental hall close to the DESY synchrotrons. Due to the vicinity of two accelerators, several transformers and other technical equipment, this can be considered as a typical example for an operating Linear Collider environment. Therefore, the results obtained there should be similar to those to be expected in the future accelerator.

To determine the system's performance, a second identical sensor was placed on the floor just below the magnet. The signals of both the feedback sensor and this second one were sampled simultaneously at 400 Hz. The transfer function of the active stabilization was calculated as the square root of the ratio of the two corresponding power spectra $\Phi_{xx}$ and $\Phi_{yy}$. The resulting transfer function is shown in figure 4, together with the theoretically expected curve. Additionally, the rms values $\sigma_x$ and $\sigma_y$ of the displacement in the frequency band $f_0$ to infinity were calculated as

$$\sigma(f > f_0) = \sqrt{\int_{f_0}^{\infty} \Phi(f) \, df}.$$  \hspace{1cm} (1)

The result is shown in figure 5.

**Future improvements**

To improve the system's performance, the application of broadband seismometers made by Guralp Systems Ltd. is
under study. These sensors provide flat velocity response in the frequency band from 0.1 to 50 Hz. Therefore, an increased feedback gain around 2 Hz is expected. Figure 6 shows a comparison of the theoretical transfer functions of the existing system with KEBE seismometers and the device under construction with these new seismometers.

Using these transfer functions $|H(f)|$ and the ground motion power spectrum $\Phi(f)$ measured in HERA Hall West, the expected rms value $\sigma$ can be calculated as

$$\sigma(f > f_0) = \sqrt{\int_{f_0}^{\infty} |H(f)|^2 \cdot \Phi(f) \, df}. \quad (2)$$

Figure 7 shows the corresponding rms values of ground and magnet motion using the transfer functions of the two systems.

**Conclusion**

As has been experimentally demonstrated, active stabi-

**References**

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PRECISION ALIGNMENT OF BPM'S WITH QUADRUPOLE MAGNETS

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Abstract

In order to minimize the emittance dilution in next generation linear colliders precise alignment of all focusing components is needed. We report on our experiences using a pulsed wire to calibrate beam position monitors with respect to the magnetic axis of the quadrupoles used in the S-Band Linear Collider Test Facility at DESY (SBLCTF). The magnetic field along the wire and the magnetic field integral is measured by observing the transverse displacement of the wire induced by a short current pulse.

Introduction

Transport of small emittance beams in next generation linear colliders demand steering of the particle beam towards the magnetic axis of the quadrupoles within a tolerance of 10 μm. For the SBLC this will be achieved with a permanent beam based alignment and a fast feedback which damps the effect of ground vibrations on the quadrupoles [5]. The procedure of the beam based alignment requires a relative precision of the BPM's of at least 4 μm and an absolute measurement of the beam trajectory with respect to the quadrupole axis within 100 μm.

The Concept

In order to avoid the errors from measuring the position of the magnetic axis relative to some external reference and back to the position of the wire used to calibrate the monitor, which is inside the quadrupole, we decided to pick up the idea of Fisher et al. [3] to use the same wire for detecting the magnetic axis. For this we use a method described by Warren [1,2] to measure the magnetic field along the wire with a strong but short current pulse. The Lorentz force acting on the wire accelerates those parts of the wire which see a magnetic field. Solving the differential equation with the initial conditions

\[ A(z, t = 0) = 0, \quad A(z, t = 0) = Q \cdot B(z) / \mu \]

at the position \( z_0 \) behind the magnet and a time \( t \) after the current pulse of charge \( Q \) [2] gives an amplitude of:

\[ A(z_0, t) = \frac{Q}{2 \cdot \mu \cdot c} \int_{z_0}^{z_0 + c t} B(z) \cdot dz, \quad \text{with} \quad c = \sqrt{T/\mu} \]

where \( \mu \) is the weight per unit length of the wire and \( c \) is the wave velocity which depends on the tensile force \( T \) stretching the wire. The amplitude is measured with a detector outside the magnet. Since the whole time depend of the signal can easily be measured with a digital oscilloscope this gives the magnetic field at every point of the wire as well as the field integral. If the wire is placed exactly on the magnetic axis, the signal should be zero for all times. A tilt between the wire and the magnetic axis can easily be measured.

Fig. 1. Magnetic field and field integral of the s-band triplet along the axis, measured with a Hall probe at a distance of 4 mm from the magnetic axis. Both magnets at the ends are excited to 18 T/m whereas the central region is not powered. The right graph shows which signals are expected from the pulsed wire measurement (see Fig. 5).

The Test Stand

An aluminum plate carries the magnet on movable stages and two rigid pillars to fix the wire. The wire is stretched through a stainless steel tube with the diameter of the monitor chamber to form an RF-tight coaxial system. At each side of the magnet a bellow is inserted to allow the movement of the magnet. Close to one end of the magnet the wire movement detector is placed. The distance from the detector to the end of the wire has to be longer than half of the magnet length in order to separate the original signal from the one reflected at the wire ends.

Fig. 2 Sketch of the test stand
The Beam Position Monitor

The beam position will be measured by a strip line monitor with 20 cm long electrodes. The vacuum chamber with the monitor fits closely to the magnet poles and is fixed at its position by reassembling the magnet.

Fig. 3. left: cut of the beam position monitor for the SBLC; right: simplified view of S-Band Test Linac Triplet (one quarter removed)

The Magnet

For these measurements we used the magnets of the SBLC Test Facility which are quadrupole triplets built in one yoke (Fig. 3). Focusing is done by the outer poles of 50 mm length whereas the middle part with 100 mm pole length excites the horizontally defocusing quadrupole field. The magnets have bore diameter of 35 mm and a maximum gradient of 20 T/m.

Positioning of the Magnet

To align the magnetic axis parallel to the wire, the magnet is mounted on a table which allows the magnet to be rotated by hand around the vertical and the horizontal axes perpendicular to the wire. The magnet can be moved in the vertical and horizontal direction by stepper motors with an absolute precision of better than 5 μm. The position of the wire is not changed.

Fig. 4 View of the test stand with divided quadrupole and mounted beam position monitor

Detection of the Wire Movement

A pulse generator produces the current pulse of up to 20 A over 10 μsec by discharging a capacitor. To measure the small transverse movements of the wire we installed both a diode laser and a photodiode in each plane. The laser beam is focused in the plane of the wire to a spot size comparable to the diameter of the wire. The center of the laser spot is then adjusted to the edge of the wire. The laser intensity that reached the photodiode depends directly on the wire position and is measured by a photodiode. The DC-photocurrent is subtracted and the amplified AC-signal is measured with an digital oscilloscope triggered by the current pulse. The noise arising from ground vibrations which cause the wire to oscillate at its first harmonic (~ 60 Hz) can be reduced efficiently by averaging over typically 4-16 pulses.

Fig. 5. typical signal of a photodiode, the distance from the wire to the magnetic axis is 50 μm in the left F-magnet and about 100 μm in the right F-magnet showing a small tilt between the magnetic axis and the wire, the middle part of the magnet (D) is not powered.

Results

Detection of the magnetic axis

To align the wire with the magnetic axis we excited only the outer quadrupoles of the triplet to 18 T/m while the inner part is switched off. First the magnet is moved transversely in both planes to minimize the wire signal. Then the magnet is rotated around its vertical and horizontal axis to get an equal signal from both excited quadrupoles. This aligns the magnetic axis parallel to the wire. Finally the signal is again minimized by a transverse movement of the magnet. With this procedure, which takes about 20 minutes, it is possible to find the magnetic axis with a precision of ±20 μm. The resolution is limited so far by movements of the wire which are induced by ground vibrations. If necessary the resolution can be improved by shielding the test stand against vibrations and by damping the wire oscillations. Fig. 6 shows the result of a vertical scan with a step size of 50 μm.
The main parameters of the measurement are listed in the following table.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>wire material</td>
<td>copper-beryllium</td>
</tr>
<tr>
<td>diameter</td>
<td>130 μm</td>
</tr>
<tr>
<td>weight per length</td>
<td>0.11 g/m</td>
</tr>
<tr>
<td>tension</td>
<td>4.5 N</td>
</tr>
<tr>
<td>sagitta inside the magnet</td>
<td>2.7 μm</td>
</tr>
<tr>
<td>group velocity</td>
<td>200 m/sec</td>
</tr>
<tr>
<td>1. harmonic of wire</td>
<td>66 Hz</td>
</tr>
<tr>
<td>charge of current pulse</td>
<td>110 μC</td>
</tr>
<tr>
<td>length of current pulse</td>
<td>10 μsec</td>
</tr>
<tr>
<td>integrated gradient of one quad</td>
<td>1 T</td>
</tr>
<tr>
<td>mechanical amplitude for 100 μm offset</td>
<td>245 nm</td>
</tr>
</tbody>
</table>

Close to the center, the wire position is given by

\[
X = X_0 + \alpha_x \frac{S_{\text{right}} - S_{\text{left}}}{S_{\text{right}} + S_{\text{left}}} \quad Z = Z_0 + \alpha_z \frac{S_{\text{up}} - S_{\text{down}}}{S_{\text{up}} + S_{\text{down}}}
\]

The data are used to fit the constants \(X_0\), \(Z_0\), \(\alpha_x\), and \(\alpha_z\). These values are unique to each monitor and will be used to correct the readout of the monitors. Fig. 7 shows the measured data for the prototype monitor. For large distances off axis the signals show the expected nonlinear behavior. The precision of this measurement is about ±10 μm.

![Graph showing BPM signals](image)

Fig. 7. measured BPM signals depending on the displacement of the wire from magnetic axis.

**Conclusion**

The detection of the magnetic axis with a pulsed wire as described here has proven to be a reliable method to calibrate beam position monitors with an absolute accuracy of ±25 μm. Further improvements are possible by reducing the wire oscillations due to ground vibrations.

**References**


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IREN TEST FACILITY at JINR*

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Abstract

The Intense Resonance Neutron Source (IREN) is under construction at the Frank Laboratory of Neutron Physics (JINR) with the 200 MeV electron linac (LUE-200) being created as a driver of IREN. The RF beam-off IREN Full-Scale LUE-200 Test Facility (FSTF) assembly is considered as a first needed stage of the Project. The main goals of the FSTF are getting a 35 MeV/m acceleration gradient using the 5045 klystron and SLED system, as well as testing the RF high power of the linac units and systems. The other linac systems (beam diagnostics, target, etc.) are being tested on the operating 40 MeV electron linac LUE-40. The FSTF scheme is presented and the examination program is discussed.

Introduction

A new time-of-flight, high resolution neutron spectrometer for investigations in the resonance neutron energy range, using the intense resonance neutron source (so-called IREN) [1], is being created by the Frank Laboratory of Neutron Physics (JINR, Dubna).

The IREN designed parameters are:
- integral neutron yield $=1 \times 10^{25}$ n/sec;
- neutron pulse duration $=400$ nsec;
- repetition rate 150 Hz.

The IREN source consists of three parts: an S-band 200 MeV driver electron linac, a photoneutron target as a converter, and a multiplying fissioning core. This scheme is not only a tribute to tradition [2] but also reflects our desire to have the advantage over other time-of-flight spectrometers, specifically over proton accelerator-based ones.

The LUE-200 traveling wave linac conception was designed by the Budker Institute of Nuclear Physics (BINP, Novosibirsk) [3,4] (see Table 1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam average power</td>
<td>$&gt;10$ kW</td>
</tr>
<tr>
<td>Electron energy</td>
<td>200 MeV</td>
</tr>
<tr>
<td>Pulse current</td>
<td>1.5 A</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>250 ns</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>150 Hz</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>$&gt;35$ MeV/m</td>
</tr>
<tr>
<td>Operation frequency</td>
<td>2856 MHz</td>
</tr>
<tr>
<td>Length</td>
<td>10 m</td>
</tr>
</tbody>
</table>

As calculations show, the efficiency of the energy transmission from the RF source to the beam $=15\%$ can be reached. So, to obtain the required $10$ kW average power of the beam, it is necessary to provide approximately $70$ kW power from the RF source. The SLAC 5045 klystron satisfies this demand optimally. Two such klystrons with 150 Hz repetition rate provide required power. Moreover, the 5045 klystron has a long life time ($=40,000$ hours), and is supplied by the pulse transformer in an assembly.

The IREN project assumes the accelerator and the multiplying target will be positioned in the buildings of the now-operating LUE-40 & IBR-30 JINR neutron source. The following strategy of the project realization has been accepted: dismantling of the operating IBR-30 installation will be begun only after receipt of a design value for the accelerating gradient of the IREN linac test-facility (see, Fig. 1).

IREN Full-Scale Test Facility

The main goals for creating FSTF are:
- obtain the 35 MeV/m accelerating gradient at a 150 Hz repetition rate;
- adaptation of the M-250 modulator for the 5045 klystron;
- accelerating sections RF of the processing and dark current studies;

![Diagram of IREN Test Facility](image)

Fig. 1. The IREN Full-Scale Test Facility layout
• testing and certification of the LUE-200 equipment before its installation on the IREN facility.

The FSTF includes the following systems:
• SLAC klystron 5045 and pulse transformer;
• accelerating section;
• pulse modulator M-350;
• SLED-cavities;
• RF oscillator and driver;
• RF feeder;
• RF control and diagnostics systems;
• vacuum system;
• other systems (protection, cooling, thermostat, timer, etc.).

Pulse Modulator M-350 for the 5045 Klystron

The 5045 klystron’s modulator (it’s name, M-350) is based on the pulse modulator M-250 which is a unit of the OLIVIN 20 MW (20 kW) klystron station for the Yerevan Physics Institute (YerPhI) injector linac [5]. OLIVIN stations were constructed and manufactured by the Russian Research and Industrial Institute of Powerful Radioconstruction (St. Petersburg). The M-350 is a pulse modulator with full discharging of the PFN and its resonant charging from a high-voltage power supply.

The parameters of the M-250 and the M-350 modulators are shown in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>M-250</th>
<th>M-350</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse power, MW</td>
<td>65</td>
<td>150</td>
</tr>
<tr>
<td>Tube voltage, kV</td>
<td>50 - 250</td>
<td>50 - 350</td>
</tr>
<tr>
<td>Output voltage of PFN, kV</td>
<td>20</td>
<td>23.5</td>
</tr>
<tr>
<td>Output pulse current, kA</td>
<td>3.6</td>
<td>6.3</td>
</tr>
<tr>
<td>Pulse flat top duration, µsec</td>
<td>8.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Leading edge duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(from 0.1 to 0.9), µsec</td>
<td>&lt;1.5</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Trailing edge duration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(from 0.9 to 0.1), µsec</td>
<td>&lt;2.7</td>
<td>&lt;1.8</td>
</tr>
<tr>
<td>RF pulse flat top uneveness, %</td>
<td>± 0.15</td>
<td>± 0.5</td>
</tr>
<tr>
<td>Repetition rate, Hz</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Forming line total capacity, μF</td>
<td>1.05</td>
<td>0.7</td>
</tr>
<tr>
<td>Forming line impedance, Ohm</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Forming line voltage, kV</td>
<td>40</td>
<td>47</td>
</tr>
<tr>
<td>Supply line power, kVA</td>
<td>150</td>
<td>200</td>
</tr>
</tbody>
</table>

One can see that the charging voltage of the PFN for M-250 and for the M-350 differ not more than 20%. Also, the values of the average charging current practically coincide. It allows us to use the charging circuit of the M-250 in the M-350 modulator after insignificant modification.

The pulse power on the M-350 load exceeds the similar parameter of the prototype by more than twice. The repetition rate of the pulses and average power in the load of the M-350 exceeds, by 1.5 times, the same parameters of the modulator M-250 at duration of the M-350 output pulse 2.3 times smaller than the duration of the M-250 pulse. The discharging circuit of the M-250 (forming device) should be greatly changed.

The PFN consists of two forming lines, which are charged from one source and discharge simultaneously on the joint load through the pulse transformer. The thyatron TGI-5000/50 (Ispolin) was tested earlier at SLAC and is now used as the switcher of the M-350 (see, Fig. 2).

Accelerating section

The disk-loaded traveling-wave waveguide is used as an accelerating structure [3]. The damping time of the field in the section is the determining parameter for efficient transmission of the RF energy from the klystron to the beam.

The type of accelerating structure was chosen to maximize this parameter. The geometry of the accelerating cells is optimized for the maximum accelerating gradient necessary to obtain a high average beam power. The accelerating sections have been designed and are being manufactured by BINP.

FSTF RF Supplement System

The RF supplement system consists of:
• master oscillator;
• RF driver amplifier;
• power amplifier using SLAC 5045 klystron;
• SLED system;
• waveguide transmission line (RF feeder);
• RF diagnostics.

The digital controlled RF frequency synthesizer with two output channels is used as a master-oscillator. The parameters of the master-oscillator are given in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Frequency range</td>
<td>2851.0 + 2860.0 MHz</td>
</tr>
<tr>
<td>Output power (each channel)</td>
<td>40 + 600 mW</td>
</tr>
<tr>
<td>Phase shift (ch. 2 vs ch.1)</td>
<td>± 180°</td>
</tr>
<tr>
<td>Discrete value of the phase shift</td>
<td>± 1°</td>
</tr>
<tr>
<td>Phase switching transition time</td>
<td>≤ 15 ns</td>
</tr>
</tbody>
</table>

The pulse preamplifier, which is part of the OLIVIN station, is used as a RF driver.

To get the high accelerating gradient (35 MeV/m), a SLED system of RF pulse compression is assumed to be used.
It consists of a 3 dB coupler, two high-Q cavities and a fast 180° phase shifter. Accurate calculations taking into account the real shape of RF pulse from 5045 klystron shows that for $\tau = 0.5\mu s$, the optimal magnitude of cavity coupling is 5.5. The SLED system is constructed and being manufactured by the Budker Institute of Nuclear Physics. The parameters of the SLED system are: RF power multiplication coefficient - 3.8; RF pulse duration shortening factor - 6.5; SLED transformation efficiency - 0.5.

There is an opportunity to measure the level and phase of the incident and reflected waves before the input of the section, in the excitation line of the klystron, as well as on its output, in the drive line of the buncher, and on the output of the section. These signals will be used for the control and maintenance of the RF system's given operating mode. The reference phase line will be stipulated for the control of the phase instability measurement and for protection of the klystron, accelerating section, and SLED cavities, as well as of the waveguide line.

**Vacuum system**

In development of the vacuum system, the following main requirements have been taken into account:
- the average pressure must be $\leq 5 \times 10^{-9}$ Torr in the accelerating section, RF feeder and SLED cavities;
- the system must be degassed at 250°C.

The vacuum system is developed by JINR. Part of the vacuum equipment is being designed and manufactured by VAKUUM PRAHA Company.

**FSTF Program**

The main purpose of the M-350 modulator's test is to obtain of the necessary parameters for the high-voltage pulse on the load according to the technical requirements, which were given in Table 2, as well as the repeatability of these parameters from pulse to pulse, and the reproducibility of the operation modes and operational reliability of the modulator, including the protection system.

The PFN of the M-350 modulator (as well as of the M-250) is being created using the IMK-100-0.05 type capacitors, which should operate close to their technical limits. At the initial stage of the creation of the M-350 modulator the specified capacities will be tested and selected according to the following criteria:
- charging voltage up to 100 kV;
- discharging depth up to 40%;
- repetition rate up to 200 Hz;
- discharging pulse duration up to 3 µs.

The next necessary stage will be the certification of the klystron equivalent for the M-350 and confirmation of the correctness of the technical decisions accepted during the development of the modulator, in particular, the study of the thermal mode of IMK-100-0.05 capacities.

The traditional cycle of the so-called "cold" RF measurements on a low level of RF power should be carried out for the accelerating sections and SLED cavities, as well as for the units of the RF feeder before their installation on the FSTF. The accelerating gradient of the disk-loaded waveguide will be measured by the spectrum of the electron dark current using the magnet analyzer in an energy interval up to 100 MeV [6]. A significant information on the parameters and operation modes of the linear accelerator can be received by phase measurements in the RF system. First of all, we mean this gives us an opportunity to fix the initial stage of the multipactions in the section or in the SLED cavities. For this purpose, the IPSTF will be equipped with the devices for high ($< 0.5\%) resolution measurement of phase shifts.

The klystron's RF test includes reception of the nominal output parameters according to its certification, and the measurement of the RF pulse envelope, as well as the sensitivity of the amplitude and phase of the output signal to small deviations of the operation mode parameters. The fast (from pulse to pulse) protection and feedback subsystems of the IREN RF system will be also tested.

The other IREN systems (control, electron and neutron beams diagnostics, target, etc.) are being tested on the operating 40 MeV electron linac LUE-40 and pulse IBR-30 booster-reactor [1]. Test studies of the instrumentation system prototype have begun here. The general parameters of the facility (RF-power signals, e-beam current, e-beam profile, thermal neutron signal, etc.) can be measured for a definite time interval and stored for subsequent analysis in on-line experiments.

**Conclusion**

Thus, the S-band linac's FSTF is being built at JINR. The reception of the 35 MeV/n accelerating gradient at the 150 Hz repetition frequency is the major problem of that facility. The received results will be used in the ditect process of constructing IREN. At the same time a modern experimental base for research in the area of accelerating technology will also be created.

**References**


* Work is supported by the JINR Plan Development of Facilities under JINR code # 0993/95/97
LUE200 - DRIVER LINAC FOR INTENSE RESONANT NEUTRON SPECTROMETER (IREN)

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141980, Dubna, Russia

Abstract

The 200 MeV electron linac as a driver of the Intense RESonant Neutron source (IREN) is being created at Frank Lab of Neutron Physics (JINR). IREN being a new neutron pulse source for time-of-flight spectrometers, should combine a high average intensity with a short pulse. The operating neutron source, the IBR-30 facility, consists of the LUE-40 linac (with an energy of 40 MeV, a pulse current of 0.3 A, a pulse duration of 1.8 μsec, and a repetition rate of 100 Hz) and a neutron multiplication target (with a gain of 200). The resulting intensity of the neutron flow is about 4.5·10^10 sec^(-1) and the pulse duration is 4 μsec. In the IREN project, a decreasing the neutron pulse duration by at least in one order is proposed. It follows that the target multiplication should also be reduced by the same order, and the average power of the new linac beam should be significantly greater than that of LUE-40. The main parameters of the new LUE-200 linac are described and the current status of the facility will be addressed for this conference.

Loss of the electron beam cannot be permitted during beam's acceleration and transportation due to the high average power. The energy spread should be limited, mainly, by optimal conditions for transporting the beam and focusing it on the phototarget. This condition limits the emittance of the beam as well, because of the high heat generation in the target body. The spot of the focused beam cannot be smaller than 20 mm.

Introduction

The scheme of the IREN facility is the following [1]. The accelerated electron beam is directed to the tungsten target-converter. The converter is the source of photoneutrons produced by the (γ, n) reactions. The W-converter is surrounded by a fuel plutonium (Pu239) core elements combined in groups (fuel assemblies).

For high-efficiency neutron production in the phototarget, the energy of the accelerated electrons must be greater than 60 MeV. The upper limit for the electron energy is determined by necessity to locate the accelerator in an existing building and hence, by the maxim achievable acceleration gradient.

The basic project of the accelerator was performed by A.Novokhatsky team (Novosibirsk) [2]. The use of 5045 SLAC klystrons [3] should provide the continuous operation regime of the facility. Finally, the main parameters of the IREN facility is shown in Table 1, in comparison with those of IBR-30 [1].

As the neutron pulse duration is, mainly, determined by the multiplication time, the electron pulse duration is chosen to be <0.3 μsec.

<table>
<thead>
<tr>
<th>Facilities</th>
<th>IREN</th>
<th>IBR-30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron integral yield, n/s</td>
<td>1·10^14</td>
<td>5·10^12</td>
</tr>
<tr>
<td>Fast neutrons pulse duration, ns</td>
<td>400</td>
<td>4500</td>
</tr>
<tr>
<td>Neutron multiplication gain</td>
<td>28</td>
<td>200</td>
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</table>

<table>
<thead>
<tr>
<th>Electron Linacs</th>
<th>LUE-200</th>
<th>LUE-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam energy, MeV</td>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td>Beam average power, kW</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>Electron pulse duration, ns</td>
<td>250</td>
<td>1600</td>
</tr>
<tr>
<td>Beam pulse current, A</td>
<td>1.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Repetition rate, Hz</td>
<td>150</td>
<td>100</td>
</tr>
</tbody>
</table>

The repetition rate of the pulses should be limited by the existing experimental conditions and must be less than 200 Hz.

The IREN project, including LUE-200, is realized by the efforts of a number of research and science centers, both from Russia and abroad. The accelerator sections, the buncher, SLED cavities, and some elements of the RF gun will be provided by the Budker Institute of Nuclear Physics (BINP), Novosibirsk. The RF feeder has been designed and manufactured is almost by the Moscow Engineering Physics Institute and ISTOK company (Moscow). The 5045 klystrons, with accessories and RF loads, will be provided by SLAC. The klystron modulators supplied by Yerevan Physics Institute are upgraded to the required parameters with the help of the Russian Institute of Powerful Radioconstruction. The vacuum equipment designer and manufacturer would be VACUUM PRAHA company. The target-converter have been designed by Science Research & Design Institute for Energy & Technology [4]. The focusing system and other elements of the transport channel will be provided by JINR.

Layout of the IREN Facility

The IREN project assumes the new facility will be positioned of in the building of the now operating LUE-40 & IBR-30 JINR neutron source (see Fig. 1). The main elements of the LUE-200 accelerator and multiplying target will be placed in the three levels of the building [5]. The area of each level's is approximately 100 m².

The electron gun, buncher, first accelerating section, and 5045 klystron with its modulator, will be placed on the second level. In the same area all DC power supplies for the focusing

* Work is supported by the JINR Plan Development of Facilities under JINR code # 0993-95/97
system should be mounted. The second accelerating section is under the first one. The 700 mm long diagnostics units will be located after the electron gun, between the accelerating sections and before the target. The second klystron with a modulator will placed on the first level.

The electron beam will be transported from the second accelerator section to the target through a 12 m long drift channel.

![Diagram of the electron gun layout](image)

**Fig. 1. IREN linac layout**

**Electron Gun**

A pulsed electron beam is emitted by the grid-controlled electron gun having 12 mm diameter oxide thermocathode. The electron gun developed by BINP for the \( \Phi \)-factory injector [2] was used as a prototype of the electron source for IREN linac. The design of the gun advanced for the vertical arrangement is shown in Fig. 2; the main beam parameters are presented in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>200 keV</td>
</tr>
<tr>
<td>Peak current</td>
<td>5 A</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>250 ns</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>150 Hz</td>
</tr>
<tr>
<td>Emittance</td>
<td>( \leq 0.01 \pi \text{ cm} \cdot \text{rad} )</td>
</tr>
</tbody>
</table>

The cathode heater and control unit of the gun are placed into a high pressure tank under a high voltage cathode potential and fed by a coaxial ferrite HV transformer \((100W \times 200kV)\). The control block is triggered with an optical channel. The basic elements of the electron gun are being made by BINP and JINR.

![Diagram of the electron gun layout](image)

**Fig. 2. The electron gun layout.**

**RF System**

The accelerating structure of the LUE-200 consists of the buncher and two accelerating sections. It was initially designed for the \( \Phi \)-factory injector at BINP. Each section is powered by a 5045 SLAC klystron with a SLED system. The length of the accelerating section is 3030 mm, so the acceleration gradient is greater than 35 MeV/m. The accelerating section and buncher is now being manufactured by BINP (Novosibirsk).

All RF components and vacuum equipment will be put together and certified at the IREN Full-Scale Test Facility (FSTF) [6]. At the present time the power supply for FSTF has been put into operation, the M-350 klystron modulator [7] is being tuned, and the SLAC 5045 klystron is being prepared for installation. FSTF program includes also RF and vacuum processing, the dark current measurement and development the RF diagnostic equipment for IREN. A numerical simulation of the IREN dark current is performed at this conference [8].

**Focusing System**

The focusing system should provide electron beam transport from 200 keV to 200 MeV. This system consists of two parts. In the first, where the beam energy is relatively low, a solenoidal focusing is used. In the second one, the beam is focused by quadrupole lenses.

The solenoidal focusing system is optimized to completely accept the beam from the gun and to compensate for the space
charge influence at the bunching step and at initial stage of acceleration.

Transportation of the beam after the first acceleration section (where the beam has an energy above 100 MeV) to the target is performed by nine quadrupole lenses.

The design of the focusing system elements has already been completed. The power supplies of the are under construction.

**Target**

The main elements of the target are shown in Fig. 3.

![Target Diagram](image)

**Fig. 3. Basic target-converter elements.**

The Be-scatterer is placed before the tungsten target to increase the size of beam spot. The W-converter is cooled by gaseous He. The vacuum space is separated from the helium one with thin stainless steel foil. The temperature of this foil, as well as the temperature of the W-target, is controlled by a set of thermocouples. Recently, this scheme was investigated experimentally on the base operating facility, IBR-30. The thermal regime of this Be-W target as well as its neutron-production ability were measured [9].

**Control System and Diagnostics**

Three beam control and diagnostics units will be mounted at the linac. Each unit contains beam current and position monitors, a beam scraper and a profile monitor.

The accelerated beam energy and energy spread should be monitored with a spectrometer. The use of a magnetic spectrometer does not appear to be optimal because of the high average intensity of the electron beam. We are studying now an opportunity to use non-destructive methods for advanced on-line beam diagnostics. Since the undulator output wavelength is a strong function of the beam energy the wavelength shift will be caused by energy shift. Observation of the optical transition radiation could provide information about beam size, emittance, etc.

The combination of high average power and high accelerating gradient cause us to pay additional attention to the thermostat system. The just-performed modernization of the existing thermostat scheme of the LUE-40 could be considered as a preliminary experiment. The accelerator section temperature vs. time dependence is shown in Fig. 4. To test the stability of the system, the temperature mode was changed from 40.0°C to 39.0°C at the moment \( t_1 \). At the moment \( t_2 \) the temperature regime was returned to its steady state 40°C. Finally the thermostat system should be verified at the IREN Full-Scale Test Facility (FSTF) [6].

![Temperature vs. Time Graph](image)

**Fig. 4.** The temperature of the accelerating section. At the moment \( t_1 \) the thermal mode was changed from 40°C to 39°C, and at the moment \( t_2 \), it was returned to 40°C.

**Conclusion**

The IREN’s team nearest plans are the equipment manufacture and adjustment of the IREN RF full-scale test facility.

**Acknowledgments**

The authors thanks to Mrs. A. Shaeffer for her help in preparing this report.

**References**


THE NEUTRON FLUX GENERATED BY THE IREN LINAC DARK CURRENT

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Abstract

The experimental study of the neutron-nuclei interaction based on the time-of-flight spectroscopy using the IBR-30 facility proceeds in the Frank Laboratory of Neutron Physics (JINR). This facility was built more than 20 years ago and needs the replacement.

In accordance with the improvement program the new facility IREN (Intense RESonance Neutron source) is under construction now. The IREN setup [1] includes the driver electron linac LUE-200 and the multiplying target. Two high gradient (35 MeV/m) linac sections will be powered by the SLAC power multiplication scheme based on the 5045 SLAC klystrons. Such a high value of electric field results in electron emission from the section walls (the so-called dark current) and could increase the neutron pulse duration.

The problem of the dark current influence on the neutron pulse parameters is discussed in this paper. The shape of the neutron pulse taking into account the dark current will be shown. The recommendations on the focusing system of the facility will also be given.

Introduction

The main goal of the neutron source improvement program is the shortening of the neutron pulse duration (350 ns for the multiplication coefficient 20) and increasing the neutron yield by a factor of two. To satisfy these conditions the average electron beam power (for the electron pulse duration 250 ns) must be up to 10 kW. The LUE-200 particle energy (200 MeV) and the corresponding gradient (35 MeV/m) are limited by the existing room height (12 m). Such a high value of the accelerating gradient could be achieved provided that the corresponding power supply system (SLED power multiplication scheme) will be used. The high value of the surface electric field results in electron RF autoemission from the section walls. These electrons could be captured by the accelerating field and form the dark current. This current depends highly on the surface quality of the accelerating sections, their processing and vacuum properties.

The RF-breakdown process in the room temperature accelerating structures is one of the problems arising in the R&D HEP Program. The problem of the dark current influence on the generated neutron flux is of great importance in the IREN facility too. This paper gives quantitative estimation of the neutron flux generated by the dark current. It is worth mentioning that the IREN accelerating sections were designed in INP (Novosibirsk, Russia) and will be manufactured there as well. They are similar to the sections used in the Φ-factory project [5]. The linac regime of the project, however, is a single bunch mode while IREN operates in a multi-bunch thus providing an increased average electron beam power. The estimations made in [4] show that the emittance growth for the last bunches of the train (due to the wake field effect) is about 20% in our case (accelerating gradient is 35 MeV/m). So, the bunches could be delivered to the target without considerable loss, but the dark current influence could possibly change this situation.

Method

The dynamics of the dark current electrons produced by the first accelerating section was computed. It is these particles that influence the neutron flux parameters (duration and amplitude). The experiments to measure the dark current were carried out in SLAC [2] and KEK [3]. In the first case the conducted experiments were aimed at studying the RF breakdown in the S-band room temperature accelerating structure. The dependence of the pulse dark current vs. the input RF-power was obtained. It was shown that with a 7-cell accelerating structure at the RF input power of 30 MW the pulse dark current amounts to 20 mA. The KEK measurements were conducted on a 3-meter S-band accelerating structure powered by the klystron with a SLED system. It was reported that the value of the pulse dark current at the input power of 200 MW was 340 mA. On the basis of these results the dependence of the pulse dark current vs. RF input power (for the IREN facility full power range) was extrapolated (see Fig. 1).

![Fig. 1 Dark current vs input power](image-url)

Before proceeding further some initial assumptions should be made: the quantity corresponding (according to Fig.1) to the integral value of the RF power distribution along the accelerating section was taken as an instantaneous magnitude of the dark current; the bunch space charge, beam
loading and wake field effects were not taken into account (space charge does not affect much the particle dynamics for these energies).

The SLED system parameters [1] and the dependence shown above (Fig. 1) fully describe the expected dark current parameters at the end of the first section (taking the channel acceptance for the normal conditions at the end of the first section (0.002 cm rad) as an electron beam emittance). In terms of these parameters the calculations of the beam dynamics in the IREN linac and focusing system have been made using the PARMELA program. About one hundred calculations for a full energy range (35 - 135 MeV at the end of the first section) have been performed.

Results

The energy acceptance of the IREN facility transport channel was computed. The ratio of the number of electrons delivered to the target to their initial number (channel transparency) is shown in Fig.2. The channel transparency significantly increases (from 0.1 to 0.7) over the electron energy range of 80-90 MeV. The upper limit of the energy acceptance (about 270 MeV) cannot be achieved with the existing power supply.

![Capture efficiency graph](image)

**Fig. 2 Channel transparency**

The dark current of the second section is not taken into account since the energy of the particles forming the current is not sufficient to reach the target. Beam envelopes for different values of the input electron energy are shown in Fig. 3. The first two cases represent the electron beam envelope for the particles with the energy less than normal (200 MeV). The size of the bunch along the channel exceeds normal about 1.5-2 times. Also the low energy electrons (< 100 MeV) are lost in the second section, so the necessity of the scrapers is obvious.

The characteristics of the dark current for the operation cycle are shown in Fig. 4. The energy gain in the sections is shown in Fig. 4a. After filling the section with RF-energy (at 0.5 μs) the total energy gain in the sections is equal to 120 MeV, which corresponds to the gradient 40 MeV/m (without

![Beam envelope graphs](image)

**Fig. 3 Beam envelope**
beam loading). The peak value of the dark current at the end of the second section vs. time is shown in Fig. 4b (0.5 T solenoidal magnetic field is applied along the first section so the low energy electrons (below 100 MeV) could be successfully delivered to the end of the first section).

The peak value of the dark current for the operation cycle is about 270 mA. The electron bunch RMS changes vs. time are shown in Fig. 4c. The first electrons reach the target 100 ns after the RF-power front edge pulse. The size of the electron beam on the target varies in time from normal to double (normal beam diameter is 2 cm.). The total electron current on the target is shown in Fig. 4e. The dark current results in the additional current pedestal with duration of up to 0.6 µs and magnitude of about 20% of the normal.

The instant neutron yield dependence could be obtained from the equation dI/dt = I + I_{ne}(t) (the constants are neglected), where I is the instant neutron yield, I_{ne}(t) - external neutron flux. The resulting neutron yield is shown in Fig. 5. The total neutron pulse duration also increases up to 0.6 µs with the pre-pulse magnitude of about 20% of the normal pulse one.

![Fig. 4 Beam parameters vs. time](image)

![Fig. 5 Neutron yield vs. time](image)

**Acknowledgments**

The authors thanks Prof. E. Laziev for his wise advises and Mrs. T. Prikhodko for her help in preparing of this paper.

**References**

SECONDARY ELECTRON MONITOR FOR ELECTRON BUNCH PHASE DISTRIBUTION MEASUREMENT WITH SUBPICOSECOND RESOLUTION

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Abstract

Secondary electron monitor using longitudinal rf-modulation of low energy secondary electrons, with initial energy in eV range, for bunch phase distribution measurement of electron linac bunches with subpicosecond resolution is considered. Analysis of limiting resolution for this method, construction particularities of the monitor, and specific example of its design for the measurement of the TTF linac beam will be presented.

Introduction

Development of electron linacs demands creation of a bunch length monitor with subpicosecond resolution that is equivalent to the measurements in frequency domain up to 1 THz or in submillimetre wave range. The monitor has to be compacted, self-calibrating, unperturbing a beam, compatible with UHV, radiation resistant.

Several approaches are known for solving this challenge. One of them consists in estimation of the rms bunch length through two beam current harmonics assuming, for example, bunch charge distribution is Gaussian [1] or using single harmonic [2] closed to the rms frequency of a beam spectrum where its amplitude is most sensitive to the bunch length changes. For the Gaussian bunch the rms bunch length \( \sigma \) can be determined from equation

\[
\frac{i_n}{i_m} = \frac{1 - \left( \frac{n \sigma}{2} \right)^2}{1 - \left( \frac{m \sigma}{2} \right)^2} \left[ 1 - \left( \frac{n \sigma}{4} \right)^2 \left( \frac{m \sigma}{6} \right)^2 \left( \cdots \right) \right] \frac{1 - \left( \frac{n \sigma}{4} \right)^2}{1 - \left( \frac{m \sigma}{6} \right)^2 \left( \cdots \right)}
\]

where \( i_n, i_m \) are beam current harmonics unknown precisely. Hence, the technique needs some one to calibrate it.

Method of interferometry of coherent radiation and the others close to it [3,4] are restricted by wave lengths being more than beam diameter or hole diameter of screen [5].

The use of incoherent radiation, for example, on a scheme: Cherenkov radiator plus a streak camera [6,7], is mainly limited due to the longitudinal chromatic aberration in the camera gap (photocathod - mesh distance) caused by initial velocity spread of photoelectrons. In plane-parallel geometry of the gap one can expect the limiting resolution till 1 ps [8].

In the paper the secondary electron monitor coming up to the above mentioned requirements more completely is presented. (The monitor based on the delta-rays is presented at this Conf. too).

It should be noted that in the best work [9] on research of time dispersion of SEM (the gap voltage was 3.6 kV) it was measured, in fact, its longitudinal chromatic aberration only, and the SEM time dispersion for metal is within 1...10 fs [12].

BPD monitor

Secondary electron monitor for bunch phase distribution (BPD) measurements with subpicosecond resolution is schematically shown in Fig.1.

Fig.1. Layout of BPD monitor (a) and geometry of its primary converter (b).

Here BPD of a primary beam (1) in a result of the beam interaction with a carbon fibre (2) under negative potential (U0) is isochronously transferred into the same distribution of secondary electrons which then, is coherently transformed into transverse one in the plane of multichannel collector (6) through rf-modulation in the gap of toroidal resonator (3) and magnet (5) allowing direct presentation the BPD on a low frequency display. Taking into account that the beam diameter is rather small (of 1...2 mm) and the smaller h-distance the less time transport spread (of the electrons) the carbon target was placed from the resonator at small fixed distance \( h = 2 \) mm, and this monitor unit is moved in the beam for a time of measurements only.

The monitor phase resolution (\( \Delta \phi \)) is mainly defined by the time transport spread (\( \Delta t \)) of the electrons on h-distance (2 mm), the shutter phase resolution (\( \Delta \phi_{sh} \)) [10] and the additional phase dilution (\( \Delta \phi_{dp} \)) caused by the beam space charge effect. Then, considering the above mentioned quantities as the independences one can estimate \( \Delta \phi \) using known algorithm from [10].

Time transport spread in primary converter

Time transport spread of the secondaries (\( \Delta t \)) at their motion in the field of charged cylindrical electrode under potential -U0 on h-distance (Fig.1,b) until the conducting wall (A-A) was obtained by numerical simulation using relativistic equations and taking for the electrons emitted from carbon their initial energy and angular distributions from [11]. Results of this calculation are presented in Fig.2, where \( f_0 \) and \( f_t \) are the initial energy distribution and temporal one in the plane A-A, respectively, for \( h = 5 \) mm, \( U_0 = 8 \) kV and 2R0 = 0.1 mm. FWHM of \( f_t \) is 0.227 ps that corresponds the time transport...
spread of two electrons with initial energies of 0.335 eV and 3.925 eV if they would move along the z axis.

Fig.2. Initial energy distribution of the secondary electrons (left) and their time distribution at the exit of primary converter at $U_0 = 8$ kV, $h = 5$ mm (right).

In Fig.3,4 are shown the dependencies of the FWHM of $f_t (\Delta t)$ vs. the electrode radius and voltage, respectively.

Fig.3. Time spread of secondary electrons in the primary converter vs. the target radius ($R_0$) for different distances $h$ (see Fig.1.b) at $U_0 = 8$ kV.

Fig.4. Time spread of secondary electrons in the primary converter vs. the target voltage $U_0$ for different target radius $R_0$ and two distances $h$ (see Fig.1.b).

The case of very large $R_0$ (more 100 mm at small $h$) corresponds the plane - parallel geometry similar to the accelerating gap (from a photocathode to mesh) in a streak camera [6,7]. One can see that using the plane - parallel geometry and voltage up to 20 kV and higher it is impossible to reach $t = 1$ ps or less at input electron size of more several tenth mm. These results are closed to one published in [8]. For our monitor $R_0 = 0.01$ mm, $U_0 = 8$ kV, $h = 2$ mm and $t = 30$ fs, i.e. $0.014^\circ$ in deg. of 1.3 GHz.

**Monitor resolution**

Beam space charge effect is the main one limiting the monitor resolution. Dependencies of the additional phase dilution ($\Delta \phi_p$) and momentum spread ($\delta \phi$) caused by the effect vs. the target place relative to the beam axis are plotted in Fig.5 for the geometry of the primary converter mentioned above and for the next beam parameters: electron energy - 10 MeV; beam radius - 0.5 mm; bunch length in phase of 1.3 GHz - 1.5; bunch population - $3 \times 10^8$. For calculation the ellipsoidal bunch with uniform density was taken. Charges induced by the beam on the target surface was not taken into account.

Fig.5. Electron phase dilution (2) and momentum spread (1) in deg. of 1.3 GHz caused by the beam space charge effect.

For the maximum values of $\Delta \phi_p$, $\delta \phi$ from Fig.5 ($\delta \phi = 0.6\%$, $\Delta \phi_p = 0.16^\circ$) and using the algorithm of calculation for the monitor resolution ($\Delta \phi$) from [10] we will get the dependence of $\Delta \phi$ vs. the electron phase at the gap entrance (gap with length and rf-voltage of 3 mm and 10 kV, respectively) shown in Fig.6.

Fig.6. Monitor resolution vs. the electron input phase in deg. of 1.3 GHz.

One can see that in the worse case the monitor resolution is reached of about $0.2^\circ .. 0.25^\circ$ of 1.3 GHz within several degrees $\phi_0$. With installation the target near the beam current maximum the resolution will be in 10 times less. Moreover, estimations have shown that account of the induced charges on the target can improve the resolution significantly. It should be noted that one of the advantages of this technique is possibility
to calibrate the monitor using thermoelectrons from the target heated by a current (more in detail of it in [13]).

Streak camera with 0.1 ps temporal resolution

To minimize in 50 times the longitudinal chromatic aberration in an accelerating gap of a streak camera [7] (photocathode - mesh distance) caused by initial electron velocity spread it is proposed instead of a plane - parallel geometry of this unit to use the geometry of the above mentioned one (see Fig.1.b). It will correspond the transition from the right to left side of the curves plotted in Fig.3. Figure 7 makes clear this proposal [14].

Fig.7. Scheme of primary converter for a streak camera with 0.1 ps temporal resolution.

Light is focused by an optic system (1) on a very narrow (about several μm) and thin photocathode (3) being under accelerating voltage of, for example, - 8 kV and placing from the entrance wall of the rf-resonator gap (with longitudinal modulation of the electrons and locked in phase with the beam bunches) of about 1 mm. For reaching high time resolution the transverse rf-modulation is not very convenient due to too much long of fringing rf-field and rf-field aberration. Holder (2) of the cathode (3) is taken very thin, of about 0.1 mm or less, from a free transit light materials to minimize the light dispersion effect. Temporal resolution for proposed device will be mainly defined already only by dispersion effects in windows of the camera, from linac, in Cherenkov radiator and light optics.

There is some more way for improving the time resolution. Time spread of the electrons through the accelerating gap is inverse proportional to root from an initial energy spread of the electrons, i.e. the electrons will have the same time of flight spread in the gap both for the energies from 0 to 1 eV and from 1 to 4 eV. Hence, with monochromatizing of the light at more high frequency one can increase the resolution but this way is not effective in comparison with the proposed one.

It should be noted that the known formula (see 5 in [6]) for estimation of the transit time spread in the gap is not valid for the values above several ps and less.

Transverse beam profile measurement with 5 nm resolution

There is some more advantage of this secondary electron technique: with help the monitor one can measure a transverse beam profile with spatial resolution of 5 nm [14]. In the case (see Fig.1) the resonator is not switched on, instead of the multichannel collector it is permitted to use a single channel one. High spatial resolution is defined by the small magnitude of projection (Δz) of the wire of the wire, which is visible from the collimator slit Δx₀, on the z axis. At the angle of view of 0.1 rad. the projection will be 1.24·10⁻³·R₀, i.e. at R₀ = 4 μm it will be Δz = 5 nm. The thickness of the region in which escaping secondary electrons are produced is about 3 nm [11]. Composition of these two distribution gives FWHM of about 5 nm, i.e. 200 points per 1 μm of a beam.

Plans

We have 6D problem to solve precisely the beam space charge effect in the monitor. The code for this is created now, and we expect to decrease the effect in 10...100 times using additional specific means. In the case we will have to increase the h-distance up to 30 mm.

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[14] Tron's proposal
METHOD OF BUNCH PHASE DISTRIBUTION MEASUREMENT BASED ON A MÖLLER SCATTERING

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Abstract

Design of a bunch phase distribution monitor with resolution in fs-time range operating on the principle of rf-sweeping of secondary electrons produced in a result of a Moller scattering in a wire target is considered. To minimize chromatic aberration the scattered electrons are separated in narrow energy band in kV-range by spectrometer installed after the monitor rf-deflector so that the planes of the electron analysis in rf-phase and energy are orthogonal to each other. Apparatus function of the monitor primary converter in a form of a time - energy distribution of the electrons passing through the hole of collimator installed in front of the rf-deflector is defined with a Monte Carlo calculation on a scheme of individual collisions.

Introduction

Method for bunch phase distribution measurement based on rf-sweeping of secondary electrons produced in a result of Moller scattering was proposed by one of the authors of the paper 25 years ago [1]. Option of this method was defined by fundamental properties of chosen physical process allowing to fulfill the measurements with resolution in fs-time range. During these years the author has carried out researches for creation the monitor realizing this method which, to some extent, had been restricted by possibilities of computers and the level of development of physical models for transport calculation of electrons in keV-energy range these time. In connection with interest to this measurements, increased extremely at present, in the paper this monitor is described. New precise calculations of electron transport in a carbon target for real geometry of the monitor have been accomplished, and some results are presented here below.

Bunch phase distribution monitor

The monitor is schematically shown in Fig.1. Delta-electrons produced in a result of a primary beam (1) interaction with carbon fibre (2) of 8 μm diameter are selected at scattering angle of 90° in a view of a narrow beam by means of a collimator (with hole of 1 mm diameter) installed in front of rf-resonator (3) on a distance 5 mm from the target (2). The phase distribution of selected delta-electrons is coherently transformed into transverse one through rf-modulation in the rf-deflector (5). The rf-deflector is a resonator of a slit-hole type the cross section of which is shown in Fig.1a where the length from point A to B along the resonator surface is a quarter of wave length. Resonance frequency does not depend on r-distance, and the last is determined by the electron transit phase. To minimize chromatic aberration the delta-electrons are also separated in narrow energy band by spectrometer (5) installed so that the planes of the electron analysis in rf-phase and energy are orthogonal to each other. Radius of main electron trajectory in the spectrometer is 100 mm. The target (2) together with the rf-deflector (5) is moved in the beam (1) for a time of measurements. Monitors are similar to the above mentioned one, but operating on the low energy secondary electrons, have been successfully realized already. As to this monitor there are two main questions which have to be solved, namely: temporal apparatus function of the primary converter of the monitor and its efficiency.

Time distribution of the delta - electrons escaping from carbon wire

Apparatus function of the primary converter is determined as a flight time of electrons from the start plane which is perpendicular to the primary beam axis and tangent the target to the finish one being perpendicular to the delta-electron beam axis and tangent the target too, i.e. the time involves the flight time of both beams. The function was calculated with Monte Carlo simulation using some results from [2,3]. The apparatus function in a view of the time distribution of the delta-electrons with energies of 10 and 50 keV within +50 eV and at the condition of their passing through the collimator hole are shown in Fig.2.

Fig.2. Time distribution of the delta - electrons with energy of 10 and 50 keV scattered by the 10 MeV electrons in the carbon fibre of 8 μm diameter.

FWHM of these distribution for the electrons with energies of 50 keV and 10 keV are 6.5 fs and 13.6 fs, respectively. It should be noted that these results have been determined for the beam radius of 1 mm, uniform beam current distribution and at installation of the target in the beam current maximum. The electron energy of the primary beam is 10 MeV.

Probability of escaping of the delta-electron captured by the collimator hole per an electron of the primary beam have been determined at the same conditions as for the time dispersion calculations. For the delta-electron energies equalled to 1, 3, 10 and 50 KeV the probabilities are 1.2×10^(-4), 5.2×10^(-5), 2.2×10^(-5) and 4.5×10^(-5), respectively. Hence, having an electron beam with 10 keV or more population for a time of measurements one can measure the bunch phase distribution with the above mentioned resolution (Fig.2).

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References

BUNCH PHASE DISTRIBUTION DETECTOR FOR THE ISTRA ION LINAC BEAM

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Abstract

Secondary electron rf-detector is the only beam diagnostic instrument at present for longitudinal profile measurement of short ion bunches. The detector with longitudinal rf-modulation of secondary electrons in capacity gap of quarter-wave coaxial resonator with a helical inner conductor is considered for the measurement (with phase resolution of about one degree of 148.5 MHz) of the ISTRA ion linac beam with pulsed current up to 200 mA at ion energy of 3..36 MeV. The detector description and bench testing results of its main units will be presented.

Introduction

The proton linac ISTRA-36 \textsuperscript{[1]} creating at ITEP for the first model of radwaste transmutation plant requires appropriate beam diagnostic provision to understand and minimize beam-loss. Detector for ion bunch phase distribution measurements with resolution of about 1° for the power beam of the ISTRA linac is discussed in this paper. This beam diagnostic instrument is required, first of all, for precise beam matching and setting up rf-parameters of the accelerator cavities. The detector is the key tool in the longitudinal beam emittance measurement system that will be also accomplished using the existing bending magnets in the linac channel. Chosen method of the emittance measurement will allow to research the beam distribution in longitudinal phase space without any model-assumption of it. First the method was proposed and successfully realised at the I-100 linac (IHEP \textsuperscript{[2]}) in 1980. Figure 1 makes clear it. The detector (9) was spaced after spectrometer (7) and at the 10 m distance from the I-100 linac.

![Fig.1. Emittance measurement system](image)

Narrow momentum width of the collimator (8) of 0.1% and small beam divergence (0.5 mrad) after collimators (5,6) allowed, in fact, to reserve the bunch phase distribution for separated part of the beam and, carrying out the same measurements at different particle momentum, to determine the distribution in the longitudinal phase space shown in Fig.2 where isolines of the beam distribution in the longitudinal phase space at different density levels (pointed in left column of the table) and corresponding beam per cents and beam longitudinal emittance measured are presented too. More in detailed of it one can find in \textsuperscript{[3,4]}.

![Fig.2. Emittance of the I-100 linac beam](image)

The principle of operation of the bunch phase distribution (BPD) detector (9) (Fig.1) has been reported elsewhere \textsuperscript{[4,5]}. Briefly, in the device the BPD of a high energy ion beam is isochronously transferred into the same distribution of the low energy secondary electrons which, then, is coherently transformed into transverse one through rf-modulation in the resonator gap (14) and spectrometer (15) allowing direct presentation it on a low frequency display (12).

Taking into account the beam space charge effect the detector realizing the same principle of operation has been chosen for the ISTRA beam.

**BPD detector**

The detector for the ISTRA linac beam proposed in \textsuperscript{[5]} is schematically shown in Fig.3.

![Fig.3. Layout of BPD detector](image)

There are some distinctions between the new detector and the mentioned above. Taking into account that the lower proton energy the higher its energy loss in the target, within considered beam energy range, the thin carbon fibre
of 8 μm diameter was chosen to decrease the fibre heating under the beam. Moreover, for that diameter and high negative voltage (of about 8 kV) applied to the target (1) the phase dilution of the secondaries on the distance (10 mm) until the collimator (2), caused by their initial energy spread, will be less than 0.01 deg. of 148.5 MHz (see Fig.3 in [6]).

To decrease the detector sizes a open quarter-wave coaxial resonator with a helical inner conductor was chosen the photo of which (before brazing) is shown in Fig.4.

![Photo of the open quarter-wave coaxial resonator of the detector (on 148.5 MHz).](image)

Fig.4. Photo of the open quarter-wave coaxial resonator of the detector (on 148.5 MHz).

At pulsed rf-power consumption of about 40 W the modulating gap voltage reaches demanded value of 2 kV. To suppress multipactoring the inductance part of the resonator contains an atmospheric air. Resonator feedthroughs are not vacuum - tight.

Multichannel collector (7) of the secondary electrons installed at the exit of the magnet spectrometer (6) allows to record a bunch phase distribution for a time less than the beam pulse duration, i.e. it will allow us to investigate changes of the phase distribution along the beam pulse. Estimations of separated pulsed charges of the secondaries at the entrance of the collector show that magnification of about 10° reached with installation of microchannel plates will be enough to record the phase distribution of the ISTRA beam in 100 points of its pulse. Below, everywhere, results of consideration will be presented for the following ion beam parameters: proton energy - 3 MeV, pulsed beam current - 150 mA, rms beam radius - 2.5 mm, beam pulse duration - 150 μs, pulse frequency - 25 Hz.

It should be noted that the detector can be installed so that the ion beam axis will be perpendicular to the plane Fig.3, then the monitor size along the ion beam will be 40 mm [4].

**Detector resolution**

The detector phase resolution (∆φ) is mainly defined by the phase dilution (∆φ₁) of the secondaries on the distance h = 10 mm, the shutter phase resolution (∆φ₂) and the additional phase dilution (∆φ₃) caused by the ion beam space charge effect. As it was mentioned above ∆φ₁ = 0.01°. In Fig.5 the phase dilution ∆φ₃ is plotted as a function of the target place relatively to beam axis. Distance between the beam axis and the collimator of 10 mm is fixed.

![Electron dilution ∆φ₃ in deg. of 148.5 MHz caused by the beam space charge effect.](image)

Fig.5. Electron dilution ∆φ₃ in deg. of 148.5 MHz caused by the beam space charge effect.

Then, considering the above mentioned quantities as the independences one can define ∆φ using known algorithm from [5]. Figure 6 shows the dependence of ∆φ vs. the electron input phase for the slit width of 1 mm of the collimator (4) and the main radius of electron trajectories in the magnet spectrometer of 50 mm.

![Detector resolution ∆φ vs. φ₀ in deg. of 148.5 MHz at U = 2 kV and for different electron energies at the gap entrance: 1 - 2 keV; 2 - 2.2 keV; 3 - 2.5 keV.](image)

Fig.6. Detector resolution ∆φ vs. φ₀ in deg. of 148.5 MHz at U = 2 kV and for different electron energies at the gap entrance: 1 - 2 keV; 2 - 2.2 keV; 3 - 2.5 keV.

One of the advantages of this technique is possibility to calibrate the detector using thermoelectrons from the target heated by a current. The ∆φ₀ resolution is determined by ratio of the relative initial momentum spread of the electrons at the gap entrance to the maximum increment of it due to the gap action which are measured by the magnet spectrometer when the gap is fed and not. Relationship U and the electron energy at the gap entrance is checked on the curve of the thermoelectron distribution in phase.

**Target heating**

There is important effect which limits the detector operation. When the temperature is beyond 2000 K the thermocurrent density can exceed the magnitudes compared with the secondary electron one. It ought to note too that for the tension of the wire it is necessary to know a
possible highest wire - target temperature because the limit of a elasticity strongly depends on the target temperature.

Taking into account that with decreasing proton energy its energy loss per unit length increases rapidly and velocity of the heat transport in the target is negligible small in comparison with a speed of heating under the beam the carbon fibre of 8 μm diameter was chosen. For this target and the above mentioned beam parameters (3 MeV) but for the pulse duration of 50 μs the maximum temperature dependence on a time is plotted in Fig.7.

![Graph showing temperature vs. time for pulsed beam current of 150 mA at 3 MeV proton energy.](image)

**Fig.7.** Carbon fibre temperature vs. the time for pulsed beam current of 150 mA at 3 MeV proton energy.

With increasing the pulse duration till 100 μs the increment of the maximum temperature for the pulse can reach 2500 K already. Hence, the main problem consists in the heating for a pulse, and the known flying wire technique [7] is not a solution for it.

There are several ways, proposed in [8], to solve this problem. Shortly, these proposals, shown schematically in Fig.8, consist in the following. First, to avoid increasing the wire heating from pulse to pulse the wire is replaced on a length equalled to a beam diameter for a time between two beam pulses by means of winding up the wire (Fig.8.a) from bobbin (1) on (2) through the area occupied by the beam (5).

![Diagram showing targets with "running" and "boiling" wires.](image)

**Fig.8.** Targets with "running" and "boiling" wires.

To decrease the wire heating, at first, the speed of "running" wire is brought up to demanded one and after that it is moved in the beam. Fig.8.b explains the same principle of operation for a wire closed on itself when the wire speed can be very high. Lastly, Fig.8.c makes clear the proposal of "boiling" wire. A boiling heat for any material is known to be the most magnitude at a heating process. Then, applying thin coating of copper (1) on a tungsten core of a wire one can keep the core at the temperature being not more than the boiling-point for a copper equalled to 2300°C. If we take this type of the wire for the RFQ2 Linac beam at CERN [9] (with proton energy 750 keV) the copper layer of 5 μm will be enough to reserve the tungsten core of 100 μm diameter because a proton range for a copper is not more it.

Besides the mentioned, to extend the temperature range we could use the delta - electrons [10]. In the case it is not necessary to apply voltage to the target.

**Conclusions**

One can conclude that there is no limit of principle for using the secondary electron detector for bunch phase distribution measurements of a ion pulsed beam with average beam current up to 10 mA now. Proposed new target technique needs its experimental researches under intense ion beam.

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DESIGN, PERFORMANCE AND PRODUCTION
OF THE FERMILAB TESLA RF INPUT COUPLERS

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Abstract

The TeV Energy Superconducting Linear Accelerator (TESLA) requires as one of its technical components a radiofrequency (rf) input coupler that transfers 1.3 GHz rf energy from the rf distribution system to a nine-cell superconducting accelerating cavity operating at a temperature of 1.8 K. The input coupler design is driven by numerous design criteria, which result in a rather complicated implementation. The production of twelve input couplers for the TESLA Test Facility (TTF) is underway at Fermilab, with the first two couplers having been delivered late in 1995. This paper discusses the Fermilab TESLA rf input coupler design, recent test results, and production issues.

Introduction

The TESLA design parameters call for the rf input coupler to transfer 206 kW peak rf power to the beam with a pulse length of 1.3 ms and a repetition rate of 10 Hz. These figures assume an accelerating gradient of 25 MV/m with a cavity Q_0 of 5e9 and a beam current of 8 mA. The design criteria for the TESLA rf input coupler are stringent, with the result being two somewhat complicated designs, one from Fermilab and the other from DESY. The design with all of its drawings and specifications is certainly a prerequisite for production, but it is not sufficient. Many technical production issues have arisen, issues which in principle are straightforward, but in practice can be difficult.

Testing of the input couplers is important to confirm their performance characteristics, yet it is not trivial to fully test the couplers under all possible operating conditions. Tests of one and two couplers on coupler test stands have been performed, and more recently tests have been performed on a complete cavity assembly in the horizontal test cryostat at the TTF. A first beam test is anxiously awaited and is expected later this year at DESY. The test results should be interpreted and understood so that design improvements may be made, with the key concern being multipacting. Comparisons of test results with multipacting predictions have been difficult to date.

Design

The Fermilab input coupler is shown in Figure 1. It features two aluminum oxide (Al_2O_3) rf vacuum windows, one being a coaxial window located near the cavity and thermally connected to the cryostat 70 K heat shield, the other being a waveguide window mounted outside of the cryostat at room temperature. Both ceramics are coated on the vacuum sides with a ~100 Å layer of titanium nitride (TiN). The windows are located at the detuned-cavity short in the standing wave pattern. Hence they see a voltage minimum at the moment of the rf pulse turn on, with a gradual transition to traveling wave conditions at beam injection. In the case of the coaxial window, which occupies a substantial fraction of a wavelength, the voltage minimum is at the upstream junction of the ceramic and inner conductor.

The coupler features three bellows on the coaxial line to allow for coupling adjustment and to accommodate cavity motion during cooldown and warmup of the cryostat. A fourth bellows is present in the coupling adjustment mechanism which connects the outer conductor of the coupler to the outer wall of the cryostat vacuum vessel. This mechanism provides a gimballed support for the coupler to allow for both horizontal and vertical motion of the cavity coupler port. Four threaded shafts linked by a chain provide for changing the coupling strength by an order of magnitude in Q_{ext}, which is normally set to 366.

The input coupler materials consist primarily of 316L (DIN 1.4404) stainless steel, OFHC copper, Al_2O_3 ceramic (99.5%), and high purity copper plating. Joining techniques include brazing for the ceramic-to-metal and the stainless-to-copper joints, and welding for stainless-to-stainless and copper-to-copper joints. The inner conductor attachment to the coaxial window assembly requires four electron beam welds. The outer conductor attachment relies on TIG welding in an oxygen-free chamber filled with helium and argon. Demountable vacuum joints use all-metal vacuum seals of the Helicoflex and Conflat types.

Production

The two main production problems have been vacuum leaks in bellows and poor adhesion of electroplated copper on stainless steel. The first design for the rf bellows called for a two-step welding process. The first step was to resistance weld a collar to the bellows neck. After resistance welding, the strengthened bellows neck was cut off at the center of the resistance weld. The second step was to TIG weld this resistance welded collar into an adapter of larger wall thickness. The first bellows received were not TIG welded to specification, and were in fact welded a second time in an attempt to correct the weld geometry. Many of these bellows developed vacuum leaks at the welds, some after having undergone all production steps without leaking.

The vacuum leaks were at first blamed on the TIG welds, and an order was placed for bellows that had only the resistance welded collars installed. Several of these units were then TIG welded at Fermilab, where contamination was observed to bubble out during the TIG welding. In some cases a multipass weld was required to get good results. Apparently the contaminants were trapped or formed (oxidation) during the

Fermilab is operated by the Universities Research Association under contract to the U.S. Department of Energy.
resistance welding process. Based on this experience, and on an improved alternative design, the original bellows design was dropped.

The new bellows design does not use an intermediate collar. The bellows neck is cut to length and slipped into an adapter and edge welded. This is a common means of bellows attachment that is generally reliable. The first of these new bellows are now being used in production. None have developed vacuum leaks to date.

There has been some concern that stress corrosion cracking might play a role in the development of vacuum leaks. Although the couplers are not used in a corrosive atmosphere, they are exposed to corrosive fluids during the copper plating process. The couplers currently under production have been vacuum oven stress relieved at 900 °C. This treatment partially anneals the stainless steel with the result being that the bellows are softened. Hence greater care must be taken in handling the couplers after the heat treatment.

The copper plating has been difficult primarily due to adhesion problems, although the surface finish has also been an issue. Acceptance tests include ultrasonic cleaning and vacuum oven bakeouts at 300 °C preceded and followed by visual inspection. Some early parts passed these acceptance tests at Fermilab, but later were partially depleted at the TTF during cleaning in a more powerful ultrasonic cleaner. Since then a stronger cleaner has been used at Fermilab. We have worked closely with the plating company to develop plating fixtures and anodes to optimize the plating process. Further, the company has set up a line devoted to the coupler plating. Each of the plating tanks is filtered and connected to a header leading to the part being plated. The plating process requires only that a series of valves be opened and closed in the correct sequence. The part being plated does not have to be moved or disassembled from the fixtures until the process is finished.

Recent Test Results

The first test of the Fermilab input coupler with a fully dressed 9-cell TESLA cavity took place in May-June of 1996 at the TTF. The cavity assembly included its helium tank, higher order mode couplers, frequency tuner, rf pickup, and rf input coupler. Previous tests in the vertical test stand demonstrated cavity gradients in excess of 15 MV/m, more than sufficient for the intended application as the capture cavity for the TTF injector. The input coupler instrumentation included charged particle pickups and vacuum gauges upstream and downstream of the coaxial window, a photomultiplier tube at the waveguide-to-coaxial transition, and temperature sensors at the coaxial window. Due to time constraints, the input coupler was not rf conditioned prior to being installed on the cavity. Hence a careful program of

Figure 1. The Fermilab TESLA input coupler design.
The conditioning process was computer controlled with the program monitoring the coupler and cavity vacuum, electron and photomultiplier signals, temperature, rf power, and cryogenic parameters. The rate of power increase is adjustable and three modes of operation are possible. The power rise mode causes the rf power to rise toward a specified power level with the primary feedback being the vacuum pressure. The program increases the rf power until a target pressure is reached, and then holds the power steady until the vacuum improves and a higher power level can be attempted. The rf power is reduced if a maximum pressure is exceeded. The second mode of program control provides for slowly sweeps the power up and down between two user-selected levels while monitoring and adjusting for excessive vacuum pressure levels. In the user control mode all readbacks are operating and data is being logged as usual, but the computer does not attempt to change the rf power level.

The rf conditioning began with the cavity and coupler at room temperature so that gases released by rf-stimulated desorption could be pumped away. The initial pulse length and repetition rate were 30 µs and 1 Hz, respectively. Nothing extraordinary was noted during the conditioning process, and a power level of 1.1 MW was reached after only 20 hours of conditioning. Vacuum, electron, and photomultiplier signals were well correlated. A behavior which has been seen previously was once again demonstrated. That is, initially the power rises very quickly and easily without being limited by outgassing, electron signals, or photomultiplier signals. Then a sudden burst of outgassing occurs, and thereafter many hours are needed to once again reach the earlier achieved power level. In this test the first burst occurred on the coupler side of the coaxial window at a power level of 105 kW after about 1.5 hours. Recovery was relatively easy and after a total of 4 hours the rf power was at 150 kW when a large burst of gas was released on the cavity side of the coaxial window. Another 14 hours of conditioning were then required to reach 200 kW, with many of those hours spent at levels below 100 kW. After reaching 200 kW, only 3 more hours were required to achieve an rf power of 1.1 MW.

During the next phase of the conditioning the rf power was ramped up and down slowly between 20 and 1050 kW to investigate intermediate power levels. The pulse length was gradually increased to 200 µs while continuing to ramp the rf power. During previous tests of various couplers at 1.3 GHz it has been observed that if a pulse length of 100-200 µs is achieved, then a pulse length of 1.3 ms will also be achievable.

On resonance coupler processing was required after cooling the cavity to 1.8 K. Various pulse lengths and power ranges were explored, and vacuum, electron, and light signals were noted. These effects decreased over time, but were not completely extinguished at the conclusion of the test. It remains to be seen whether or not the vacuum, electron, and light signals will be completely eliminated through further conditioning. The cavity exhibited some field emission loading, and a few cavity processing events were observed as the rf power was increased. At the end of the test the cavity was warmed and recooled to test for coupler performance degradation due to migrating gases. No degradation was observed.

The analog and digital amplitude and phase regulation systems were tested and the cavity was operated pulsed at 10 Hz while maintaining 800 µs flat top gradients in excess of 15 MV/m.

A second test of a fully dressed cavity has been completed in August. The coupler behavior was very similar to that observed in the previous test. The cavity did not exhibit field emission loading and was operable at gradients up to ≈25 MV/m at the full pulse length and repetition rate.

**Future Experiments**

Calculations and experiments indicate that multipacting may occur in the coaxial line portion of the input coupler. A technique that has proven effective in suppressing multipacting in coaxial lines at CERN is to apply a DC bias between the inner and outer conductors. A special input coupler featuring a DC blocking capacitor in the waveguide-to-coaxial transition is under preparation and should be tested later this year. The capacitor is a Kapton disk metallized on each side. The disk will be sandwiched between the two halves of a split doorknob as shown in Figure 2.

![Figure 2. The design for the DC bias experiment.](image)

First tests will take place at Fermilab and will be conducted under standing wave conditions. If these tests are successful, a coupler modified for DC biasing will be delivered to the TTF for tests with a cavity in the horizontal test cryostat.

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**References**

MILLIMETER-WAVE RF STRUCTURES

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Abstract

Recently RF-structures have been proposed for frequencies between 30 and 140 GHz. These structures are planar and doublesided (open) and suited for fabrication by lithography. Two technologies are available: Deep X-rays with plastic resists (thickness < 0.8mm) or UV-light with doped glass resists (thickness up to several mm). The paper presents structure developments for different applications. The status of wafer manufacture, fabrication and alignment techniques will be discussed.

Introduction

High aspect ratio microstructure technology (HARMST) has developed to a degree that high precision submillimeter components can be built, such as actuators, gears, electrostatic motors, pumps etc. The idea of applying these techniques to develop high frequency accelerator components was proposed first in 1993 [1]. In the mean time structures for different applications have been reported, see e.g. [2] and [3]. The principle of all these structures consists of two metallic slabs supporting match-box like recesses which form cavities when the slabs are facing each other, Fig. 1. The typical lateral dimensions of the boxes are 0.5 to 2 mm and the depth is between 0.5 and 1 mm. Tolerances are in the order of half a percent.

Fig. 1. Basic arrangement of planar structures.

The most promising technique for fabricating such structures seems to be deep X-ray lithography (DXRL), etching and plating, known as the LIGA process [4]. The fabrication of two-dimensional structures with perpendicular walls, good surface quality and submicron precision has been demonstrated. Problem areas are the fоторесist, PMMA plastic, the high depth of the structures, the long exposure time and high costs. An alternative solution is UV-lithography (UVL) with fotosensitive glass [5]. This technology is better suited for deeper structures, avoids all the problems with organic materials and is appreciably cheaper. On the other hand it has a purer surface quality and it is more difficult to keep the required tolerances.

Both technologies are being pursued. The masks for the lithography have been fabricated and first show-pieces of one half of a structure are made. In parallel, efforts are directed towards the alignment of the two halves and the engineering of a stand-alone structure unit.

A Standing-Wave 94 GHz RF Structure

Once the basic geometry of planar structures was found, as shown in Fig. 1 and described in ref. [1], the believe was that standing-wave structures with constant RF gradients and well-separated modes may have certain advantages as compared to traveling-wave structures. Therefore, a side-coupled structure, similar to the ones mentioned in ref. [2], was designed. The operating frequency was chosen to be 94 GHz (a satellite band where RF equipment is available). Its geometry is shown in Fig. 2 and the RF parameters are given in Table 1. The period length corresponds to π-mode operation. The beam aperture, in principle a free parameter, is a trade-off between different requirements connected to bandwidth, shunt-impedance and beam-induced fields.

Fig. 2. Geometry of the standing-wave structure; \( g_1 = 2.40, \) \( w = 2.29, \) \( g = 1.34, \) \( t = 0.25, \) \( w_1 = 2.14, \) \( 2b = 2.29, \) \( 2a = 0.75 \) (in mm)

### Table 1: RF parameters of the structure in figure 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_0 )</td>
<td>94 GHz</td>
</tr>
<tr>
<td>( r/Q_s )</td>
<td>81.5 kΩ/m</td>
</tr>
<tr>
<td>( r )</td>
<td>295 MΩ/m</td>
</tr>
<tr>
<td>( v_e/c_0 )</td>
<td>0.0113</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>24 m⁻¹ attenuation length</td>
</tr>
<tr>
<td>( k_o )</td>
<td>12.10⁻³ V/pCm fundamental mode loss-factor</td>
</tr>
</tbody>
</table>

As can be seen, the group velocity is uncomfortably low. It could strongly be increased by cutting down the side-walls to the coupling-cells. But this would require a two-step LIGA process which we consider to be too expensive. Therefore, we
keep this geometry for the moment and try to remedy the
problem later. An estimate of the number of cells gives 31
which was lowered to 21 in order to get a reasonable mode
separation. Two structures are positioned on one wafer and
powered, via a power splitter, from a single feed line, Fig. 3.

**A 108 GHz RF Undulator**

The basic mechanism of an electromagnetic undulator is
similar to the conventional undulator with magnets. The
equivalent magnetic field is given by

$$B_{eq} = \left(1 + \frac{Z_0}{Z_w}\right) \frac{E_0}{c_0} = 2 \frac{E_0}{c_0},$$

where $Z_0$ is the free-space wave impedance, $Z_w$ is the
waveguide impedance and $E_0$ is the transverse electric field.
The undulator period is

$$\lambda_u = \frac{\lambda_0 \lambda_g}{\lambda_0 + \lambda_g},$$

with $\lambda_0$ and $\lambda_g$ being free-space and waveguide wavelength,
respectively.

A part of the undulator operating at 108 GHz is shown in
Fig. 4. It consists of the basic structure, as given in fig.1, with
30 cells, input and output coupler and matched cells at both
ends. The parameters, taken from ref. [3], are given in table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0$</td>
<td>108 GHz</td>
</tr>
<tr>
<td>$r/Q_0$</td>
<td>144 kΩ/m</td>
</tr>
<tr>
<td>$r$</td>
<td>312 MΩ/m</td>
</tr>
<tr>
<td>$\nu_0/c_0$</td>
<td>0.043</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>13.5 m⁻¹</td>
</tr>
<tr>
<td>$B_{eq}$</td>
<td>0.33 T</td>
</tr>
<tr>
<td>$E_0$</td>
<td>10 MV/m</td>
</tr>
<tr>
<td>$\lambda_u$</td>
<td>1 mm</td>
</tr>
<tr>
<td>$k_0$</td>
<td>0.047 deflection parameter</td>
</tr>
<tr>
<td>$2a$</td>
<td>6 mm gap height</td>
</tr>
<tr>
<td>$N$</td>
<td>80 periods of a length of 80 mm</td>
</tr>
</tbody>
</table>

After the upgrading the Advanced Photon Source (APS) will
provide an electron beam up to 750 MeV with 1mA average
current and a low enough emittance to drive the undulator.
The radiation has been calculated and the first harmonics are
expected at 4.0 and 5.2 keV with a brightness around 8×10¹¹
photons/sec/0.1% bandwidth/mrad².

**A 34 GHz Flat-Field Traveling-Wave Structure**

The accelerating field in planar structures is not indepen-
dent of the transverse position. It depends on $x$ and $y$ and the
transverse electromagnetic forces are of quadrupole character.
This particular property can be used for focusing the beam as
proposed in [2]. But in some applications it may be detrimen-
tal. In that case one can flatten the field in a certain central
area for instance by capacitive loading as shown in Fig. 5.

![Fig. 5. A planar traveling-wave structure with input and output couplers and capacitive cavity loading.](image)

The structure was designed for a 2π/3-mode at 34 GHz.
The depth of the structure is 1.6 mm which is probably too
deep for fabrication with DXRL. We have chosen it therefore
as an example to apply and study the UVL process.

**Structure Fabrication**

The simplified LIGA process consists of making an X-ray
mask, preparing a substrate and covering it with a fotosresist
(PMMA plastic), exposure, developing, etching away the
developed part and electroplating the structure. The require-
ments for high aspect ratio structures are thereby very de-
manding; good adhesion of the resist, no dissolution of unex-
posed resist, high mechanical stability, low internal stresses
during exposure and development and compatibility with
electroplating.
A DXRL mask for the undulator structure was constructed through an intermediate mask at the center for X-ray lithography in Stoughton. A plating base of Ti/Au with 75/300 A was written by an e-beam and 3 μm of Au was plated on the intermediate mask. For the final mask 25 μm Au was plated on a structured Si wafer. The substrate was of diamond finished copper with a Ti coating of less than one micron. On the coating a 1 mm thick PMMA film was cast and annealed at temperatures between 100 and 170 °C for one to three hours. The exposure was done at the ALS, Berkeley, and later on at the NSLS, Brookhaven. Different developers are being used. The electroplating process and the subsequent surface finishing is still not fully finished.

In parallel to the work on the undulator structure an intermediate X-ray mask for the standing-wave structure was built at the PMT, Karlsruhe, Germany. It is a 2.5 μm thick Au mask on a 2 μm thick Ti membrane. Next steps will be the fabrication of a 12 μm thick mask and the study of the developing process.

Besides the DXRL work, the fabrication of the 34 GHz traveling-wave structure was started at the Technische Universität Ilmenau, Institute for Glass and Ceramics, Germany. The purpose of this development is to prove that the lower frequency structures with a depth of more than 1 mm can be fabricated by UVL. The process is very similar to LIGA. As a photosist serves doped Li2O-Al2O3-SiO2 glass. The part of the glass which will be exposed forms a special crystal phase with a 30 times higher solubility than the unexposed part. Subsequent tempering (developing) and etching creates the microstructured glass plate. In the next step, the structured side of the plate has to be covered by evaporated copper as a starting layer for the electroplating process. Finally, the left-over glass will be etched away and the structure machined to its final state. Five microstructured glass matrices have been fabricated and a first copper structure was made. Problem areas are glass purity and homogeneity, copper evaporation into deep structures and tolerances.

**Engineering of the Structure**

A 10 MV/m accelerating gradient will typically cause some 340 kW dissipation per m structure corresponding roughly to an average power flux of 3.4 W/mm². A pulsed operation with a duty cycle D will lower the heat dissipation by the factor D. Nevertheless, in some applications the cooling will be problematic. Two different techniques are being pursued. A standard pipe cooling with a manifold as shown in Fig. 6a and an advanced microchannel cooling, Fig. 6b.

Standard cooling pipes have surface heat transfer coefficients in the order of α = 1 W/cm²·°C. Therefore, for the above given power flux and a tolerable temperature gradient of 10 °C, pulsed operation with a few percent duty cycle would be required. Micro-channels have heat transfer coefficients between 10 and 30 W/cm²·°C and the structures could either be operated with higher gradients or with duty cycles between 10 and nearly 100%.

Another major concern is the alignment of the two halves with respect to each other. Circular holes could be produced with the lithographic process and could be used to center the two halves by means of small steel balls, see Fig. 6a. The solid mechanical connection then follows from diffusion bonding the side-shoulders. An extensive program is also going on to make use of alignment and bonding techniques developed for micromachined electron microscopes [6]. V-grooves are machined into the wafer, see e.g. Fig. 1, and precision glass fibers are placed into the grooves and bonded and clamped in place. Vacuum pumping is provided through the gap between the two halves.

![Fig. 6. Cross-section of an RF-Structure with a) cooling pipes and b) microchannel cooling](image)

**References**

MEASUREMENT OF THE BEAM POSITION IN THE TESLA TEST FACILITY LINAC

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Abstract

The transverse beam position has to be measured at each superconducting quadrupole in the TESLA Test Facility Linac with a resolution of better than 10 μm. Therefore, a cylindrical cavity excited in the $TM_{110}$-mode by an off-center beam was chosen, also because of the limited longitudinal space and the cold environment. The amplitude of the $TM_{110}$ and its phase with respect to a 1.517 GHz reference signal are measured in a homodyne receiver. For the experimental area, stripline monitors having a resolution of better than 100 μm were developed. The averaged position of the whole bunch train of Injector I is measured using the amplitude-to-phase conversion. This paper summarizes the designs and some ‘beam position measurements’ in the laboratory.

Introduction

In order to establish a technical basis for a superconducting linear collider, the TESLA Test Facility is an essential part of the development of injectors, accelerating cavities, cryostat and new diagnostic techniques [1].

Because of special requirements three different types of beam position monitors will be used in the TTF: Buttons (Injector I), cylindrical cavities (inside the cryostats, attached to the quadrupoles) and striplines (experimental area). The purpose of this note is to discuss the cavities and the striplines, to describe the electronics, and to present measurement results on both types. Unfortunately, due to the delay in the installation of other components we still do not have any operating experience.

$TM_{110}$-Cavity

For the alignment of the quadrupoles a single circular cavity was designed because of the limited longitudinal space and the desired resolution of 10 μm in a cold environment. The amplitude of the $TM_{110}$-mode excited by the beam in the cavity yields a signal proportional to the beam displacement and the bunch charge. Its phase relative to an external reference gives the sign (up/down, left/right). Both $TM_{110}$-polarizations have to be measured to get the x- and y-offset. After cooling down, the seventh harmonic of 216.7 MHz has to be within the $TM_{110}$-bandwidth to avoid an active tuning system inside the cryostat. The antennae are replaceable to allow a pre-tuning by adjusting the coupling before cooling down.

In addition, two ('warm') cavities working at room temperature were built. Their temperature is stabilized in a thermostat and can be changed to tune the monitor slightly (about 20 kHz/K).

In both cases CrNi was chosen as the cavity material to measure individual bunches spaced at 1 μs (Injector II). Most of the parameters given in Table I were calculated with URMEL, whereas the resonant frequencies and the coupling factors were measured at room temperature.

<table>
<thead>
<tr>
<th>parameter</th>
<th>'cold' cavity</th>
<th>'warm' cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>cavity radius $R_0$</td>
<td>115.2 mm</td>
<td>117.0 mm</td>
</tr>
<tr>
<td>cavity length $l$</td>
<td>52.0 mm</td>
<td>52.5 mm</td>
</tr>
<tr>
<td>beam pipe radius $r_{10}$</td>
<td>39.0 mm</td>
<td>29.75 mm</td>
</tr>
<tr>
<td>loss factor $k_{110}$</td>
<td>0.24 V/pC</td>
<td>0.23 V/pC</td>
</tr>
<tr>
<td>unloaded $Q_{110}$</td>
<td>2965</td>
<td>3025</td>
</tr>
<tr>
<td>frequency $f_{110}$</td>
<td>1.513 GHz</td>
<td>1.517 GHz</td>
</tr>
<tr>
<td>coupling $\beta_{110}$</td>
<td>1.31</td>
<td>0.95</td>
</tr>
<tr>
<td>coupling $\beta_{10}$</td>
<td>0.1</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Figure 1: Cavity BPM with HOM absorber.

Since the field maximum of the common modes is on the cavity axis, they will be excited much stronger than the $TM_{110}$ by a beam near the axis. The estimated resolution near the electrical center is only 60 μm, due to residual signals even at $\omega_{110}$. This can be reduced by combining two opposite outputs in a field selective filter [2]. Because of the limited space inside the cryostat, a stripline hybrid was used outside. The rejection of common field components is limited by its finite isolation between the $\Sigma$- and the $\Delta$-port; an isolation of 20 dB brings the theoretical resolution down to less 6 μm. In addition, a frequency sensitive $TM_{10}$-rejection of about 69 dB is required to detect a beam displacement of 10 μm.
The resolution near the electrical center of the cavity is limited by the thermal noise of the electronics, too. Assuming a cavity without perturbations and a bunch charge of 32 pC, a S/N-ratio of 140 can be estimated for a beam offset of 1 μm from the cavity center [2].

Signal processing
The TM\textsubscript{110}-amplitude is detected in a homodyne receiver by mixing the cavity output and a reference signal down to DC (Fig. 3). When the beam is on the right, the system can be set up to give positive video polarity. The signal changes the phase by 180° when the beam moves to the left, and for a centered beam it becomes zero.

The stopband attenuation of the bandpass filter is more than 70 dB. Together with the hybrid and the coupling factors this gives a frequency sensitive common mode rejection of about 100 dB. Because of the isolation of the hybrid and between both TM\textsubscript{110}-polarizations, the full aperture was divided into two measurement ranges.

By using a Quadrature IF Mixer, no additional phase stabilization for the reference is needed. The mixer LO/RF-isolation determines the dynamic range of the electronics. After passing low-pass filters and bipolar video amplifiers, the signal may be either viewed directly on an oscilloscope for adjustment, or digitized by 12-bit ADCs for the quadrupole alignment.

Test results
Bench tests were carried out on a stainless steel prototype to determine the resolution near the center and to test the electronics. Therefore, the cavity was excited by an antenna, fed by a network analyzer. A resolution of about 5 μm was measured in the frequency domain [2].

In addition, a prototype was tested at the CLIC Test Facility (CERN) to demonstrate the principle single bunch response and to measure the TM\textsubscript{110}-amplitude as a function of the relative beam displacement. The BPM was installed in the spectrometer arm and the beam was moved vertically by changing the current of the steering coil.

A 250 MHz signal from the timing system was fed to a step recovery diode and the 6th harmonic was mixed with the Δ-signal. The output of the electronics vs. the relative beam position is shown in Fig. 5. Due to the measurement position, the mechanical setup and some machine parameters it was not possible to measure the minimum detectable signal near the center.
**Stripline Monitors**

Stripline monitors were selected for the experimental area and a temporary beamline because of the relaxed requirements - 100 \( \mu \)m resolution around the center - and the warm location. All monitors consist of four 50 \( \Omega \) coaxial striplines, positioned 90 degrees apart in azimuth (Fig. 6). The housing for the one in the dipole arm has a larger beam pipe diameter (100 mm instead of 60 mm).

![Figure 6: Design of the Stripline BPM.](image)

The BPM body is machined from a single block of stainless steel, four holes and the beam aperture are drilled. Each electrode is 175 mm long and shortened at the end; the geometrical coupling factor is approximately 3%. The main distortion in the transition from the electrode into the cable is caused by the feedthrough, selected for mechanical reasons. All 9 monitors were built and tested at DESY-IfH Zeuthen.

![Figure 7: Stripline monitor, vacuum cover removed.](image)

The electronics to detect the \( \Delta \)x signal of two opposite electrodes were built and tested (signals, linearity, drift) by INFN-LNF [3]. Since the signal has to be measured on a time scale of a few microseconds, the usage of a single channel for all electrodes and a multiplexing scheme was impossible. Hence, the signal processing is done in the frequency domain by using the amplitude-to-phase conversion scheme together with heterodyning (intermediate frequency of 50 MHz). The generation of a normalized output (position vs. current) over a wide dynamic range is the main advantage of this system. Furthermore, it is relatively insensitive to electromagnetic noise.

A peak-to-peak noise of less than 4 mV was measured, corresponding to a position resolution of about 40 \( \mu \)m. This agrees very well with bench test results, where the position of a thin wire was changed until the first 'significant' readout of the electronics was detected (see also Fig. 8, from [4]). The whole system (monitor and electronics) gives a linear response for off-center positions up to 5 mm.

All monitors and the first electronics module are now at DESY Hamburg, awaiting a real beam.

![Figure 8: BPM test-stand at DESY-IfH Zeuthen.](image)

**Acknowledgements**

It is a pleasure to thank our colleagues from INFN Frascati, especially P. Patteri, for developing, building and testing the stripline electronics. Finally, we acknowledge the technical support from DESY-IfH Zeuthen and from BESTEC Berlin-Adlershof.

**References**


PRESENT AND FUTURE PERFORMANCE OF THE DELTA INJECTOR LINAC

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Abstract

After a two years period of construction the routine operation of the 100 MeV electron linear injector started in summer 1995. The linac serves as injector for the 1.5 GeV DELTA- (Dortmund Electron Test Accelerator)- synchrotron radiation facility. In its major parts the linac has been constructed out of parts of the old Mainz 400 MeV linac (final shut down in 1989). The linac consists of a new developed 50 keV gun and a 4 MeV buncher for longitudinal pulse compression and two travelling wave structures. In the present state of operation the linac delivers a 70 MeV, 300 mA beam within 2-20 nsec at 10-100 Hz.

The paper covers design and performance of the linac and its components including monitoring, transverse and longitudinal optics together with experimental results and the expected performance of the linac after modifications concerning the rf-transmitters and part of the rf-network.

Introduction

The DELTA-facility at the university of Dortmund [1,2] is a 3rd generation 1.5 GeV synchrotron radiation light source. The storage ring Delta is fed by the full energy booster synchrotron Bodo (Booster Dortmund) operating as a ramped storage ring with a maximum repetition rate of 0.2 Hz. This rather low injection rate and the necessity to run the booster in single bunch operation in order to drive an FEL [3] in the Delta ring imply short beam pulses at high currents to be delivered from the injector.

In 1989 the 400 MeV electron linac at the university of Mainz was finally shut down and the decision has been made to use major parts of the old components (accelerators as well as the modulators and the rf-network and klystrons) offered by the Mainz authorities to reconstruct a 100 MeV linac fulfilling the above requirements.

Setup and Layout of the DELTA Linac

General Performance

Two of the old Mainz $\beta = 1$ S-band accelerator sections powered with 20 MW each produce a 100 MeV output beam. To ensure operation at high currents in the ampere range the front end had to be totally rebuilt. For longitudinal pulse compression a 3.8 MeV buncher section (LAL, Orsay, LIL-type [4]) is installed at the front end together with a 50 keV electron gun with incorporated prebuncher. The main design values are listed in Table 1. The schematic layout is shown in Figure 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>operating frequency</td>
<td>2998.55 MHz</td>
</tr>
<tr>
<td>electron gun</td>
<td>50 kV, 2 A, 2 ns, 1-100 Hz</td>
</tr>
<tr>
<td>longitudinal pulse compression</td>
<td>prebuncher and 3.8 MeV</td>
</tr>
<tr>
<td>output beam energy</td>
<td>100 MeV</td>
</tr>
<tr>
<td>output current</td>
<td>1 A, 2 ns, 1-100 Hz</td>
</tr>
<tr>
<td>$\Delta E/E$</td>
<td>+/- 2%</td>
</tr>
<tr>
<td>abs. output emittance</td>
<td>$\epsilon &lt; 1 \pi mm mmrad (100%)$</td>
</tr>
</tbody>
</table>

Table 1: General design performance of the linac

Low Energy Part of the Linac

Set up. A triode electron gun with 50 kV extraction voltage has been developed [5] based on the old Mainz gun-body. Based on the EIMAC Y796 cathode the extraction optics produces a beam waist directly in front of the prebuncher cavity (65 mm downstream the cathode). EGUN calculations result in an rms-emittance of $\epsilon = 16 \pi mm mmrad at 2.6 A$.

The single cell reentrant cavity incorporated in the gun-body is followed by a short buncher section manufactured by LAL, Orsay (see Table 2). It is equivalent to the buncher operating at the LIL-injector at CERN [6].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>0.45 m</td>
</tr>
<tr>
<td>resonator type</td>
<td>on-axis-coupled, 2\pi/3-mode standing wave</td>
</tr>
<tr>
<td>shunt impedance, Q</td>
<td>23 M\Omega/m, 13600</td>
</tr>
<tr>
<td>$\beta$-profile</td>
<td>$\beta = 0.92, 0.98, 1.00$</td>
</tr>
<tr>
<td>number of cells</td>
<td>6 plus 2 endcells</td>
</tr>
<tr>
<td>energy gain (ref. particle)</td>
<td>3.8 MeV (1.7 MW)</td>
</tr>
<tr>
<td>accelerating gradient</td>
<td>16 MV/m (1.7 MW)</td>
</tr>
</tbody>
</table>

Table 2: Performance of S-band buncher section.

Transverse Optics. The injection energy of 50 keV and a beam current of 2 A together with the high accelerating gradient (16 MV/m) of the buncher give rise to strong defocusing forces. Since the prebuncher is part of the gun-body and should be located close to the buncher no space was available to install a large-scale low energy solenoid transport line as it has been done at the LIL-Injector at CERN [4,6]. Due to the available space we installed two solenoids built in house (Leff= 5.5 cm, Bmax= 300 G and Leff= 40 cm, Bmax= 2200 G, see Figure 1 and 2). A small size quadrupole triplet is mounted in front of the first accelerator section to match the beam emittance to the acceptance of the downstream linac part. The transverse beam dimensions have been calculated with the program ENVEL [7], which solves...
the envelope equation taking into account emittance, space charge and focusing forces as well as the defocusing forces generated by the prebuncher and buncher rf. Figure 2 shows that the beam is well confined under nominal operating conditions.

**Longitudinal Pulse Compression.** An output energy spread of ΔE/E = +/- 2% for a substantial fraction of the beam can be obtained if the phase spread at the entrance of the main accelerator sections is limited to 23°. PARMELA-calculations showed quite similar results compared to the calculations at CERN [4]. Even for an input energy of 50 keV, the best bunching efficiency is obtained at 16 MV/m accelerating gradient of the buncher which corresponds to an energy increase of 3.8 MeV. Due to the quite large distance of 24 cm between prebuncher and buncher the theoretical value for the bunching efficiency was calculated to I_m(23°)/I_m(360°) = 40% at 2 A gun current. The bunching efficiency is strongly related to the accelerating gradient of the buncher and decreases drastically with reduced rf-power (see below).

**High Energy Part of the Linac**

**Accelerator Sections.** We installed two of the old Mainz accelerator sections (CGR-MeV) to increase the energy from 3.8 MeV to the nominal output energy of 100 MeV. These sections are of the 2n/3-mode travelling wave type and had been installed in Mainz for replacement of the older n/2-type structures and for upgrading the linac. Unfortunately no information was available about these structures. From theoretical considerations and from direct measurements we obtained the data given in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>length of section</td>
<td>4.2 m</td>
</tr>
<tr>
<td>field mode</td>
<td>2π/3, travelling wave</td>
</tr>
<tr>
<td>group velocity v/c</td>
<td>0.011 - 0.036</td>
</tr>
<tr>
<td>filling time</td>
<td>0.7 μsec</td>
</tr>
<tr>
<td>Q</td>
<td>10,000</td>
</tr>
<tr>
<td>shuntimpedance</td>
<td>42 MΩ/m</td>
</tr>
<tr>
<td>iris aperture diameter</td>
<td>30 - 20 mm</td>
</tr>
<tr>
<td>attenuation</td>
<td>0.62 Np</td>
</tr>
<tr>
<td>max. RF-power</td>
<td>20 MW at 4.5 μsec.</td>
</tr>
</tbody>
</table>

Table 3: Performance of the accelerator sections

**Transverse Optics.** We are not using the built-in solenoids above the accelerator sections but installed a tripllet between the sections and one more quadrupole at the end of the linac as first part of the transfer-line to the booster [2].

**RF-System and RF-Network**

The RF-system and the corresponding network is shown in Figure 1 (status end of this year). It consists mainly of two modulators and two klystrons with 20 MW output power. The modulators and the PFN-networks have been rebuilt out of the old parts from Mainz in a more compact way and produce a 270 kV, 240 A pulse with a pulse length of 4.5 μs with a maximum rep. rate of 100 Hz. To feed the high energy accelerator section the two rf output waveguides of the old F2042E klystron are combined under vacuum and need a
careful adjustment of the rf phase via waveguides with adjustable cross-section. Between the rf-windows we use 2 bar abs. SF6. For the low energy part of the accelerator we still have an old F2042E klystron operating [8], where we use only one output waveguide to ensure operation for the beam injection into the DELTA rings. This old klystron will be replaced during the autumn shut down by the new TH2100 type providing more than 20 MW with one rf-output flange.

**Beam Monitoring**

Three TM010-mode cavities with circular cross-section operating at the linac frequency are installed. High coupling of the output antennas and low Q-values give very sensitive and reliable information for 2 ns beam pulses and the achieved pulse compression. The beam position is obtained with three installed cavities with quadratic cross-section operating in a mixed TM210- and TM120-mode.

For transmission measurements we use two wall current monitors downstream the buncher and at the end of the linac, where also a fast Faraday-Cup is mounted.

**Present Status of the Linac**

The first beam was launched in October 1994 (60 MeV) and two weeks later accelerated to 75 MeV. From March until summer 1995 the linac was operating for the beam injection into the booster Bodo with an overall transmission of only a few percent.

After changes concerning the transverse focusing in the low energy part [8] and a careful cleaning of the buncher (electron multipactoring during operation in summer) the beam was accelerated to 78.1 MeV in October 1995 with an overall beam transmission of 20% with a still rather large energy spread of $\Delta E/E > +/-10\%$ caused by the low available rf-power of $< 1$ MW instead of 1.7 MW necessary for the design operation of the buncher (see above). Routine operation was achieved since end of 1995 for the commissioning of Bodo and Delta. Table 4 summarizes the actual beam data.

| extracted gun current | 1.5 A  |
| beam pulse structure  | 2 - 20 nsec |
| output beam energy   | 60 - 78 MeV |
| output energy for Bodo | 68 MeV |
| output beam current  | 300 mA, 20% transmission |
|                      | 90 mA, $\Delta E/E = +/- 2\%$ |
| abs. output emittance| $< 0.8 \pi \text{ mm mrad (100\%)}$ |

Table 4: Status of the present linac performance

At the present time the injector of the DELTA facility offers a 90 mA beam at 68 MeV within an energy spread of $+/ - 2\%$ at variable pulse lengths of 2 - 20 nsec. This results in a 300 $\mu$A - 3 mA average beam current accelerated in the booster and an increase of stored beam current in the storage ring of 100 $\mu$A - 1 mA every 5 - 6 sec.

**Future Upgrade**

To speed up the filling time for the storage ring, the first F2042E klystron will be replaced during the autumn shut down by the more or less compatible TH2100 klystron equipped with only one rf output waveguide. An rf power of more than 20 MW is then available for section 1 and the design buncher operation at 1.7 MW can be easily obtained resulting in a better transmission at a reduced energy spread and increased output energy according to the specification (Table 1). In a later stage (summer 1997) also the second klystron will be replaced by the new type. An available output energy of more than 100 MeV will naturally facilitate the injection into the booster since magnetic remanence effects are drastically reduced [1].

Due to the high current levels the distance between prebuncher and buncher has to be decreased. This will result in a better bunching efficiency but will require more effort concerning transverse focusing.

**Acknowledgments**

The authors would like to thank the Mainz university, the MAMI-staff and the staff of ELSA, Bonn.

**References**


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Status of the TESLA Test Facility Linac

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Abstract

The TTF linac, a major effort of the TESLA Test Facility, is now in the installation phase. The components have been built by an international collaboration and are presently set up at DESY/Hamburg. A first injector has been installed and tested since the beginning of the year and can provide 8 mA beam current within 800 μs long macro pulses at 216 MHz bunch repetition rate. The first cryomodule containing 8 superconducting cavities is expected for spring 97. The accelerated electron beam (140 MeV) can then be transported to the high energy experimental area which is presently being set up and contains all necessary beam diagnostic elements. The commissioning of all beam transport and diagnostic components at injector energy (10-15 MeV) will be done before the module installation. It will be followed by the commissioning of the RF control system needed to manage the individual phases and amplitudes of the superconducting cavities. An optimized operation can be expected before the installation of the remaining linac modules. Plans for the future use of the TTF Linac as a driver for a Self Amplified Spontaneous Emission Free-Electron Laser are mentioned.

Introduction

Within the high energy physics community there is a widespread consensus that an electron-positron linear collider with a center of mass energy of 500 to 1000 GeV and luminosity above \(10^{33}\) (cm\(^{-2}\)sec\(^{-1}\)) should be considered to provide for top analyses and for discovery reach up to a Higgs mass of more than 350 GeV. Therefore several test facilities are underway to develop key technologies. Small beam emittances, and especially beam sizes at the interaction point of such a linear collider have to be achieved with very large average power beams. Thus a collider linac becomes also most attractive for next generation synchrotron radiation sources.

One of the approaches to a 500 GeV collider is the usage of superconducting (s.c.) accelerating structures. The international TESLA [1] collaboration is following this approach. A test facility, located at DESY with major components flowing in from the members of the collaboration, is trying to establish a well-developed collider design.

The facility includes infrastructure to prove the feasibility of reliably achieving accelerating gradients above 15 MV/m in series production. The TESLA linear collider would rely on superconducting structures operating at 1.3 GHz with a gradient of 25 MV/m and an unloaded quality factor of \(5 \times 10^9\) at \(T=2K\). Besides cavity preparation and testing, the TESLA Test Facility (TTF) is also going to show the successful operation of these accelerating structures assembled in a test string. An electron beam will be accelerated in modules of 8 s.c. cavities each.

The TTF Linac

The experience gained on the TTF linac will feed directly into the TESLA linear collider design. Therefore both designs are similar with respect to a number of aspects, e.g. cavity and cryostat design, but also as many beam parameters as possible. A very complete description of the TTF Linac can be found in [2].

The main components of the linac are the injector, a first cryomodule housing 8 s.c. cavities, a 12 m long warm section including beam diagnostics, and further cryomodules followed by a beam analysis area. The main parameters of the linac are listed in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>TTF Linac Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>390 MeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>8 mA</td>
</tr>
<tr>
<td>Pulse length / rep. frequency</td>
<td>0.8 ms / 10 Hz</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>15 MV/m</td>
</tr>
<tr>
<td>Quality factor (Q_0)</td>
<td>3 (\times 10^6)</td>
</tr>
<tr>
<td>Heat load at 2K</td>
<td>86 W</td>
</tr>
<tr>
<td>Number of cavities/modules</td>
<td>24 / 3</td>
</tr>
</tbody>
</table>

The installation of the linac is being carried out in different stages which each allow the acceleration of the beam followed by the delivery to the diagnostic area with its high energy beam dumps. Since the TESLA design values for the bunch charge and beam current rely on an RF gun which is still in the development and test phase, the first stage of installation starts with an injector consisting of a thermionic 250 kV source (40 kV gun, grid controlled, followed by an electrostatic column), a 216 MHz subharmonic prebuncher, a standard nine-cell s.c. cavity, and a 15 MeV beam analysis station. The s.c. cavity is installed in its own cryostat and powered by a 200 kW klystron.

The 10-15 MeV injector beam is injected into the first cryomodule in which acceleration up to about 140 MeV will be possible. Two quadrupole triplets are used for matching the transverse phase space.

Cryomodule and Cavities

The first cryomodule is a standard unit and also a prototype for the large collider. Similar modules would constitute the main body of the TESLA linac. Each one
contains eight nine-cell π-mode cavities, and in the case of TTF a s.c. quadrupole doublet combined with a cold resonant cavity beam position monitor. The liquid helium distribution and cold gas recovery system are incorporated into the cryostat. The cryostat design principle is to make the individual accelerating modules as long as possible and combine them to strings fed by a single cold box. This should result in low static losses (typically 0.2 W/m at 2K) and important cost reduction [3]. The cavities are suspended from the helium gas return pipe which serves as a reference girder. Each cavity is equipped with its RF power input coupler, two higher-order-mode (HOM) output couplers, an RF fundamental pick up, and a frequency tuning mechanism.

The individual cavities have their own Ti helium vessel welded around it, the beam tubes and the connections for the RF couplers being inside the insulating vacuum. Shielding of the cavity against the earth magnetic field will be provided to allow for high unloaded quality factors, i.e. low static heat losses.

The quadrupole package includes a superferric quadrupole doublet, transverse steering coils (two pairs, one each for permanent corrections and for vibration studies/control), the transverse beam position monitor (cylindrical RF cavity, TM110 mode) mentioned above, and a higher order mode absorber. Operation temperature of the quadrupole package is 4 K.

The first module will be equipped with a large number of temperature sensors as well as vibration sensors. Alignment during cooldown will be monitored using optical methods and in addition to this using a stretched wire system [4]. The latter can be used also during linac operation.

The beam transport system between the end of the first module and the diagnostic area consists of four almost equal sections, each of them 12 m in length, and including a view screen, a beam position monitor (stripline or resonant cavity), a quadrupole doublet, and a pair of steerers. For pumping, three titanium sublimation pumps (1000 l/s) and three smaller ion pumps (80 l/s) per section are used.

**Beam Analysis Area**

The beam analysis area behind the end of the last cryomodule serves as a room to measure relevant beam parameters, i.e. beam position, beam size and emittance, beam energy and energy spread, beam current and transmission through the linac, bunch length and shape. Some parameters will be measured as a function of the bunch number in the 800 μs long bunch train, others as an average over some part of the train, or for a series of it. The extensive use of optical transition radiation (OTR) is planned.

The beam analysis area has a length of about 15 m. It consists of two straight sections. One is in line with the linac axis, the other one is a dispersive section behind a high energy spectrometer dipole magnet. Both sections contain quadrupole doublets and wire scanners, view screens (OTR), and stripline beam position monitors. Toroids are used along the linac to measure the charge transmission up to one of the two beam dumps which complete the whole TTF Linac set up.

**Second Stage of Installation**

In a second stage of the set up an RF gun will replace the above mentioned thermionic source. Two of the laser driven guns are in the test (TESLA gun, high 8 nC bunch charge) and construction phase (FEL gun, reduced 1 nC bunch charge, very low 1mm mrad emittance) respectively. Both guns use a 1.5 cell 1.3 GHz cavity fed by a 5 MW klystron. The photocathode will be made from Cs₂Te. The installation will permit the use of the presently installed injector or one of the two RF guns alternatively.

The second stage also includes the replacement of the first 12 m long beam transport section by a magnetic bunch compressor and its diagnostics. The next two sections of the beam line will be exchanged by cryomodules connected in series. The fourth section will take up three undulator modules [5]. The experimental area stays almost unchanged. At the above mentioned gradient of 15 MV/m the achievable energy is then 390 MeV.

**Present Status**

**Injector**

The complete 250 keV beam line has been installed at DESY. The design beam characteristics have been obtained and tests on different components and monitors have been performed [6]. Table 2 gives the results of some measurements.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Injector Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current</td>
<td>Design: 8 mA</td>
</tr>
<tr>
<td>Energy</td>
<td>250 keV</td>
</tr>
<tr>
<td>Pulse length</td>
<td>0.8 ms</td>
</tr>
<tr>
<td>Micro pulse width</td>
<td>&lt;640 ps</td>
</tr>
<tr>
<td>Micro pulse rep. rate</td>
<td>216 MHz</td>
</tr>
<tr>
<td>rms emittance</td>
<td>&lt;5 mm mrad</td>
</tr>
</tbody>
</table>

After the successful test of the horizontal cryostat, the s.c. capture cavity has been installed inside. At present, first RF tests of the cavity are carried out. The first cold test is scheduled for 9/96 and should reproduce the previously reached gradient of 17 MV/m. The installation of the capture cavity and the following matching section is planned for 10/96.

**Cavity and Coupler Performance**

To date, 15 cavities from different manufacturers have been delivered. Tests have been performed on 13 of them [7]. Very encouraging results have been obtained. In cw mode,
heat treated cavities reached fields in excess of 20 MV/m with $Q_0$ higher than $5 \times 10^9$. The best result is a field of 26 MV/m with a $Q_0$ of $3 \times 10^{10}$. The same cavity was just measured in the horizontal test cryostat in pulsed mode (200 kW input power) with its final RF couplers mounted: a degradation of the gradient was not observed. For some cavities, however, the quench field is around 12 MV/m (cw); an increase of the surface resistance with field appears, but no field emission has been observed. Investigations are underway to understand if this is caused by material problems or by the production technique.

**Future plans**

The plans for the use of the TTF Linac to operate a VUV light source yielding a coherent, very bright beam of photons with wavelength tunable between 20 and 6 nm are well developed. The modification of the TTF Linac set up is under preparation; together with the installation of modules #2 and #3 the set up will be completed by all components needed for a proof of principle experiment. The FEL gun as well as the undulator - the most complicated parts of the experiment - are under construction. Further information can be found in [9].

**Conclusion**

The first stage of the TTF Linac will be finished at the beginning of next year. A first beam is expected for spring. Then the rest of the year 97 will be devoted to experiments with this beam, and to the preparation of the remaining modules and the high charge injector. A test set up for the FEL gun will be operated at DESY; the final tests for the TESLA gun will be accomplished at FERMI LAB. Experiments on the free electron laser are scheduled for 1998.

For the longer term future, it is planned to increase the linac energy to 1 GeV, thus extending the linac length by optimized versions of TESLA components.

**References**

[1] The TESLA (TeV Energy Superconducting Linear Accelerator) R&D effort is carried out by a number of institutions which includes IHEP, TU Berlin, Max Born Institute Berlin, Cornell Univ., Cernnow Univ., TH Darmstadt, DESY, TU Dresden, DSM/DAPNIA Saclay, JINR Dubna, Fermilab, Frankfurt Univ., IN2P3/LAL Orsay, IN2P3/JINP Orsay, INFN Frascati, INFN Roma II, INFN Milano, FZ Karlsruhe, INP Novosibirsk, Polish Acad. of Science, IHEP Protvino, SEFT Finland, UCLA Dep. of Physics, Warsaw Univ., Wupperal Univ.


FIELD ENHANCEMENT OF A SUPERCONDUCTING HELICAL UNDULATOR WITH IRON

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Abstract
The productions of positrons in sufficient quantities is one of the necessities for either the TESLA or the S-Band Linear Collider project. One of the promising possibilities is to guide the high energy electron beam through a superconducting helical undulator producing synchrotron radiation which would in turn be directed onto a target for positron production [1,2]. To generate sufficient radiation for this purpose from an undulator with inner radius of 2mm and a 14mm period, an on-axis radial field of at least 0.8 T would be required. Calculations were carried out to ascertain whether this field was attainable and what effect the addition of iron in between the superconducting coils would have. An arrangement with iron helices interleaved with helical current coils and a cylindrical yoke for the return flux was optimised. With a current density of $900 A/mm^2$ and a period length of 10mm, fields of up to 1.3 Tesla were calculated. The increased fields obtained lead to a possible reduction in the overall length of the structure and more flexibility in the choice of electron beam and undulator parameters.

Introduction
A helical undulator has two advantages compared to a planar wiggler: The energy of the primary electron beam can be lower, since high photon energies can be reached with a short period, high field device. Whereas a source with a planar wiggler can only operate with a minimum beam energy of at least 150GeV, a source with a helical undulator may be operated down to an energy of $\sim 100-120$GeV. In addition the photons of a helical undulator close to the radiation axis are circularly polarized. Highly polarized positrons can be generated if the outer part of the photon beam is scraped off. Thus the same helical undulator could be used for the production of positrons [2] with a low polarization (~30%) at lower beam energy (~120GeV) and for highly polarized positrons (~60%) at high beam energies ($\geq 250$GeV).

Geometry of a helical undulator with iron
A helical field can be produced by a pair of conductors wound to form a double helix as sketched in Figure 1. The current in the two conductors is equal and flows in the opposite direction. Thus the central axial magnetic field is canceled and a transverse field pattern appears. The field on the z-axis is approximated by:

$$B_x = B \cdot \sin \left(2\pi \frac{z}{\lambda} \right), \quad B_y = B \cdot \cos \left(2\pi \frac{z}{\lambda} \right)$$

An analytical formula for an iron free undulator was derived by Blewett and Chasman [3] as:

$$B = 2.385 \cdot 10^{-4} \left[ T \cdot \text{mm} / A \right] \cdot I \cdot \lambda \left[ e^{-5.68\lambda/\lambda} - e^{-5.68\lambda/1} \right]$$

An on-axis field amplitude, $B$, of 0.9T is reached when the current density, $I = 900 A/mm^2$, the undulator period $\lambda = 12$mm, the coil inner radius, $r_1 = 2$mm, the outer radius, $r_2 = 6.8$mm. A width of 1/3 $\lambda$ is assumed for the conductor of the coil.

In order to include the effects of iron magnetostatic calculations were carried out using the numerical code MAFIA [4]. The problem was discretised in a cylindrical coordinate system with 230 000 mesh points. As a first step the analytical result was checked without the addition of iron. The agreement was better than 98%.

First a double helix of iron was included between the conductors. Figure 2 shows the undulator with the filaments simulating the conductors and the double helix of iron. The on-axis field was increased by about 50%. Next the undulator was enclosed in a return yoke, which gave another 50% in field amplitude. A variation of the current density between 600 and 900 A/mm² revealed no significant limitation due to saturation of the iron. Since the yield of the positron source depends on both the period and field of the undulator, the period length was reduced to 10mm before the optimization of the geometry. A bore radius of 2mm was chosen, the current density was fixed at 900A/mm².

A cross-section of the upper half of a helical undulator with the double helix of iron between the coils and a return yoke is shown in Figure 3.
A two dimensional model in x-y coordinates of an equivalent planar wiggler was used for the preliminary optimization of the coil height, coil width and yoke height. Although this is rather far from the actual helical geometry, the results were reasonable enough to provide the starting parameters for the 3D optimization. A model was then chosen, using the most promising 2D configuration as a starting point.
Figure 2 Solid model of the undulator as it is used in the numerical calculations with current filaments and iron between the conductors.

Figure 3 Cross-section of an undulator with iron between the conductors and return yoke (shaded area).

For the three dimensional calculations the current in the superconducting coils has to be distributed among a number of filaments. Very careful discretisation and placing of these filaments was necessary to ascertain the effect of varying the coil height and width. The mesh had to be exactly adjusted so that no variation of current occurred close to the axis as this would have an additional effect on the on-axis field, even though the integrated current density was the same.

Optimization of the geometrical dimensions

The radial on-axis field $B_r$ as a function of the coil height $h$ is shown in Figure 4. The field depends strongly on $h$ up to about 4mm after which the curve begins to level off.

A coil height of 5.5mm was chosen with a yoke height of 5mm, then a coil width of 2.8mm produced a definite optimum. Varying the yoke height, $y$, from 3-7mm had very little effect on the on-axis $B_r$ field, even though there was considerable saturation. The maximum permeability in the yoke, varied between 30 and 50.

![Graph](image)

Figure 4. Radial magnetic field amplitude $B_r$ as function of the coil height $h$ with constant inner radius $r_i$ of 2mm.

Table 1 summarizes the optimized undulator parameters. For comparison the parameters of an undulator with equal period but without iron are given.

<table>
<thead>
<tr>
<th></th>
<th>undulator with iron</th>
<th>undulator without iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>undulator period $\lambda$</td>
<td>10.0 mm</td>
<td>10.0 mm</td>
</tr>
<tr>
<td>inner radius $r_i$</td>
<td>2.0 mm</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>coil width $w$</td>
<td>2.8 mm</td>
<td>3.3 mm</td>
</tr>
<tr>
<td>coil height $h$</td>
<td>5.5 mm</td>
<td>4.0 mm</td>
</tr>
<tr>
<td>yoke height $y$</td>
<td>5.0 mm</td>
<td>—</td>
</tr>
<tr>
<td>on-axis field $B_r$</td>
<td>1.3 T</td>
<td>0.62 T</td>
</tr>
</tbody>
</table>

Table 1 Optimized parameters for an undulator with iron in comparison with an iron free undulator. The current density is 900 A/mm².

* At this coil height the on axis magnetic field reaches 90% of the field of a coil of infinite height.

The magnetic field is increased by more than a factor of 2 due to the iron and the optimized geometry. These parameters enable the length of the undulator to be reduced from 150 m for the iron-free undulator to ¬100 m.

Discussion of possible improvements

The maximum current density that can be reached in a superconducting cable depends on numerous parameters, such as the copper to superconductor ratio, the number of strands and the winding density, the insulating material, the manufacturing process, the magnetic field at the cable and the temperature. Therefore the maximum current density cannot be determined without a detailed technical design of the magnet. The small bending radius favours the use of thin bands as cable. Due to the strong dependence of the field on the radius one might try to obtain the highest current density close to the undulator axis. We have restricted our calculations to a current density of 900A/mm², based on the experience with the HERA magnets. The maximum field at the conductor, that limits the allowable current density, is found to be only 2.9T. Recent developments in the field of fabrication techniques [5] indicate considerable
improvements in the tolerable current density especially at low fields. With a higher current density both the undulator period and the overall length could be further reduced. For a period of 8mm, a current density of 1700A/mm² is necessary to reach the desired field of 1.5T. This undulator would allow the operation of the positron source to start with an electron energy of 100GeV. A different approach would be to increase the bore radius of the undulator in order to facilitate the construction and the operation of the device. Increasing the bore radius from 2mm to 2.5mm, while leaving all other parameters as presented in Table 1, would require a current density of 1500A/mm² for a field of 1.3T. In this case the field at the conductor is 3.2T. These current densities are attainable with modern NbSn conductors.

Field profile and tracking results

The radial on-axis magnetic field of an undulator with the specified dimensions is a purely harmonic function of the longitudinal coordinate. No contributions of higher harmonics could be resolved within the resolution of the simulations. Figure 5 shows the radial field amplitude as function of the radial position in comparison with an analytic result for an iron free undulator [3] and a simplified analytical formula which approximates the field of the iron loaded structure given by [3]:

\[
B_r = -B_0 \left[ (1 + \frac{k^2}{2} (3x^2 + y^2))\sin(kz) - \frac{1}{2} k^2 xy \cos(kz) \right]
\]

\[
B_z = B_0 \left[ (1 + \frac{k^2}{2} (x^2 + 3y^2)) \cos(kz) - \frac{1}{2} k^2 xy \sin(kz) \right]
\]

\[
B_\theta = -B_0 (1 + \frac{k^2}{2} (x^2 + y^2)) \left( x \cos(kz) + y \sin(kz) \right)
\]

\[
k = \frac{2\pi}{\lambda}, \quad B_0 = \text{on-axis field amplitude}
\]

where \(\rho\) is the cyclotron radius of the particle in the field \(B_\theta\).

For a 250GeV electron the radius \(r\) is 4nm at a field of 1.3T. Off-axis particles move through a somewhat higher field with an additional field gradient. The trajectory becomes an elliptical helix with eccentricity ∼12% for an offset of 1mm.

The radiation of an helical undulator is circularly polarized only near the radiation axis, while radiation emitted at angles larger than ∼1/γ is transversely polarized. In order to be able to scrape off the transversely polarized radiation it is necessary that the electron beam is focused through the undulator onto the conversion target, so that the spot size of the radiation on the target is dominated by the opening angle of the radiation. This requires, besides an excellent beam emittance of the order ∼10^-10 mrad, that no focusing occurs within the undulator. The tracking calculations show that the natural focusing of the undulator is so weak that it can be completely neglected for the positron source. The trajectories in the helical undulator are, however, strongly influenced by the edge field at the entrance of the undulator. Nonlinear kicks can occur if the field is not properly designed.

In the tracking simulations the end field was modeled by a tapered onset of the field given by:

\[
B_0 = 1.35T / \left( 1 + \exp(-z/0.002m) \right)
\]

With this end field only a dipole kick of ∼0.4μrad occurs at the entrance of the undulator which can easily be compensated. No detailed calculations of the real end field of the undulator have been performed since the end field is closely connected to the technical design of the undulator. The calculations show, however, that the nonlinearity of the kick at the entrance of the undulator can be sufficiently reduced, if the end field is appropriately tapered.

Acknowledgment

We would like to thank W. Decking who provided the code for the tracking calculations.

References

IMPROVED ELECTRON BEAM SOURCES FOR COMPACT LINEAR ACCELERATORS

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Abstract

The design and main parameters of electron beam sources for accelerators are described. Two designs of cathode assemblies for RF electron injectors were developed. For increasing lifetime of the sources lanthanum hexaboride single crystal emitters are used. Indirect heated disc cathodes with diameter 4-6 mm and thickness 1.5 mm ensure beam current up to 10 A and small surface erosion rate under ion bombardment. The latter parameter is 3-4 times smaller than for lanthanum hexaboride polycrystal emitters. The described electron sources will be used for compact linear accelerators.

Introduction

For linear accelerators which are used in applied fields it is especially important reliability and stability performance of all systems incorporated, including injector. A number of electron sources designs are used in compact electron linacs. The most critical element of the injector is the emitter, which in considerable degree defines the performance characteristics of the whole beam generating system. As a rule, thermionic cathodes emitters are used in applied electron linacs. Wire emitters are simple, but they have low operation time and stability, considerable beam emittance. Disc and bar cathodes require more complicated assembly design, but ensure high stability and electron brightness, large operation period without taking apart. Good beam formation is also very important in many fields. The most exact beam parameter describing transverse beam dynamics is beam brightness at gun output. It was shown in [1, 2] using analysis of beams parameters at the output of many linacs, that one of the most important factors defining the transverse formation quality is a beam brightness at the injector output, which normalized value is maximum in the injector and decreases during the beam acceleration. Taking into consideration these conclusions it is very important for high output linac beam brightness to obtain minimal value of transverse emittance in the electron source, which is defined by many factors including stability of emission characteristics, cathode position, etc. The purpose of this work was to develop the designs of electron sources for compact electron linacs of 3 and 10 GHz range with improved performance characteristics of the output beam. As they will be used in industry, special attention was paid to the reliability of the design, reproducibility of the emitter position after emitter changing, convenience in handle.

Description of the design

As it was shown earlier, the solid emitters are preferable for obtaining high quality electron beam and this type was chosen for the electron sources developed. The cathode material is lanthanum hexaboride, which combines high emission current density, considerable resistance to active gases poisoning and ion bombardment, low evaporation rate. This material is also very advantageous in case of linac injector because of periodic air exposures during taking apart. The cathode diameters were chosen in the range of 4-8 mm and the indirect heating method with electron bombardment from auxiliary cathode was used. As a result of a number of both theoretical and experimental investigations the cathode assembly design was developed (see fig. 1).

Fig. 1. Scheme of the cathode assembly.

It consist of a hollow cone-shaped cathode holder 1, a lanthanum hexaboride cathode pill 2, a hollow cone-shaped component 3 for pressing the pill 2 to the holder 1 and a ribbon heater 4, which produces an electron flow to bombard the cathode 2. Because of the cathode material is sufficiently fragile, it is necessary to ensure elastic pressing of cathode pill to the holder during the whole working period. During the heating and cooling of cathode and other components termodeformations in component 3 lead to gradual deformation of its elastic elements. Original feature of proposed cathode assembly is execution of this component 3 with the projections 5 at the larger side of the cone. These elements are placed in the region of low temperature and thus the influence of nonelastic deformations in these projections can be considerably decreased. Another important difference of this cathode assembly is an auxiliary cathode - heater 4. It made of a refractory metal strip, which is supplied by cuts in emitter part alternately spaced from both sides. In this case the cathode heating is more uniform.
and the undesirable influence of magnetic field connected with heating current can be minimized. These improvements developed lead to increase of cathode working life and improvement of beam formation quality. Both in technological electron beam guns and electron injectors the most frequent reason for gun to be out of work is a damage of strip or wire heater. To eliminate this deficiency we suggested the following manner and arrangement for above cathode assembly. A screen made of refractory metal is situated between the heater 4 and the cathode 2. Power supplies produce electric fields in the spaces heater-screen and screen-cathode, which accelerate electrons towards the screen. The heating of this screen to high temperature is provided by electron bombardment from the heater 4. Screen heated to high temperature radiates the heat flow towards the cathode 2 and heats it. After the cathode reaches his working temperature it begins to emit electrons from both sides. One electron flow ensures main beam and the electrons from opposite side are accelerated towards the screen and bombard it. From this moment the heater 4 can be switched off because the heating of the screen is provided by electron bombardment from cathode 2, which in turn is heated by the radiance from the screen. In this device the heater 4 is used in short periods of turning on only and the working period of the whole cathode assembly increases many times.

![Fig. 2. Overall view of the cathode assembly (in the right bottom corner).](image)

This manner ensures more uniform heating of the cathode and avoids erosion of the cathode surface by electron bombardment in usual methods. The cathode assembly, designed with using these solutions, is shown in fig. 2.

Another important problem of electron beam guns design is stable and reliable operation of high-voltage electric isolator assembly. We developed several reliable high-voltage assemblies with alumina ceramics isolators. They ensure stable work with voltages up to the 100-120 kV and lead-in four different voltages in vacuum part of a gun. All of above designs were tested, applied in industry and showed good results.

**Performance characteristics**

A number of electron guns for technology and linacs were developed on the basis of above design solutions. The main parts of the electron gun is shown in fig. 3.

![Fig. 3. The main parts of electron gun high voltage assembly.](image)

Accelerating voltage can vary from 20-30 kV up to 100 kV. Continuous beam current is controlled from several mA up to 1 A by variation of grid voltage within 0-5 kV. Power consumption of cathode assembly is equal 50-60 W. It allows gun to operate without compulsory water cooling for four and more hours. The heat released by cathode assembly is transferred to the gun components via liquid dielectric-castor oil or special silicon oil. In the latter case it is possible for gun to operate for about ten hours without turning off. This design is very advantageous in case of portable linac or if electron gun is to move inside technological vacuum chamber. Vacuum conditions under which the electron gun has capacity for work are extended to 0.1 Pa, however the working period of cathode assembly sharply decreases. It equals tens hours under such high pressure. In high vacuum (less 0.001 Pa) the working period is equal hundreds hours. Comparison of operation period of lanthanum hexaboride emitters of various technological production was carried out. The above value for single crystal cathodes is considerably higher than for polycrystal ones (in 3-4 times).

Electron beam formation is carried out by both electrostatic optical system and electromagnetic focusing lens. They provide convergent beam at the gun output with crossover diameter less 1 mm and beam currents up to 1 A. High power density permits to carry out such technological processes as electron beam welding of thick metal components. These guns were used in aviation industry for welding and thermoprocessing of various components. The gun with 60 kV and 1 A beam ensures joining of steel details with thickness up to 100 mm and aluminium alloy components with thickness up to 300 mm.

Electron technological guns are supplied with fast electromagnetic deflecting systems of ring-shaped type,
which provides scanning of electron beam over large area. Such devices were used for surface hardening of various important components, for example working surface of ball-bearings for oil industry. Electron beam processing forms surface layer of 1-2 mm thickness with high hardness up to 62 HRC which increases working period of ball-bearings to 50% and more. Electron injector for 10 MeV travelling wave linac was developed. Energy of electrons at the gun output 40 kV, beam current 2 A, pulse length duration 4 mc. The assembly drawing of this injector is shown in fig. 4.

![Assembly drawing of electron source for linac.](image)

The gun design includes the same cathode assembly and high-voltage isolator. This injector is now assembling and will be tested. The guns described can be used in various fields of physics and industry. The authors are ready to fruitful cooperation with organizations interested.

**References**


30 YEARS OPERATION OF 25 MeV PROTON LINAC I-2 IN ITEP
AT BEAM CURRENT OF 200-230 mA

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Abstract

The first in Russia strong-focusing 25 MeV proton linac-injector I-2, computations, design and construction of which
have been carried out under the guidance of Prof. I.M.Kapchinsky, will celebrate this autumn its 30-th anniver-
sary. Output current of the beam at energy of 25 MeV is 200-230 mA, down time is less than 0.5% of schedule time of about 5000 hour/year. Launched a decade before RFQ epoch coming the linac I-2 is the “living witness”
of its physical project adequation to requirements of beam dynamics and adhere to assigned stringent tolerances that
determines so long machine life.

Introduction

The first in Russia strong-focusing 25 MeV proton linac I-2 was launched on November 1966. Its physical ground,
design and construction were implemented by ITEP Linac Division under the direct leadership of Prof. I.M.Kapchinsky
[1-4].

The purpose of the 25 MeV machine construction was to serve as a prototype of the ITEP proton synchrotron (PS) and to be as a prototype of an 100 MeV injector for 70 GeV IHEP PS developed only 1 year later. The main contribution in the linac I-2 project and its implementation besides ITEP was done MRTI being the principal technology designer of RF

cavities, RF supply system, RF tuning procedures, mechanics, cooling etc. and Efremov Institute (NIIEPA) which was responsible for preinjector, design of drift tubes and their dc supply. The project was performed under the general supervi-
sion of academician A.L.Mintz (MRTI) and vice-academician V.V.Vladimirsky (ITEP).

All principle decisions were carefully tested on the models and prototypes. The choice of optimum poles contour of drift
tube quadrupole lenses ensures absence the sixth harmonic of the field and comparative simplicity of their manufacturing [5,6].

Very soon after the start-up the project beam current of 130 mA was achieved [7]. Beginning from 1967 till today
linac I-2, being Injector the 2nd after the first 4 MV Van-de-Graaf, have continuously operated day by day delivering to
PS through HEBT accelerated beam current of about 200 mA during 4500-5500 hours per each year in average [8,9].

Accurate accordance of physical I-2 project to beam dynamics requirements and its strong adhere to assigned toler-
ances defined the long life of the machine developed before RFQ epoch coming.

The main features of the linac design and some unusual technical decisions of its technology systems are presented.

Characteristic Features

The linac I-2 has two 148.5 MHz resonators (on 0.7-6 and 6-24.6 MeV) with 20 and 35 drift tubes containing in pairs
high-current quadrupoles of opposite signs forming FOD and FOPDOD types of focusing periods. The acceleration period
in the first cavity is 2βλ; it simplified the quadrupole arrangement in tight volume of drift tubes. Note, that different
acceleration periods in cavities strongly impeded later an acceleration of other ion types.

The r.m.s. error of drift tubes initial alignment is about 35 µm in transversal plane and <0.02% of the accelerating
period length in the axial direction.

Drift tubes were adjusted by special alignment units on hard girders which are supported on a special long foundation
that had ensured the stable conditions in spite of happened dismantle (by explosion) of one of neighbouring building
and erection of the other one. The use of the developed drift tube alignment method [10] which ensure to check its positions
without opening of resonators approved a good many years stability of the accelerating-focusing channel.

Both cavities of Ø1.37 m are housed in stainless steel tanks of Ø1.8 m and length of 18.4 m. At first we used 7 high
throughput (8000 l/s each) oil pumps with liquid nitrogen traps and in spite of good vacuum of 3–5·10⁻⁷ mm Hg rather
often we suffered difficulties at RF power feeding after schedule shut-downs. The transition to 40 titanium discharge
250 l/s pumps (without of traps) ensured the working vacuum on the level of about 2·5–10⁻³ mm Hg, but excluded almost
completely multipactoring or breakdown in cavities. At this transition we replaced the ordinary gas supply system of
duplamateron ion source by original one with exhaust valve decreasing the gas flow from 600-800 to 10 cm³/h [11].

Note, that our cavities and vacuum tank after their closing in 1966 were never opened any more. After beginning opera-
tion with filament cathode we are using the cold cathode in duplamateron type ion source. Mo and Cu cold cathodes
ensure their unusual long service from several weeks to more than one year [12]. The full output current is 1200-1500 mA
at pulse duration up to 30 µs and average repetition rate to 1 pps. The proton component constitutes as much as 80-85%.
Technological systems upgrade and matching channel redesign resulted the extreme high pulse proton current of 230 mA
In 1984 helium ion beam current up to 300 mA has been obtained from duoplasmatron with cold cathode [13]. In checking runs He\textsuperscript{2+} ions have been accelerated to full energy at beam current about 2 mA [14,15]. Today the cold cathode duoplasmatron ion source with cooling upgrade is tested in CW mode at proton beam current of 10-12 mA.

The injection energy of 703 keV is adjusted by stabilized 40 kV modulator exciting the IT-800 pulse transformer that generates 700-750 kV semisinusoidal 1 ms pulses [16] with proton injection on the top of each one.

At accelerator modernization the matching channel aperture was increased up to \( \varnothing 90 \) mm, thus restriction of transversal beam sizes occurred in the section between buncher and the first drift tube with aperture diameters of 40 mm and 20 mm, respectively. The matching channel structure simplification was achieved by using long-focusing optics properties of the accelerating column. The beam current of 420 mA at maximum phase density of 1200-1500 mA/cm-mrad is transported to the first drift tube [17]. The output beam emittance measurement showed the beam of 100 mA and more occupied always the whole channel acceptance of 1.2 cm-mrad. So, marginal value of normalized emittance for 100% particles increased in the linac channel from 0.4 cm-mrad on the input of the first drift tube to 1.2 cm-mrad at the output of the machine [18,19].

Numerous original methods and tools were developed during experimental beam dynamics investigations [20] on the linac: parametric resonance study [21], method of fixed tuning spectrometer for longitudinal oscillations frequency measurement [22], period switching-off method for transverse oscillations observation [23] etc. The set of apparatus was developed for emittance measurement at the input and output of the accelerator [24], as well as for accelerated beam RF structure observation [25].

The most noticeable failures happened during 3 decade were as follows:

- penetration of oil vapors in cavities at sudden losses of ac supply line; very slow and long time RF voltage increasing is required for burning down of that vapors;
- two destructive breakdowns of 750 kV winding isolation of HV pulse transformer; the last version of the coil has operated without failure since 1975;
- production stoppage of output power tubes GI-4A aroused a modernization of whole RF supply system based now on more powerful tubes GI-27A [26];
- failure of the last quadrupole in the matching channel placed into vacuum tank on the first cavity outer wall.

This failure threatened to a whole dismantle of the linac structure and very long shut-down of its operation. The output linac current with mismatched LEBT channel decreased to 60-65 mA that was not enough for normal injection in PS.

In order to avoid the opening up of the tank with old solidified rubber seal we insert along the axis into \( \varnothing 40 \) mm aperture of the spoiled lens a small REC quadrupole developed in ITEP [27] with right adjusted gradient and polarity but having an inner diameter only 20 mm. It was the most simple solution. It seems to be the first experience of unclosed REC quadrupole operation in high vacuum volume of linac nearby to the proton beam [28]. Thus we restored required matching conditions and now only some more careful adjustment of the transportation through LEBT is necessary to obtain the former output beam current of 230 mA.

The output HEBT system [29,30] consists of 3 lines provided with pulse bending magnets and set of quadrupole doublets and triplets. It forms injection line with debuncher, measuring line with dc analyzing magnet and line for physical and chemical experiments, short-live radionuclide production [31] and radiation tests at 6 or 24.6 MeV (or in the air after output foil on 2 MeV less) at average proton beam current of 2 \( \mu \)A [32,33].

**Conclusion**

The linac I-2 is the very old working machine deprived modern computerized diagnostics and control apparatus but as a matter of fact due to the greatest in the world output pulse current and other good physical parameters of the beam it may be a retentive memory to the first author of the project Prof. I.M.Kapchinsky, who published a lot of papers and 4 books [34-37] devoted to analysis of the methods for obtaining high intensity ion beams. The books have played in the world the significant role in development of the ion linacs fundamental theory and engineering practice with beam currents in vicinity of the Coulomb limits.

During a time of design, construction and upgrades of the linac it has been proposed numerous inventions on original physical methods and technical solutions (partly described in the papers below) introduced in acceleration practice. They defined a good operation and reliability of the machine. Results obtained at the linac I-2 development, launching and high beam current experiments were used on the similar stages in the following strong-focusing machines in Russia.

**References**


Invited Talk Session WE1

Chairman: R.A. Jameson

Wednesday, August 28, 1996
ATF LINAC COMMISSIONING

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Abstract

Accelerator Test Facility (ATF) [1] is now under construction in the TRISTAN Assembly Hall in order to generate a extremely low emittance beam for linear collider studies. It consists of 1.54GeV S-band Linac, beam transport line, damping ring and extraction line. The S-band Linac is an injector of the damping ring which supplies a multi-bunch train beam which is 20 bunches with $2 \times 10^{10}$ electrons/bunch and 2.8 ns bunch spacing. The newly developed techniques which are high gradient accelerating unit, precise alignment system, beam energy compensation system, compact modulators, multi-bunch beam monitors are used in this linac. The commissioning of the linac was held on November 1995. The beam experiments on a high gradient acceleration and a beam energy compensation for the transient beam loading were performed. The results of these experiments are shown.

Introduction

The main purpose of ATF is to develop an extremely low emittance beam and to demonstrate that one of main key issue of a linear collider is solvable. ATF linac is not only a injector linac of the damping ring but also a test-stand of common key components to realize a linear collider such as multi-bunch beam generation, high gradient acceleration, beam loading compensation and instrumentation development. The construction was started since 1991 in the TRISTAN Assembly Hall in KEK which was a building of 120m x 50m width. The reinforcement of the floor driving many piles into the ground was done at first to support heavy concrete shield blocks of tunnels and to avoid floor vibration. The construction of linac was started on October 1992. The 80 MeV electron beam by the preinjector part of the linac[2] has been utilized to test structures and monitors since August 1993. The main part of the linac and the beam transport line to the damping ring has been constructed for about two years. The commissioning of the linac was then held on November 1995. The accelerated beam energy was 1.3GeV for both single bunch and multibunch. In this stage, the damping ring and the extraction line are still under construction. The performance and development status of ATF linac are summarized in detail. The beam experiments of high gradient acceleration and beam loading compensation are also described.

ATF Linac Sub-system

The ATF linac summarized in Table 1 is consist of 80MeV preinjector, 8 regular accelerating units, two unit of energy compensating structures. The special concern on the

high gradient acceleration, beam loading compensation, active alignment system and fast and precise beam instrumentation are also paid.

80MeV Preinjector of Linac[2]

The role of preinjector is to generate 20 multi-bunch of $2 \times 10^{10}$ electrons/bunch with 2.8 ns bunch spacing and to inject it to 1.54GeV Linac. Since the bunch length less than 10ps(FWHM) is required to meet the energy acceptance of the damping ring, the buncher cavities are designed to have low R/Q values in order to reduce beam induced voltage which affects to bunching of successive bunches.

The extraction of multi-bunch from ordinary thermionic gun is done by applying RF wave of 357MHz to the grid[3]. The extracted bunch has 1ns(FWHM) and 3A peak current with 200kV energy. The bunch is shrunk to 15ps(FWHM) by the two 357MHz SHB cavities and the 7 cell traveling-wave 2856MHz buncher cavity. After bunching, the bunches are accelerated up to 80MeV by a 3m structure, then go into the Linac regular section. One klystron is used in the preinjector which is operated at 60MW, 1µs with no SLED. It supplies an rf power into the 3m structure together with the buncher cavity.

<table>
<thead>
<tr>
<th>Beam Energy for DR</th>
<th>1.54 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>85 m (from Gun to linac end)</td>
</tr>
<tr>
<td>Accelerator Structure</td>
<td>2m/3mode constant gradient</td>
</tr>
<tr>
<td>Total length</td>
<td>3m</td>
</tr>
<tr>
<td>Total number</td>
<td>16</td>
</tr>
<tr>
<td>Accelerating Field</td>
<td>52 MV/m</td>
</tr>
<tr>
<td>Maximum Peak Field</td>
<td>30 MV/m</td>
</tr>
<tr>
<td>Nominal with Beam</td>
<td>2.856 GHz</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>200 MW/structure</td>
</tr>
<tr>
<td>Feed Peak Power</td>
<td>Klystron Peak Power 80 MW</td>
</tr>
<tr>
<td></td>
<td>Klystron Pulse Length 4.5 µs</td>
</tr>
<tr>
<td></td>
<td>Number of Klystrons 8</td>
</tr>
<tr>
<td></td>
<td>Pulse Compression Two-iris SLED</td>
</tr>
<tr>
<td></td>
<td>Power Gain 5.0 (average )</td>
</tr>
<tr>
<td>S-band Preinjector Beam Energy</td>
<td>80 MeV</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>20</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>$2 \times 10^{10}$ electrons</td>
</tr>
<tr>
<td>Bunch Separation</td>
<td>2.8 ns</td>
</tr>
</tbody>
</table>

Table 1 1.54 GeV ATF Linac Parameters

High gradient accelerating unit [4]
An 1.54GeV beam energy is required within about 85m of total Linac length including preinjector, quadrupole magnets and beam monitors, because of the limited length of the building. A high gradient of 30MeV/m is necessary for the beam acceleration. The limit of accelerating gradient in the accelerating structure is determined by the break down of the electrical field and the intensity of the field emission current. Since the break down comes from the field emission current, to reduce the field emission current is a key point to get a high gradient field. From the conclusion of the high gradient experiment which we have done for several years, the effort for high gradient structure has done as listed below;

1. keep cleanness during fabrication and tuning in order to avoid dust and contamination on the surface of the structure.
2. the input and output coupler are carefully designed to avoid field enhancement like tuning dimple.
3. use HIP(Hot Isostatic Press) OFHC for the disks to reduce voids between crystal grains.

As a result, a maximum peak gradient of 52 MV/m was achieved with 200MW peak rf power input in the one of regular unit.

Using these high gradient structures, the regular accelerating unit is composed by 80MW klystron, two-iris SLED and two 3m structures. This system can generate 400MW peak power rf from the SLED (200MW peak power rf into 3m structure) and 240MeV energy gain (Fig. 1).

![Block diagram of the high gradient accelerating unit](image)

**Energy Compensation System**

In multi-bunch acceleration, a beam energy decreases from the front to the end gradually by a transient beam loading of the structures. Since the maximum energy acceptance of damping ring is ±1% and since a variation of bunch spacing is not acceptable, the new energy compensation scheme for the multi-bunch was developed. Using the accelerating structure which is operated in slightly higher frequency, the front bunches can get deceleration and the rear bunches can get acceleration. To cancel out an energy spread within a bunch, the other structure which is operated in lower frequency of the same amount with opposite slope is used. With this system the energy spread among bunches can be reduced from about 5% to 0.2% peak to peak. In order to simplify the timing system, the frequency deviation was chosen to 4.327 MHz which is just twice of damping ring revolution frequency[6]. Consequently all of the frequencies are fully synchronized. The system consist of two klystrons and 3m structures which are operated in 2856+4.32MHz and 2856-4.32MHz each. The maximum output of klystron is 50MW, 1μs square wave which can compensate maximum 80MeV beam energy in one unit.

**200MW compact modulators [7]**

A 200MW modulator development has been continued since 1987. In total eleven modulators, seven of them are supplied by the one common DC power supply. Four of them are independent type which are supplied by 200V AC. The main effort of this development is focused on the total size, stability and efficiencies which will directly affect on the scale of the linear collider machine. The use of the compact self-healing type capacitors makes the PFN more compact. The packing of each device into the modulator box was rechecked to make high density packing. By discarding the electric standard for spacing of high voltage device in Japanese industry, 1.5m x 2.5m width and 2.2m height modulator was realized for the three of them. To make a hold-on time of thyatron shorter, the charging into the PFN is initiated by the command from the controller(command charging). To avoid reverse voltage on the thyatron, a tail clipping diode circuit are added. By these method, the lifetime of the thyatron will be longer. The energy loss of the de-Qing circuit is collected by a simple circuit which makes 5% saving of wall plug power.

**Wire Alignment System [4]**

The stages of the linac have an active mover mechanism and wire position sensors. In order to monitor the stage position and to align the whole stages, two stretched wires are used with the length of about 85m. The wires are stretched in both side from the preinjector stage to the end of the linac. The sag of wires are calculated in each sensor position as far as no kink on wires and assumption of uniform wires with no creep and no friction on the wheel. The center position of wire sensors mounted on the support stage are calibrated in its calculated position in the calibration stand. Each sensor mount is fixed to the reference surface of the stage which is machined with less than 10μm in accuracy. In this way, when the stages are aligned so as to get the wire position into the center of the sensors, the reference surface of the stages are
aligned to the wires in straight. The resolution of position sensor is 2.5μm and the accuracy of center finding is ±30μm. The wire position is detected by a synchronous detection of the signal from the differential coils using 60kHz current on the wire.

Since the stretched wires had a big sag of a few cm greater than the calculated value at the initial alignment, the alignment of the stage has been done by using the telescope and the alignment target. The alignment sections are divided to five sections and connected them by partial superposition. As the first result of the telescope alignment, the stage reference edges were lied in the range of ±250μm. The further study will be done on this alignment problem.

Beam Position Monitors

In order to measure the orbit in the linac and the beam transport line, the BPM system was installed and commissioned on February 1996. The pickup chambers are 6 button-type BPM for the pre-injector part and 24 stripline-type BPM for the linac and the beam transport line. The stripline type BPM which has 80mm length of strip and 30mm inner diameter has a resolution of 1μm for 2×10¹⁰ beam charge together with the high precision track&hold electronics[9]. Fig. 2 shows the cross-section of the stripline BPM chamber used in the linac. These BPM chamber are installed in the reference stage gider of the linac by the precision support.

![Fig. 2. Stripline BPM chamber](image)

The relay multiplexing is used for the detection electronics which consist of 5 set of the track&hold electronics of x and y position detection. The measurement of beam position is done by 6 pickups multiplexing for each set. The measured orbit of the beam is corrected by the program “SAD”. The convergence of the correction into ±1mm deviation is attained by around 4 iterations.

Multi-bunch Beam Monitors

In addition to ordinary monitors such as toroid current monitor, screen profile monitor, stripline beam position monitor and bunch length by streak-camera, we are developing bunch by bunch position, size and current monitors which measures each bunch in the 20 bunch train. The preliminary result of gated beam size measurement done by using a fast gated camera on OTR light and gated gamma detection in the wire scanner is reported in elsewhere [1,7]. The fast current measurement using wall-current monitor and gated position measurement using fast sample-hold circuit are now under developing.

Control System

The control computers are VAX cluster which consists of one main control computer(alpha), one hardware interface computer (VAX4000) which is connected to the hardware device by the CAMAC serial highway, and four workstation terminals. V-system is adopted as a control software for the window system. In order to connect to the program ‘SAD’ running on the HP workstations in the different place, and to support the experiment data processing, the Macintosh computer is used together with the VAX station. As a real-time control information, the CATV(cable TV broadcasting) system is introduced for monitoring beam signals on the oscilloscope, screen profile, streak-camera image and so on.

RF Processing of Accelerating Unit

A high power test of the regular accelerating unit has been done using one of the accelerating unit from January 8 to February 13, 1994. The power was raised up to 80MW, 4.5µs at the output of the klystron. The input peak power of each 3m structure was about 200MW with SLED cavity. The total processing time was about 600 hours with 200 hours system check and SLED tuning. The rest units were processed from September 29 to November 28 1995 during night only. The day time was spent for the wiring of magnet and monitors, alignment of the linac and construction of the beam transport line. The power level of the klystron output was reached to 44MW average at the commissioning time. After few months operation, it was raised to 62MW average. The main reason of this lower operation power level comes from the modulator over-current trip initiated by the electrical noise.

Beam Commissioning

The beam commissioning of ATF Linac was begun on November 22 with insufficient rf processing level. The emittance of 80MeV injection beam was measured at first. Then the optics which was the matching calculation result from ‘SAD’ by using the measured emittance was set. The delay timings of rf pulse with beam were adjusted by measuring a difference between BPM signal and rf signal. The phase of rf then searched to get good transmission. The orbit was also adjusted by using screen profile monitors. Once the
beam went through the linac, the rf phase and timing were adjusted precisely to get the highest beam energy. After 5 days above beam tuning, the single bunch of 1x10^10 was accelerated up to 1.3GeV by the average gradient of 25.5MeV/m, and the multibunch of 6 bunches/pulse were also accelerated with the intensity 1x10^9/bunch. The energy spread of the single bunch was 1%/FWHM and the normalized rms. emittance was 2x10^-4. The intensity was raised up to about 2x10^10 during the operation for the several experiments. However, the transmission ratio of the beam current from the exit of preinjector to the end of the linac was about 60% at around 1x10^10 or over. The reason of this low transmission was investigated, and found that it came from the low energy tail of the energy spread which slipped out from the acceptance of the optics. The energy of the beam which is still below the required. The reason comes from the modulator over-current trip problem which is caused by an interference with an electrical noise. This is now under fixing.
On February 1996, the BPM system was installed and commissioned as mentioned above. The measured orbit of the beam is corrected by "SAD". The beam operation of linac became easy than before. The linac is now operating routinely for various beam experiments of linear collider R&D. To summarize the performance of this linac, the achievement are listed in Table. 2.

<table>
<thead>
<tr>
<th>Maximum Beam Energy</th>
<th>1.42 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Gradient with beam</td>
<td>28.7 MV/m (average)</td>
</tr>
<tr>
<td>Maximum Klystron Power</td>
<td>62 MW (average)</td>
</tr>
<tr>
<td>Accelerated Intensity: single bunch</td>
<td>1.7 x 10^10</td>
</tr>
<tr>
<td>: multi-bunch</td>
<td>7.65 x 10^8 (total)</td>
</tr>
<tr>
<td>Energy Spread : single bunch</td>
<td>0.4 % (FWHM)</td>
</tr>
<tr>
<td>: multi-bunch with ECS</td>
<td>~ 0.3 % (FWHM)</td>
</tr>
<tr>
<td>Emittance ( \gamma x ) : single bunch</td>
<td>1.3 x 10^-6(1\sigma, at Inj.)</td>
</tr>
<tr>
<td>: multi-bunch</td>
<td>not measured</td>
</tr>
</tbody>
</table>

Table. 2. Achievement of the Linac

Energy Compensation Test

In order to confirm the principle of this compensation scheme, the beam test was performed by using the 2856+4.32MHz structure only at the beginning. Since the klystrons of the energy compensation system (ECS) were not ready at that time, the regular unit klystron was switched to the ECS structure. The frequency of the ECS is generated by the single side-band modulator which combines the signal of 4.32MHz with the carrier of 2856MHz. The measurement of beam energy for each bunch was done by using BPM after the bending magnet of the beam transport line. The multibunch signal from the BPM was measured by the digital oscilloscope of 1GHz bandwidth. After the adjustment of the beam timing with rf pulse, the phase of rf was set to an appropriate value to get a maximum deceleration for head bunches and a maximum acceleration for tail bunches. Then, the rf amplitude was set to get a flat energy distribution for all the bunches. The effect of the ECS is successfully demonstrated in the case of 10 bunches with 4x10^9 each bunch and 20 bunches with 7x10^9 each bunch intensity[1]. The calculated energy difference by the beam loading was 5% for 20 bunch case, the ECS by 2856+4.32MHz frequency could compress it to 0.5% by 25MW rf power.

![Energy Compensation](image1)

Fig. 3. Energy of each bunch with and without ECS

![Energy Spread](image2)

Fig. 4. Energy Spread of each bunch with and without ECS

After the installation of two sets of ECS modulator and klystron, a beam test of this regular ECS system was held on July 1996 using both 2856+4.32MHz and 2856-4.32MHz frequencies[10]. The OTR monitor combined with a bending magnet was installed for the measurement of energy and energy spread of multibunch beam in order to confirm the ECS performance. The bunch charge was limited to 1.5x10^9 each by the radiation control alarm which was caused by an emitted radiation from the OTR monitor. The measured relative energy of each bunch by the BPM demonstrate the ECS compression performance shown in Fig. 3. The power

550
level of the klystron was around 2MW in this low charge compensation. The energy decrease at front of the bunches seems to come from the position shift caused from the side tail cut by the collimator.

The energy spread of each bunch, on the other hand, was measured by the OTR monitor with the 3ns gated camera[11]. Fig. 4 shows the energy spread with ECS and without ECS in the case of 2.5x10^9 each bunch. Although the measured spreads are scattered around 0.3% FWHM, there is no big difference even with this ECS. The observed waveform of multi-bunch beam by the wall-current monitor is shown in Fig. 5 in the case of the same charge. The monitor is placed at the downstream of the linac in front of the first bending magnet of the beam transport line.

![Waveform of multi-bunch beam](image)

**Fig. 5. Waveform of the multi-bunch beam**

**Schedule toward Damping Ring commissioning**

After the commissioning of the Linac in 1995, the installation of Damping Ring components was started in urgent. Almost all the magnets, chambers and active stages were ordered during 1995. The fabrication of these component are almost finished. The installation will be finished till November 1996. Then, we will have the beam commissioning of ATF Damping Ring on December 1996.

**Acknowledgment**

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**References**

CLIC TEST BEAM FACILITIES - STATUS AND RESULTS

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Abstract

CERN is studying the feasibility of building a 1 TeV c.m. e^+e^- linear collider (CLIC) based on 30 GHz accelerating structures and RF power production from a low energy, high intensity drive linac. Two major challenges of the CLIC two-beam scheme are the generation of the high intensity drive beam and the extraction of 30 GHz RF power using transfer structures. Two test facilities are currently being used to study these specific problems. The CLIC Test Facility (CTF) is a purpose-built CERN facility to study the generation of the drive beam by photo-injectors, the generation of 30 GHz RF power, and the testing of components. This facility has produced single bunch charges of 35 nC with a bunch length of 14 ps (FWHH) and up to 76 MW of 30 GHz RF power. It is at present being updated to a 10 m long two-beam test accelerator producing 480 MW of 30 GHz RF peak power and accelerating electron bunches with gradients of 80 MV/m. The FEL Test Facility at CESTA (Bordeaux) is being used to study the generation of the CLIC drive beam by direct bunching at 30 GHz. This facility has recently made the first direct observation of beam bunching by a high power microwave FEL. The status of these two test facilities and the results obtained are given.

Introduction

CERN is studying the feasibility of building a compact 1 TeV c.m. e^+e^- linear collider based on normal conducting travelling wave accelerating structures operating at 30 GHz and a gradient of 80 MV/m, and RF power production from a low energy (3 GeV) high intensity drive linac [1]. The design luminosity of 10^{34} cm^{-2}s^{-1} is obtained by colliding 30 bunch pairs per RF pulse. With a bunch spacing of 1 ns this means an RF pulse length of about 45 ns.

Typical peak powers of 150 MW/m are required along each of the 6.25 km long main linacs. The two-beam scheme avoids the thousands of individual klystrons, modulators and RF compression units required by the classical approach. There are no active RF components in either of the linacs resulting in a particularly simple tunnel layout.

Generation of the drive beam and extraction of 30 GHz RF power from the drive beam using transfer structures is one of the major technological challenges of the CLIC two-beam scheme. The drive beam consists of trains of 30 bunchlets (spaced at 1 cm) with 50 nC/bunch and a σ = 0.6 mm. It is proposed to generate this beam either directly using the bunching capability of an FEL or by combining the outputs of a battery of photoinjector linacs. The bunch trains are accelerated to 3 GeV using a 250 MHz superconducting linac. In the drive linac the bunched beam is progressively decelerated in transfer structures as RF power is supplied to the main linac.

An alternative scheme based on an isochronous storage ring is also under study. This would also require a photo-injector source and the beam would be accelerated by a 1.5 GHz SC linac.

Two test facilities are currently being used to study the above-mentioned technological challenges of the CLIC scheme. 

(i) The CLIC Test Facility (CTF) is a purpose-built CERN facility to study the generation of the drive beam by photo-injectors, the generation of 30 GHz RF power, and to test components.

(ii) The FEL Test Facility at CESTA (Bordeaux) is being used to study the generation of the CLIC drive beam by direct bunching at 30 GHz.

The CTF layout (CTF 1995) is shown in Fig.1.

![Fig.1 Schematic layout of CTF](image-url)
CLIC Test Facility (CTF1)

CTF1 was built to (i) study the production of short, high charge electron bunches from laser illuminated photocathodes in RF guns, (ii) generate high power 30 GHz RF pulses by passing bunch trains through transfer cavities for testing CLIC prototype components, (iii) test beam position monitors.

The CTF1 electron source consists of a laser-driven S-band photoinjector producing single bunches or trains of up to 48 bunches with a spacing of 10 cm and a momentum of 12 MeV/c. Introducing a correlated longitudinal energy spread by adjusting the RF phase of the photoinjector and passing the bunches through the magnetic chicane produces a longitudinal bunch compression [2]. Final acceleration to 65 MeV/c is obtained using a 1 m long S-band travelling wave (TW) section (NAS). A 1.5 m long drift space between the TW section and a magnetic spectrometer is reserved for testing CLIC prototype components with beam. Energy is extracted from the beam by a 30 cm long TW section (CAS1) to provide short high power 30 GHz RF pulses. This power is then used to feed either a second identical CLIC structure (CAS2) or used to supply power to other CLIC prototype components. The decelerated beam then either goes to a dump, or is turned through 180° by bending magnets at the end of the line and is re-accelerated by the second high gradient CAS2 section. The facility is operated at a repetition rate of 10 Hz.

Photo-injector

The photo-injector consists of a 1+2 -cell S-band RF gun followed by a 4-cell SW booster cavity [3]. A Cs$_2$Te photocathode in the first 1/2 cell of the gun produces the electrons when illuminated by 262 nm wavelength light (fourth harmonic of the Nd:YLF laser). Multiple bunches are made by splitting the laser pulse into a train of pulses each spaced by one 3 GHz wavelength. A maximum laser energy before splitting of 1.0 mJ per pulse is available. The laser pulse length is 8 ps FWHM. The RF gun is routinely operated with a peak cathode field of 110 MV/m.

Photocathodes

The Cs$_2$Te photocathodes are prepared in a laboratory [4] and are transported under vacuum and installed into the gun using a specially designed transfer system. The initial quantum efficiency (QE) is more than 10%. It however drops rapidly over the first 30 hours of operation and then stays at a level of about 2% for several weeks (see Fig. 2). The photocathode only deteriorates when the RF is on. A GaAs cathode, prepared by SLAC, was tested up to 85 MV/m in the RF gun to test its high voltage holding capability. This result is an important step in the study of the production of polarised electrons using RF guns.

Electron bunches

A maximum single bunch charge of 35 nC has been obtained from the gun-booster with a laser spot of about 10mm diameter. The length and emittances of the electron bunches are measured with a streak camera using the light pulse produced by the interaction of the bunch with a transition radiation monitor or a Cerenkov monitor. After the gun-booster cavity the bunch length is typically 10 ps (FWHH) with a charge of 10 nC. The bunch compressor is used to reduce the length of single bunches by a factor of two to four depending on the charge, the minimum measured was 3 ps FWHH. At low charge per bunch transverse normalised emittances of about 30 mm.mrad are observed. With high charge per bunch both the transverse emittance and the bunch length are blown up by space charge effects at low energy. The maximum charges measured at various positions along the beam line in both single and multibunch operation are given in Table 1.

<table>
<thead>
<tr>
<th>Position in beamline</th>
<th>Single bunch (nC)</th>
<th>48 bunches (nC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exit photo-injector</td>
<td>35</td>
<td>450</td>
</tr>
<tr>
<td>Exit TW section</td>
<td>20</td>
<td>160</td>
</tr>
<tr>
<td>Exit CAS1</td>
<td>7</td>
<td>81</td>
</tr>
</tbody>
</table>

Table 1: Maximum measured charge in CTF1

In the photo-injector the single bunch charge is limited by space charge forces whereas in multibunch operation the maximum charge is limited by the available laser energy. In the 3 GHz TW section, the beam loading limits the multibunch charge. Beam is lost at the 4 mm diameter aperture restriction in CAS1 at high charges due to emittance growth caused by space charge forces, transverse wakefields and chromatic errors in focusing quadrupoles due to beam loading.
30 GHz Power generation

Significant amounts (>1 MW) of 30 GHz power can only be extracted from the CAS1 section by using bunch trains. Peak power pulses 27 ns long of 76 MW with a 3 dB bandwidth of 12 ns have been generated using trains of 48 bunches with a charge per bunch of 3 nC. This power level corresponds to a decelerating field in the CAS1 section of 124 MV/m. In spite of these very high fields, which are well above the CLIC nominal accelerating gradient of 80 MV/m, no sign of RF breakdown or the need to condition has ever been observed. The accelerating field in the second CLIC CAS2 structure is determined from the difference between the maximum energy gain and energy loss of the beam as its phase with respect to the beam-induced RF accelerating field is varied. The highest average re-accelerating gradient obtained in this structure was 94 MV/m.

30 GHz Power tests

One of the principle uses of the CTF1 has been the testing of CLIC prototype components using either a bunched beam directly or using 30 GHz pulsed power. The following components were tested with 27 ns 60 MW power pulses: (i) 10 cm section of flexible WR28 waveguide (ii) high power stainless steel waveguide load, (iii) WR28 phase shifter, (iv) high gradient test section consisting of a sharp stainless steel point in a piece of standard WR28 waveguide (the aim of this test was to provoke a breakdown to examine breakdown behaviour). No evidence of RF breakdown was observed in any of these tests. High frequencies combined with short pulse lengths are apparently very forgiving.

Testing 30 GHz components with beam

The following components were tested with beam. (i) A 30 GHz transfer structure with two output waveguide channels. The measurements revealed unacceptable field inhomogeneities which subsequent simulations indicated would create serious transverse blow-up and energy dispersion effects. (ii) A 30 GHz transfer structure with four output waveguide channels. Going to four channels substantially improved the field homogeneity.

(iii) A 30 GHz BPM system. The set-up consisted of two resonant E_{11} cavity BPMs to reduce beam jitter effects. A super-heterodyne receiver was used in the signal processing electronics to obtain charge independent horizontal and vertical positions in each BPM. Independent 0.1 μm resolution micromovers were used for displacement calibration. An upper limit on BPM resolution of ±4 μm was demonstrated [5], the measurement being limited by shot to shot angular jitter of the CTF1 beam.

(iv) Two large aperture button type 4 GHz bandwidth BPMs for the CLIC drive beam with associated signal processing system. A resolution of 0.2 mm was demonstrated.

Coherent radiation monitor test

Bunch length measurements were made for the TESLA test using a coherent radiation monitor that they are investigating [6]. A clear signal increasing as the square of the charge - the coherent radiation signature - was obtained. It was demonstrated that the device could be used to optimise the bunch compressor setting.

CLIC Test Facility (CTF2)

CTF1 has achieved all its objectives and has clearly demonstrated the principle of the two-beam acceleration scheme. It will be upgraded in stages during the period 1996-1998 to a two-beam test linac (the so-called CTF2) with the following main goals [7].

(i) To study the feasibility of the two-beam acceleration on a larger scale than CTF1 with beam parameters as close as possible to those proposed for CLIC.

(ii) To design and construct a fully-engineered representative active-aligned test section of the 30 GHz drive and main linacs using nominal CLIC components working at nominal RF powers and accelerating fields.

(iii) To develop drive beam generation technology.

(iv) To compare measurements and CLIC beam dynamics simulations.

(v) To help estimate the realistic cost of a representative part of the CLIC complex.

The proposed layout of CTF2 is shown in Fig.3.
Drive linac

The drive beam train (48 bunches spaced at 10 cm) of 640 nC total charge is generated by the new S-band 2×8-cell RF gun [8] equipped with a Cs₂Te photocathode and driven by the same CTF1 laser. It is accelerated to 62 MeV/c by two new 0.65 m long high charge, high gradient (60 MV/m) TW structures (HCS) built for CTF2 by LAL (Orsay) [9]. These structures, designed to minimise both beam loading and transverse wakefield effects, work at two slightly different frequencies (2998.55±7.81 MHz) to provide beam loading compensation to reduce the energy spread along the train. After passing through a magnetic bunch compressor, the bunch train is used to drive six CLIC transfer structures (CTS). A transfer structure consists of a 15 mm diameter beam tube coupled through four diametrically-opposite slots to four periodically-loaded rectangular waveguides. Each 70 cm long CTS provides enough power to drive two CLIC accelerating sections (CAS) with 40 MW, 12 ns long, 30 GHz power pulses. In a first stage when the drive beam charge is not yet at the nominal value of 640 nC one CTS will be used to power one CAS. In this configuration 453 nC are required to produce 40 MW at the CAS input.

Main linac

The probe beam will consist of two bunches only. The first bunch will have the CLIC nominal charge of 1.3 nC. The second weaker bunch of 0.1 nC will possibly be used to probe the wakefields induced by the first. The two bunches will be generated by the existing 1.5-cell CTF RF gun and laser and will be accelerated with the existing LAS section to 40 MeV before entering the string of 30 GHz high gradient (80 MV/m) CLIC accelerating sections. Most of these sections will be the constant impedance type but damped structures will be added if and when they become available.

Active alignment system

In order to minimise problems due to misalignments and at the same time to simulate the CLIC tunnel configuration as closely as possible, both 30 GHz linacs will be equipped with the support and active pre-alignment system developed for CLIC in the Alignment Test Facility. The RF structures and all beamline components are supported by precision v-blocks on 1.4 m long silicon carbide box-section girders. The ends of two adjacent girders are connected via link rods to a common platform that ensures continuity of transverse position whilst permitting full rotational freedom. The platforms are activated by three 0.1 μm resolution stepping-motors (two in the vertical plane for vertical displacement and axial rotation, and one in the horizontal plane). The triplet focusing unit in the drive linac and the doublet unit in the main linac are each supported and can be moved independently of the beam lines by similar stepping motor drivers. An accurate active alignment of the two linacs is obtained by referencing all moveable elements to a stretched wire running along the length of each linac by means of high precision capacitive position transducers. The reference in the vertical plane is provided by an hydraulic leveling system. The main linac will be equipped with a CLIC 30 GHz BPM system and this could possibly be used at a later date for beam-based active alignment tests.

Present status and future planning

The two 3 GHz linacs are complete except for the two HCS sections which will be installed at the end of 1996. In the meantime the 1 m long NAS section will be used. Two 30 GHz modules will be installed for the end of 1996 and two more in 1997 and 1998. With all six modules installed the drive linac will produce a total peak power of 480 MW and the main linac will accelerate the probe beam to 320 MeV. In an ultimate stage, in order to provide the capability to test elements above their nominal field, the drive beam is expected to be increased to 1 μC. A new 2 and 1/2-cell RF gun is at present being designed to meet this requirement and is expected to become available in 1997. With 1 μC 217 MW would be produced at the TRS output and if used to power a single CAS would generate an on-axis accelerating field of 176 MV/m.

CESTA Test Facility

It was suggested some years ago that the CLIC drive beam could be generated directly with the required 1 cm spacing by using the bunching properties of an FEL powered by an induction linac [10]. A collaboration to study this proposal was set up between CERN and the Centre d'Études Scientifiques et Techniques d'Aquitaine (CESTA) in Bordeaux. An experiment has been made using the 1 kA 2.2 MeV induction linac LELIA as power source and has resulted in the first direct observation of bunching of a relativistic electron beam by a high power FEL interaction. The work reported here was carried out by the CESTA group [11] and more detailed information is given elsewhere in this conference.

A schematic layout of the experiment is shown in Fig.4. The induction linac is composed of 10 injector cells and 12 accelerating cells. Each cell is powered with a 100 kV 80 ns FWHH pulse. The 10 injector cells produce 1 MV at the thermionic cathode enabling 1 kA of beam to be extracted. The 1 MeV beam is then accelerated to 2.2 MeV by the 12 accelerating cells. Solenoidal magnets (1 kG maximum field) are used downstream of the cathode to focus the beam. Steering magnets are used to maximise transmission efficiency. The measured geometrical emittance at the end of the injector is 130π mm.mrad. A short two magnet transport section is used to transfer the beam from the exit of the linac (diameter 150 mm) to the entrance of the wiggler (diameter 40 mm). Half of the 1 kA beam is lost during this transport process. The 2.88 m long wiggler magnet is formed from a double helix copper winding which is powered by a 10 kA 280 μs current pulse obtained by discharging a 50 kJ capacitor bank.
The wiggler produces a circularly polarised magnetic field of up to 3 kG on its axis with a period of 12 cm. The first six wiggler periods are strapped together to create an adiabatic entry into the wiggler with a gradual increase in the transverse momentum of the electrons, the same technique is used over four periods at the exit. The FEL works in the amplifier mode, the 500 ns long input signal is provided by a 100 kW 35 GHz magnetron. A tungsten wire grid is used to launch the wave into the circular waveguide of the FEL interaction region. As a result of the electron beam interaction with the EM wave in the field of the helical wiggler the beam becomes bunched and the input power is amplified. The extent of beam bunching is measured optically by analysing the Cerenkov radiation produced by the beam hitting a 5 mm thick silica target placed at different on axis positions at the exit of the wiggler. The Cerenkov light is detected with a streak camera and stored on a CCD camera. Viewing the light through a 0.3 mm slit gives the distribution of the light intensity along the beam.

Fig.5 FEL generated 35 GHz bunched beam (horizontal scale time of 278 ps)

A typical scan showing a distinct bunch structure is shown in Fig.5 for a time interval of 278 ps at a position 27.5 cm from the wiggler exit. The bunch spacing corresponds to the FEL frequency. The 35 GHz modulated current component is about 150 A or approximately 30% of the total current. Inside the wiggler a vertical scan of the beam shows it to be bunches over its 5 mm diameter. At 80 cm from the wiggler exit the portion of the beam that displays bunching is reduced to a 0.5 mm spot. This reduction is due in part to longitudinal space charge forces but also depends on the magnitude of the solenoidal field used to extract the beam.

**References**


REVIEW OF BEAM DYNAMICS AND INSTABILITIES IN LINEAR COLLIDERS

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Abstract

An important issue for a next generation \(e^+e^-\) high energy linear collider is the preservation of the beam quality through the acceleration in the linac. Recent design studies at different laboratories adopt very flat beams at the collision point to minimize beamstrahlung. Therefore most problems are related to the vertical single bunch dynamics which is determined by chromatic effects in the quadrupoles and wakefield effects in the accelerator structures due to the misalignment or vibrations of these linac components. Almost all linear collider designs consider multiple bunches in each rf pulse to raise the luminosity. The cumulative beam break-up instability due to long range wakefields (HOMs, higher order modes) is a severe problem for all multi-bunch schemes. Only the damping and detuning of the HOMs in the accelerator structures can reduce the long range wakefield effects. This report reviews several topics with respect to the preservation of the longitudinal and transverse beam quality in next generation linear collider designs. Single and multi bunch issues are covered.

Introduction

Several linear collider designs are being considered to achieve \(e^+e^-\) collisions at a center-of-mass energy of 500 GeV with upgrade potentials to the TeV range. These collider studies include the following international collaborations: TESLA (coordinated by DESY), a linac using 1.3 GHz superconducting cavities, the SBLIC (also coordinated by DESY), based on S-band rf-technology, the JLC (coordinated by KEK), including 3 approaches with accelerating structures operated at S-, C- and X-band frequencies, the NLC (coordinated by SLAC), a X-band linac, VLEPP (coordinated by BINP), also using an rf-frequency in the X-band, and CLIC (coordinated by CERN), a two beam accelerator with 30 GHz rf-structures. An overview of these designs can be found in [1, 2].

A schematic layout of a linear collider complex is shown in Fig. 1. The actual layout of a linear collider differs from design to design. Some designs use a two stage bunch compression system, others use the spent \(e^-\) beam for an undulator based \(e^+\) source, to mention only two possible differences to the shown schematic layout. The electrons and positrons are injected into damping rings to produce very small emittance beams, which are accelerated to 250 GeV in the main linac. The beam is delivered to the final focus system which focus the bunches to a very tiny spot at the Interaction Point (optional two I.P.'s). The different linear collider designs are aiming at luminosities in the range of

\[ \mathcal{L} \approx 5.0 \ldots 10.0 \cdot 10^{33} \text{ cm}^{-2} \text{s}^{-1}, \]

with a vertical beam size of \(\sigma_y \approx 3 \ldots 20 \text{ nm}\) at the (I.P.). To achieve this goal it is necessary not only to produce beams with very small emittances of

\[ \gamma\varepsilon_x \approx 330 \ldots 1400 \cdot 10^{-8} \text{m} \quad \gamma\varepsilon_y \approx 5 \ldots 25 \cdot 10^{-8} \text{m} \]

but to preserve this emittance during the acceleration in the main linac. The most critical plane is obviously the vertical. A comparison with the 1995 data from the SLC [3], where the emittance dilution in the vertical plane is controllable to \(< 60\%\) (initial \(\gamma\varepsilon_y = 200 \ldots 300 \cdot 10^{-8} \text{m}\) at 1.2 GeV), demonstrates clearly the challenge of the design goals of a future linear collider.

![Figure 1: Linear Collider, schematic overview.](image)

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The increase of the transverse emittance of the beam is ultimately due to the misalignment or vibrations of the linac components, i.e. mainly the accelerator structures and the focusing magnets. When a bunch traverses an accelerator structures off-axis, wake field effects kick the tail of the bunch even more off-axis. Fig. 2 shows schematically how a bunch develops a banana shape while it is passing through several accelerator structures.

![Off-axis tail](image)

**Figure 2:** Wake field effects in the accelerator structures.

Furthermore, chromatic effects will affect the focusing of the bunches in the quadrupole magnets since the bunch is not monochromatic. Quantum excitation in the damping ring will produce an initial uncorrelated energy spread in the bunch. Additionally, a correlated energy spread of the bunch is induced by the rf-fields (acc. mode and wakes) in the accelerator structures.

Almost all existing linear collider designs, except VLEPP, consider the acceleration of a bunch train in one rf-pulse. The acceleration of multiple bunches has the advantage that the efficiency (AC power to beam power) of the linac is larger compared to a linac operated in a single bunch mode producing the same luminosity. Additionally, less synchrotron radiation is produced by beamstrahlung during the bunch collision, which improves the conditions for the high energy physics experiments with respect to the width of the luminosity spectrum and the backgrounds. Furthermore, the single bunch wake fields can be less severe since a lower single bunch charge can be used. Unfortunately, several complications are added due to transient beam loading and long-range transverse wake fields. The cumulative beam break-up instability, first investigated at SLAC [4], due to higher order dipole modes (HOMs) is a severe problem. These HOMs have to be damped and/or detuned to avoid this instability.

**Single Bunch Dynamics**

First consider the longitudinal dynamics of a single bunch. The bunch length is determined by the bunch compressors and is already frozen at injection into the main linac since the injection energy is at least 3 GeV. Longitudinal short-range wake fields will add to the initial uncorrelated energy spread a correlated one. Furthermore the slope of the rf-wave will influence the energy spread of the bunch, i.e. part of the wake-induced energy spread can be compensated if the bunch is properly placed off the rf crest. An energy spread will give rise to chromatic filamentation of betatron oscillations and dispersive effects in misaligned quadrupoles.

Fortunately, a correlated energy spread can be used to reduce the filamentation of the emittance when the bunch performs coherent betatron oscillations. This technique, called BNS damping [5], is based on the increased focusing of the low energy tail of the bunch. Since only the tail is driven off axis by transverse wakes, these effects will partly cancel. But randomly misaligned quadrupoles will still cause an increase of the emittance due to dispersion. Sophisticated orbit correction methods are needed to minimize these effects.

The bunch is focused by quadrupole magnets which are arranged in a FODO lattice, characterized by the scaling of the beta function and the phase advance with the energy. Almost all designs use a constant phase advance of about $\mu \approx 90^\circ$ and a scaling of the beta function $\beta \sim E^a$ with $a = 0 \ldots 0.5$. The average of the beta functions in the focusing quads ($\beta_{\text{max}}$) and in the defocusing quads ($\beta_{\text{min}}$) is related to the FODO cell length $L_{\text{cell}}$ and the quadrupole strength $K$ in the following way:

$$\frac{\beta_{\text{max}} + \beta_{\text{min}}}{2} = \frac{L_{\text{cell}}}{\sin \mu} \cdot \frac{1}{[K l_q]} \cdot \frac{2}{\cos \mu/2}$$  \hspace{1cm} (1)

($l_q$ is the length of the quadrupole). The choice for the lattice parameters depends on the balancing of transverse wake field and dispersive effects. The scaling constant $a$ is mainly determined by the BNS-damping condition. TESLA uses $a = 0 \ldots 0.2$, while most other designs use $a = 0.5$. Actually the lattice is changed in steps which follow approximately the $\beta \sim E^a$ scaling law. Fig. 3 shows as an example the beta function of the SBLC design.

![Beta function along the linac](image)

**Figure 3:** Scaling of the beta function along the linac. (Example: SBLC, $a = 0.5$).

Suppose that uncorrelated random kicks $\theta_n$ are applied to the bunch along the linac. The rms orbit change at the end of the linac (index f for final) is given by

$$\gamma_f \langle \beta_f \theta^2 \rangle = \frac{1}{2} \sum_n \gamma_n \beta_n \langle (\theta_n)^2 \rangle.$$  \hspace{1cm} (2)
The kicks at different positions $n$ are transformed to an offset at the end of the linac via the $R_{12}$ transport matrix element. Adiabatic damping is included using the relativistic factor $\gamma_n = E_n/(mc^2)$. The kicks give rise to an emittance dilution if different parts of the bunch are affected differently.

This is indeed the case for dispersive effects. The kick depends on $|K| l_q$ and the energy spread $\delta = \Delta p/p$ in the bunch:

$$\theta(\delta) = |K| l_q (1 - \delta) y_q$$

(3)

(The bunch goes through the quadrupole with an offset $y_q$.) The relative emittance growth due to dispersion depends on the energy spread, the rms value $(y_q^2)$, acceleration gradient and average FODO cell length $(L)$ in the following way:

$$\Delta \epsilon_N \epsilon_N \sim \frac{(y_q^2)}{(L)^2 \text{gradient} \epsilon_N}.$$  

(4)

The kicks due to transverse wake fields are given by:

$$\theta(s) = \frac{N e^2}{m_0 c^2 \gamma} W'_\perp(s) l_a y_a,$$

(5)

where $N$ is the single bunch population, $l_a$ the length of one accelerator structure, $y_a$ the offset of the bunch with respect to the axis of the structure and $W'_\perp$ is the transverse wake potential per length at the tail of the bunch (measured in V(C m$^{-2}$)) depending on the longitudinal position $s$ in the bunch (see Fig. 2). The transverse wake potential scales with the third power of the rf-frequency $f_{rf}$ of the accelerator structure and with the square root of the bunch length $\sigma_z$. Using the equations (2) and (5) the scaling law for the relative dilution of the normalized emittance is obtained:

$$\Delta \epsilon_N \epsilon_N \sim \frac{N^2 f_{rf} \sigma_z}{\text{gradient} \epsilon_N}.$$  

(6)

Using the parameters from references [1, 2] the transverse wake field effects are compared in Fig. 4. The right hand side of equation (6) is calculated for each design and the results are normalized to values obtained for the TESLA parameters. All designs but VLEPP are using multiple bunches. The larger bunch population (VLEPP $N = 20 \cdot 10^{10}$) explains the difference between the NLC and the VLEPP designs, both using a rf-frequency in the X-band.

To limit the emittance dilution to reasonable limits also for the high rf-frequency linear collider designs it is necessary to align the accelerator structures with higher precision. NLC accelerator structures have been built with a 3 $\mu$m precision. Furthermore, at SLAC S-band accelerator structures have been aligned with a precision of 13 $\mu$m with respect to the beam using signals from higher order modes [6]. Furthermore one can gain from a stronger focusing and a higher gradient. Additionally, it is $l_a \sim 1/\text{gradient}$, i.e. the length of an accelerator structure $l_a$ will be shorter and the emittance growth smaller:

$$\Delta \epsilon_N \epsilon_N \sim (y_q^2) (\beta_0) l_a \frac{N^2 W'_\perp^2}{\text{gradient} \epsilon_N}.$$  

(7)

The filamentation of the bunch emittance due to betatron oscillations can be significantly reduced by the BNS-damping technique, which was already mentioned together with the correlated energy spread due to longitudinal wakes and the slope of the rf-wave. Consider the orbit difference of the head and the tail of the bunch $\Delta y = y_{tail} - y_{head}$. The difference due to transverse wake fields is $\Delta y_{wake} \sim \int ds \beta(s) N W'_\perp(s) y(s)$, while the effect due to dispersion is given by $\Delta y_{disp} \sim \int ds \beta(s) \delta(s) K(s)$. Both effects cancel if the following BNS-damping / autophasing energy spread is maintained during the passage of the bunch through the main linac:

$$\delta(s) = \delta_{BNS} \left(\gamma(s)/\gamma_0\right)^{2a-1},$$

(8)

with

$$\delta_{BNS} \sim N W'_\perp s b_0 \frac{\beta_0}{\tan \mu/2}.$$  

(9)

The required BNS energy spread is constant along the main linac when the beta function is scaled with the square root of the energy. BNS-damping is not needed in the case of the TESLA design since the wakes are small due to the relative low rf-frequency of 1.3 GHz.

![Scaling of wake effects](image)

**Figure 4**: Comparison of the transverse wake fields effects for the different linear collider designs.

The quadrupole magnets and the accelerator structures can be aligned with a precision of about 100 $\mu$m rms by a careful survey. The length of the "ideal" reference line is about a betatron wavelength at the end of the linac (say 500 m). The beam position monitors (BPMs) can also be aligned with a precision of better than $\sigma_{BPM} = 100 \mu$m rms with respect to the magnetic center of the quadrupole magnet. The usual beam steering (one-to-one correction), which zeros the BPM readings, is not sufficient to avoid a dispersive emittance dilution in a future linear collider. The situation can be significantly improved by special orbit correction techniques, often called beam based alignment. The basic idea is to use difference orbit measurements in addition to the absolute orbit measurements. The precision of difference orbits depend only on the resolution of the BPMs, which is better than (say)$\sigma_{res} = 5 \mu$m. Especially the DF steering algorithm [7] minimizes:

$$\sum_i \frac{y_i^2}{\sigma_{BPM}^2} + \frac{\Delta y_i^2}{\sigma_{res}^2} \rightarrow \min.$$  

(10)

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The orbit and difference orbit measurements enter into the equation with weight functions which are inversely proportional to their precision. The difference orbits are taken for different beam energies or equivalently with different quadrupole strength settings. Furthermore, different bunch charges can be used. The stability of the linac during the measurements has to be much better than the BPM resolution.

**Multi Bunch Dynamics**

The acceleration of multiple bunches in one rf-pulse adds several complications to the beam dynamics. Strong transient beam loading will cause a bunch-to-bunch energy spread, which will amount to 20% (SBLC, NLC, JLC) if not compensated. In a traveling wave accelerator section the first bunches of a train gain more energy than the later ones. The transient beam loading can be significantly reduced by the following methods:

- staggered timing
- klystron drive power control
- klystron phase control
- SLED pulse shaping

Using these techniques the problem of bunch-to-bunch energy spread can be completely cured for the price of providing additional rf-power for the control.

Staggering the timing of the klystron pulses with respect to the bunch train is a non-local method to reduce the bunch-to-bunch energy spread. The other methods are more local ones based on a control of the amplitude or the phase of the rf. The drive power of the klystron can be used to ramp up the output rf-amplitude as the bunch train passes the accelerator section. This may have the disadvantage that the klystron is not always operated at saturation. An almost local method is achieved by a control of the rf-phases of two accelerator sections, which can be mutually in or out of phase with opposite sign. During the passage of the first bunches the two sections are out of phase and the transient beam loading is canceled. A SLED system is an rf-pulse compression technique which transforms a longer rf-pulse into a shorter one using a special cavity to store the first part of the rf-pulse. After a phase switch the second part of the rf-pulse is combined with the pulse from the cavity. The SLED pulse decreases during the beam pulse. The rate of the decrease can be adjusted to minimize the energy spread [8]. This SLED pulse shaping can be achieved by an rf amplitude modulation or a programmed phase variation.

Another very severe problem arising from a multiple bunch operation is the cumulative beam break-up instability. The transverse long range wake potential is the sum over several modes characterized by the frequency \( \omega_n = 2\pi f_n \), the Q-value \( Q_n \) and the transverse shunt impedances:

\[
W_{\perp}(s) = \sum_{\text{modes}} 2k_{\perp n} \sin(\omega_n s/c) \exp(-\omega_n s/c),
\]

\[
(k_{\perp n} \sim (R/Q)_n \text{ is transverse wake amplitude of the n-th mode.})
\]

These modes are excited by the bunches when the pass through the accelerator structure off-axis due to misalignment of the structure or injection error. The excited fields drive subsequent bunches of the train even more off axis leading to an even stronger excitation of the modes in the next accelerator section (see Fig. 5). The bunch offsets from the axis grow exponentially:

\[
y_{\text{end}} \sim \exp(\sqrt{T_{\text{pulse}}} W_{\perp} / T_{\text{pulse}}) \quad [9].
\]

![Figure 5: Cumulative beam break-up of a bunch train due to HOM's.](image)

The instability can be suppressed by a special design of the accelerator structures. The cures are:

- detuned structures
- HOM dampers
- iris coating with lossy material
- choke mode cavity.

A detailed discussion of the subject can be found in [10]. The strongest damped structure is the choke-mode cavity, proposed for the JLC-C design and already tested at S-band [11]. For the TESLA design a light damping of the HOMs to \( Q \sim 10^4 \ldots 10^5 \) is sufficient due to the large bunch spacing of 0.7 \( \mu s \).

**Special Issues, Ideas, Activities**

Mechanical motion of the quadrupole magnets due to ground motion can significantly degenerate the beam collision conditions in a linear collider. Diffusive ground motion processes can be described by the so-called ATL - rule:

\[
\sigma^2 = A \cdot t \cdot l,
\]

the rms displacement \( \sigma \) of two points separated by the distance \( l \) growth with \( \sqrt{t} \). \( A \) is nearly constant over a large frequency range. Measurements for \( A \) are site dependent (\( A \approx 1.0 \cdot 10^{-8} \ldots 1.0 \cdot 10^{-5} \mu m^2/(m s) \)). This type of random ground motion can also deteriorate the performance of beam based alignment techniques. Systematic geological motion of the bedrock, which can be dominant at some sites, is less important since the effects can be corrected. Even quadrupole jitter can be reduced by feedback systems.

**Feedback systems** are of general importance for linear colliders. At the SLC the orbit and the energy of the beam are controlled by feedback loops [12]. A feedback system can transform a tolerance on \( |y(t)|^z \) (say a vertical position) into one on \( |y(t) - y(t - \tau)|^w \), where \( \tau \) is the delay between two measurements. Due to this delay the feedback works only for frequencies \( f < f_{\text{res}}/6 \) in the spectrum of the motion/jitter of \( y \), if the sampling rate \( 1/\tau \) is the repetition rate of the linac. It is difficult to operate a feedback loop on the beam even at frequencies
greater than $f_{rep}/20$. Generally one may distinguish orbit feed-
backs which correct the average orbit operated at a low sampling
rate and fast orbit feedbacks using fast kickers.

Fig. 6 shows the principle of a slow orbit feedback. The av-
average bunch position of the train is measured and corrected for
the next pulse (or later pulses), which can never be perfect due
to the delay $\tau = 1/f_{rep}$. This is especially a problem if the rep-
etition rate of the linac is low. Therefore another variant of feed-
back loop is needed for the TESLA design ($f_{rep} = 5$ Hz). Fig. 7
shows the principle. The offset of the first bunch is measured and
the offsets of the trailing bunches in the same pulse are corrected
by a fast kicker. The effective repetition rate for the TESLA de-
sign will be 1.4 MHz. The bunch-to-bunch offset fluctuations
due to long range wake fields are small for the TESLA design.

Different from the feedback shown in Fig. 7 would be a feed-
back loop which samples from pulse to pulse but affects individ-
ual bunches. A multi-bunch pattern which is stable from pulse
to pulse could be corrected by a very fast kicker.

Quadrupole jitter causes beam position jitter at the I.P. and
degenerates the luminosity. Mechanical quadrupole motion can
be measured by a geophone and corrected by a mover on the
quadrupole support. A feedback system running with a sampling
rate of 2 kHz has been successfully tested at DESY [13]. It was
possible to stabilize the quadrupole motion to about 20 nm.

The contribution of resistive wall wakes to the wake field ef-
effects is usually small. Nevertheless, these wake fields are impor-
tant for very short bunches ($\sigma = 25 \mu m$), which are considered
for Free-Electron-Laser facilities with very small tolerances for
the energy spread. Furthermore, resistive wall effects have to be
taken into account for collimators with small apertures.

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**Figure 6:** Schematic presentation of an orbit feedback system.

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**Figure 7:** Fast orbit feedback system. Example: TESLA.

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Invited Talk Session WE2

Chairman: H.D. Haseroth

Wednesday, August 28, 1996
ACCELERATING STRUCTURES FOR MULTIBUNCHES

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Abstract
Although the interaction between the beam and the fundamental mode is by far the strongest multibunch effect (beam loading), this process can be compensated by choosing an appropriate mode of operation (staggered timing, shaping of klystron pulses etc.). In contrast to this, higher order mode effects depend strongly on mechanical tolerances and require special structure designs to prevent multibunch beam break-up and emittance dilution: Cell-to-cell and structure-to-structure detuning are based on small variations of the cell geometry to decouple the long range wakefield contributions. On the other hand effective HOM damping in long traveling wave structures with either one or few dampers is limited by the existence of trapped modes and the low velocity of energy propagation. Even reduced requirements of damping together with detuning can be fulfilled only with a large number of damper cells. Therefore different concepts of damping with strong impact on the structure design are proposed.

Introduction
To avoid emittance dilution due to short and long range wakefields the bunch charge is limited, so that only a small fraction of the cavity energy can be transferred to a single bunch. Therefore, for effective operation, most linear collider studies consider multibunch operation to increase the power conversion efficiency $\eta = Q_c V_{acc}/f P_d$ and the filltime efficiency $\eta_{\text{fill}} = m_f/\tau_m + m_f f$.

<table>
<thead>
<tr>
<th>Structure</th>
<th>$\tau_m / \text{ns}$</th>
<th>$m_f$</th>
<th>$f / \text{ns}$</th>
<th>$\eta$</th>
<th>$\eta_{\text{fill}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TESLA [1]</td>
<td>515</td>
<td>1130</td>
<td>708</td>
<td>0.98</td>
<td>0.61</td>
</tr>
<tr>
<td>SBLC [3]</td>
<td>790</td>
<td>333</td>
<td>6</td>
<td>0.40</td>
<td>0.72</td>
</tr>
<tr>
<td>JLC-C [4]</td>
<td>281</td>
<td>72</td>
<td>2.8</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td>JLC-X [2]</td>
<td>110</td>
<td>85</td>
<td>1.4</td>
<td>0.54</td>
<td>0.52</td>
</tr>
<tr>
<td>NLC [5]</td>
<td>100</td>
<td>90</td>
<td>1.4</td>
<td>0.55</td>
<td>0.56</td>
</tr>
<tr>
<td>CLIC [6]</td>
<td>12</td>
<td>50</td>
<td>1.0</td>
<td>0.73</td>
<td>0.81</td>
</tr>
</tbody>
</table>

On the other hand multibunch interactions due to long range wakefields have to be taken into account. The beam loading of monopole modes - especially of the fundamental mode - are by far the strongest long range effects, but they are insensitive to manufacturing and alignment tolerances and predictibly reach a predictable steady state. Several modes of operation controlling the klystron timing, phase and/or amplitude are known to compensate this effect sufficiently. In contrast the excitation of fields with higher azimuthal order depend on the offset and tilt of the beam compared to the structure axis. Therefore transverse wakefield effects which cause emittance dilution can only be controlled by structure design, the straightness and the alignment. Active alignment is used to avoid the excitation of transverse wakefields while the rf-structure design intrinsically suppresses the relevant part of the long range wake - either by damping or detuning. Any alignment technique is limited by the straightness of the structure (mechanical structure design), the sensitivity of higher order mode pickups (rf-design), injection errors and the accumulation of alignment errors along the LINAC. Both methods, the suppression as well as the alignment allow the requirements for the other one to be relaxed.

Dipole Long Range Wake
The dominant contribution to the transverse wake of one accelerating section is produced by dipole fields and can be written as

$$W_2(s, r, r_1, r_2) = \frac{r_1 \cdot \cos(\varphi_1 - \varphi_2) \cdot w_r(s)}{w_r(s)}$$

with $r_1, \varphi_1, r_2, \varphi_2$ the offset coordinates of the source and witness charge and $s$ the longitudinal distance between source and witness. The normalized transverse wake function $w_r(s)$ can be split into a resonant term $w_r(s)$ and a transient term $w_r(s)$. The resonant part can be expressed by eigenmodes

$$w_r(s) = \sum_k k_s \frac{c}{\omega_s} \sin \left( \frac{\omega_s s}{c} \right) \left\{ \begin{array}{ll} 0 & \text{if } s < 0 \\ 2 & \text{else} \end{array} \right.$$  

Usually this equation is modified by damping terms with the time constants $\tau_s = 2Q_0/\omega_s$ to take into account small losses e.g. due to the wall conductivity. As the cutoff frequency of the beam pipe is approximately two to three times higher than the operation frequency only modes below this limit are trapped in the section and can be considered as 'undamped'. Even for higher modes the velocity of energy propagation is typically small compared to $c$ so that the damping time is much higher than $L/c$ (with $L$ section length). Therefore it is convenient to use this description (together with the corresponding longitudinal component) for beam dynamics simulations of weakly damped structures. For strongly damped structures $w_r(s)$ is directly calculated in time domain.

The requirements for the suppression of the long range wake, derived from beam dynamics simulations, depend on many parameters (such as the bunch charge, acceleration gradient, focussing strength and tolerable emittance growth). Nevertheless for most design studies a rough criterion can be given: for the CLIC [6] and the X-band sections [7] the transverse wake for following bunches has to be reduced by at least by a factor of 100 compared to the peak wakefield. The simulations for the SBLC structure indicate that a factor of 10 is necessary [3], and for TESLA a suppression factor of 2 is more than sufficient [8].

The sums of loss- and kick-parameters to a certain frequency $f$
\[ G(f) = \sum_{f \leq f_0} k_f, \quad H(f) = \sum_{f \leq f_0} \frac{c}{\omega_0} k_f \]

illustrate the net effect of mode density and strength. Fig.1 gives an impression of the frequency distribution of \( k_f \) and the spectrum of \( w_f(s) \). This diagram was calculated for a constant gradient structure with 180 cells very similar to the SBLC section, but it is typical for most disc loaded structures. In the frequency range below \( 4f_0 \) about ten separated passbands can be distinguished\(^1\) for individual cells in a periodic approximation. Although these bands are not identical for different cells in a tapered structure, certain frequency ranges can be related to particular bands. In this sense even in aperiodic structures many modes can be addressed by band numbers.

\[ \begin{array}{c|c|c|c}
  f/f_0 & G(f) & H(f) \\
 0 & 1 & 0.1 \\
 1 & 1.5 & 0.3 \\
 2 & 2 & 0.6 \\
 3 & 2.5 & 1 \\
 4 & 3 & 1.5 \\
 5 & 3.5 & 2 \\
 6 & 4 & 2.5 \\
 7 & 4.5 & 3 \\
 8 & 5 & 3.5 \\
 9 & 5.5 & 4 \\
 10 & 6 & 4.5 \\
\end{array} \]

Fig. 1. Normalized sum of loss- and kick-parameters, \( G = G(1.5f_0), H = H(1.5f_0) \).

**The First Dipole Band**

The first step in fig. 1 at \( f/f_0 = 1.3 \ldots 1.5 \) corresponds to the lowest dipole band. As most design effort and most HOM calculations were dedicated to this band the step is normalized to one. The absolute values \( G_0 \) and \( H_0 \) depend on the precise cell shape (e.g. the ratio of coupling hole diameter to wavelength) but they can roughly be estimated by

\[ \frac{G_0}{L} = \frac{\sum k_f}{L} = \frac{80}{\varepsilon_0 \lambda_0^4}, \quad \frac{H_0}{L} = \frac{\lambda_{HOM} G_0}{2\pi} = \frac{9}{\varepsilon_0 \lambda_0^3}. \]

The peak value of the transverse wake, which is essentially caused by modes of the first dipole band, is approximately \( 2H_0 \). This gives a relation for the absolute requirements of wakefield suppression.

<table>
<thead>
<tr>
<th>Band</th>
<th>( \frac{L}{N_{\text{bunch}}} )</th>
<th>( \frac{\sum k_f}{L} )</th>
<th>( \frac{\max(w_f(s))}{L} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TESLA</td>
<td>1</td>
<td>3.6</td>
<td>810 \times 10^{12}</td>
</tr>
<tr>
<td>SBLJ</td>
<td>6</td>
<td>1.1</td>
<td>95 \times 10^{12}</td>
</tr>
<tr>
<td>JIL-X</td>
<td>1.5</td>
<td>0.65</td>
<td>13 \times 10^{14}</td>
</tr>
<tr>
<td>NLC</td>
<td>1.8</td>
<td>0.63</td>
<td>13 \times 10^{14}</td>
</tr>
</tbody>
</table>

\(^1\) Contribution of the first dipole band.

**Higher Dipole Bands**

The contribution of the 2nd, 4th and 5th dipole band to the normalized kick-parameter sum is only a few percent for each. In constant impedance sections (such as CLIC) this contribution is essentially caused by one mode which cannot decohere with other oscillations. Only a continuous cell-to-cell detuning is necessary to decrease the transversal wake for the succeeding bunches below 1%. This is already reached with conventionally designed constant gradient sections. Significant steps higher than 10% can be seen for the 3rd band (\( f/f_0 = 2.3 \)) and for the 6th band (\( f/f_0 = 3.2 \)). The effect calculated in [9] for the NLC structure is smaller, but could only be avoided by tapering the iris thickness of the NLC and JILC-X structures to improve the detuning. For the SBLC structure the 'natural' CG detuning is sufficient for the 3rd band, but the synchronous frequencies of the 6th band are too close for all cells. Therefore a slight tapering of the iris thickness is necessary as well.

**Very High Modes**

The influence of very high modes (above the sixth passband) is neglected for two reasons: the decay time \( \tau_0 = 2Q/\alpha \) decreases at least with \( \omega^3 \) and the spectral power density in a loss free structure decays asymptotically with at least \( \omega^5 \). The first argument is certainly right for damped structures, but in undamped sections with 100 cells or more the energy dissipation in the walls and the power flux into the beam pipe or through high power couplers does not prevent decay times in the order of or above \( \tau_0 \). The second argument was verified for the SBLC structure by a direct calculation of the transverse long range wake in the frequency range below \( 10f_0 \). This frequency range is still too small to estimate the exponent of the spectral decay, but a significant drop could be observed. The frequency contribution above the sixth passband (\( 3.3f_0 \)) appears as stationary noise with the rms amplitude 0.01 \( \max(w_f) \) for \( s > 40 \lambda \).

**Bunch-to-Bunch Damping**

Bunch-to-bunch damping means that the damping time is at least of the order of the bunch repetition time. This is the only method to reduce wake fields in CI structures (more precisely: not detuned structures) but it is also used in tapered structures to ensure - independent from the detuning - that all HOMs are damped. On the one hand a higher order mode needs a quality factor equal or below \( Q = \tau_0 \pi f_0 / \text{ind} \) to be damped during the bunch repetition time \( \tau_0 \) by the factor \( d \). On the other hand the maximal damping is limited by the velocity of energy propagation and the distance between HOM dampers. The following estimations are based on a simple propagation model. They are valid if the decay length \( \nu \alpha / Q_0 f_0 \) is large compared to the cell period. With **dampers at the structure ends** the quality cannot be reduced below \( Q = \omega_0 \tau_0 / A \), where \( \tau_0 \) is the HOM filltime. \( \nu_0 \) is given for CI structures by \( L / \nu_0 \) and for smooth tapered structures can be estimated by \( L / f_0 \nu_0 \nu_0 \). However the theoretical \( Q \) values are by far not reachable for trapped modes.
Only TESLA with its large bunch distance and small damping requirement is well below this limit. Therefore two couplers at the beam pipes of every nine cell cavity are sufficient for both polarization planes. Nevertheless the detuning of the end cells (due to the beam pipes), their different polarization (due to the coupler polarization) and manufacturing tolerances may cause trapped or tilted field distributions with little energy at the coupler with the matching polarization. As the cell to cell coupling of modes below the cutoff frequency of the beam pipe (TE_{111} and TM_{111}-like modes) is large, their field pattern is not very sensitive to this effects. Tilted modes above f_c are either damped by the coupler at the cavity end or the coupler at the next cavity. To “untrap” TE_{111}-like modes an asymmetric end cell tuning (with modified cavity curvature) is used [10].

Using several dampers along a section provides stronger absorption, but even with perfect absorbers, the distance between dampers cannot be greater than L_c=2\sqrt{c/f_a} [11]. (This equation is applicable to tapered structures provided that V_p, the local group velocity, is approximately constant over the length L_c.) For LC projects with small bunch spacing it would be necessary to place dampers every few cells in order to fulfill the requirements for the first pass band. As it is difficult to manufacture and tune sections with a high number of special cells and as real absorbers are less efficient than ideal ones, structures with one damper per cell (for at least one polarization plane) are preferred.

The “HOM free” choke mode cavity [4] in fig. 3 is foreseen for the JLC-C section. The choke is a sharp notch-filter which only traps the accelerating mode inside the cavity. All other modes can propagate out of the cavity without large reflections at the choke. A good broad band absorber is necessary to terminate the outgoing cylindrical wave. Compared to a conventional disc loaded structure the quality of the accelerating mode is reduced by 13% and approximately 13% of its field energy is stored in the choke filter so that the shunt impedance is lowered by 25%. As also the beam loading is also reduced, only 15% more input power is necessary to achieve the same loaded gradient.

For the new CLIC multibunch parameters purely damped structures are being investigated [6]. Therefore either two or four radial output waveguides couple to each cell. The two waveguide version uses T-shaped waveguides which directly couple to the cell. In principle this type of coupler is suitable for both polarization planes, but to avoid asymmetric damping it is turned by 90 degrees from cell to cell. The four waveguide version uses iris coupling - which is more difficult to fabricate - but reduces the additional losses to about 5%. Time domain simulations with perfectly terminated waveguides obtained less than 1% of the single bunch total transverse wake for the following bunches in a frequency range below 4.7f_c.

Cell-to-Cell Detuning

The interference of several modes in a narrow frequency range can be used to suppress the wake field by detuning. If the frequency spacing of modes is small compared to c/s the sum for the normalized wake can be approximated by an integral

$$w_r(s) = \int F(\omega) \sin \left( \frac{\omega s}{c} \right) d\omega \quad F(\omega) = 2k(\omega) \frac{c}{\omega} \frac{\partial n}{\partial \omega}(\omega),$$

with continuous functions for the loss parameter k and the mode density \(\partial n/\partial \omega\). If we consider the contribution of only one band, F(\omega) is a narrow function with the center frequency \(\omega_c\). The envelope E(s) of the wake function is given by the magnitude of the Fourier transformation of F(\omega-\omega_c). In the range of a few bunch distances a very good approximation for w_r(s) and F(\omega) can be found from the ‘uncoupled model’ [9]: the parameters \(\omega_0\) and \(k_0\) of the complete (coupled) solution are replaced by the synchronous parameters \(\omega_{0c}\) and \(k_{0c}\) which can be calculated for the periodic approximation of each individual cell. On a longer scale the oscillations may rephase to some extent and after a very long distance the oscillator phases are randomly distributed which leads to the rms amplitude

$$\langle w_r(s) \rangle = \sqrt{\frac{2}{\sqrt{2}} \sum k_c^2 \exp(-i\omega_c / cQ_c)}.$$

Constant Impedance Structures

For conventional disc loaded structures F(\omega) is determined by the generic cell geometry, the cell number N and the damping parameter \(\tau_0=0.5\sin(P_c/P_{ac})\). To a good approximation it rises linearly from F(\omega_0)=F_{ac}k_{0c}/\omega_{0c} to F(\omega_{0c})=F_{ac}\propto k_{0c}/\omega_{0c}. The envelope is

$$\frac{E(s)}{E(0)} = \frac{\sin(\Omega s)}{\Omega s} + i A \left( \frac{\sin(\Omega s)}{\Omega s^2} - \frac{\cos(\Omega s)}{\Omega s} \right)$$

with A=(F_{ac}/F_{ac}+F_{ac}) and \(\Omega=(\omega_{0c}-\omega_c)/2c\). Usually the second term is negligible for the third and later bunches. According to this model the wake of the first dipole band of the SBL2 structure (with \(f_{ac}=320\text{MHz}, F_{ac}/F_{ac}=1.38\)) is below 5\% of the peak value for all following bunches. The calculation of the long range wake by a loss-free, double-band coupled oscillator model indicates that the wake is below the 5\% level for the next 120m and recoheres to 30\% after 132m.

Detuned Structures

Three cavity parameters are used for the JLC-X and NLC sections to tune the accelerating mode and to detune the first and some higher dipole bands. As mentioned before the iris thickness is used to spread the synchronous frequencies \(\omega_{0c}\) of the third and sixth dipole band. Therefore the pairs of cell and iris radii are uniquely defined for every group velocity \(v_g\) of the accelerating mode. In contrast to CI structures the group velocity profile is not adjusted with respect to the accelerating mode but to obtain a particular frequency response.
$F(\omega)$. One idea was to produce minima of $E(z) = \sin(\Omega z)/(\Omega z)$ at the positions of the next bunches ($s = n t/c$) but the present proposals use a truncated Gaussian distribution

$$F(\omega) \propto \exp \left(-0.5 \left(\frac{\omega - \omega_0}{\Delta \omega}\right)^2\right) \quad \text{for} \quad 2(\omega_r - \omega_r) < \Delta \omega.$$  

$\Delta \omega/\omega_0$ is essentially determined by the structure parameter $\tau = \ln(P_r/P_s)$ and $\omega_0/\Delta \omega$ is set so that the envelope function for the second bunch drops below 0.01 $E(0)$. Calculations for the NLC structure based on coupled oscillator models show that the envelope function resurges after $L = 10\text{m}$ above the 1% level. To verify that the detuning works as expected, a full scale prototype of the detuned NLC structure has been build and was measured in the ASSET test facility [11]. The measurement is in good agreement with the prediction over the first 60cm but for the rest of the $L$-range significant differences (values even above 0.01 $E(0)$) are observed. This is explained by an 1.5 $\times$ 10^4 rms fractional error of the cell dimensions. At larger distances the prediction would better agree with the data if the $Q$ of the modes used in the calculations were lowered from the assumed value of 6500 to about 4000. Measurements of the loaded $Q$, however, show no evidence for the smaller values.

### Section-to-Section Detuning

The wake function of two or more successive structures can be added to a total wake field if the length of the combined sections is still small compared to the betatron wavelength.

A **systematic detuning** of multiple sections is limited by manufacturing tolerances. For a randomly distributed frequency error with the rms width $\langle \delta \omega \rangle$, the effective transverse error-wake can be estimated by

$$\frac{\langle w_n \rangle}{\max(w_n)} = \frac{s}{c} \frac{\langle \delta \omega \rangle}{\sqrt{2M}N} \quad \text{for} \quad \frac{s}{c} \frac{\langle \delta \omega \rangle}{\sqrt{2M}N} \ll 1$$

(M is the number of sections). Even for one section it is difficult to keep $\langle w_n \rangle$ below the desired level with realistic manufacturing tolerances. Therefore systematic section-to-section detuning is not considered for the present LC projects.

A **random detuning** of the center frequencies by $\delta \omega_n$ leads to the envelope

$$\frac{1}{M} E_\perp(s) = \frac{1}{M} \sum_{m} E_\perp(s) = E(s) \frac{1}{M} \text{Re} \left\{ \sum_{m} \exp(i \delta \omega_n s / c) \right\}.$$

If the arguments of the exponential function are in the order of $i\pi$ or larger the effective envelope is $E(s)/\sqrt{2M}$. As all sections of a LINAC are randomly detuned the particle dynamics over many betatron wavelength is affected and an 'effective' value of $M$ cannot trivially be determined.

### Damping and Detuning

The recoherence of the wakefield in purely detuned structures takes place on a time scale $\tau_L = L/c$ which is short compared to the fill time $\tau_f$ and therefore short compared to the length of the bunch trains considered in most LC design studies. Only a weak additional damping in the order of $Q = \pi \tau_f / \tau$ is needed to suppress the long range wake. For the SBLC structure an average $Q$ value of 3000 is needed, the goal for the NLC damped and detuned structure (DDS) of 1000 even allows the cell and alignment tolerances to be relaxed.

For the concept ‘**weak damping with few dampers**’ a large variety of coupling geometries and structure-damper configurations have been investigated. Due to the existence of trapped modes, damping cells inside a section are needed. E.g. for the SBLC structure, dampers would be needed at least three positions, so that one damper is in the trapping range of each mode. Unfortunately even a damping cell inside the trapping range can be completely ineffective. This is the case for damping cells with two fundamental-mode-waveguides per polarization plane which do not break the dipole symmetry. To overcome this, either more or more complex one-cell-dampers (with broken symmetry, more than two waveguides or waveguides with more than one propagating mode) are required. Another disadvantage of special damping cells is their interference with the detuning: ‘weak damping with few cells’ needs an optimal cell-waveguide coupling which drastically disturbs the detuned short range wake. This effect can be lowered by increasing the number of dampers and reducing their coupling strength. The extreme is ‘**weak damping with one damper per cell**’.

Usually the HOM-absorbers are separated from the accelerating mode by a special coupling geometry and/or frequency selective elements, but even with artificially increased losses at a part of the resonator surface, it is possible to achieve the needed selectivity [12]. Therefore the iris tips of all SBLC cells are covered by a material with ten to twenty times higher surface resistivity, as can be seen in fig. 2b. This decreases the quality of the accelerating mode by 5%, but the effective shunt impedance is lowered by less than 2.6%. As the iris coating is located exactly where the highest surface field strength occurs, investigations are necessary to prove the high power capability. The first tests with steel and Kanthal coated cells under conditions corresponding to an unloaded gradient of 25MV/m showed no evidence of surface break-down effects. Further measurements aiming to the doubled field in the 1TeV version are in preparation. To minimize the HOM excitation by active structure alignment, each section is equipped with two HOM pickups. One will be located near the front end, and one almost at the 2/3 point of the section length. The

---

1 The waveguide-structure configuration is a three port system. Due to the unitarity of the scattering matrix not all waves from the periodic structure can be diverted to the waveguide absorber.
coupling to the circumference pickup waveguides is a compromise between the necessary resolution (about 10μm) and the perturbation of the ω0, k, distribution.

The damping of the NLC structure [13] is provided by a set of four waveguides that run parallel to the structure (see fig. 2c). In a localized sense the field in a tapered structure can be approximated as the superposition of forward and backward traveling waves. If their phase advance is close to that of the manifold waveguides, their energy can be drained to absorbers at the ends of the manifold waveguides. Additionally the excitation of all ‘trapped’ modes can be detected at these terminating loads. For each mode the coupling condition is fulfilled in the range of only few cells, therefore the damping can be controlled locally. The structure dimensions are determined in the following succession: the thickness and beam hole dimensions of the coupling irises are taken to be the same as those of the purely detuned section to retain their ω0, k, distribution. To reach the desired damping, the depth of the circumferential coupling holes and the widths of the waveguides are tapered. Finally the cavity radii are adjusted for the 2π/3 accelerating mode. For the first 2/3 of the cells the depth of the manifold coupling holes is positive so that the shunt impedance degradation is less than 3%. In the last third the waveguides protrude into the cells which causes an increasing degradation to a maximum of about 5%.

Summary and Conclusion

Concepts for the suppression of long range wakes are presented for all multibunch LC design studies which take into account a large frequency range. With the exception of the SBLC iris coating, the NLC damped and detuned structure and the CLIC proposals, all techniques have been investigated in test structures. Besides refinements of the theoretical models and further test setups, economical manufacturing methods will have to be developed.

References

LASER ION SOURCE DEVELOPMENT FOR HEAVY IONS

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Abstract

For light ions, Laser Ion Sources have already found their application (e.g. Dubna). At CERN a source for heavy ions with the final characteristics Pb\(^{16+}\), with current of 5 - 10 mA, a pulse length of 5 - 6 µs, a normalised 4 x rms emittance of 0.2 - 0.4 mm mrad, is under development. Topics like the required laser energy and performance, the ion beam transport and the acceleration are discussed. The different phases of the realisation of this source and its status are presented.

Introduction

In the late 80s the concept of a Lead-Ion Accelerating facility at CERN was under discussion, so laser ion sources became of interest. In 1988 a 50 J carbon dioxide laser was acquired to assemble an experiment (Fig.1). In 1991 first results were reported [1]: Pb26+ was observed, a group of ions of charge states around 20+ providing current densities of 1 mA/cm\(^2\) was obtained. From the start, most of the studies were carried out together with ITEP, involved in plasma physics and a branch of the Kurchatov Institute at Troitsk, TRINITI. There, lasers 2-3 times higher in energy became available, and the generation of Pb ions around charge 25+ at current densities of 0.3 mA/cm\(^2\) per charge state, was observed. At the beginning of 1994, Al ions, generated in the Laser Ion Source (LIS), were accelerated in a radio frequency quadrupole (RFQ). Currents of more than 1 mA per charge state of Al\(^{19+}\) to Al\(^{13+}\), were observed [2], the pulse length was several µs. This achievement, together with the results with heavy ions, encouraged us to direct our development work towards a source capable of providing ions for the Large Hadron Collider (LHC)[3]. The scheme retained in the LHC feasibility study is based on an ECR source and a low energy storage ring. The approach based on a LIS is pursued as an alternative solution. In this report a possible configuration of a source and a pre-accelerator is sketched. Attention is focused on some key elements. The different phases of realisation of a complete device are described. In this context, the present experiment and its preliminary results are analysed. Building such a device is a matter of many years. New technologies may in the future lead to solid state lasers and sources, providing sufficient ion yield at much higher charge states. How we intend to cope with these trends is discussed briefly in the section on recent developments.

![Diagram](image)

**Fig.1.** Configuration of a Laser Ion Source

Requirements from a Source

For heavy ion experiments, the LHC demands a luminosity \( L = 3.2 \times 10^{34} \) cm\(^{-2}\) s\(^{-1}\) / bunch. The machine is designed to obtain this value with 9.4 \times 10^7 ions / bunch at a normalised 1 rms emittance of \( \sigma_n = 1.5 \times 10^{-6} \) m-mrad.

The LHC filling scheme described in [4] and the present performance of the different machines lead to our target value at the extraction electrodes of the LIS:

\[
1.4 \times 10^{10} \text{ ions of Pb}^{16+} \text{ in a pulse of } 5.5 \mu\text{s},
\]

\[
\sigma_n (\text{rms}) = 0.05 \times 10^{-4} \text{ m-mrad, every } 1.2 \text{ sec.}
\]

A Possible Configuration of a Source with Pre-accelerator

The configuration should consist of
1) A laser of 100 J.
2) A photon transport system of sufficient length to decouple the laser from the target.
3) A target capable of producing \( 10^6 \) shots without replacement.
4) An extraction system for accelerating Pb\(^{16+}\) to 9.6 keV/u.
5) A low energy beam transport channel (LEBT).
6) An RFQ, accelerating Pb⁺⁺ from 9.6 to 250 keV/u.
7) A beam line with switch yard in Linac3 [5].

Key Elements

At present, design concentrates on (i) a new laser and (ii)
the construction of the ensemble “target-illumination-ion
extraction”.

The results of the present experiment should later allow
the choice of the definitive LEBT (e.g. a multi element
filter line or a straight line (e.g. 2 solenoids)).

(i) The Laser

The present 50 J laser, well suited for many of the
preparatory experiments, fails as final laser as repetition
rate, energy per pulse and stability from shot to shot are
too low.

In experiments and plasma simulations, the charge state with
the highest abundance as function of laser power density and
focal spot size was established (see Fig. 2 [6]). Current
density was found to scale linearly with energy.

\[ \frac{\phi}{\phi_0} = 150 \mu m \]
\[ \frac{\phi}{\phi_0} = 50 \mu m \]
\[ \frac{\phi}{\phi_0} = 30 \mu m \]
\[ \frac{\phi}{\phi_0} = 25 \mu m \]

![Charge-State as Function of Power Density](image)

Based on these results and keeping the aperture of the
extraction electrode sufficiently small (emittance is a
function of the diameter), laser energy and plasma expansion
length could be estimated [7]. The set of data, scaling laws
and the result are summarised in Table 1.

A very important observation was that from the total laser
energy only the photons reaching the target area within the
first 30 ns and the Airy spot, contribute to the ion yield.

The energy within these constraints is termed useful energy
\((E')\). In a free-running laser, \(E'\) can become as low as 25 %
of the total energy. The non-useful energy contributes,
however, to the damage of the target and contamination of
the optical elements.

Total Energy \(E_{\text{total}} = 80\) J,
50% in pulse of 30 ns, 50% in spot with \(d = 100\) µm
\(\rightarrow\) useful \(E' = 20\) J, \(\rightarrow P = 8 \times 10^{12}\) W/cm²

observed:
- with highest abundance: 25
- at \(l = 3.5\) m, \(\tau = 8\) µs for ions around \(z = 25\),
- at \(l = 3.0\) m, \(j = 1.2\) mA/cm² in aperture \(\Omega = 34\) mm
relations, leading to the set of “key data”:
- \(\tau \propto l^{3}, j \propto l^{5}, h \propto E'\), \(j_{25}, = 15\%\) of \(j\).

key data:
- with a laser of \(E' = 80\) J in 30 ns, focused to \(d' = 200\) µm,
- a current density \(j_{25}, = 1.12\) mA/cm² at \(l = 2.6\) m should
be obtained.

The pulse should last \(\tau = 6\) µs. Through the extraction
aperture \(\Omega\), a current of 10 mA should flow.

\[ P = \text{power density}, \ l = \text{plasma expansion length}, \ d', \ d = \text{spot diameter of central diffraction pattern of laser beam at the target with intensity contour } I = 1/e \star I_{\text{peak}}, \]
\[ j = \text{current density of group of charge states around 25+} \]

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Estimation of Laser Energy and Plasma Expansion Length for the Final Set-Up, based on Experimental Data</th>
</tr>
</thead>
</table>

Another characteristic of a free running laser is the variation
of pulse form from shot to shot due to excitation of different
longitudinal modes (Fig.3). This effect is considered
responsible for most of the ion current variation (±25 %).

![Pulse Shape of a Self locking Laser](image)

These problems may be solved by using a laser system of a
master oscillator and a power amplifier (Fig.4), working in
single transverse mode (TEM₀₀) and single frequency.
The completion of the LJS for the LHC can be seen in 4 phases:
1) Integration of the laser ion source in an accelerator environment, matching the different beam parameters with respect to beam brightness.
2) Demonstration that this device can be tamed with respect to plasma instabilities.
3) Device scaling to "operational" dimensions
4) Integration in Linac3.
We are in phase 1. Next year we will enter phase 2, when a master oscillator will be installed and the present 50 J laser converted to an amplifier.
In parallel, the design of the final amplifier will proceed, construction and integration of the new source ensemble into the experiment is envisaged. Up-grade of the final LEBT may become necessary, and the design of a mean energy beam transport (MEBT) should start.
Phase 3, should see the up-grade of the RFQ to 250 keV/u for Pb^208, and the integration of the 1 Hz - 100 J laser system.
Phase 4 is still far future. Getting the beam into the MEBT of Linac3 will demand a switchyard.

**Present Experiment, Preliminary Results**

A schematic diagram of the set up is shown below.
The experiment is described in detail in [8], shown in Fig. 6. The main characteristics of the laser can be found in Table 4. 50 J is the nominal energy per pulse. The laser parameters have been optimised with respect to ion yield. Under these conditions, 30 J is drawn. About 7.5 J contribute to the yield of Ta^{18+} - Ta^{26+} ions. A power density P = 1.6 \times 10^{13} \text{ W/cm}^2 is achieved. At present we use Tantalum. Ta^{18+} is, in its charge to mass ratio, very similar to Pb^{18+}. It is preferred to Pb due to less contamination of the target area and longer life time (less cratering of the target). Later Pb^{18+} will be used as well.

The relative abundance of ions, passing the extraction electrode, is shown in Fig. 7.

![Graph showing the abundance of ions for the unaccelerated plasma](image)

**Fig. 7.** Abundance of ions for the Unaccelerated Plasma, a) \( \gamma \) independent of charge state, b) \( \gamma \) scaling with kinetic energy, c) \( \gamma \) proportional to charge state.

Measurements of the secondary emission coefficients \( \gamma \) for the detector material, CuBe, bombarded by heavy ions, are still missing for ions with mean energies of 2.5 keV/q. For these energies the two mechanisms for the generation of secondary electrons, (i) due to kinetic energy and (ii) due to potential energy seem to overlap. The three distributions in the graph indicate the "uncorrected" measurement, and two corrected ones. The true distribution will be somewhere in between b) and c).

The LEBT, consisting of two solenoids, had to be designed on the basis of preliminary parameters, measured under conditions very different from the final set-up; TRACE was used for beam simulations. Now, the program PATH [9,10] (based on TURTLE) which allows multi-particle tracing and the representation of magnetic elements by field tables, will be used to optimise the beam transfer. The RFQ is described in [11,12]. Some characteristics are given in Table 2.

<table>
<thead>
<tr>
<th>Design ion:</th>
<th>charge 18+, mass 208 a.m.u.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input energy:</td>
<td>6.9 keV/u</td>
</tr>
<tr>
<td>Output energy:</td>
<td>100 keV/u</td>
</tr>
<tr>
<td>Transmission:</td>
<td>90%</td>
</tr>
<tr>
<td>Current per charge-state:</td>
<td>10 mA</td>
</tr>
<tr>
<td>Acceptance:</td>
<td>300 mm*mrad, total, unnorm.</td>
</tr>
<tr>
<td>Longitudinal emittance:</td>
<td>12 deg*keV/u, 1 rms value</td>
</tr>
</tbody>
</table>

**Table 2 Main characteristics of the RFQ**

Its performance measured with protons is close to design. The feared sparking from plasma photons entering the RFQ, occurs very frequently. This RFQ is designed for peak currents of 30 mA, 19 mA are available now. To test the RFQ to its full performance, the present charge to mass ratio of 0.11 will be decreased to 0.086, working with Ta^{16+} or Pb^{18+}.

The performance of the experiment is given in Table 3. The LEBT is at present the weak element in the chain. Matching of the extraction to the RFQ is yet not achieved.

<table>
<thead>
<tr>
<th>pos.</th>
<th>mean current in 5 ( \mu \text{s} ) (mA)</th>
<th>( \varepsilon ), ( 4 \times \text{rms} ) (mm*mrad)</th>
<th>full ( \Delta E/E )</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60, (peak 80)</td>
<td></td>
<td></td>
<td>( \Theta = 30 \text{ mm}, \ l = 1 \text{ m}, \ U = 60 \text{ kV} ) ( \text{max} = 100 \text{mA} ) ( \text{at} = 0.9 \text{ m} )</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>250</td>
<td>18 charge-states in 3-8 ( \mu \text{s} ) ( \text{max: Ta}^{20+} )</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10, (peak 19)</td>
<td></td>
<td>0.11 ( \qquad 0.025 )</td>
<td>no modulation ( 60-65 \text{ kV} ), modul.</td>
</tr>
<tr>
<td>4</td>
<td>2.0, (peak 9) ( \text{Ta}^{20+} : 1 )</td>
<td></td>
<td></td>
<td>( \Theta = 0.5 \text{ mm} ) ( 6 \text{ charge-states} )</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td></td>
<td>0.05</td>
<td>( 5 \text{ charge-states} ) ( \text{Ta}^{18+} - 22+ )</td>
</tr>
</tbody>
</table>

**Table 3 Summary of Preliminary Results**

The positions are 24 mm after extraction (1), 79 mm after extraction (2), spectrometer after LEBT (3), RFQ in-input plane(4), 90 mm after RFQ (5), behind spectrometer after RFQ (6). \( U = \) extraction voltage, \( \Theta = \) aperture of Faraday cup, \( l = \) plasma expansion length.

**Recent Developments**

Today, CO\(_2\) lasers with high energies, at high pulse rates, are field proven. Energies and pulse characteristics to provide the needed particles from the target, are known. In the past, solid state lasers in the energy range of 20 - 100 J with pulse rates of 1Hz were not available. The problem was heat dissipation (solved in CO\(_2\) lasers by circulating gas stream). Diode pumped lasers, where the pumping efficiency is much higher than with flash lamps may break this limitation and performance to cost ratio may become more favourable for solid state lasers than for gas lasers.

In parallel to this development, it could be shown that ions with charge states, much higher than 20-30 (Ta\(^{26+}, \text{Pb}^{18+}\)), can be obtained [13] at shorter pulse duration and laser wave lengths, 10 times shorter than for CO\(_2\), yet with low particle yield. An ion linac without a stripper may become a reality in the future.
To follow these developments as tightly as possible, our collaboration has been enlarged.
A brief overview on lasers, available in this collaboration is given in Table 4.

<table>
<thead>
<tr>
<th>Institute</th>
<th>Lasers</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN</td>
<td>CO$_2$, 50 J, 10.6 μm, 50 ns FWHM, 0.05 Hz free running oscillator (FRO)</td>
</tr>
<tr>
<td>ITEP</td>
<td>CO$_2$, 10 J, 10.6 μm, 50-65 ns, fro, 1 Hz CO$_2$, 20-40 J, 10.6 μm, 50-65 ns, 0.07 Hz</td>
</tr>
<tr>
<td>TRINITI</td>
<td>CO$_2$, 100 J, 10.6 μm, 30 ns, fro, 0.02 Hz other, master - oscillator / power amplifier systems, CO$_2$, max 300 J</td>
</tr>
<tr>
<td>ASCR Prague</td>
<td>Iodine photodissociation, 50 J, 1.315 μm, 300 - 500 ps, also higher harmonics of 2nd, 3rd order, then 25 J, time between shots: several minutes, master oscillator / power amplifier</td>
</tr>
<tr>
<td>IPPLM Warsaw</td>
<td>Nd:glass, 15 J, 1.06 μm, 1 ns, 2×30 J, 1.06 μm, 0.5 ns Nd:glass, 2 J, 1.06 μm, 1 - 2 ps, all systems master oscillators / power amplifier time between pulses 20 minutes</td>
</tr>
</tbody>
</table>

Table 4 Lasers at the Collaborating Institutes

Conclusion

Reaching nearly 20% of the finally required amount of ions for Pb$^{208}$ for the heavy ion Tantalum, see Table 5, is encouraging.

However, much attention will still have to be spent on laser performance, particle transmission from the extraction electrodes to the RFQ and lay-out and construction of the ensemble target - extraction - illumination to reach the required source performance.

The experimental set-up with its RFQ and the numerous beam diagnostic devices, should allow us to evaluate the beam brightness.

Table 5 Parameters at Out-let of the RFQ

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>27 Al 10+</td>
<td>&lt;2</td>
<td>3</td>
<td></td>
<td>140</td>
<td>1.73</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>181 Ta 20+</td>
<td>1.6</td>
<td>2</td>
<td>0.08</td>
<td>100</td>
<td>1.47</td>
<td></td>
</tr>
<tr>
<td></td>
<td>208 Pb 25+</td>
<td>7-8</td>
<td>5</td>
<td>0.07</td>
<td>13</td>
<td>250</td>
<td>2.32</td>
</tr>
</tbody>
</table>

Acknowledgements

Maintaining and improving of operational systems has become the main work load of the permanent staff, steadily shrinking. We would like to thank all those who despite their increasing daily duties find the time to help us at this experiment: the teams, taking care of magnets, mechanical elements, radio frequency, survey and the vacuum equipment.

References

BEAM TEST RESULTS OF THE INS RFQ/IH LINAC

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Abstract

A linac complex for radioactive beams has been constructed at INS, which comprises a 25.5-MHz split coaxial RFQ (SCRFQ) with modulated vanes and a 51-MHz interdigital-H (IH) linac. The SCRFQ accelerates ions with a charge-to-mass ratio \( q/A \) greater than 1/30 from 2 to 172 keV/u. The beam from the SCRFQ is charge-stripped by a carbon-foil, and is transported to the IH linac through two magnetic-quadrupole doublets and a 25.5-MHz rebuncher cavity. The IH linac accelerates ions with a \( q/A \) greater than 1/10, and the output energy is variable in the range of 0.17 through 1.05 MeV/u. Beam tests of the linac complex performed with \( N^2+ \) ions show that the output beam energy and transmission efficiency agree well with predictions.

Introduction

A short-lived nuclear beam acceleration facility has been constructed at INS, which is a prototype for the exotic nuclei arena of the Japanese Hadron Project [1]. The facility comprises an SF cyclotron, an ISOL and a heavy-ion linac complex. The short-lived nuclei, produced by bombarding a thick target with a 40-MeV 10-μA proton beam from the existing SF cyclotron, are ionized in an ion source, mass-analyzed by the ISOL, and transported to the linac complex through a 60-m long beam line. The linac complex comprises a 25.5-MHz split coaxial RFQ (SCRFQ) with modulated vanes and a 51-MHz interdigital-H (IH) linac, as shown in Fig. 1.

As a front-end structure of the linac complex, we employed an SCRFQ, because the cavity diameter is smaller than 1 m even at a low frequency such as 25.5 MHz. The SCRFQ accelerates ions with a \( q/A \) greater than 1/30 from 2 to 172 keV/u [2]. After charge stripping, the IH linac, 5.63 m in total length, accelerates ions with a \( q/A \) greater than 1/10 up to 1.05 MeV/u, which comprises four tanks and three magnetic-quadrupole triplets between tanks [3]. Since the tanks are excited separately by four rf sources, it is possible to vary the output beam energy continuously in a range from 0.17 to 1.05 MeV/u by adjusting the rf power levels and phases. The duty factor of the linac complex depends on \( q/A \) of the ions: nearly 100% at \( q/A \geq 1/16 \), and given by \( 270 \times (q/A)^2 \times 100\% \) at \( 1/17 \geq q/A \geq 1/30 \).

In the stage of completion of the SCRFQ, the low-energy beam transport (LEBT), and first quadrupole doublet in the medium-energy beam transport (MEBT), we conducted beam tests of the SCRFQ, by using stable-nucleus ions, \( N^+ \). After beam tests, the IH linac, the rebuncher cavity, the second quadrupole doublet in the MEBT, and a momentum analyzer in a high-energy beam transport (HEBT) were aligned precisely on the beam line down the SCRFQ. After low-power tests of the IH and rebuncher cavities, we conducted their high-power tests for aging the cavities. On March 29, 1996, we succeeded in the first acceleration of the SCRFQ/IH linac with a \( N^2+ \) beam. This paper describes the linac construction and the beam test results.

![Figure 1: Layout of the heavy-ion linac system.](image-url)
**Split Coaxial RFQ (SCRFQ)**

**Construction of the cavity**

The SCRFQ has been constructed on the basis of the studies of a prototype. Design parameters of the SCRFQ are summarized in Table 1. The cavity (0.9 m in inner diam., 8.6 m in length) comprises four unit cavities, whose structure is nearly same as that of the prototype. In the new cavity, we didn’t use the vane coupling rings installed in the prototype, because they caused appreciable shift of the resonant frequency in high-power operations. The unit cavity comprises three module-cavities as shown in Fig. 2. The material of the tank is mild steel, whose inner wall is plated with copper to a thickness of 100 μm, and that of the inner structure except the vanes and spacing rods is oxygen-free copper. The vanes are made of chromium-copper alloy containing Cr of 1%, and the spacing rods are copper plated stainless steel.

<table>
<thead>
<tr>
<th>Design parameters of the 170 keV/u SCRFQ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency (f)</strong></td>
</tr>
<tr>
<td><strong>Charge-to-mass ratio (q/A)</strong></td>
</tr>
<tr>
<td><strong>Kinetic energy (T)</strong></td>
</tr>
<tr>
<td><strong>Input emittance (ε_input)</strong></td>
</tr>
<tr>
<td><strong>Normalized emittance (ε_n</strong></td>
</tr>
<tr>
<td><strong>Vane length (lv)</strong></td>
</tr>
<tr>
<td><strong>Number of cells (radial matcher)</strong></td>
</tr>
<tr>
<td><strong>Interwave voltage (V)</strong></td>
</tr>
<tr>
<td><strong>Max. surface field (E_s,max)</strong></td>
</tr>
<tr>
<td><strong>(2.49 Kilpatrick)</strong></td>
</tr>
<tr>
<td><strong>Mean aperture radius (r_0)</strong></td>
</tr>
<tr>
<td><strong>Minimum aperture radius (a_min)</strong></td>
</tr>
<tr>
<td><strong>Max. modulation index (m_max)</strong></td>
</tr>
<tr>
<td><strong>Margin of bore radius (a_min/a_beam)</strong></td>
</tr>
<tr>
<td><strong>Final synchronous phase (θ_r)</strong></td>
</tr>
<tr>
<td><strong>Focusing strength (B)</strong></td>
</tr>
<tr>
<td><strong>Max. defocusing strength (Δ_θ_r)</strong></td>
</tr>
<tr>
<td><strong>Transmission efficiency</strong></td>
</tr>
<tr>
<td>at 0 mA input</td>
</tr>
<tr>
<td>at 5 mA input</td>
</tr>
</tbody>
</table>

*(for q/A=1/30 ions)*

The module length, 0.7 m, was determined so as that the droop of the vanes due to the gravity might not exceed 35 μm, and the cavity diameter, 0.9 m, so as that the resonant frequency might be 25.5 MHz. The electrodes comprising the vanes and the spear-shaped back plates are supported by stems. The stem-flanges are arranged at equal distances by spacing-rods. By introducing the spacing-rods, it became possible to align the vanes with an accuracy better than ±40 μm before installation in the unit-cavity tank. The unit cavity is cooled by eleven water channels running in parallel. Total flow rate for one unit cavity is about 290 l/min, and the temperature increase of the water is less than 1.4°C under a 30% duty operation with a peak power of 90 kW. After completion of the four unit-cavities, we aligned them in an accelerator room with an error less than ±50 μm.

The vane tip geometry has following features: the transverse radius of curvature of the vane-tip (r_v) is variable in the low-energy part, about 1 m long in the first unit cavity, and the r_v is constant at the mean aperture radius (r_0) in the high-energy part. The vanes in the first unit cavity were machined by means of a three-dimensional cutting technique, and for the other vanes a two-dimensional cutting technique was used. For each vane-tip geometry, we made a correction on the aperture parameter a and modulation m (A10 correction) to bring the actual field close to an ideal one.

![Structure of the unit cavity](image)

**Figure 2: Structure of the unit cavity.**

**Rf aspects**

We tuned the resonant frequency and the longitudinal voltage distribution by changing locally the inter-electrode capacitance and the stem inductance. For changing the capacitance, C-tuners of the copper plates (170 or 120 mm in height, 30 mm in width, 3 mm in thickness) were attached on the back-plates so that a plate confronted a stem with a distance of 25 mm. In order to flatten the longitudinal voltage distribution, C-tuners (170 mm in height) were installed in the 1st module, and other tuners (120 mm in height) in the 2nd and 12th ones; the number of tuners is four per module. Further fine tuning was performed by adjusting the stem inductance between the 6th and 7th modules. After tuning, the longitudinal distribution was fiat within ±1%, and the azimuthal field imbalance within ±1%. The resonant frequency was 25.46 MHz, and the unloaded Q-value 5800. From their values and total capacitance between electrodes, 1616 pF, the resonant resistance (R_v) is derived to be 22 kΩ. The final tuning to 25.5 MHz is performed by means of piston tuners.

The high-power operation was conducted for aging the cavity and for calibration of the interwave voltage (V_v). The rf source generates a max. power of 350 kW in peak with a duty factor of 30%. The input power (P_in) is transmitted into the cavity through a 6-m coax (WX-120D) and a loop coupler. By using four 500-l/s turbo-molecular pumps, the cavity is kept at a vacuum of 5 × 10⁻⁷ Torr without power input. So far, we have achieved the goal interwave voltage of 109 kV at a duty factor of 15%.

We figure out interwave voltage from the output voltage (V_ML) of a monitor loop attached to the 12th module cavity. We obtained the calibration constant, V_v/V_ML = 10,388, by measur-
ing the endpoint energy of X-ray from cavity. From the relation, \( R_p = \frac{V_r^2}{2P_{in}} \), the resonant resistance was derived to be 24.55 ± 0.44 kΩ under high-power operation. This value is higher than 22 kΩ, which we obtained in low-power test. The increase of the resonant resistance may be due to the \( Q \)-value improvement through the aging.

**Interdigital-H Linac**

**Construction of the cavities**

The design parameters of the IH linac are listed in Table 2 together with the low-power test results. The synchronous phase is -25° to assure a stable longitudinal motion. In order to obtain the high shunt impedance, the accelerating mode is π-π, and no transverse focusing element is installed in the drift tubes. The inner diameters of the 1st through 3rd tanks are a little bit larger than that of 4th one, so that the resonant frequencies are kept to 51 MHz without reducing the shunt impedance. Each gap length between drift-tubes is equal to one half of the first cell length. Both end structures of the cavity, i.e., the magnetic flux inducers and the gaps between end-wall and ridge, are determined experimentally so as that the longitudinal field distribution becomes flat over a cavity.

The material of the tank is mild steel, whose inner wall is plated with copper to a thickness of 100 μm, and that of the ridges, drift-tubes and stems is oxygen-free copper. For tuning the cavity, three kinds of tuners are used: a capacitive tuner (C-tuner), four inductive end tuners (end L-tuner), and an inductive piston tuner (L-tuner). The C-tuner is a manually movable disk (19 cm in diam.) facing a ridge. The L-tuner is moved automatically to compensate the frequency shift due to the temperature change. The structure of the 4th tank is illustrated in Fig. 3.

**Rf aspects**

The results of the low-power tests are summarized in Table 2. The resonant frequencies \( f_{initial} \) of four tanks were tuned with C-tuners to 51 MHz \( f_{tuned} \). Without any particular tuning, we obtained the gap-voltage distributions almost flat except at the tank ends. From the measured unloaded \( Q \)-values \( (Q_o) \) and field distributions in the gaps, we figured out effective shunt impedances \( (Z_{eff}) \), and then the rf powers \( (P) \) required for accelerating the \( q/A = 1/10 \) ions up to 1.05 MeV/u.

**Table 2**

Design parameters and low-power test results of the IH linac

<table>
<thead>
<tr>
<th></th>
<th>Tank1</th>
<th>Tank2</th>
<th>Tank3</th>
<th>Tank4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{out} ) (keV/u)</td>
<td>294</td>
<td>475</td>
<td>725</td>
<td>1053</td>
</tr>
<tr>
<td>( L_{tank} ) (cm)</td>
<td>68</td>
<td>90</td>
<td>115</td>
<td>153</td>
</tr>
<tr>
<td>( D_{tank} ) (cm)</td>
<td>149</td>
<td>149</td>
<td>149</td>
<td>134</td>
</tr>
<tr>
<td>( R_{bore} ) (cm)</td>
<td>1.0</td>
<td>1.2</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>( D_{drift} ) (cm)</td>
<td>3.8</td>
<td>4.4</td>
<td>4.6</td>
<td>5.2</td>
</tr>
<tr>
<td>No. of cells</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>( V_{gap} ) (kV)</td>
<td>200</td>
<td>250</td>
<td>315</td>
<td>370</td>
</tr>
<tr>
<td>( f_{initial} ) (MHz)</td>
<td>51.084</td>
<td>51.134</td>
<td>51.180</td>
<td>51.003</td>
</tr>
<tr>
<td>( f_{tuned} ) (MHz)</td>
<td>51.000</td>
<td>51.000</td>
<td>51.000</td>
<td>51.000</td>
</tr>
<tr>
<td>( Q_o )</td>
<td>11681</td>
<td>12387</td>
<td>16230</td>
<td>18490</td>
</tr>
<tr>
<td>( Z_{eff} ) (MΩ/m)</td>
<td>264</td>
<td>289</td>
<td>268</td>
<td>218</td>
</tr>
<tr>
<td>( P ) (kW)</td>
<td>10.5</td>
<td>15</td>
<td>25</td>
<td>39</td>
</tr>
<tr>
<td>( \Delta V_{gap} ) (%)</td>
<td>±2.0</td>
<td>±2.9</td>
<td>±3.5</td>
<td>±2.2</td>
</tr>
</tbody>
</table>

The capacities of the rf sources for the 1st through 4th tanks are 12kW, 22kW, 30kW and 50kW, respectively. The rf sources were connected to the tanks through about 20-m coaxies (WX-77D for the 1st through 3rd tanks, WX-120D for the 4th tank). Each of the 1st and 2nd tanks is evacuated by a 500-l/s turbo-molecular pump, and each of the 3rd and 4th tanks is by a 1500-l/s one. The obtained vacuum pressures are in the range of \( 10^{-7} \) Torr under no power feed. The high-power aging was conducted for the Nb+ beam acceleration test, in which 70% of the max. gap voltage was required at a duty factor of 15%. The time spent in aging conducted at a duty factor of about 20% was about 12 hours per cavity.

**Beam Transports**

As shown in Fig. 1, the LEBT consists of a 2.45-GHz ECR ion source, a 90° bending magnet, two quadrupole magnets, and four einzel lenses [4]. The ion source produces stable nucleus beams. The bending magnet separates ions with different charge-to-mass ratios. The quadrupole magnets are used for making the vertical beam size small in the bending magnet and for matching the transverse phase spaces at two focal points. The momentum resolution of the ion separating system is 0.65%. A double-slit emittance monitor (EM1) and a Faraday cup (FC1) are installed at the RFQ entrance.

The MEBT between the SCRFQ and the IH linac comprises a charge stripper (carbon foil of 10 μg/cm²), a rebuncher and two quadrupole doublets [4]. This transport system has a total length of 3.76 m. Since the frequency of 25.5 MHz was required for the rebuncher, a double-coaxial resonator with 6 gaps was developed to maintain the size small and power low [5]. The emittance monitor (EM2) is separated into two parts: the front slit is near the RFQ exit, and the rear one is between the quadrupole magnets. The Faraday cup FC2 measures the current of drift-
through ions (both of accelerated and unaccelerated ions), and FC3 the current of accelerated ions only. The emittance monitor (EM3) and the Faraday cup (FC4) were located at the entrance of the IH linac. The EM3 comprises four moving slits. The vacuum chamber containing EM3 and FC4 was made compactly so as to be installed in a small space (38 cm in diam. and 15 cm in length) just before the first tank of the IH linac. The Faraday cup (FC5) cooled by a water channel was located at the exit of the IH linac. The momentum analyzing system in the HEBT was set up at the downstream of the IH linac. This comprises a quadrupole doublet, a dipole magnet, a vertical slit with a width of 4 mm and a charge collecting plate (FC6). This system has a energy resolution of less than 1% for the 1-MeV/u ion beam, which has the design emittance of the IH linac. The beam energy was estimated from the magnetic field measured by a hole probe.

**Beam Tests**

Performance of the SCRFQ

We measured the transmission efficiency as a function of the interwave voltage. The RFQ operated at 25.47 MHz with a duty factor of 5%. The N⁺ beam had the input emittances, 17 and 22 π cm-mrad in the x-x' and y-y' planes, and the current was about 0.22 mA in peak at FC1. The measurement result is shown in Fig. 4 along with a simulation. The horizontal scale is the normalized interwave voltage, \( V_n = V_{\text{av}}/50.68 \) kV. The measured transmission efficiency of drift-through ions (○ in the figure) is defined by \( I(FC2)/I(FC1) \), where \( I(FC1) \) is the beam current from the Faraday cup i, and that of accelerated ions (●) by \( I(FC3)/I(FC1) \). The simulation was done by using the PARMTEQ-H version including the higher-order-multipole fields calculated by Crandall [6]. At the nominal interwave voltage \( (V_n = 1) \) the measured transmission efficiency is 90%. This is close to the designed value of 91.4% with a matched input beam with \( \varepsilon_n = 0.06 \) π cm-mrad. The measured output emittance profiles were inside of the design ellipses, with \( \varepsilon_n = 0.06 \) π cm-mrad.

![Figure 4: Transmission efficiencies vs normalized interwave voltage.](image)

If the beam with a design energy is injected into the tank4, we can adjust the gap voltage and the rf phase experimentally by comparing the measured function with the simulated one. As a result, we set the gap voltage and rf phase to give the nominal output energy. The voltages and phases of the other tanks were also set by the same method as that for tank4.

After adjusting the gap voltage and rf phase, we optimized parameters of the focusing elements to increase the transmission efficiency of the IH linac. Figure 6 shows the beam energy spectra measured at six operating modes, and figure 7 the transmission efficiencies of almost 100% for five operating modes. For example, "IH-Tank3" in the figure shows the result obtained when the SCRFQ and the 1st through 3rd IH-tanks are operated and the 4th tank is not operated.

As seen from "IH-Tank4", the beam was accelerated up to the max. design energy, 1.05 MeV/u. The measured energy spreads \( \Delta T/T \) are listed in Table 3 with the calculated values given in

![Figure 5: Output beam energy vs accelerating phase; (a) is the simulation and (b) the measurement.](image)
Figure 6: Energy spectra for six operating modes.

Figure 7: Transmission efficiency for five operating modes.

Figure 8: (a) Emittance profiles at the RFQ entrance, (b) at the RFQ exit, and (c) at the IH-linac entrance.

parentheses, where $\Delta T$ is defined by $2\sigma$ of the spectrum containing 90% ions. The emittance profiles were measured at the RFQ entrance, the RFQ exit and the IH-linac entrance as shown in Fig. 8. The bars indicate measured 90% emittance profiles of a N$^{2+}$ beam, and the solid-line ellipses the designed ones with an area of $\epsilon_n = 0.06 \pi$ cm-mrad. The broken-line ellipses in figure (c) show the designed acceptance of the IH linac with 0.24 $\pi$ cm-mrad normalized.

<table>
<thead>
<tr>
<th>$T$ (keV/u)</th>
<th>RFQ</th>
<th>Tank1</th>
<th>Tank2</th>
<th>Tank3</th>
<th>Tank4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>172</td>
<td>293</td>
<td>476</td>
<td>726</td>
<td>1059</td>
</tr>
<tr>
<td>(172)</td>
<td>(294)</td>
<td>(475)</td>
<td>(725)</td>
<td>(1053)</td>
<td></td>
</tr>
<tr>
<td>$\Delta T/T$ (%)</td>
<td>1.56</td>
<td>1.65</td>
<td>1.97</td>
<td>1.15</td>
<td>1.12</td>
</tr>
<tr>
<td>(1.06)</td>
<td>(1.77)</td>
<td>(1.65)</td>
<td>(1.02)</td>
<td>(0.63)</td>
<td></td>
</tr>
</tbody>
</table>

**Concluding Remarks**

The beam tests of the SCRFQ with a N$^+$ beam showed following results: 1) the transmission efficiency exceeds 90% at a design voltage, 2) the form of the transmission measured as a function of the interplane voltage and the emittance profiles of the output beam agree well with PARMTEQ prediction.

The beam tests of the SCRFQ/IH linac with a N$^{2+}$ beam showed following results: 1) for five operating modes, the output beam energy and its spread agree fairly well with the design values, when the gap voltage and accelerating phase of each tank of the rebuncher and IH linac are set to the design values, and 2) the transmission efficiency of the IH linac is nearly 100%, when the transverse focusing elements are optimized. From the beam test results obtained so far, we can say the performance of the SCRFQ/IH linac is close to the designed one.

**Acknowledgments**

We express our thanks to T. Nomura for his encouragement, M. Imamura, S. Shibata and M. Wada for his help in the work. The SCRFQ and IH linac were fabricated by Sumitomo Heavy Industries, Nihama Work. The rf power sources were fabricated by Denki Kogyo Co., Ltd, and IDX Corporation. The HEBT was constructed by staff in nuclear physics division at INS. The computer works were done on FACOM M780 and VP2100 in the INS Computer Room.

**References**

CONCEPTUAL DESIGN OF A SUPERCONDUCTING HIGH-INTENSITY PROTON LINAC

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Abstract

High-intensity continuous wave (cw) proton linacs have been proposed as neutron spallation sources for accelerator transmutation technology applications. These linacs have energies and currents around 1 GeV and 100 mA. Linac designs using room-temperature copper technology require significant microwave power and the cost of operation is high. Superconducting linacs, because of their insignificant wall losses, provide an attractive alternative. Recently, a superconducting design has been developed at Los Alamos National Laboratory (LANL). To make sure the high availability required by the application is satisfied, the design is based on demonstrated superconducting technology. The resulting design reduces power and operating costs, and offers high operational flexibility, high power upgradability, and low beam loss.

Although a superconducting linac offers many advantages for neutron spallation source applications, a proton superconducting linac has yet to be built. Unanswered design feasibility questions concern the multipacting characteristics of elliptical cavities with $\beta (v/c)$ less than one and the effects of proton beam spill on the long-term superconducting characteristics of niobium. Both issues can be resolved by straightforward tests.

Introduction

High-intensity RF proton linacs have been proposed as neutron sources for research and accelerator-driven transmutation technologies [1]. High-intensity RF proton linacs are attractive alternatives to reactors as a neutron source because linacs can be operated very safely and do not produce high-level radioactive waste. Also, the beam-pulse format of a linac-driven neutron source allows additional flexibility in time-of-flight measurements, which is beneficial for research needs. Projects based on high-intensity proton linacs include the Accelerator Production of Tritium (APT) [2], the European Spallation Source [3], and Accelerator Transmutation of Waste [4]. Each design uses proton linacs with typical beam energy and current of 1 GeV and 100 mA, requiring hundreds of MW of power to operate. These linacs use copper structures operating at room-temperature. Although room-temperature structures have been successfully demonstrated, their cavity resistive power losses are significant, typically more than 25-MW.

Superconducting (SC) RF linacs can be an attractive alternative to room-temperature linacs because of their negligible cavity losses. SCRF linac technology has been under development since the early 1970s. SCRF cavities are now in use in various accelerator centers, including KEK, DESY, CERN, and CEBAF, (recently renamed the Thomas Jefferson National Accelerator Facility). CEBAF is a notable demonstration of SCRF linac technology [5], with 334 cavities configured similarly to the proton linac needed for neutron source applications. Given the commitments made by LHC and TESLA [6] in SCRF technology, SCRF can be viewed as the future of accelerator technology.

Recently, studies have been completed on use of SCRF linacs to produce high-intensity proton beams [7] [8]. Results from these studies show that the SCRF linac is technically feasible for accelerating high-intensity proton beams. Besides greater power efficiency, the SCRF linac offers high availability and low beam loss, which are important performance requirements for linacs considered for neutron sources. During a recent APT study, an SCRF linac design was developed and its performance investigated [7]. Important technical issues and R&D efforts needed to provide additional information have been identified.

In this paper, the advantages and technical issues of using a high-intensity SCRF linac as the driver for a neutron source will be described using the APT SCRF linac design.

High-Intensity SCRF Linac Design

The APT SCRF linac [7] has been designed with demonstrated SCRF technology. It is intended to show what can be achieved without extensive R&D efforts. The design, therefore, is very conservative.

The baseline room-temperature APT linac design has a low-energy section and a high-energy section [2]. The low-energy section, which brings the beam to 100 MeV, includes an injector, a radiofrequency quadrupole (RFQ) linac, and a coupled-cavity drift-tube linac, and the high-energy section is a coupled cavity linac. In the SCRF design (Fig. 1), the high-energy section is replaced with a SCRF linac. The SCRF linac has two constant-$\beta$ sections made up of identical cryomodules, where $\beta$ is the relativistic factor equal to the ratio...
of the beam velocity and the speed of light. Figure 2 shows the two designs of these cryomodules. The cryomodules are separated by doublet quadrupole magnets that provide the transverse focusing. Table 1 summarizes the linac parameters.

![Diagram of cryomodules](image)

**Fig. 2 Layout of a) medium-β section, b) high-β section.**

<table>
<thead>
<tr>
<th>Table 1: Superconducting linac parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Current</td>
</tr>
<tr>
<td>Energy of SC Sections</td>
</tr>
<tr>
<td>Final Beam Power</td>
</tr>
<tr>
<td>Cavities per RF Module</td>
</tr>
<tr>
<td>Cavities per cryostat</td>
</tr>
<tr>
<td>Cells per cavity</td>
</tr>
<tr>
<td>RF power/ cavity</td>
</tr>
<tr>
<td>RF power &amp; coupler</td>
</tr>
<tr>
<td>Accelerating gradient, E.T</td>
</tr>
<tr>
<td>Aperture radius</td>
</tr>
<tr>
<td>Nominal operating temperature</td>
</tr>
<tr>
<td>Cavity RF power loss (total)</td>
</tr>
<tr>
<td>HOM power (total)</td>
</tr>
<tr>
<td>Static heat leak</td>
</tr>
<tr>
<td>Number of β sections</td>
</tr>
<tr>
<td>Number of cavities</td>
</tr>
<tr>
<td>Number of cryostats</td>
</tr>
<tr>
<td>Number of klystrons</td>
</tr>
</tbody>
</table>

RF power is a major design consideration because of the amount needed. Because they cost less per watt of power, larger size RF units are preferred. However, a larger RF unit means further levels of power splitting to reach the lower power level that a power coupler can handle. Too many levels of power splitting can cause difficulties in RF control. Considering the klystron size, the power handling capability of couplers, and RF control, the resultant APT design uses a 1-MW klystron to supply power to four cavities. Each cavity will use two 105-kW power couplers.

To minimize RF power splitting, a power coupler with the highest power carrying capability should be used. A survey of the power carrying capability of existing power couplers (Table 2) showed that a power level between 100 to 150 kW is achievable, consistent with the choice of 105 kW for the APT power coupler. Figure 3 shows a schematic of the power coupler design. A coaxial power coupler has been chosen because it has been used in most SCRF cavities. The coaxial power coupler consists of a 3-1/8" coaxial line with antennatype termination. To minimize the multipactoring caused by gas condensation, the coaxial power coupler is designed for baking. Multipactoring limits were investigated by comparing data obtained by Kindermann for the CERN coupler [9] and with the recently-published scaling law [10]. The coupler uses warm windows located outside the cryomodules sufficiently far from the beam to minimize beam-induced window breakdown. The use of two windows provides redundancy for higher availability. The coupling coefficient will be adjustable over 10 dB using a copper-plated stainless steel hydroformed bellows in the outer conductor. The adjustability allows minimization of reflected power during operation.

<table>
<thead>
<tr>
<th>Table 2: Demonstrated power coupler capability with beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>CERN</td>
</tr>
<tr>
<td>KEK (TRISTAN)</td>
</tr>
<tr>
<td>DESY</td>
</tr>
<tr>
<td>CESR</td>
</tr>
<tr>
<td>KEK (AR)</td>
</tr>
</tbody>
</table>

![Diagram of power coupler](image)

**Fig. 3. Schematic of power coupler.**

Figure 4 shows the RF system architecture. The power source is a 1-MW klystron at 700 MHz protected by a circulator. It supplies power to four cavities. Cavity field
signals from these four cavities are summed and used in feedback control of the klystron. Beam dynamics show that the linac maintains good performance if the amplitude and the phase of the sum of the cavity fields are controlled, respectively, to 1% and 1°; and the fields of individual cavities controlled to 3% and 5°. This RF control specification is expected to be achievable, given experience at CERN and DESY.

Fig. 4. RF system architecture.

An elliptical cell shape, commonly used in SCRF cavities, will be used here (Fig. 5). Because of the lower $\beta$, the cell is significantly shorter than the $\beta=1$ elliptical shapes in electron SC accelerators. Although one-point multipacting is not expected for elliptical shape cells, two-point multipacting, particularly for $\beta=0.48$, may exist due to shorter cell length. Shorter cell length may also reduce the mechanical rigidity of the cavity structure. Figure 6 shows the cavity design. The cavity will be operated at a gradient of 5 MV/m, corresponding to a peak surface field of 16 MV/m. This gradient is well demonstrated in existing SCRF cavities with elliptical cells. At this gradient, field emission and thermal breakup (quench) are not expected. The cavities will be operated at a temperature of 2-K to minimize cryogenic power and to provide better quench resistance. They will be fabricated with solid niobium with an RRR-value of 250. Fabrication and processing procedures will be similar to those used for the CEBAF cavities [11]. In addition, high-pressure rinsing will be used. Heat-treatment is not planned because it is not needed at this field gradient and can reduce the mechanical strength of the niobium.

Fig. 6. Schematic of cavity design.

Figure 7 shows the cryomodule design. The cryomodule contains two cavities. Its design is based on the CERN LEP wrapup design [12]. Both a motor-driven tuner and magnetostrictive tuner are included in the design. The cryogenic system is based on the CEBAF cryogenic system, which has demonstrated availability of 97%. To satisfy a higher cooling requirement and to increase the availability of the cryogenic system, three CEBAF units will be used and a liquid helium storage facility will be provided.

Fig. 7. Medium-$\beta$ cryomodule.

Because of the power handling constraints of the power coupler, the SCRF cavities have only 4 cells. Their lengths are short compared to room-temperature structures, and have large velocity acceptance as a consequence. Figure 8 shows
the transit time of cavities with different numbers of cells when the cavities are used for particle velocity (β) other than the design particle velocity (β₀). The transit time, which is a measure of the efficiency of acceleration, peaks when β is equal to β₀ and decreases when β is change from β₀. Cavities with fewer cells can accelerate efficiently for a wider range of β and have a large velocity acceptance. The efficiency reduction can easily be compensated with a slightly higher gradient. The large velocity acceptance offers availability and upgradability advantages that will be described in the following section.

![Fig. 8. Transit time factor versus β](image)

**Performance Advantages of a SCRF Linac**

The performance requirements of a high-intensity proton linac used as a neutron source are the following: high availability over scheduled operation time; low beam loss allowing hands-on maintenance; high power efficiency for low operating cost; and upgradability to higher power level. The APT SCRF linac described here has advantages in satisfying all these performance requirements.

SCRF linacs can achieve high availability because the short cavities have large velocity acceptance. Only two cryomodule designs are needed for the whole high-energy section. The limited number of designs will reduce prototyping efforts and allow provision of ready-to-go spares. Beam dynamics also showed that, because of the large velocity acceptance, the linac is tolerant of single-point failures. The linac can continue to operate with single-point failures such as the loss of cavities, cryomodule, quad magnet and klystron. Operation experience at major SCRF accelerators shows that, as for room-temperature linacs, the RF system is the major source of unavailability. Because the SCRF linac requires 25% less RF power, it can be more reliable than a room-temperature linacs. Preliminary availability estimates of the APT SCRF linac indicate that the required availability is achievable. The present APT SCRF linac design produces 5% extra beam power to cover any unexpected availability shortfall.

SCRF linacs can achieve low beam loss because of their large beam aperture radius. The aperture radii are, respectively, 5 and 7.5 cm for the medium- and high-β sections. These radii are large compared to the typical aperture radius (<2.5 cm) used in the room-temperature structures. The beam size is minimized with strong quadrupole doublet focusing. The SCRF linac achieve ratio of aperture-to-rms beam size as large as 26. The large velocity acceptance of the SCRF linac also allows better tolerance to beam mismatch.

Depending on the design of the room-temperature linac, the required RF power and ac power for a SCRF linac is at least 25% less than for a room-temperature linac. The savings in operating cost will amount to $20 M per year for APT because of the reduced power usage.

Because of the large velocity acceptance in a SCRF linac, beam power can be upgraded by increasing the beam energy, in addition to by increasing the beam current. For the same linac, beam power can be increased by increasing the field gradient, the RF power, and the power coupler capability. The option to upgrade beam power by increasing beam energy is not possible for a room-temperature linac without lengthening the linac, generally requiring extensive facility modification.

**Technical Issues**

Although a cavity field gradient of 5 MV/m is conservative considering field emission and thermal breakdown limits, multipacting can limit achievement of such a field. Multipacting usually occurs at low field gradient. It depends on the secondary electron coefficient of the cavity surface and satisfaction of resonant conditions. Although multipacting has been eliminated in high-β (β=1) cavities by using elliptical cell shapes, the multipacting property of a medium-β cavity still needs demonstration. The lower-β cell shape is significantly shorter than the β=1 cell shapes (Fig. 5) and its multipacting property may be different. The APT project has designed experiments to investigate multipacting of single-cell lower-β cavities. This information will determine the starting energy of the SCRF linac.

The SCRF linac has been used mainly for electron acceleration. There are few data on the interaction of Nb with proton beam spill. Proton impingement on Nb may cause the Nb to be activated or to lose its superconducting properties. Excessive activation of Nb may prevent timely maintenance and extend the mean time of repairs, reducing facility availability. Proton impingement can cause defects and impurities in Nb and change the thermal and electrical conductivities of the Nb. These changes will be shown as a change of the RRR value of the Nb. It can also change the surface resistivity of the Nb cavities and consequently the Q-values of the cavities. Experiments have been designed to measure these radiation effects. First, experiments are being carried out to irradiate Nb samples with proton beam at Saturne and Brookhaven National Laboratory. The activation of Nb will be measured and compared to other structural materials such as stainless steel, copper, and aluminum. The change of RRR value will be measured as a function of proton fluence to find the change in the bulk thermal and electrical conductivities. Second, a 3-GHz single-cell cavity will be irradiated at cryogenic temperature at LANSCE, Los Alamos.
National Laboratory. The changes in the Q-value of the cavity will be measured as a function of proton fluence. The possibility of Q-value recovery by warming to room temperature will also be investigated. The results of this experiment will help in specifying the additional capacity of cryogenic power required to compensate for a decrease in Q-value. A similar experiment has been completed at Saturn recently, although the irradiation was done at room-temperature. There has been no observed decrease of Q-value.

As discussed earlier, power coupler capability is important design information for determining RF architecture. Power coupler design will be developed and tested at a test stand under different operation conditions. The information obtained will be used to optimize linac layout and cost.

Summary

A SCRF design has been developed for a high-intensity proton linac which will be used as the driver for neutron sources. This design is conservative, using current SCRF technologies. As well as lowering operating cost, the design offers performance advantages in availability, beam loss, and upgradability, which are important for the application as a neutron source.

Reference


* Work supported by US Department of Energy

584
Invited Talk Session TH1

Chairman: H. Klein

Thursday, August 29, 1996
SMOOTH TRANSVERSE AND LONGITUDINAL FOCUSING IN HIGH-INTENSITY ION LINACs

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Abstract

We examine ion linac designs that start with a high-energy radio-frequency quadrupole (RFQ) followed by either a drift-tube linac (DTL) or a coupled-cavity drift-tube linac (CCDTL). For high energies, a conventional CCL follows the CCDTL. High RFQ output energy allows tailoring the transverse and longitudinal focusing strengths to match into the following structure. When the RFQ beam enters a higher-frequency structure, the DTL or CCDTL starts with a low accelerating gradient and large negative synchronous phase. The gradient and phase both ramp up gradually to higher values. Other changes later in the machine are also gradual. Beam-dynamics simulations show that these linacs require no separate matching sections. Applications include a cw 100-mA H⁺ beam from a 350-MHz, 6.7-MeV RFQ injecting a 700-MHz CCDTL and CCL; a 7% duty 28-mA H⁺ beam from a 402.5-MHz, RFQ and DTL injecting 805-MHz structures; a cw 135-mA D⁺ beam produced by a 175-MHz, 8-MeV RFQ and DTL; and a 2.4% duty, 80-mA H⁺ beam using a 433-MHz 10-MeV RFQ and a 1300-MHz CCDTL. The machines take advantage of the considerable flexibility of the CCDTL. Designs can use a variety of different transverse focusing lattices. Use of two coupling-cavity orientations permits a constant period even when the number of drift tubes per cavity changes along the linac.

Introduction

For the past two years, we have been incorporating the CCDTL [1] structure into conceptual designs of several high-intensity ion accelerators. We have concentrated on designs that require no separate matching sections between linac sections with different rf structures. Table 1 lists parameters for four applications. Of all the designs, the Accelerator for Production of Tritium (APT) is in the most advanced state of development. We are now building the 6.7-MeV (RFQ) [2,3] as part of a low-energy demonstration facility for APT.

Other accelerator designs we have studied differ in details from the APT, but follow similar design strategies. Work on the National Spallation Neutron Source (NSNS) has just begun [4]. This conceptual design study is a collaborative effort by five US national laboratories (ORN, LBNL, BNL, ANL, and LANL). Recent design studies [5] for the International Fusion Materials Irradiation Facility (IFMIF) accelerator do not include a CCDTL. However, the Los Alamos design in Ref. 5 uses matching strategies at the RFQ-to-DTL interface similar to those developed for the CCDTL. For medical isotope production, our design concept [6] is a compact machine consisting of an RFQ and CCDTL.

These designs offer advantages that stem from four key features: 1) a uniform focusing lattice throughout the major portion of the linac, 2) external location and separate mechanical support of the electromagnetic quadrupole magnets, 3) flexible modular physics design and mechanical implementation, and 4) compact, high-frequency structures. These features help to reduce beam loss and, hence, also reduce potential radioactivation of the structure. They should result in easy alignment, fast serviceability, and high beam availability.

Using the APT Linac as an Example

In this paper, the APT design serves to illustrate the techniques that help achieve smooth focusing and acceleration throughout the linac. We mention features of the beam-dynamics, rf-structure, and mechanical engineering design. Parameters listed for the APT linac in Table 1 correspond to the reference design of a room-temperature copper structure. Several other papers [7,8,9,10,11] at this conference provide more technical details of this work.

The APT project includes a superconducting option [12] for the high-energy portion of the machine. The physics and engineering design of the superconducting (SC) components is approaching the maturity of the room-temperature reference design. Work is now in progress on an integrated design that will use room-temperature structures discussed in this paper up to about 217 MeV proton energy. The SC linac consists of two constant-length PODO lattices. The first one uses $\beta = 0.64$ cavities and the second uses $\beta = 0.82$ cavities. Transitions between linac sections do not require separate matching sections. Careful attention to maintaining constant average focusing strength through the transitions provides the match.

RFQ Features For a Smooth Transition

Our recent RFQ designs employ several features near the RFQ exit that help match the beam into the following structure. These include:

- A gradual reduction in the transverse focusing resulting in a larger bore radius,
- A reduction in the usual loss of longitudinal focusing by ramping the vane voltage and making the synchronous phase more negative,
- A transition cell in which the vane-tip modulation drops to zero, and
- An exit radial matching section.

In order to apply the technique of reducing the transverse focusing strength, the final RFQ energy must be high compared to most previous RFQ designs. For example, the APT RFQ energy is about 6.7 MeV, which requires a long (8 meter) structure described in Ref. 2 and 3. In the design now under construction we were able to reduce the transverse, zero-current phase advance per period to about 20 degrees. The focusing period is four times longer in the 700-MHz CCDTL than in the 350-MHz RFQ. Thus, 20 degrees/period in the RFQ provides a smooth transition to 80 degrees/period in the CCDTL.
Table 1. Accelerator Design Summary for a Few Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>APT</th>
<th>NSNS</th>
<th>IFMIF</th>
<th>Medical Isotopes</th>
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<tr>
<td>Ion Species</td>
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<td>H⁺</td>
<td>D⁺</td>
<td>H⁺</td>
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<tr>
<td>Peak Beam Current (mA)</td>
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<td>27.7</td>
<td>135</td>
<td>80</td>
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<td>Duty factor</td>
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<table>
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<tr>
<th>RFQ Parameters</th>
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<tr>
<td>Frequency (MHz)</td>
<td>350</td>
<td>402.5</td>
<td>175</td>
<td>433</td>
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<tr>
<td>Injection/Final Energy (MeV)</td>
<td>0.07/6.7</td>
<td>0.05/2.5</td>
<td>0.100/8.0</td>
<td>0.075/10.0</td>
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<td>Length (m)</td>
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<td>6.7</td>
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<td>Peak Structure Power (MW)</td>
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<td>to be determined</td>
<td>1.2</td>
<td>2.4</td>
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<tr>
<td>Peak Beam Power (MW)</td>
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<td>0.07</td>
<td>1.1</td>
<td>0.8</td>
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<td>Peak Surface Electric Field</td>
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<td>1.8 Kilpatrick*</td>
<td>1.8 Kilpatrick</td>
<td>1.8 Kilpatrick</td>
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Parameters for RF structures after the RFQ

<table>
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<tr>
<th>Structures Types</th>
<th>CCDTL/ACCL</th>
<th>DTL/CCDTL/ACCL</th>
<th>DTL</th>
<th>CCDTL</th>
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<td>Structure Frequencies (MHz)</td>
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<td>402.5/805/805</td>
<td>175</td>
<td>1300</td>
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<tr>
<td>Final Energy (MeV)</td>
<td>1300</td>
<td>1000</td>
<td>40</td>
<td>30/50/70</td>
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<td>Cavity $E_0$ (MV/m)</td>
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<td>1.8</td>
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<tr>
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<td>FFDD/FODO</td>
<td>FODO</td>
<td>FODO</td>
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<td>Transverse Focusing Period</td>
<td>8 Bₐ (700 MHz)</td>
<td>8/16 Bₐ (805 MHz)</td>
<td>2 Bₐ (175 MHz)</td>
<td>16 Bₐ (1.3 GHz)</td>
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<td>Total Length (m)</td>
<td>1152</td>
<td>570*</td>
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<td>29.9</td>
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<td>Radial Aperture (cm)</td>
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<td>1.3 Kilpatrick</td>
<td>1.3 Kilpatrick</td>
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<td>100*</td>
<td>3.1</td>
<td>4.4</td>
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<td>Peak Beam Power (MW)</td>
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<td>27.7</td>
<td>5.4</td>
<td>4.8</td>
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<td>Number of RF Modules</td>
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<td>64*</td>
<td>6</td>
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<td>Klystron Power (MW)</td>
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<td>3 to 7</td>
<td>0.5</td>
<td>to be determined</td>
<td>1</td>
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</tbody>
</table>

*Estimates based upon current design parameters.

The transition cell described by K. Crandall [13] eliminates energy gain or loss in the following radial matching section. This feature frees the designer to choose the length of the radial matching section for the transverse match into the CCDTL magnetic quadrupole channel. The increased longitudinal focusing achieved by tailoring the vane-tip modulation reduces the phase width of the exit beam. The shorter bunch eases capture of the beam in the CCDTL.

The RFQ-CCDTL Transition

Figure 1 shows the first few focusing periods of the CCDTL structure that starts at 6.7 MeV. The gradual ramp in the synchronous phase $\phi_s$ starts at $-60^\circ$ ensuring a large enough rf "bucket" to capture 100% of the beam. (The term synchronous phase here refers to the design particle's average phase with respect to the rf-field peak in a 2-gap cavity. For a given cavity with cells designed for fixed $\beta$, the true $\phi_s$ would be $-90^\circ$.) The ramp in $\phi_s$ eventually stops at $-30^\circ$. However, the first two cavities are exceptions. The first CCDTL cavity has $\phi_s = -90^\circ$ and a larger field amplitude than subsequent cavities. The second cavity operates at $\phi_s = -30^\circ$. This scheme compensates for the lack of any longitudinal focusing from the RFQ transition cell to the first CCDTL cavity. Reference 8 provides additional numerical details. Unlike conventional matching sections, these matching cavities are an integral part of the CCDTL structure described in the next section. Their phases and amplitudes are locked to the subsequent cavities through side coupling cavities. The relative longitudinal spacing between cavities determines the synchronous phase.

Matching the CCDTL to the average longitudinal focusing strength in the RFQ results in a low accelerating gradient $E_0$. Both the phase and the accelerating field vary gradually as the beam energy increases. By 12 MeV the synchronous phase has reached about $-40^\circ$, and $E_0$ has increased from 1.68 to 2.2 MV/m. Figure 4 of Ref. 7 shows how $E_0$ varies throughout the entire accelerator.

The first four quadrupole lenses in the CCDTL match the beam from the RFQ in both transverse planes. In Figure 1, the quadrupole magnets are approximately centered in the spaces between cavities. Including a beam-line valve before the first

![Figure 1](image_url)
cavity required a modified layout. The structure's flexibility allowed a redesign in which all the cavities were shifted downstream with respect to the fixed magnets.

**Cavity-Type Transition at 8.1 MeV**

The first 24 accelerating cavities, up to a beam energy of 8.1 MeV, are single-drift-tube cavities of length 3βλ/2. The drift spaces between cavities are 5βλ/2 long. Electromagnetic quadrupole (EMQ) singlets and diagnostic elements occupy the drift space. A transverse focusing period consists of a cavity, a focusing EMQ, another cavity, and a defocusing EMQ. This FODO lattice has a period of 8βλ at 700 MHz. For the low particle velocity (β = 0.12 to 0.13) in this part of the linac, 3-gap cavities of length 5βλ/2 would have a higher effective shunt impedance than 2-gap cavities. But at low β, they do not leave enough room for the magnets. We can use inefficient 2-gap cavities for the lowest-energy section of the CCDTL because the accelerating gradient is low to match the longitudinal focusing strength at the RFQ exit.

As the accelerating gradient increases, we start paying a power penalty in the 2-gap cavities. At the lowest β that has enough room for EMQs in the length 3βλ/2, we switch to the more efficient 3-gap CCDTL. Figure 2 shows the transition at 8.1 MeV. We use the term “segment” to refer to one or more contiguous accelerating cavities between two focusing magnets. The nominal length of this 3-gap cavity segment is 5βλ/2. For structures in which the cavities share a common wall, the nominal length would equal the actual cavity length (including half the wall thickness). However, these APT segments contain only single 3-gap cavities. To support the vacuum loading, we use a somewhat thicker wall, so not all of the 3βλ/2 space between cavities is available for EMQs. The same situation applies to the end cavities for all the different types of CCDTL and CCL segments.

By comparing the first two figures, it is evident that some adjustment of the EMQ spacing is necessary to avoid an abrupt change in spacing where the 3-gap cavity segments start. The EMQ must fit inside the first 3βλ/2 space between cavities. To accommodate this requirement we gradually shift each EMQ slightly upstream in successive spaces. Thus, the actual spacing between EMQs is just under the nominal 4βλ and the magnetic focusing lattice remains smooth across the transition. The focusing magnet in the last 5βλ/2 space is as far upstream as possible. In the next space, we fill the available space with another 1βλ-long cell on the upstream side of the following cavity.

**Two-Cavity Segments Start at 20 MeV**

Figure 3 shows the next transition at about 20 MeV, where the structure changes to pairs of one-drift-tube CCDTL cavities. This transition includes the first of several increases in the bore radius. A compromise between shunt impedance considerations and the consequences of beam particles striking the accelerating influence the selection of the cavity bore radius. The bore radius affects the shunt impedance ZT mainly through the transit-time factor T. A smaller bore improves ZT, but increases the likelihood of beam loss. On the other hand, relatively little damage or radioactivation of the structure occurs if low-energy particles strike the surface.

Beam-dynamics simulations [8] show that an initial CCDTL bore radius of 1.0 cm is sufficient to capture the entire RFQ output beam. No beam is lost even with the expected misalignment of the EMQs. The RFQ beam edge is very sharp, essentially free of any halo. The pole-tip inner radius of the EMQs at 6.7 MeV is 1.4 cm. The magnets fit over stainless-steel bore tube, which is brazed into the accelerating structure through a short bellows. At 20 MeV, the bore radius increases to 1.25 cm. Two more increases occur within the 2-gap, 4-gap section of the line. The next step to a radius of 1.5 cm occurs at about 31 MeV, and then another step to 1.75 cm occurs at 55 MeV. At each step in bore radius, the structure efficiency decreases, but then it recovers as the cell lengths increase in a section of fixed bore radius.

**CCL Segments Start at 100 MeV**

Figure 4 shows the transition to 6-cavity CCL segments, which occurs at about 100 MeV. The drift space between
segments remains $\beta\lambda$ in length and the bore radius remains 1.75 cm through this transition. At 125 MeV, the bore radius increases to 2.0 cm. Starting at about 157 MeV, the segments become groups of seven cavities with a drift space of length $\beta\lambda/2$. At this point we also make the last increase in the bore radius to 2.5 cm. This structure and the lattice period of 8$\beta\lambda$ both continue all the way to 1.3 GeV. Figure 5 shows the last 7-gap segment of the linac.

![Figure 5](image)

**Figure 5.** The high-energy section consists of segments with seven CCL cavities. Each cavity and the space between segments is $\beta\lambda/2$ long.

### Accelerating Gradient Across Transitions

In a linac such as APT with its constant 8$\beta\lambda$ focusing period after the RFQ, the transverse focusing strength per unit length remains constant through transitions in accelerator structure type. The key to maintaining a smooth average longitudinal focusing strength is an adjustment of the accelerating field $E_0$ at each structure transition. In this regard, we distinguish between $E_0$ and the axial field gradient averaged over the active cavity length, and the "real-estate" gradient, which includes the transit-time factor as well as the packing fraction. We define the packing fraction as the ratio of active structure in a period to the period length. We present three examples of how $E_0$ changes at transitions in the APT linac. Figure 6 plots the accelerating gradient for several segments of the APT linac on either side of the change in cavity type at 8.1 MeV (see Fig. 2). Each point represents a cell containing a single accelerating gap. There are two cells per cavity below the transition energy and three cells per cavity above it. The average axial field is constant within a cavity, so points appear in pairs of equal $E_0$ below 8.1 MeV and in groups of three above the transition. In this case, the bore radius remained fixed at 1.0 cm, so the transit-time factor differs only slightly between cavity types. The main difference is the change in the packing fraction.

Figure 7 shows $E_0$ and $E_0T$ for several segments on either side of the change in bore radius at about 31 MeV. The cavity type on both sides of the transition is the same, consisting of 2-cavity, 4-gap segments. Because the packing fraction does change, the real-estate gradient (not plotted) is just $E_0T$ reduced by the constant factor 0.75 through this energy range. The larger-bore cavities require a higher field level because of a ~5% reduction in the average transit-time factor. These changes in the field level occur within the same rf module. Unequal coupling-slot sizes on either side of a coupling cavity introduce the required step in the field level in adjacent accelerating cavities. We set the slot sizes during the low-power tuning of the structure before furnace brazing the copper assembly.

Figure 7 illustrates an important effect included in the new PARMILA code [14] used to simulate the beam-dynamics performance of the CCDTL. The outer gaps in these 4-gap segments have a lower transit-time factor $T$ than the inner gaps because the axial electric field penetrates into the connecting bore tubes. Inner gaps share one Dirichlet boundary between cavities, which improves $T$ relative to the end gaps. The larger bore degrades $T$ for both inner and outer gaps, but the degradation in the outer gaps is worse. Thus, above 31 MeV, there is a larger difference in $E_0T$ between the inner and outer gaps.

The third example includes a change in the bore radius from 2.0 to 2.5 cm as well as an increase in the packing fraction from 0.75 to 0.875. Figure 8 shows the transition from 6-cell CCL segments to 7-cell CCL segments at 157 MeV. Again, $E_0$ is constant through a segment containing either 6 or 7 cavities. Transit-time factors for the end cells are noticeably lower relative to the inner cells of a segment. This effect is not as pronounced as in Fig. 7 because the cells are longer. The particle velocity $\beta$ has increased from 0.25 to 0.51.

![Figure 6](image)

**Figure 6.** Accelerating gradient through the transition at 8.1 MeV. The bore radius (and hence $T$) does not change. The packing fraction increases from 0.375 to 0.625.

![Figure 7](image)

**Figure 7.** Accelerating gradient through the transition at 31 MeV. At this transition, the bore radius increases from 1.25 cm to 1.5 cm. The packing fraction remains constant at 0.75.
Two Coupling-Cavity Orientations

Successive accelerating gaps are $\pi \beta \lambda / 2$ apart, where $n$ is an integer. Within the same CCDTL cavity $n = 2$, and for adjacent CCL cells $n = 1$. When successive gaps are in different cavities, the type of coupling cell between accelerating cavities depends upon whether $n$ is even or odd. Figures 1 to 5 include examples of both schemes. Drift lengths noted in the figures are $\beta \lambda / 2$ shorter than the distance between the gap centers. The flexibility of two coupling-cavity orientations offers important advantages. First, it allows changes in the rf cavity type (for improving efficiency) without changing the focusing period. Second, it permits a large packing fraction throughout the major portion of a high-energy linac such as the APT.

Further explanation might be helpful. Coupling cells are nominally unexcited in a chain of cavities operating in the $\pi / 2$ structure mode. In conventional coupling cells, the axial electric field of the TM_{030} mode is parallel to the beam axis and the magnetic field has the same direction at both slots. This cavity remains unexcited in the $\pi / 2$ mode because the magnetic field of the two adjacent cavities drive it with equal and opposite strength. Thus, the conventional cavity orientation is appropriate for odd $n$ where adjacent accelerating cavities have fields that differ in phase by 180 degrees. The sideways mounted cavity works for even $n$. Fields at the two slots are in opposite directions, so the cavity remains unexcited if the adjacent cavities are in phase. Side-coupled linacs have used conventional coupling cells for many years. We have successfully tested sideways-mounted coupling cavities on several CCDTL low-power models.

Conclusion

We have discussed design procedures for high-current ion linacs that help to achieve smooth transverse and longitudinal focusing throughout the accelerator. Examples of rf structures from the 100-mA cw linac for APT served to illustrate the design strategies. Beam-dynamics simulations discussed in other papers at this conference show no growth in the transverse emittance and only small growth in longitudinal emittance.

Acknowledgement

This work is supported by the US Department of Energy.

References


DESIGN ISSUES FOR HIGH-INTENSITY, HIGH-ENERGY PROTON ACCELERATORS

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Abstract

High-intensity, high-energy proton beams are required in various fields of science and industry, including pulsed-spallation neutron experiments, nuclear-physics experiments, and nuclear-waste transmutation. We have various possible accelerator schemes for these purposes. The advantages and disadvantages of the parameter choices are summarized while emphasizing the importance of understanding the halo-formation mechanisms in order to settle various controversial issues. The beam current to be accelerated is actually limited by the amount of beam loss, which is critically dependent upon the amount of beam halo, both longitudinal and transverse. The optimum design is also dependent upon the future performances of the key components, such as high-intensity, low-emittance ion sources. Thus, we should concentrate our efforts on the development of these components in order to realize these machines. Some examples of the efforts being made in this direction are presented.

Introduction and the Time Structure of a Beam

The scope of this paper is to list various topical controversial issues concerning the design of high-intensity (typically more than 0.1 mA), high-energy (more than 1 GeV, but less than several 10 GeV) proton accelerators, and to hopefully present possible solutions, or to propose directions for further research and development. Examples of these machines are listed in Table 1 [1-8].

The optimum design of an accelerator is dependent upon its detailed specifications. The specifications for intensity and energy are still insufficient for optimizing the design. Other important factors are the time structure and emittance of the beam. Typical examples of useful time structures are shown in Fig. 1 (a few 100 ns, a few 10 ns, CW or nearly CW). The beam as shown in Fig. 1 b) is required for spallation neutron experiments [10] with a high energy resolution, based upon the time-of-flight method. That shown in Fig. 1 c) is useful for muon spin rotation/resonance/exchange experiments [11] in order to study mainly material science. An average current as high as possible is required for nuclear-waste transmutation/incineration [12], while a long-pulse or nearly CW beam is usually requested for nuclear-physics experiments(Fig. 1 d) [13]). A relatively low emittance (typically an unnormalized 90% emittance of around 2π mm-mrad) is necessary for the latter.

The beam represented by Fig. 1 b) and c) (a peak current of a few 10 A) cannot be obtained directly from an ion source, the maximum peak beam current of which is on the order of 100 mA. This is the reason why we need a synchrotron ring with a revolution time of a few 100 ns. A typical schematic accelerator complex thus comprises an injector linac and a synchrotron ring. The highest possible beam current will be filled up in the ring, and will then be fast-extracted. The ring is used as a compressor with a pulse length equivalent to its revolution time in this case. Additional bunch compression with a bunch rotation is possible down to a few 10 ns (Fig. 1 c)) in a ring by applying a high voltage [9,14].

On the other hand, if what one needs is only a high average current, for example a few 100 mA, a unique solution would be a CW proton linac. However, if the necessary average current is much lower than the possible peak beam current in a linac, the CW proton linac scheme is extremely expensive. The best choice is again the accelerator complex comprising a linac and a ring, where the ring is used as a stretcher [9,14]. The beam is slowly extracted from the ring in this case. If the necessary energy exceeds around 3 GeV, one more ring should be built as in the case of JHP [7].

Beam Loss

Among the various technical problems involved in building high-energy, high-intensity proton accelerators, beam loss is among the most crucial. It should be realized that the beam current to be accelerated is really limited by the amount of beam loss. Beam loss in the high-energy region not only gives rise to a radiation-shielding problem, but also to the radioactivity of the machine itself. The radioactivity should be reduced to a certain level which would allow hands-on maintenance (at worst around 5 nA/m/GeV [15]; hopefully, much less). Accidentally, this level of the radiation can be shielded by a reasonable amount of concrete down to an environmentally allowable level.

At present it is believed that the behavior of the beam core can be well controlled during the injection, acceleration, and extraction processes. Also, we perhaps understand some mechanism concerning the growth of rms- or 90%- emittance during the acceleration in linacs. However, beam loss

| Table 1 | Examples of the operational and planned high-intensity, high-energy proton accelerators. The first three columns show the operational machines, while the others are planned. The MMF linac is partly operational. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Energy (GeV)    | 0.8             | 0.8             | 24              | 0.6             | 1.33            | 1               | 3               | 50              |
| Injection Energy (GeV) | 0.07           | 0.8             | 1.5             | 0.6             | 1.33            | 1               | 0.2             | 3               |
| Repetition Rate (Hz) | 50             | 20              | 0.56            | 100             | 50              | 60              | 0.3             |
| Average Current (mA) | 200            | 70              | 5               | 500             | 3,800           | 1,000           | 200             | 10              |
| Total Power (MW) | 0.16            | 0.056           | 0.12            | 0.3             | 5               | 1               | 0.6             | 0.5             |
| Ref. | [1] | [2] | [3] | [4] | [5] | [6] | [7,8] | [7,8] |

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at a level $10^{-7} /\text{m/GeV}$ arises from the beam halo, the generation mechanism of which has not yet been fully understood. The difficulty to reliably estimate the beam loss gives rise to controversy for determining the optimum design.

![Diagram of time structure of high-intensity proton beam](image)

**Fig. 1. Typical examples of time structure of the high-intensity proton beam.**

For this reason, considerable efforts [16] have been devoted to a theoretical study of the beam-halo generation mechanism. For example, it was shown that the halo is formed from particles interacting with the core oscillation or breathing [17]. A recent computer-simulation result [18] has shown that a beam with a hard core eventually results in a soft beam during the course of 1.3-GeV acceleration in the ESS proton linac [5], although no error in the alignment or accelerating field is included. Since a halo comprising a fraction of $10^{-6}$ of the total beam current grows far beyond the Gaussian tail, these kinds of halos cannot be recognized by watching only the rms-emittance growth.

It is quite common that non-linear phenomena are strongly influenced by the error field [19], such as a deviation from the ideal focusing or accelerating system in the present case. The information which is really necessary to design high-intensity, high-energy proton accelerators is quantitative in the form of tolerance, by which the halo formation can be minimized. Unfortunately, it is still impossible to obtain quantitative information, since this kind of simulation presently consumes a tremendous amount of computing time.

Until a quantitatively reliable estimate becomes possible, we have no other way than to follow the design principle to minimize the rms-emittance growth, keeping the difference in mind. Nevertheless, the principle seems to be qualitatively applicable to minimizing the halo formation from the general characteristics of non-linear phenomena. It has been theoretically known that emittance growth arises due to the following mechanisms: the charge-redistribution from the given one to a uniform one [20], the energy transfer among the longitudinal and transverse oscillations [21], rms-mismatching [22] and structure resonances [22]. In particular, the latter two mechanisms imply the effect of a deviation from the ideal focusing and/or accelerating systems within the framework of non-linear space charge dynamics, which is perhaps common in both halo-formation and rms-emittance growth.

**Rapid-Cycling Synchrotron versus Storage Ring**

There are two ways of obtaining MW proton beams with a $\mu$s pulse duration: combining a full-energy linac and a storage ring, or combining a low-energy linac and a rapid-cycling synchrotron (RCS). However, if the specification exceeds about 5 MW, or requires upgradability, the former option is only a choice regarding the space charge limit in a ring and a relatively short stay of the beam in the ring. By adding a relatively inexpensive storage ring (compared with RCS), and by increasing the pulse length of a linac, one can double the power in this case. The RCS option requires a larger number of powerful RF cavities in order to rapidly accelerate the beam, and ceramic vacuum chambers with RF shields to eliminate any eddy current which would otherwise be induced by rapidly changing magnetic fields.

However, if the beam current is limited by the beam loss during the injection process, the lower injection energy has some advantages, since the radioactivity is roughly proportional to the beam energy. A beam loss of approximately an order of magnitude higher will be allowed in 200-MeV injection than in 1.334-GeV injection. One may partly attribute the success of ISIS [1] to its low injection energy (70 MeV) to RCS. Since the beam-loss mechanism in a ring is another, or more difficult problem, to understand, it is not yet a settled problem which is more advantageous between the two options if the beam power does not exceed a few MW.

It should be appreciated that magnet lattices have been devised in order to realize a negative, or extremely small, momentum compaction factor [23], by which no transition need be crossed during acceleration. The beam loss otherwise arising from the transition crossing will be drastically eliminated. This kind of lattice has been extensively and carefully tested in Super ACO [24], showing the validity of the theory.

If beam-halo formation is unavoidable in a linac, and if high-energy injection is necessary regarding the space-charge limit, a series of halo collimators [5] should be installed, particularly in longitudinal phase space, in order to eliminate the halo, which would otherwise result in a beam loss during injection. The longitudinal collimators must be located in the high-dispersion, (hopefully) low-$\beta$ region. In any case, the beam loss should be localized by the halo collimators.

**Ion Source**

If one has to inject the beam into the ring for an order of several hundred $\mu$s or turns, it should comprise negative hydrogen ions. In contrast to positive ions, negative ones can be injected with the same condition as that of circulating positive ions until the time is limited by other effects, such as the space-charge limit and/or beam instabilities and/or
Coulomb scattering in a charge-exchange foil. At present no ion source simultaneously meets all the requirements (typically, a peak current of several 10 mA, a normalized 90% emittance of 1 π mm-mrad, a pulse length of several 100 μs, a repetition of several 10 Hz, without or with a very small amount of Cs) for MW machines. It is, again, very difficult to predict what will be the current limit of a single negative hydrogen ion source in the future. This is another reason for controversy regarding choosing parameters. In any case, the highest-possible peak beam current (of course, stably obtainable) of negative hydrogen ions with a reasonably low emittance (a normalized 90%-emittance below 1 τ mm-mrad) should be improved by carrying a more extensive study and developing ion sources.

At first, the volume-production type of ion sources was considered to be advantageous regarding not only high brightness, but also the elimination of Cs vapors. There are some indications that the Cs vapors reduce the discharge limit, possibly being harmful to the high-field operation of the following RFQ. However, a source without Cs has produced only a peak current of 16 mA with a normalized 90% emittance of 0.5 π mm-mrad [25]. Since it has been indicated that the introduction of a very small amount of Cs vapor drastically (approximately by a factor three) improves the beam current, even in the volume-production type [26], it is important to empirically test the effect of this amount of Cs on the discharge limit in the RFQ. It seems to be quite possible that a small amount of Cs vapor is practically harmless.

On the other hand, if a beam current of negative hydrogen ions continues to be by an order of magnitude smaller than the proton beam for the same emittance, proton injection would be another choice for a 0.1-MW machine.

Frequency Issue

The frequency is another important parameter which needs to be determined. Conventional proton linacs have been using around 200 MHz for the drift-tube linac (DTL). Most of the recently proposed designs have suggested the use of a higher frequency (300 MHz to 400 MHz) for the following reasons.

If one doubles the frequency, it is possible to halve the number of particles per bunch. In addition, the focusing period becomes more frequent both longitudinally and transversely. As a result the space-charge effect would be approximately halved. Computer simulations have been attempted in order to confirm the above expectation. For a fair comparison between the low- and high-frequency schemes we need optimum designs for both schemes, although we have no reliable algorithm which can generate the optimum parameters for reducing the emittance growth and halo formation. In spite of this difficulty, some computer simulations indicate that the higher frequency scheme is more advantageous [27].

The best advantage of the higher-frequency scheme is the use of klystrons, which are the most powerful and stable rf power sources, and having mature engineering techniques.

It is difficult to increase the frequency of the low-energy front DTL further, if one wishes to contain quadrupole electromagnets in drift tubes in order to keep the flexibility for the future upgrade of the peak beam current. This is the reason why we choose 324-MHz DTL to accelerate the beam from 3 MeV.

RFQ

An RFQ linac [28] is an ideal device, in which both longitudinal and transverse focusings are incorporated together with the ideal adiabatic bunching. Therefore, it is preferable to use the RFQ up to the highest-possible energy [29]. However, the field of a conventional four-vane RFQ is difficult to stabilize if the RFQ is elongated over four wavelengths in order to accelerate the beam up to typically 3 MeV. The dispersion curve [30] of the RFQ clearly shows the reason for the difficulty in field stabilization. The dipole (TE11n) mode is easily mixed with the accelerating quadrupole (TE210) mode, since the frequencies of these modes become close together. Although a Vane-Coupling Ring (VCR) [31] could solve this problem, by increasing the frequencies of the dipole modes, it cannot be used for a high-duty machine, because it is difficult to water-cool. The π-mode Stabilizing Loop (PISL) [32] is easy to water-cool while keeping similar beam stabilizing characteristics to that of the VCR. Another solution may be to use a four-rod RFQ [33], for which we should again find a special water-cooling device. Together with a recent further development for elongating the RFQ [34], it has been proposed to use an RFQ of up to 8 MeV.

However, the transition energy from an RFQ to a DTL should be carefully chosen by taking into account the detailed design of the medium-energy transport for matching the beam both longitudinally and transversely. In addition we should find the optimum space for installing the chopper. In the ESS design the 5-MeV RFQ is separated into two parts, between which the chopper is located at 2 MeV [5]. The beams of the two RFQ's are funneled together into the DTL by choosing the frequency of the two RFQ's as one half of that of the DTL. In this case one should find some means to minimize the emittance growth and halo formation during the funnelling process.

Accelerating Structure

Before discussing the DTL it is useful to introduce the concept of a separated DTL (SDTL) [35], in which the focusing magnets conventionally contained in the drift tubes are located outside. Since the drift tubes become free from the constraint of containing the quadrupole magnets, the shunt impedance of the SDTL can be optimized even further. In addition, the drift tubes become significantly easier to fabricate by removing the magnets, resulting in a drastic reduction in the cost of the DTL. It is, however, controversial what should be the transition energy from the conventional DTL to the SDTL. Needless to say, the focusing quality of the SDTL is inferior to that of the conventional DTL (the focusing period of the SDTL is longer than that of the DTL). If one wishes to have a better quality in order to overcome various space-charge effects, one should choose a higher transition energy. We are at present assuming a transition energy of 55 MeV for the JHP.

There may be several versions of SDTL: a Bridge-Coupled DTL in narrow [36] and wide meanings and a Coupled-Cavity DTL [37]. The choice of a specific version requires a significant trade-off study, including the detailed engineering design.

A discussion concerning the choice of the high β structure is omitted here, since it is detailed in Ref. [38]. However, the
choice is again dependent upon understanding the halo-
formation mechanism. The transverse electric kick [39]
existing in the side-coupled structure (SCS) gives rise to a
slight amount of continuous transverse oscillation of the beam
core, possibly resulting in halo formation. We have not yet
obtained any reliable quantitative conclusion for this
possibility. If it is really significant, the annular-ring coupled
structure (ACS) is the one which has the balanced
characteristics of both the shunt impedance and the field
symmetry [40]. The importance of the field stability, in
particular, against the heavy beam loading stressed in Ref. [39]
is justified by a recent study [41].

It is another issue as to at what energy one should make
the frequency jump from low frequency to high frequency, or
any other abrupt transition, if necessary. The frequency jump
at lower energy is preferable from a power-saving point of
view. In addition, the beam loss arising from the frequency
jump at a lower energy can be managed more easily than that
at a higher energy. However, the ratio of the acceptance to the
emittance is higher in the case of a high-energy frequency
jump due to adiabatic damping, favoring the high-energy
option from the beam-loss viewpoint [29]. It should also be
noted that a low-energy, high-frequency structure is difficult to
fabricate, particularly to equip it with water-cooling channels
for a high-duty machine.

**SCC versus NCC**

It appears to be energy-saving to use a super-conducting
cavity (SCC) structure. This is true only if the beam pulse is
longer than a few ms, since the filling time of the typical
super-conducting structure is of several 100 μs under
practically "reasonable" beam loading. In a long beam-pulse
machine the SCC approach (see also Ref. [42]) implies the
following additional advantages over the normal-conducting
cavity (NCC) scheme (sometimes referred to as room-
temperature cavity). First of all, we can use large bore radii,
which are impractical in an NCC scheme due to the increase
in power dissipation. This is advantageous regarding a
reduction in the beam loss. (This is only true if the present
theories concerning the halo formation correctly predict the
behavior of the halo, which is characterized by a saturation in the
halo-envelope development. Otherwise, the large bore radii
can give rise to a delay in beam loss to the high-energy
region, resulting in more radioactivity.) Second, we can use a
higher field gradient, typically 5 MV/m and hopefully 40
MV/m, than that of the NCC (typically around 1 MV/m for
CW). The former is determined by the power capability
through input couplers or by the refrigerator power
consumption, while the latter is usually determined by
optimizing both the capital and operational costs. Since the
RF power becomes expensive both capitally and operationally
as the pulse is elongated [38], the total shunt impedance must
be increased by elongating the NCC's, which is, by decreasing
the field gradient. Third, the stored energy in the SCC system
is extremely higher, being immune against any variation of the
beam loading [43,44], as in the case of beam chopping.

On the other hand, the amplitude-phase control is more
difficult than the NCC scheme, since the beam loading is
extremely heavier than the power dissipation. It is noted that
the tolerance of the amplitude-phase control in proton
accelerators is much more severe than in electron accelerators.

It will also be necessary to carefully investigate the radiation-
damage effect on the superconductivity, although there is no
evidence that it is fatal.

If one uses the SCC, it is possible to use a low peak
current in order to ease the space-charge problem. However, if
one wishes to inject the beam into a ring, there is a limit in
the number of turns by which higher-order resonances can be
excited. The number can be significantly reduced by the tune
spread due to the space-charge effect, being the same order of
magnitude as that of the typical filling time, as mentioned
above. In addition, the beam instability and the Coulomb
scattering by the charge-stripping foil limit the number of
possible turns for injection. A careful study is still necessary
in order to settle the problem of whether the SCC scheme is
really advantageous if the injection to a ring is required. The
SCC scheme is definitely useful for a multi-purpose facility,
for example, including multi-storage rings, nuclear-waste
transmutation test area and others, like the new version of the
JAERI project [45] (the multi-storage rings are not included
in this project).

**Injection Schemes to a Ring**

There are two kinds of longitudinal capture schemes in a
ring: one is an adiabatic capture [46], while the other uses a
chopper. The chopper system should be more advantageous
than the former regarding beam loss during the capture
process. However, we have no established chipping scheme
for the several-MeV RFQ, although there are some proposed
schemes. For example, a series of two subsequent RFQ's will
be used in the ESS linac with a chopper in between the two
RFQ's. For the JHP linac a low-Q deflecting cavity is under
investigation with the same frequency as those of the RFQ and
DTL, in between which the chopper is located [47]. It is most
important to eliminate the beam during the beam-chopped
period rather than the nominal values of the rise and falling
time of the chopper.

Other important features required for high-intensity proton
rings are painting in the ring acceptance, both longitudinally
and transversely, in order to suppress the space-charge effect.
The bunching factor should be decreased by some means, such as
2nd-harmonics cavities [48] or barrier cavities [49].

**Conclusion**

After LAMPF/PSR and ISIS were built, extensive studies
were performed in order to improve the design of high-
intensity, high-energy proton accelerators. The experience
obtained by operating these accelerators has been playing an
important role in the studies. However, since no such machine
has been built afterwards, we have had only a few chances to
test the new theories. This is the main reason why we have so
many controversial issues. It is really necessary to build a new
machine with an improved design on the basis obtained from
the LAMPF/ISIS experience and others.

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REVIEW OF NEW DEVELOPMENTS IN THE FIELD OF INDUCTION ACCELERATORS (ELECTRONS AND IONS)\(^*\)

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INTRODUCTION

Induction machines have the unique capability of delivering very high current and peak power in a pulsed mode. It was the need for high power for fusion that led Nicholas Christofelius in the 1950's to invent and build Astron, the first induction accelerator [1]. Since then, various high power applications have led to the construction of the Electron Ring Accelerator (ERA) [2], Experimental Test Accelerator (ETA) [3], Advanced Test Accelerator (ATA) [4], the flash radiography machine FXR and the high repetition rate machine, ETA II [5], which was designed to deliver high average power as well as high peak power. The largest of these machines is ATA with design goals of 50 MeV and 10 kA. All of the high current electron machines since ERA are "short-pulse" devices (~50 ns). Meanwhile, the invention of heavy ion fusion in the 70's led to the development of induction machines for ion acceleration [6]. For this application, the devices tend to have long pulses (>1 μs). The induction machines for ions and electrons operate on the same principle. The pulse length difference between electron and ion machines is historical and incidental, although long-pulse devices lead to different approaches to magnetic material and pulse power technology than short-pulse machines.

While some of the past applications, particularly those related to the Strategic Defense Initiative, have come and gone, the need for high power continues to exist in energy, environment, national defense, and basic sciences. In this paper, we will review three ongoing applications, one in fusion energy, one in defense, and one in high energy physics. Induction machines for heavy ion fusion [7], for radiography in hydrodynamic tests [8], and for relativistic-klystron two-beam accelerators [9] are areas of active research. Induction machines have also been considered for other applications such as treatment of nuclear wastes [10], neutron spallation sources [11], and μ μ collider components [12]. These applications will not be reviewed here because of space limitations. In addition, the inductive voltage adder (IVA) technologies are described in a separate paper in these proceedings [13]. The three applications we will review were chosen to demonstrate that with vastly different goals, different machine parameters, and very different architectures, a similar set of performance objectives has led to technological advances along closely parallel paths.

In any large machine, the economic issues of cost and efficiency, and the technological issues of machine and beam performance are equally important considerations. We hope to show how these factors have affected the development paths in these three areas. We will first summarize recent activities in each one of these fields, and then proceed to describe issues and advances in the control of beam energy flatness, emittance preservation, and beam instability suppression. While these issues are common to all accelerators, the fact that we are working with very intense beams and long pulses makes the challenges of induction machines unique. For the purpose of this review, we will broadly include the induction accelerators proper, as well as their injectors.

RECENT DEVELOPMENTS

Heavy Ion Fusion

Induction linac technology has been the primary approach to the heavy ion fusion driver in the U.S. The baseline scenario [6, 7] consists of multiple beams of heavy ions, sharing common (large) induction cores. These beams are focused by electrostatic quadrupoles in the front end, and magnetic quadrupoles at the higher energies. The beams are many microseconds long in the front end, and are compressed eventually to about 10 nanoseconds at the target. To hit a target spot of several millimeters within a reactor of several meters in diameter, the ion beams must have low emittance and less than a percent of energy spread [14]. The ions are non-relativistic and space-charge-dominated, and collective effects play a central role in the beam dynamics.

Early experiments at LBL had demonstrated transport of space-charge-dominated beams in electrostatic quadrupole channels (SBTE) [15] as well as the simultaneous acceleration of four beams (MBE-4) [16]. An ongoing experiment at LBL seeks to demonstrate the combining of four separate beams into one with acceptable emittance growth [17]. Beam combining is motivated by the economics of the fusion driver where attractive cost savings could be realized with many beams in the front end and fewer beams at higher energy. Small scale tests of magnetic quadrupole transport, final focusing, and beam bending are also planned in order to address the beam dynamics issues anticipated in the final driver.

An alternative accelerator architecture in a recirculating configuration [18] where induction cores and magnetic transport lines are being reused as the beam is recycled about 100 times is also being studied, both in a driver-design study [19] as well as in a small-scale recirculator experiment at Lawrence Livermore National Laboratory [20]. This scenario involves higher technical risks, but the architecture has the potential of large cost reductions for the driver. Recirculator studies have led to development of advanced technology elements such as very fast and flexible switching at high repetition rates [21].

In addition to these small scale experiments, much of the HIF engineering effort has been directed to the cost reduction of key components, such as the magnetic material, the electrostatic and magnetic focusing elements, alignment

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techniques, etc. [22]. Underlying much of these physics and engineering studies is the ultimate goal of making heavy ion fusion as competitive as the lowest cost energy options in the market.

An equally important programmatic goal is to work towards the production and control of driver-scale beams. An injector with driver-scale energy (2 MV), current (0.25 μC/m, or 800 mA of singly charged potassium ions), and emittance (normalized edge emittance of less than 1π mm-m) was constructed and successfully operated at LBL [23]. The beam parameters are required to be constant over the entire pulse of 1.5 μs. Such a demonstration was essential as a first step towards the highly controlled beam performance required for the ultimate fusion driver. Detailed measurements of beam current, energy, envelope, and transverse phase space were also essential for validating 3-D PIC codes which have been developed to model performance of fusion drivers [24]. The agreement between experiments and simulations have been excellent thus far [25]. Various experiments to transport, focus, and bend space-charge-dominated beams have been performed, using this beam, and more are planned.

**Radiography for Hydrodynamic Tests**

Development of induction machines for X-ray radiography are ongoing in the U.S. and in France. The goal is to design machines with 3 to 4 kA of electrons, 15 to 20 MeV and about 60 nanoseconds, low emittance (ε_{x} = 1200πmm-m) and minimal energy variation (Δp/p < 1%), to impinge upon an X-ray target for the imaging of hydrodynamic events.

The DARHT (Dual Axis Radiographic Hydrodynamics Test) facility [8], under construction at Los Alamos National Laboratory, will consist eventually of two independent induction accelerators. The first arm is under construction, using technologies that are similar to the ETA II. The French machine AIRIX [26] has design goals that are quite similar to the first arm of DARHT. Full scale test stands at LANL (Integrated Test Stand, ITS) and at CESTA (PIVAIR) are addressing key engineering and beam dynamics issues. The second arm of DARHT may have multiple pulse capability over a microsecond duration, but is otherwise quite similar in current and energy to the first arm. While DARHT I and AIRIX are short pulse machines, and are based on ETA II type technologies, DARHT II has the options of ETAII-like cells with advanced 4-pulse switching, or long-pulse technologies similar to those of Heavy Ion Fusion. These options are under active study.

More advanced machines for hydrodynamics are also under study. The ETA II machine at Livermore is in fact being reconfigured to study the beam dynamics of one such advanced scheme (the Advanced Radiographic Machine ARM). The proposed scheme accelerates several long pulses each of which is "cut" into several shorter pulses at extraction by means of fast kickers. These short segments of the beam are then transported through separate beamlines to produce X-ray images at different angles and at slightly different times. These manipulations clearly require excellent control of the beam, and successful demonstration of beam chopping will undoubtedly advance the art of beam control.

**Relativistic-Klystron Two-Beam-Accelerator**

The relativistic-klystron two-beam-accelerator is a combination of the klystron technology with induction technology for an efficient high frequency rf power source for high gradient linear colliders. A key physics issue that has recently been demonstrated is the reacceleration of bunched beams [27]. An experiment using the ATA injector which provides a beam of 5 MeV and 1 kA was "chopped" into small bunches at 11.4 GHz by a transverse beam chopper. The chopped beam was then made to traverse three extraction cavities and two intervening reacceleration induction cells. The power levels measured at the three extraction cavities were consistent with simulations, and the measured rf phase was stable over the beam pulse.

While the ATA experiment provides a first demonstration of reacceleration, a full-scale efficient two-beam-accelerator, must of necessity be a long device with challenging drive beam dynamics issues. A new scheme recently proposed (TNLNC) [28] offers the possibility of a low cost and efficient architecture with acceptable drive beam stability. The scheme was based on the observation that the peak rf power levels of 180 MW/m required for high-gradient upgrades (100 MV/m unloaded) of the X-band linear colliders studied by SLAC (NL) [29] and KEK (JLC) are, by induction linac standards, rather low, and can be generated by a low current (600 A) and low-gradient (300 kV/m) drive beam at an operating energy of 10 MeV. Reacceleration is provided by induction modules of 100 kV and 300 ns. This induction module has almost twice the volt-seconds of an ATA cell (250 kV, 70 ns), comparable axial lengths, but only one-half the diameter, and one-quarter the transverse area (see Figure 1). This compact cell is made out of a low-cost magnetic material (Magne) and low-cost ferrite permanent magnet quadrupoles. In addition, the bore diameter is very small (5 cm), and is possible because of the relatively low current of 600 A, operating in a "betatron node" mode for beam break-up control. The pulse-power system consists of a low-voltage architecture with a pulse-forming-network switched by ceramic thyatrons powering a series of small 20 kV cores. This pulse power system bypasses the voltage step-up transformer of the usual klystron modulators, and the rf source requires no rf pulse compression. This simple architecture is expected to have high efficiencies. Detailed cost and efficiency estimates indicate that such a machine could be an attractive power source candidate for future colliders.

The feasibility of this new device depends critically on the ability to control beam breakup and other beam dynamics issues. Simulations to date show acceptable beam behavior, but experimental demonstration is essential. A prototype machine RTA [30] with 8 to 12 rf extraction cavities over 8 to 12 meters of reacceleration is being built at LBL to test these beam dynamics issues. Construction of this new machine also offers the opportunities for detailed engineering, costing, and efficiency checks on critical components.

**ADVANCES IN INTENSE BEAM CONTROL**

While the applications and activities associated with induction accelerators have been varied and diverse, yet the
quest for improved beam control is a recurring theme in most applications. In this section, we will describe advances in three areas.

**Energy Flatness**

The three applications share a common goal of minimal energy variation over the entire beam pulse. In heavy ion fusion, the final objective is to deliver several megajoules of heavy ions onto a small target spot several mm in diameter. Final focus requires that the energy spread from head to tail be small at accelerator exit, (Δp/p ~ 0.1%). It is therefore important to have control over the entire beam pulse at every stage from injector to target. At the LBL 2MV injector, energy flatness is attained by a combination of a flat MARX voltage pulse and a well controlled current extraction pulse. The MARX voltage was designed to have 4 to 5 μs flat-top (Δp/p<0.1%) to accommodate the entire beam pulse plus transit time through the injector column. The pulse extraction pulsar has a tunable pulse forming network which was tuned to yield an energy flatness, as measured by an electrostatic energy spectrometer at injector exit, of ±0.15% over the pulse body (see Figure 2a). During the fall and rise of the beam pulse, there are strong space charge forces which lead to high energy at beam head and low energy in beam tail.

![Energy spectrometer measurements for: (a) Ion beam from Heavy Ion Fusion Injector. (b) Electron beam from ITS at injector exit. (c) Electron beam from ITS after acceleration. Courtesy LANL for Figures 2(b) and 2(c).](image)

Radiography for hydrodynamic tests have similar final focusing requirements since the electron beam must hit a sub-millimeter spot on the target to produce X-ray for high resolution imaging. In both the ITS at LANL as well as PIVAIR at CESTA, spectrometer measurements have demonstrated flat-tops of less than 1% over 60 ns both at injector exit as well as after acceleration through several induction cells (see Figures 2b and 2c).

Relativistic klystron two-beam-accelerators require very good energy flatness because of rf phase stability requirements. In the RTA, for example, ±0.3% energy flatness is required eventually to achieve 5th phase stability over 12 meters of rf extraction and reacceleration (12 extraction cavities). This requirement must be satisfied from the gun through every stage of the RTA front-end. During 1996/97, gun construction is in progress, and we have demonstrated 1% energy flatness over 200 ns in a full-scale induction cell under a resistive load. This is a first necessary step towards an acceptable 1 MV gun which is made out of 24 such induction cells.

**Emittance Preservation**

Low emittance is essential for HIF if the heavy ion beams are to hit the small target spot at the center of the fusion
chamber. Although the final emittance of $\text{En} \geq 10 \text{ } \pi \text{mm-mV}$ required is a factor of 10 to 100 larger than the emittance at source (consistent with source temperature). Nevertheless, care must be taken at each step to minimize emittance growth. The issue of emittance growth has been central to experimental and theoretical beam dynamics studies at the LBL 2 MV Injector.

The LBL HIF injector column consists of four sets of electrostatic quadrupoles arranged to accelerate and focus the ion beam simultaneously (see Figure 3). The interdigital structure of the quadrupoles is intrinsically 3-dimensional with associated higher order multipoles. The beam is dominated by space charge effects. In addition, a third order kinematic effect is present when low energy beams are focused by strong electrostatic quadrupoles leading potentially to phase space distortions. All these effects can lead to emittance growth. The design of the electrostatic quadrupole injector was performed using the 3-D PIC code WARP3d, and the column geometry and voltages were optimized to minimize emittance growth at the design current and voltage. The measured phase space is in good agreement with 3-D simulations over a broad range of parameters. The normalized edge emittance of less than $1 \text{ } \pi \text{mm-mr}$ meets the initial design goal.

![Figure 3. In an electrostatic quadrupole injector, the electrodes are arranged to accelerate and to focus the ion beams simultaneously.](image)

While much has been learned about emittance growth mechanisms in space-charge-dominated beam, recent observations of rapid density fluctuations in the transverse plane as the ion beam propagates down a six-quad matching section beyond the injector exit was quite unexpected, and has led to further emittance growth (by another factor of two) down the transport line. Whether the observed density fluctuations are due to some space-charge instabilities, or source irregularities, or a combination of both, is still under active studies.

Radiographic machines have similar emittance requirements imposed by final focusing. ITS and PIVAIR employ a technique where the beam emittance is deduced from measurements of envelope changes after the beam exits a solenoidal lens of varying magnetic field. The measured normalized edge emittance of $1200 \text{ } \pi \text{mm-mr}$ is consistent with final focus requirements.

Relativistic-klystron two-beam-accelerators have tight emittance constraints which come primarily from the requirement that the beam must be transported through multiple extraction cavities. In the case of RTA, the 4 MeV, 600 A bunched beam must be able to go through 10 or 12 cavities with an inner radius of about 8 mm. The required normalized edge emittance is $800 \text{ } \pi \text{mm-mr}$. Although the corresponding emittance at source is $80 \text{ } \pi \text{mm-mr}$, one must again be very cautious with emittance preservation as the beam undergoes acceleration, transport, chopping and bunching. Simulations to date from extraction to chopper entrance have yielded beams with normalized edge emittance of $400 \text{ } \pi \text{mm-mr}$.

**Beam Breakup Instability**

It is well-known that the transport of high current in induction machines is limited by the beam breakup instability. In the ATA machine, although the design current of 10 kA could be produced at the source, the beam develops large transverse oscillations, leading to the loss of beam tail long before it reaches the design energy of 50 MeV. At least three different ways of controlling BBU are known and proposed. Some are well-tested, while others are studied theoretically, with actual experimental demonstration still to be performed.

The technique of reducing BBU by de-Qing of induction cavities is well-known. The addition of ferrite dampers to reduce the Q of induction gaps is a standard technique. Every cavity design requires careful shaping of gaps to minimize the transverse impedance. The AMOS code, which calculates impedances in the presence of ferro-magnetic material, was first written to model induction gaps, and has been used quite successfully for the design of ETAIi and DARHT cells. Whether AMOS could be used for the modeling of induction cores with Metglas remains an open question. But the design of induction gaps with minimal impedance is a key issue for all applications.

In addition to the reduction of transverse impedance, Landau damping is known to be an effective way of controlling transverse instabilities. Laser guiding, which allowed the transport of high current through ATA, introduces Landau damping by the nonlinear space charge forces from the non uniform distribution of ions in the channel. In TBNLC, the bunched beam is maintained in stable rf buckets by inductively detainted rf extraction cavities. These rf buckets have a natural energy spread of a few percent. BBU simulations have shown that this amount of energy spread is enough to damp the BBU instability associated with the extraction gaps to a manageable degree. Without Landau damping, transport of a 600A beam through a 300 m long two-beam-accelerator, as proposed in TBNLC, would be impossible.

There is one additional BBU mode for the drive beam of TBNLC, at a much higher frequency of 14 GHz, associated with the HEM$_{11}$, mode of the rf extraction cavities, which is quite virulent, and Landau damping alone cannot control this high frequency instability sufficiently. One additional "trick" was introduced to put it under control. The scheme involves the arrangement of the focusing channel so that adjacent extraction cavities are separated by exactly one betatron period. In this scheme, the displacement in every rf cavity is identical, even though the transverse kick experienced by the beam through successive cavities is additive. The growth of instability in this scheme is linear rather than exponential. We have studied the sensitivity of this scheme to errors in focusing fields and/or energy errors. The simulations indicate that errors of about 1% in either field or energy is tolerable.
While the Landau damping of the low frequency BBU, as well as the betatron node scheme for the high frequency BBU, have been shown in simulations to be effective methods of control, experimental demonstration is highly desirable. The RTA machine, a prototype two-beam accelerator, is under construction at LBL. When operating at full-scale, this machine is capable of testing these critical BBU control mechanisms.

CONCLUSION

We have briefly reviewed recent development in induction accelerators for heavy ion fusion, radiography for hydrodynamic tests, and for relativistic klystron two-beam accelerators. I have attempted to show how much of our activities has been motivated by cost reduction and improved beam control.

Control of intense beams is key to the success of the applications. Even though the architecture and parameters of the three applications are vastly different, yet the goals of energy flatness, emittance preservation, and BBU control are common to all. Significant advances have been made in these areas, although a lot more work needs to be done. Induction technology, when compared to the more conventional rf accelerators, is a relatively young field. Yet its unique capability for high current and high peak power merits continued aggressive development.

REFERENCES

Invited Talk Session TH2

Chairman: S. Fukumoto

Thursday, August 29, 1996
TERA PROGRAMME: MEDICAL APPLICATIONS OF PROTONS AND IONS

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Abstract

The most recent applications of hadron accelerators to tumor therapy are reviewed and the Italian Hadrontherapy Programme is presented in the framework of what is done and planned in the rest of the world.

This programme foresees three independent but coherent activities:

(i) the construction in Milano of a large National Centre for Oncological Hadrontherapy based on a 22 m diameter synchrotron, with 3 rooms for proton treatment and 1 room for ion treatment (which can control radioreistant tumours);

(ii) the construction (financed by Istituto Superiore di Sanità, Rome) of a novel 3 GHZ linac which will accelerate protons to 200 MeV. The second part of this linac can also be used as 200 MeV booster for protons accelerated to 60–70 MeV by high current cyclotrons;

(iii) a multimedia information network (RITA) connecting the Associated Centres with the Centres having hadron beams, so to select before any travelling the patients to be irradiated.

Introduction

Approximately 50% of the 10'000 accelerators running in the world are devoted to medicine and/or biology [1]. About 80% of all the biomedical accelerators (4'000 in 1994) are devoted to radiotherapy with either X-rays [2]; very few of them are used for hadrontherapy. Hadrontherapy is discussed in this paper with particular reference to the Italian Hadrontherapy Programme promoted by the TERA Foundation.

Hadrontherapy with protons and ions

Fifty years ago Bob Wilson remarked that the Bragg peak of monoenergetic protons, and of other charged hadrons, easily allows to deliver the dose with millimetric accuracy, what is now called a "conformal" treatment of deep seated tumours [3]. To reach 25 cm in soft tissues the kinetic energy of the protons has to be 200 MeV. For carbon ions, the most used hadrons after protons, one needs 4500 MeV, i.e. 375 MeV/u. Since the width of the Bragg peak of monoenergetic particles is very narrow, to irradiated thick targets the energy of the charged particles has to be modulated in time either by an absorber of variable thickness or by changing the energy of the accelerator.

With a Spread Out Bragg Peak (SOBP) of 8–10 cm, the distal fall-off of the dose takes place in 2–3 mm and the surface dose for proton (carbon ions) is typically 70% (50%) of the peak dose at 20–25 cm depth. These conditions are much more favourable than the ones of X-rays, which have a roughly exponential absorption in matter. Due to the convenient macroscopic energy distribution, a truly "conformal" therapy can be performed with only one or two directions of incidence of the hadron beam. Moreover the total energy delivered to the surrounding healthy tissues is definitely lower than in X-rays conformal radiotherapy which uses 6–12 crossed beams [2]. This allows an even larger tumour dose than in CRT for sites which are surrounded by critical tissues, as in the brain.

At the end of 1995 about 16000 patients had been treated with proton beams over the world [4] and about 150 with carbon ions at HIMAC (Heavy Ion Medical Accelerator Centre) in Japan [5]. The pioneering work done in LBL with helium ions (about 2000 patients) and neon ions (about 500 patients) has been discontinued in 1992 [6]. Nowadays carbon ions (Z=6) are considered to be better suited than helium (Z=2) and neon (Z=10) ions for the treatment of radioreistant tumours, because the stopping power (or LET=Linear Energy Transfer, which for a given velocity is proportional to Z²) is less than 100 MeV/cm at the entry point (so that in the first traversed layers they behave roughly as X-rays and protons) but is definitely larger than 100 MeV/cm in the spread out Bragg peak, which covers the tumour. Such a high LET is suited to treat radioreistant tumours, i.e. the slowly growing hypoxic tumours which are insensitive to both X-rays and protons and represent about 10% of all tumours treated with X-rays. Thus light ions, and in particular carbon ions, have the double property of a favourable dose distribution (crucial for a conformal radiotherapy) and of a large LET (necessary for the cure of radioreistant tumours).

Protontherapy of eye melanomas, requiring 60–70MeV protons, is performed in many, also European, centres. Deep seated tumours are treated in one dedicated hospital-based centre (at the Loma Linda University Centre in California [7]) and in ten centres which originally were, or still are, nuclear research centres:

- CPO Orsay,
- GWI Uppsala,
- HCL Boston,
- ITEP Moscow,
- IUCF Indiana,
- JNRI Dubna,
- LINPh St.Petersburg,
- NAC Faure,
- PMRC Tsukuba,
- PSI Villigen.

It is seen that only two of them are in the European Union (CPO and GWI). The HIMAC facility in Chiba (Japan) is fully dedicated to ion therapy [5]. Together with Loma Linda, this is the only hospital based dedicated hadrontherapy centre. As discussed below, in the next years the situation will change, in particular outside Europe.

In all these centres the lines transporting the hadron beam to the patient are fixed. In Loma Linda instead they are they consist in three 10 m high rotating isocentric gantries which allow the irradiation of the patient from any angle. The alignement procedure is long: typically 20–30 minutes.

Until now no patient has been treated with a properly directed pencil beam (active beam spreading system). All centres use a scattered beam of hadrons properly shaped in space and energy with absorbers and collimators.

Active systems have been recently tested in PSI and GSI and will be used on patients towards the end of 1996. At PSI a compact gantry and a voxel scanning system for protons has been constructed [9], while the carbon beam of the GSI synchrotron will be used to irradiate patients with a horizontal raster scanned pencil beam [10]. In future all facilities will have active spreading systems, but medical doctors still prefer the passive method which is proven and guarantees an uniform irradiation in the transverse plane. Active system will have to be very reliable to be accepted.
Number of Potential Patients

In Europe (3.2 x 10^8 inhabitants) about 50% of all the tumours are irradiated with high energy photons. This corresponds to more than 600,000 new X-ray treatments per year, which implies about 60,000 new patients with radioresistant tumours, who could profit from radiotherapy. To substantiate this large figure many clinical trials are needed at HIMAC, GSI and possibly other new iontherapy centres.

For protontherapy solid clinical results exist for brain, eye, spinal cord tumours and few other sites. Salivary glands, prostates and cervices have also been treated. A conservative analysis made in the framework of the TERA programme (described in Ref. [11]) concluded that about 5% of X-rays patients would profit (i.e. about 30,000 in Europe). In a study for Europe Gademian obtained much larger figures: 280,000 patients, of which about 25,000 first priority cases [12]. Similar results are contained in a recent unpublished report prepared for the National Cancer Institute by H.D. Suit and collaborators of the Massachusetts General Hospital (MGH).

Since a multigantry centre can treat about 1,000 patients/year (each one for 20 sessions lasting 20–30 minutes each) one conservatively concludes that in Europe there is space for at least twenty protontherapy centres aiming at improving the local control of tumours close to critical organs.

In the world by the year 2000 there will be at least four new dedicated facilities for hadrontherapy, on top of Loma Linda and HIMAC. Two of them (one in USA and the other in Japan) are based on the cyclotron designed by IBA [13]. For the Japanese centre of Kitshawa (Chiba) IBA has teamed up with Sumitomo. The American Centre (NPTC) will have two rotating gantries; it is being built in Boston by Mass General Hospital (MGH) and utilizes all the knowledge collected at the Harvard cyclotron. The Japanese centre is very similar; it will also be ready by 1998.

While these two centres will have only proton beams, in the Prefecture of Hyogo (Japan) a proton and ion centre is under construction and will be ready in 2001. The investment of 275 M$ includes a 50 bed hospital. Mitsubishi Electric is building the accelerator and the highefficiency facilities. The purpose is similar to the one of the Italian CNAO (see later).

The fourth funded hadron accelerator, to be presented below, is a novel 3 GeV linac, which has been designed in the framework of the Italian Hadrontherapy Programme, initiated in 1992 by the TERA Foundation.

The TERA Foundation and the Hadrontherapy Programme

The Foundation was created to collect funds and employ a staff fully devoted to the Hadrontherapy Programme. In 1996 more than twenty people work fulltime on the projects of the Foundation, whose 1995 budget was about 1'300'000 kLit (1kLit = 1DM). In fall 1991 INFN (the Italian Institute for research in fundamental nuclear and subnuclear physics) decided to finance the research part of this activity; since then the support to the twelve Sections and Laboratories of INFN now working on the Programme has increased: in 1996 it is about 800'000kLit. ENEA (Ente Nazionale per le Nuove tecnologie, l'energia e l'Ambiente) joined the Programme in spring 1993 to contribute to the design of "compact" accelerators for protontherapy, a project led since then by Luigi Picardi of ENEA-INN, Frascati. Also in 1993 the physicists of Istituto Superiore di Sanità (the Italian National Health Institutes sited in Rome) decided to join the Hadrontherapy Programme and requested and obtained funds for the construction of a proton accelerator.

Three Committees coordinate the research and development activities done in the framework of the Hadrontherapy Programme:

- the Pathologies and Treatments Committee,
- the Radiobiology Committee,
- the Dosimetry and Microdosimetry Committee.

Their activities, not presented here, are common to all the projects of the Programme.

As far as the direct intervention of the TERA Foundation is concerned, the design and construction activities of the Hadrontherapy Programme are organized in three projects:

- (1) The planning and the construction of a National Centre for Oncological Hadrontherapy (CNAO), a healthcare and research structure of excellence which will be the focal point of all the hadrontherapy activities and — being equipped with proton and ion beams to be used in parallel — will be able to treat with protons about 1'000 patients per year, and at a later stage, an equal number with carbon ion beams.

- (2) The design and the construction of a certain number of Protontherapy Centres equipped with proton accelerators, of small dimensions and relatively cheap, possibly built by Italian industries; each of these will treat at least 200–300 patients a year with a proton beam and about double that number with an added treatment room. This is the "Compact" Accelerator Project PACO.

- (3) The creation of an informatics and organisational network, called RITA (Italian Network for Hadrontherapy Treatment), which will connect the Associated Centres — distributed throughout Italy (and abroad) and situated in the public oncological institutions and in private clinics — with the Centres where proton and ion beams will be made available. The specialized medical and physics staff in these Associated Centres will be able to discuss in remote through multimedia connections the clinical cases, with the experts of the Hadrontherapy Centre and those of the Protontherapy Centres by using the most modern informatics means. They will exchange diagnostics images and some of the physicians at these Associated Centres (sometimes after using conventional radiotherapies) will even be in a position to plan a successive treatment for their patients, which will then be irradiated in one of the Centres where hadron beams are available.

The first two projects are described in the following Sections. For lack of space the RITA network and other Italian hadrontherapy projects not under the direct TERA responsibility will not be further discussed.

The CNAO Project

From the beginning of 1992, the Foundation is engaged in the design and realization of the hadrontherapy centre CNAO based on a synchrotron which can accelerate protons to at least 250 MeV and carbon ions to at least 4500 MeV (i.e. at least 375 MeV/u). This will be a centre of excellence devoted to tumour hadrontherapy of more than one thousand patients/year, to clinical research in cancer therapy and to R&D in the fields of radiobiology and dosimetry. The first study was completed in spring 1994 and published in the form of a "Blue Book", which describes versions A and B of the Centro Nazionale di Adroterapia Oncologica (CNAO). Since the volume was much

In 1995 CERN funded a small research activity (the TERA Group) formed of part-time physicists and engineers who, since then, contribute to the design of the medical synchrotron for protons and ions, which is at the heart of the CNAO project. At the beginning of 1996 a new optimized study of such a synchrotron was started at CERN under the leadership of Dr. Philip Bryant. Five TERA staff members and two doctoral students from the ASTRON Project (Vienna) participate in the study, which aims at finding new optimized solutions for the synchrotron and the isocentric proton gantries. GSI (Darmstadt) — where at the end of 1996 Gerald Kraft and collaborators will start patient treatment with carbon ions — has the responsibility for the design of the ion injector and of a gantry for carbon ions.

For a medical synchrotron the intensity of the extracted beams poses no special problem, since $10^{11}$ p/s and $3 \times 10^9$ ions/s are enough. The issue is the time uniformity of the spill since, due to the magnet ripples, synchrotron pulses have time structures at many frequencies; this makes the active spreading of the beams particularly difficult. At HIMAC [5] this problem has been partially solved with an accurate (to few 10^-3), but costly, stabilisation of the magnet power supplies.

The new study of the medical synchrotron is thus taking time uniformity of the extracted beam, which lasts about one second, as the highest priority, as already done at LEAR for much longer time scales.

The work is not yet completed, but the main ideas behind a solution, possibly to be combined with other methods, can be explained with reference to Fig. 1, in which the transverse beam size is represented. Due to the unavoidable ripples in the dipoles and quadrupoles, the resonance lines (drawn at 45°) can be thought to oscillate continuously in the directions indicated by the arrows. When the beam is uniformly pushed to the resonance, for instance with a betatron core which has no ripple, the movement of the resonance lines produces a time disuniformity. To reduce the effect the part of the beam which is closer to the resonance can be made moving much faster, so that the extracted beam is less sensitive to the ripples.

![Fig. 1. The figure represents the extraction process. The arrows indicate the effect of the magnet ripples and the dashed areas the densities of the beam.](image)

While the design of the machine goes on, TERA physicists and engineers have defined a new layout of CNAO (version D). An image is given in Fig. 2.

![Fig. 2. The layout of CNAO. The proton/carbon synchrotron has an average diameter of 22 m. The centre will have three rooms for proton treatment and one with an horizontal beam of ions. The building is extendable for constructing other therapy rooms.](image)

In December 1995 the TERA Foundation offered to six Hospital and oncological Institutes of Milano and Pavia to form a Consortium and realize the National Centre for Oncological Hadrontherapy in Milano. The Policlinico Ospedale Maggiore offered a site and on June 17, 1996, an instrument of understanding among the six institutions and TERA was signed.

As mentioned above, the status of CNAO is described in the Blue Book and in the Addendum [11]. In summer 1996 a second one is in preparation. It describes the layout of version D and it will be ready by October 1996.

**The "Compact" Accelerator Project PACO**

The second project of the Hadrontherapy Programme, PACO, was started at the beginning of 1993. For about three years four working groups designed *different* types of 200 MeV proton accelerators with the aim of eventually comparing their characteristics and costs. The work done is described in the recently printed "Green Book" [14].

As a starting point, the apparently vague notion of "compact accelerator and gantry" is quantified with the aim of reducing the cost of protontherapy. The national centre CNAO is designed as a centre of excellence where the best performances will be achieved for both protons and carbon ions. To reduce the costs, ions (and thus the treatment of radioresistant tumours) should be forgotten and "compact" accelerators should have somewhat more modest goals, of course *without compromising the health care possibilities*. It is obvious that striking such a balance is difficult and the conclusions are somewhat arbitrary. It is worthwhile reproducing the definition here because the adjective "compact" has been and still is misunderstood.

In the framework of the Hadrontherapy Programme, a proton facility for therapy deserves the adjective "compact" if:

1. it accelerates a minimum of $2 \times 10^{10}$ protons per second to an energy of at least 200 MeV reliably and reproducibly, so to have a running efficiency close to the one of present conventional electron linacs (98%);
it is possible to install the accelerator, the control room and the power supplies in a shielded bunker and a service area covering a total surface of less than 300 m²;

(3) it has a consumption — during irradiation — of less than 250 kW;

(4) costs, without buildings, not more than 17 million kLit (about 11 M$); this cost should include a rotating gantry with all the control and dose distribution systems, and should be able to run with both passive and active spreading systems;

(5) a second gantry should cost less than 3 million kLit (about 2 M$);

(6) a 70 MeV beam for eye therapy should also be foreseen and provided at low cost, if desired.

The required beam characteristics and field dimensions, not discussed here, are such that a "compact" accelerator can treat 85% of the about 5000 patients/year treatable with the proton beams of CNAO.

The different solutions studied by the Hadrontherapy Collaboration for the "compact" proton accelerators are: a conventional synchrotron, a high-field synchrotron, a high-frequency linac and a superconducting cyclotron. A room temperature cyclotron was not considered since IBA is producing it. Instead a chapter was written by P. Cohills and Y. Jongen on a simplified and cheaper version of the IBA facility.

These five types of accelerators are described in five chapters of the Green Book. The remaining chapters are devoted to the status and future plans of the network RITA and of the three activities coordinated by the three Committees mentioned above. There is no space here to discuss these subjects.

The Green Book was prepared in connection with the entering of Istituto Superiore di Sanità in the field of hadrontherapy.

The TOP LINAC of ISS

In fall 1993 the Physics Laboratory — directed by Prof. Martino Grandolfo — of Istituto Superiore di Sanità, which was since long active in the fields of proton radiobiology and dosimetry, decided to request special funds for the construction of a prototype of a "compact" accelerator (and its rotating gantry) and to finance R&D programmes in the fields of radiobiology, dosimetry, networking, pathology and treatment planning. This programme is now known as the TOP Project of ISS, where TOP stands for "Terapia Oncologica con Protoni". The initial funds (60’000’000 kLit) were allocated in 1994 and appropriated in 1995 with the understanding that about 80% of this sum had to be spent for the construction of a prototype of a "compact" accelerator, of a type yet to be decided. A contribution of 2’330’000 kLit was granted at the end of 1995. Requests for about the same total amount are pending.

In September 1995 draft copies of the Green Book were distributed to the members of the Scientific Committee of the TOP project. After auditioning the persons responsible of the various designs and considering the still limited funds available (8’330’000 kLit) in December 1995 the Committee advised ISS to concentrate on the construction of the first part of the high-frequency linac [15], whose injector should also be capable of producing PET isotopes. Istituto Superiore di Sanità accepted this advice and in spring 1996 found a convenient site located in between the buildings of ISS and of the oncological Institute Regina Elena. After the decision of ISS the PACO project was terminated since its mission was accomplished.

![Fig. 3. The low current 3 GHz protontherapy linac to be constructed in Rome by ISS, ENEA and TERA under the direction of L. Picardi (ENEA).](image)

The 3 GHz proton linac, designed in the framework of the Hadrontherapy Programme, solves the challenge of accelerating low energy protons with a high frequency linac, in itself a scientifically interesting problem.

As shown in Fig. 5, the high frequency linac is made of three sections: a ten MeV injector of lower frequency (which can also produce PET isotopes), a new accelerating structure named Side Coupled Drift Tube Linac (SCDTL), which has been patented by ENEA, and a conventional Side Coupled Linac (SCL). Each SCDTL tank contains 5 or 6 drift tubes. About 1 cm long with a 3-4 mm diameter hole. Permanent magnets located between adjacent tanks focuses the accelerated beam. The SCDTL section accelerates protons to 70 MeV, and is the one financed at present. The SCL part will be built next and bring the beam to 200 MeV.

The overall TOP linac project is coordinated by Dr. Salvatore Frullani (ISS) and Dr. Luigi Picardi (ENEA) and has been nominated responsible for the construction of the high-frequency linac. The new project was presented to the authorities and the public on June 24, 1996, during the Second National Day on Hadrontherapy, held in Rome in the auditorium of Institute Regina Elena.

The advantages of the high frequency proton linac with respect to, for instance, a cyclotron are: (i) the beam emittance is ten times smaller, so that the gantry can be lighter and less expensive; (ii) the beam energy can be varied continuously between 140 and 200 MeV, as required by the tumour depth; (iii) the accelerator has no problem of injection and extraction; (iv) a linac is modular and can be constructed in pieces; (v) when looked closely, the surface occupied by the centre is not much larger than the one needed by a cyclotron.

A 3 GHz Linac Booster for Protoncyclotrons

With small modifications the SCL part of Fig. 3 can also be used as a booster of a 60–70 MeV proton cyclotron. A Section of the Green book is devoted to this option, which is very interesting because in the world there are at least twenty 50–70 MeV cyclotrons which could be transformed in facilities for protontherapy of deep tumours. In the Green Book the study has been made with reference to the 62 MeV cyclotron of
the Cyclotron Unit of the Clatterbridge Hospital (UK) [16]. In a total length of 13 m, 9 modules formed of 4 tanks and powered by 9 klystrons bring the proton beam from 62 to 200 MeV. The repetition rate is 400 Hz, which is good for a voxel active spreading of the beam. The overall linac capture efficiency, taking into account the fact that the linac acceptance is about three times the cyclotron emittance, is $1.5 \times 10^{-3}$, so that the average proton current at 200 MeV is 10 nA. The plug power is about 100 kW. By switching off klystrons it is possible to vary the proton energy between 140 and 200 MeV.

The non-profit TERA Foundation is looking at present for partners interested in transforming their cyclotrons in a 200 MeV variable energy facility for protontherapy.

Cost of Protontherapy versus other Oncological Treatments

In Chapter 16 of the Green Book P.Chauvel and collaborators (Centre Antoine-Lacassagne, Cyclotron Biomedical, Nice) show that a protontherapy centre based on three gantries would be economically competitive with a centre of X-ray conformal radiotherapy (CRT), which use more than six cross-fired X-ray beams, if the accelerator and the gantries require investments not larger than the costs chosen in the definition of a "compact" accelerator: about 11 MS for the accelerator and the first gantry, and about 2 MS for each added gantry [17]. This would allow, taking into account both of the lifetime of the facility and of the cost of the staff, to charge about 1000–1100 DM for each 30 min session of protontherapy, so that a complete average treatment of 20 sessions would cost not more than 22'000 DM. This is a crucial point for the future developments of affordable hospital based protontherapy.

![Image](image_url)

Fig. 4. The SCL part of the protontherapy linac can be used as a booster for a 60–70 MeV cyclotron. The parameters are given in Ref. 16.

To understand the meaning of this figures it is worth recalling that X-ray radiotherapy is the cheapest of all oncological therapies. In fact, precise evaluations by G.Gademann [12] and by E.Borgonovi et al. of the Bocconi University [18] indicate that while a conventional radiotherapy costs between 6'000 and 7'000 DM, an average oncological surgery costs 15'000 DM and a heavy chemotherapy for a systemic tumour goes up to 60'000 DM. Recent calculations indicate that an average CRT with X-rays treatment may cost 17'000–19'000 DM.

Comparing these figures with the ones possible with a "compact" proton accelerator and gantry system of the cost indicated above, and taking into account the cost of the failures, Chauvel et al. conclude that protontherapy is economically competitive with CRT. This argument represent a strong incentive to develop cheap proton accelerator and gantries, which do not require special buildings for the installation and consume little plug power. In a few years we shall know wether this interesting challenge has been met.

I am very grateful to Philip Bryant, Marco Pullica, Sandro Rossi and Mario Weiss for helping me in preparing this review.

References

[4] The statistics are published in Particles the journal of the Particle Therapy Coordination Group (PTCOG).
MEDICAL APPLICATIONS OF ELECTRON LINACS

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Abstract

Electron linear accelerators ("linacs") are today the primary equipment of a modern radiotherapy department. Indeed the majority of the patients referred for radiation therapy are treated with linacs, for at least part of the treatment.

The current machines produce photon beams with energies ranging from about 4 to 20 MV. This energy range is sufficient to treat most of the tumours, even those which are deep seated. Attenuation of the photon beams in the tissues is nearly exponential and, in typical conditions, 50\% of the maximum dose is obtained at 17 cm in depth for a 8 MV beam and at 20 cm in depth for a 18 MV beam. A treatment is rarely performed with a single beam, but a combination of several beams adequately orientated allows the radiation-oncologist to deliver the prescribed dose to the target volume without exceeding the tolerance of the surrounding normal tissues.

In addition modern linacs allow us to apply electron beam therapy. Electron beams have, in the tissues, a limited penetration which depends on energy. Electron beam therapy is thus suitable to treat superficial (or semi-deep seated) tumours; it is often used as a "boost" and is then combined with photon beam therapy.

Special techniques using linacs are reviewed: total body irradiation for bone marrow grafting and stereotactic radiosurgery with photon beams, total skin irradiation and Intra-Operative-Radiation-Therapy (IORT) with electron beams. Lastly, conformation therapy is at present a very promising field in great expansion. It aims at matching as close as possible the actually treated volume and the clinical target volume. Conformation therapy requires accurate acquisition of patient data, 3-D treatment planning and a strict quality assurance programme.

This paper will be published on the World Wide Web (Linac96 Proceedings) when it becomes available.
THE SUCCESS AND THE FUTURE OF EPICS

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Abstract

During the past five years, the control system software toolkit called EPICS (Experimental Physics and Industrial Control System), has developed from a comparatively small code co-development effort between Los Alamos National Laboratory and Argonne National Laboratory into an international collaboration on real-time distributed control systems. The wide application of this set of tools is the result of a combination of high performance, scaleable distributed control and well defined open interfaces between system layers that encourage users to add extensions. These extensions can subsequently be reused by others, adding to the utility of the tools. This paper will describe the architectural features that have supported these extensions, some of the new extensions produced by the 58 projects currently using EPICS and some of the new functions and interfaces we are planning to add to this control system toolkit.

Introduction: EPICS' primary functions and architecture - a basis for collaboration

The development of EPICS started with a few fundamental user-driven requirements. Heading the list was the need for a control system that could be expanded easily and could concurrently support subsystem development and commissioning as well as integrated operation of an entire accelerator facility. A maximum level of functional flexibility in the control system software without additional programming was also a prime requirement. Further, the software needed to provide excellent real-time performance to close control loops in and between subsystems. These and other functional requirements were met in the original design of the EPICS control system toolkit that employs a client/server architecture for data transport to all system components and a modular, "process model" database for data acquisition and control.

Two structures fundamental to EPICS success

The two structures are: a distributed control system architecture based on client/server data communications and a modular "process model" database. The requirement to provide independent subsystem operation as well as integrated system control in a scaleable control system was addressed by the first of these fundamental structures, a distributed control system architecture-based on a client/server data communications design[1]. The server module resides in each one of the system controllers along with that controller's portion of the distributed database. From there, the server is able to send any value, calibration, alarm status, etc. to any client application, e.g., a display, archiver, etc., that requests that data by name. The multiple instances of the server in a control system respond to a request for data by searching for the named data in their local portion of the distributed database. If a server has the requested data in the local portion of the database, it responds to the request and the client then initiates a connection to that data. This allows any of an arbitrary number of data-using clients to receive data from any of an arbitrary number of data-supplying servers without the client needing to know the location or other attributes of the data. The result is an easily scaleable control system which can operate as separate independent controllers in an integrated system.

Fig. 1. Distributed Control System Architecture

The functional flexibility requirements were met by EPICS' second fundamental structure, a modular "process model" in the EPICS database[2]. A process model was embodied in a unique active database distributed to the many controllers in a control system. The process model consists of a set of input, process and output records in the database that are scanned by time or event. An input record for any type of data source can be selected from an extensible set that includes discrete (binary), analog and waveform (array) input records. These input records, when scanned, will interact with software...
drivers and acquire data from the facility through a wide variety of supported VME, VXI, CAMAC, or industrial data acquisition modules. The data measurement thus acquired can be linked to one or more of a set of process records that can transform the data, or contain a feedback controller (e.g. PID), or can generate a sequence of outputs. These outputs can be linked to discrete, analog, positioner, etc. output records which provide feedback to the facility. Input and output records may be used independently for supervisory control or linked with process records in an almost unlimited variety of combinations to provide automatic control for most of a facility's data acquisition or control needs.

The EPICS database is generated by data-driven configuration tools and for most data acquisition and control no additional programming is required. Using these tools, the control system implementers can respond rapidly to changes in control requirements. Using EPICS client/server data communication called "channel access", an X-Windows based operator interface can display any of the input, process, output, status, alarm, etc., values in the database from anywhere on the control system network. These fundamental structures and a set of tools for creating process databases, for creating operator displays and for archiving data were in the initial software toolkit that was the basis for the EPICS collaboration.

**Collaboration with large facilities produce new requirements and developments**

The next phase of EPICS development began with code development collaborations with several large facilities then under construction. During control system development for these large facilities, new requirements were identified and the set of interfaces in EPICS were extended.

**Client Extensions**

The original client/server channel access data communication network defined an interface between the hardware, driver, data acquisition, control, and database functions on the server side and other control system functions such as data display, operator control, archive, analysis, etc., on the client side. This clean client/server interface was the basis for the first major expansion of EPICS when we began our collaborative co-development effort in 1989. The Advanced Photon Source (APS) at Argonne National Laboratory, uses EPICS to control a linac, a positron accumulator ring, a booster, a storage ring and a large number of x-ray beamlines. To respond to facility requirements to monitor the alarm status of 160,000 data channels distributed over more than 100 controllers, APS designed and implemented an alarm manager client to group, sort, log and acknowledge alarms as well as a knob manager to connect a hardware knob to controllers and a general purpose monitor and control tool, Probe. The APS team also interfaced the EPICS channel access client software to several commercial data analysis and presentation packages including PwWave and WingZ enabling the analysis of any data item in the system.

Later, they implemented a MOTIF based operator interface to add drag and drop capabilities to the operator interface. Outside Paris, SACLAIM added SL-GMS as an operator interface client based on their need for a richer set of display objects to provide the control required for the Tesla Test Facility injector development program. A client interface to Dataviews was implemented at Lawrence Berkeley Laboratory (LBL), for use on the Gamma Sphere project while the University of Chicago developed and contributed an interface to Interactive Data Language. The channel access client interface continues to support a large and growing set of extensions to the EPICS toolkit.

**Database Record and I/O driver extensions**

The EPICS database records comprise another clean extensible interface, especially after the APS team defined and implemented an interface to separate the input/output records and the hardware driver software layer. Many new record types have been developed including signal select, data compression, timer, sequence, interlock, fanout, magnet setpoint, beam position monitor, etc. Almost every institution that has subsequently used EPICS responded to the clean hardware driver interface by contributing dozens of additional drivers for a multitude of hardware types and modules. APS produced the GPIB and Bitbus drivers supported under EPICS or a small independent operating system (HideOS). The CAMAC driver was built and then improved by a collaboration between TJNAF (formerly CEBAF), the Duke University FEL team and LANL. CAMAC is used as the primary I/O interface for the 100K channel central control system for the recirculating beam superconducting linac at TJNAF and for the proton storage ring at LANL. ProfiBus and Siemens HI bus drivers were produced by DESY for use on the cryogenic controls at HERA. The CANbus has been implemented by DESY, Royal Greenwich Observatory (RGO) and BESSY for use on the Synchrotron Light Source and industry pack support has been produced by DESY and LANL.

![Fig. 2. Clean Interfaces Support Independent Development and Provide an Incremental Upgrade Path to Avoid Obsolescence](image-url)
Multiple platform support developed

Many programs that were using EPICS to build and integrate control systems needed to develop and run the code on their local Sun, HP, DEC, UNIX workstation platforms. Many ports of EPICS to different platforms resulted: The port of the channel access client codes and development platform to Solaris was done at the RGO; to HPUX at TINA; to DEC UNIX at the University of Chicago and SLAC; the database is being ported to LynxOS at NASA Langley, and the channel access client was ported to Windows 95 and Windows NT at LBL. Changes to the original Sun UNIX installation procedures were extensive and resulted in clean, documented and easy to use procedures to build and install EPICS systems at new sites. Today, APS provides EPICS software distribution to many R&D institutions and a significant part of the documentation support on the Internet for the EPICS community. The balance of the EPICS documentation is served on the WWW from LANL and TINA.

Operational reliability demonstrated

This fully distributed system with no single point of system failure took long strides toward demonstrating reliability in continuous facility operation. EPICS, used for HERA cryogenic controls for monitoring 6000 channels by 5 IOC’s, has run without rebooting for their eleven month operational cycle. At Argonne and CEBAF the majority of IOCs run reliably[3][4]. One reliability issue occurs when the front end controller is left with too little available memory. This is easily resolved by dividing the application into two IOCs or adding memory. The other issue occurs when sub-bus controllers, particularly the bitbus controller, gets hung and requires a reset on the VME bus. This problem has been traced to a defect in the controller’s bitbus interface chip. Most installations do not experience these problems. The EPICS collaboration and toolkit is currently in use at over 50 installations and has provided improved control system reliability and significant cost savings.

<table>
<thead>
<tr>
<th>Project</th>
<th>#signals</th>
<th>#IOC</th>
<th>#workstations</th>
<th>status</th>
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<tbody>
<tr>
<td>APS</td>
<td>175,000</td>
<td>130</td>
<td>20 ws</td>
<td>Mostly reliable*</td>
</tr>
<tr>
<td>HERA Cryo</td>
<td>6,000</td>
<td>4</td>
<td>1 ws</td>
<td>reliable operation</td>
</tr>
<tr>
<td>Tesla Test Inj</td>
<td>600</td>
<td>4</td>
<td>2 ws</td>
<td>reliable operation</td>
</tr>
<tr>
<td>KeckII</td>
<td>1,500</td>
<td>2</td>
<td>2 ws</td>
<td>reliable operation</td>
</tr>
<tr>
<td>FSR</td>
<td>2,500</td>
<td>4</td>
<td>6 ws</td>
<td>reliable operation</td>
</tr>
<tr>
<td>Duke BEL</td>
<td>2,500</td>
<td>6</td>
<td>3 ws</td>
<td>reliable operation</td>
</tr>
<tr>
<td>FEP II RF</td>
<td>8,400</td>
<td>8</td>
<td>2 ws</td>
<td>80% complete</td>
</tr>
<tr>
<td>BESSY</td>
<td>15,000</td>
<td>15</td>
<td>4 ws</td>
<td>construction</td>
</tr>
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<td>APS Beamline</td>
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<td>22</td>
<td>10 ws</td>
<td>reliable operation</td>
</tr>
<tr>
<td>CEBAF</td>
<td>125,000</td>
<td>40</td>
<td>8 ws</td>
<td>Mostly reliable**</td>
</tr>
</tbody>
</table>

* a bitbus controller mishandles comm. errors and requires a VME reset
** memory fragmentation causes ca-client connections to be refused when IOCs are run with over 7,000 process records on 16 MegRAM

Other functional additions

During the period where large user facilities were joining the collaboration, many incremental changes occurred to make EPICS easier to configure, more secure, and more portable. Channel access improvements supported data communication connections across a wide area network allowing users to access data even though the data source (server) was not on their local area network. This provided support for more widely distributed control networks as well as providing the ability to improve system communication bandwidth by isolating network traffic on sub-nets while still providing integrated access to the data. Shortly afterwards access control was added to channel access to provide a level of data and control security. The original access control evolved at APS and LANL to provide data security for facility parameters that need to be protected from read or write access by some users or locations during specific modes of operation. Graphical tools for database definition with hierarchical capability and multiple instantiation were developed to simplify and speed the conversion of the nearly 100,000 channels in the TJNAF control system to EPICS. The ability to have a database make references to data in other databases without concern for their location on the network, the ability to change channel addresses and data links during operation and to directly load database and record types in an ASCII format all provide more powerful and flexible logic definition to the application engineers. This work was done in a collaboration with the controls groups of KEK, LANL, and APS. These functions became even more important as large user facilities became operational.

Support for commissioning and high-level control

The early EPICS tools were adequate for construction and testing physics research facilities, however, they were not adequate for commissioning complex accelerator facilities and telescopes. New facility commissioning tools were needed. In response, the APS community developed a suite of command line tools based on Self Describing Data Sets (SDDS)[5] with modular functions that could be linked together to provide quick turnaround data acquisition, data analysis, visualization, and high-level control, such as bumps, global orbit correction and ad-hoc experiments. Tcl/TK user interfaces have been built on top of these SDDS tools to make them more friendly for operators. TJNAF is developing interactive graphical tools to provide similar data analysis functions modeled on the high level tools at SLAC[6]. In addition, TJNAF has developed a model server called ARTEMIS and integrated this beamline model with their EPICS real-time data system. The late conversion of the TJNAF control system to EPICS delayed the development of these commissioning tools until recently. KEK on the other hand, has already interfaced their modeling code, SAD, to the EPICS system for use during operation at TRISTAN in preparation for the KEK B-factory[7]. These commissioning tools have been successfully used to identify and determine the root cause of beam control problems within an operations shift and to optimize beam control parameters.
A higher-level interface is defined

As these high-level tools have been developed, the need to provide data abstractions at a level higher than the individual control system channels provided by channel access and to integrate non-real-time data, such as beamline configuration, became apparent. TJNAF developed an application program interface (API) called common devices, CDEV[8], that provides this level of abstraction. For example, using CDEV all the separate data and control channels used to power, cool, control and monitor a power supply and a beamline magnet could be represented by a higher level abstraction that can be named as a single object, e.g., “quad n”. This level of abstraction simplifies the interface between a beamline model and the control system by hiding the hardware and data dependencies associated with a particular instance of the power supply connected to a coil with its associated cooling and power, etc. CDEV currently supports the channel access client as well as CORBA bindings. It also provides the ability to re-map the control system name space thus keeping high level applications from being modified when the low level organization changes. This interface is viewed as a mechanism to make high level applications shareable even at installations that do not use EPICS. A distributed client/server based archiver and the X-based display manager are both slated to use this interface. CDEV itself continues to evolve with a higher level of organization in the form of collections of devices in a future release.

Taking advantage of a multi-lab collaboration

Learning to work together effectively was a significant ingredient in the success of this work[9]. It became evident that research programs needed to be able to do independent system development to meet the requirements of their projects. The clean interfaces that make many of the extensions simple to add are a portion of this success[10]. The resource to re-integrate this work is provided by the APS controls group. The support for learning, installing, extending and trouble shooting the system is provided by all experienced members of the collaboration. KEK supports other projects in Japan, APS supports their many beamline users, CEBAF supports their experimental users, central project groups in large distributed collaborations like the Gemini telescope and the BaBar detector support the multitude of universities that are associated with them. It is impossible to quantify the value of this working relationship, but nearly all members will point to this cooperation and support as one of the major benefits of using EPICS.

The results of collaborations with large facilities

During this phase of the collaboration, we successfully learned how to effectively co-develop software to port the tools to various platforms and environments, to provide clean interfaces for extending the tools, and to effectively employ the expertise of the collaboration members. The fundamental architecture was demonstrated to scale up to a 100,000 signals distributed over more than 100 single board computers with up to 30 operator workstations. 60 Hz closed-loop control, distributed interlock implementation, the use of on-line modeling and adaptive control were all demonstrated to be supportable in the EPICS point-to-point distributed client/server model. As the toolkit became more completely developed, projects began to experience the cost advantages in using the shared development of EPICS. Most of the initial development costs of implementing a control system could be avoided by starting with EPICS.

New system requirements and future EPICS developments

Now that APS and TJNAF are completing commissioning and beginning operation as user facilities, there is a need for hundreds of experimenters to have simultaneous access to current accelerator parameters and historical data. Since these data requests connect directly to the front-end computers controlling the process in the present architecture, the additional data communication load could impact the operation of the facility. Providing a gateway to concentrate requests for current data from multiple clients would allow many users to access data from the primary control network while limiting the impact of these many connections on the control network. This gateway has been implemented by APS and is under test. Hundreds of users will be able to observe data from the gateway while only one connection is made to each of the data sources in the control network. The additional latency introduced by a gateway is not critical as these users do not require high performance, real-time operation. The collection and distribution of archived data raises other issues. DESY has successfully used CORBA to distribute archived cryogenic system data. More stringent performance requirements may lead TJNAF to develop new archive data visualization tools that can correlate large numbers of channels of current and historical data.

Extended support for alternate data sources

Another major change in EPICS will soon create an interface in place of the previous tight bond between the process database and the database server. Responding to user requests for the ability to serve data from legacy data stores, to serve data from the various workstations on a control network, and to serve data from alternate operating systems; a portable channel access server[11] has been developed under a distributed computing environment, DICE, grant. This module defines a new system interface that allows legacy or other non-EPICS control systems to serve data to any EPICS client. It also enables processes, such as analysis or modeling programs, running in workstations on the control network, to supply data to displays, archivers or other clients. In the current alpha release, this server runs under Solaris and provide the ability to connect other data stores into EPICS.
The portable server is being ported to VxWorks to replace the existing channel access server. With this new capability, it will be possible to integrate existing systems and other datastores (such as relational databases) and to port the EPICS database into other operating systems such as Windows NT, LynxOS, or UNIX.

Lower cost small data/control systems

Small experiments or independently developed components need a control system solution that is packaged as a single box with no expensive components required for software or hardware, yet which is able to integrate into a larger facility or distribute its data. Presently the minimum sized EPICS system is one client (workstation) and one server (a single board CPU running VxWorks) with some I/O modules. In the future, we plan to develop a single computer solution for small data/control applications while maintaining the client/server architecture so that the single computer application can be easily integrated into a larger control environment if and when it becomes necessary.

System Data Available to Every Desktop

If we are to make all the control system data available to the desktops of physicists, commissioners and engineers, the current support for data to PCs through an X-client will need to be expanded to include native visualization tools under Windows NT and Windows 95. Extremely large systems, such as slow control for detectors with over a million signals, present new challenges in configuration management and distributed name resolution. The challenges in performance and labor cost for systems another order of magnitude larger than those operational today is being studied. Graphical configuration tools and relational database configuration tools have replaced some of EPICS original text-based tools to improve user friendliness and to respond to the demands for configuration control at large facilities. Specialized tools are being developed for accelerators, detectors and astronomy applications. Tools to provide data to users on any platform on the network are also being developed. There is continual improvement aimed at reducing the manpower required to define and maintain applications while providing users with more convenient desktop access to their data.

Support for new hardware technology

As industry provides higher speed and higher accuracy hardware as well as lower cost platforms, the collaboration continues to take advantage of these developments. Originally, we used VME, GPIB, and Allen-Bradley industrial I/O. As other institutions joined, industrial offerings changed, and existing systems were integrated, support for CAMAC, VXI, Bit-Bus, and serial devices were added. Future support will be provided for the PCI and compact PCI bus with the IOC software running in industrial PCs. The extensible driver interface in EPICS has enabled any user to add I/O support.

The APS has taken advantage of FDDI and Ethernet hubs to increase network bandwidth. ATM is also becoming a cost effective answer to increasing network bandwidth. As a result, any new and promising technology (as well as old existing technologies) can be easily integrated.

Conclusions

The collaboration has successfully extended the base set of tools by taking advantage of well defined interfaces and productive cooperation. Today's core set of EPICS tools has been successfully used at green field sites and existing facilities with up to 160,000 signals controlled by 100 single board computers with 30 operator interface terminals spread over 3 kilometers in accelerator control, particle detectors, astronomy and other research areas. Minimally funded projects have been able to use high performance, distributed control technology. A large and diverse group of projects have found a common set of capabilities, but more importantly, they found the means to extend the core set and then reintegrate the extensions into a more capable toolset. The modular architecture allows continuous developments that eliminate obsolescence. Through the combined efforts of many institutions we continue to extend control system capabilities, reduce costs, and employ new technologies.

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Operational Experience with the CEBAF Control System*

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Abstract

The CEBAF accelerator at Thomas Jefferson National Accelerator Facility (Jefferson Lab) successfully began its experimental nuclear physics program in November of 1995 and has since surpassed predicted machine availability. Part of this success can be attributed to using the EPICS (Experimental Physics and Industrial Control System) control system toolkit. The CEBAF control system is one of the largest accelerator control system now operating. It controls approximately 338 SRF cavities, 2300 magnets, 500 beam position monitors and other accelerator devices, such as gun hardware and other beam monitoring devices. All told, the system must be able to access over 125,000 database records. The system has been well received by both operators and the hardware designers. The EPICS utilities have made the task of troubleshooting systems easier. The graphical and text-based creation tools have allowed operators to custom build control screens. In addition, the ability to integrate EPICS with other software packages, such as Tcl/Tk, has allowed physicists to quickly prototype high-level application programs, and to provide GUI front ends for command line driven tools. Specific examples of the control system applications are presented in the areas of energy and orbit control, cavity tuning and accelerator tune up diagnostics.

Introduction

The 4 GeV CEBAF accelerator at Thomas Jefferson National Accelerator Facility (Jefferson Lab) is arranged in a five pass racetrack configuration, with two superconducting radio-frequency (SRF) linacs joined by independent magnetic 180° transport arcs. The continuous electron beam is composed of three interlaced variable intensity beams that can be independently directed from any of the five passes to any of the three experimental halls. This allows three simultaneous experiments at the same or different energies and currents. Electrons are emitted through a thermionic cathode or a polarized laser cathode that is being commissioned. Presently only one experimental hall, hall C, is fully operational, with hall A in the final commissioning stages.

The control system for the accelerator is based upon EPICS (Experimental Physics and Industrial Control System) [1]. The control system follows the so-called standard model, which is a client server system consisting of a collection of UNIX workstations and X-terminals connected by a network to multiple servers running device control software [2]. CEBAF uses a switched Ethernet network which allows simple scaling to higher bandwidths as needed. The servers are VME based single board computers running the EPICS real-time database, and the client computers are HP work stations.

In 1993 CEBAF decide to convert from TACL (Thaumaturgic Automated Control Logic) to the EPICS control system [2]. The integration has been one of evolution where the two control systems were allowed to coexist as the change was being made. This made commissioning easier and did not overly stress the controls group.

Using the CEBAF control system as a platform, engineers, physicist and operators developed the tools necessary to commission and run the machine. Control screens have been built and customized as needed by both the operators and the hardware designers [3, 4]. High level applications programs for energy and orbit control have been developed through software packages such as tcl/tk [5, 6, 7, 8, 9]. The following discussion will describe in detail these applications of the CEBAF control system.

Screen Development

One of the problems with commissioning large accelerators is that many of the screens have been developed by the designers, engineers and physicists. The control screens they have built are rarely useful for the day-to-day operators. The expert screens contain too much information and detail to be useful. At CEBAF most of the screens have evolved into more user friendly screens designed by the operators. The EPICS graphical and text based creation tools, and scripts and other tools, are relatively easy to learn and operators have been encouraged to do this. Visual screens have been developed that allow the operator to identify problems quickly and make adjustments. These screens make it easy for operators to clear faults, initiate automated routines, access programs for documenting hardware problems and get to more complex expert screens for detailed trouble shooting. The combination of visual screens and automated scripts has greatly decreased the time required to identify and recover from problems associated with a large accelerator [3].

To help the operators develop their screens, an aggressive screen management system has been put into place [4]. Each operator can develop a prototype screen, but to get it approved for general use it must meet some basic criteria. Guidelines concerning color, size and naming conventions have been issued.

* Work supported by the Department of Energy, contract DE-AC05-84ER40150.
In addition user feedback is very important; screens that are not being used are removed. While this may seem overly structured it does insure that the screens are consistent and that documentation is completed.

One of the largest and most complex systems to monitor is the RF system. It consists of 338 independently controlled superconducting accelerating cavities and 13 warm cavities for beam processing, chopping and separating. The expert screen for a superconducting cavity contains over 70 signals that are continuously monitored and is much too busy and complicated to use in day-to-day operations. One example of an operator developed screen is the RF status screen (figure 1) [3].

- Buttons to access databases for documenting changes made to individual cavities.
- Reset buttons to clear common RF faults.

This screen is highly visible, and with a glance an operator can tell that something is wrong with the RF system. In most cases the operator will never need to go beyond this screen once the RF is operating.

If it is necessary to get to more detailed screens they are only a button away. The screens are treed in a fashion from lowest to highest in detail so you can continue to jump down to the screen with most functions and information. Controls screens for magnet, beam instrumentation and many other systems have been developed in a similar fashion.

High Level Applications

At Jefferson Lab the brunt of the application programming fell upon the operational physicists [5]. They formed close working bonds with both the subsystem designers and the software programmers. In most cases applications were developed when it was necessary or would greatly enhance the commissioning process. Table 1 gives a detailed list of the programs developed and their functions.

<table>
<thead>
<tr>
<th>Program</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display Library</td>
<td>Assists in the building of display pages</td>
</tr>
<tr>
<td>Slow Feedback Locks</td>
<td>Keeps the beam at correct energy and orbit</td>
</tr>
<tr>
<td>On-Line Comments</td>
<td>Database established to assist in the RF maintenance</td>
</tr>
<tr>
<td>Autokrest</td>
<td>Automated program to phase cavities</td>
</tr>
<tr>
<td>Save/Restore Interface</td>
<td>Saves and stores operational set points</td>
</tr>
<tr>
<td>Linac Management</td>
<td>Adjust cavities and quadrupoles to specific energy</td>
</tr>
<tr>
<td>Autosteer</td>
<td>Helps to steer beam through arcs and minimize orbit</td>
</tr>
<tr>
<td>On-Line Procedures</td>
<td>Operators can access procedures directly to X-terminals</td>
</tr>
</tbody>
</table>

Table 1

Application programs

Most of the high level applications were developed and prototype using the Tcl/Tk programming Toolbox [6,7]. The graphics user interface (GUI) is based on an interpretive shell called “wish”, which is programmed in the Tcl language[7]. The Tcl language has a set of features geared toward event driven programming which is perfect for control systems where exceptions are more common than straight command flow. Tcl has worked well with the EPICS channel access routines. It can also be mated with computational software such as MatLab, numerical recipes, and optics codes such as DIMAD. We have extended the
Tcl language by adding C compiled routines. By adding C routines the prototype programs have been made faster and more efficient and not reliant on the CPU thirsty Tcl language.

**Slow Orbit and Energy Lock**

The most important high level applications are those pertaining to energy and orbit lock. Energy and orbit lock are necessary since CEBAF is a multipass machine that has independent transport arcs for each pass. Therefore it is imperative that some form of feedback is utilized to insure the beam stays within the energy and orbit apertures. The ultimate requirement of the locks is to insure that the beam energy and energy spread are maintained, and to a lesser extent that no beam scraping occurs. The locks are also used for steering the beam to the proper orbit. This essentially makes the accelerator modular since a single lock sets the launch into each arc or pass.

The design approach has been one of eliminating the most pressing energy or orbit related drifts instead of meeting our stringent beam requirements right away. The locks that were first developed have been termed “slow locks” which eliminated most of the diurnal drifts and allowed the accelerator to be commissioned. The slow locks are used on a daily basis and without them the accelerator would only be able to function for short periods of time. Without the locks the accelerator would require expert attention from an operator many times an hour! By quickly developing the slow locks we were able to develop a more comprehensive fast lock system that has allowed CEBAF to meet our beam specifications without delays in initial operation.

As the machine was commissioned the locks have been upgraded to include more exception handling features for detecting beam loss and device failure. The locks made it possible to commission the accelerator by allowing operators to concentrate on new transport lines instead of continually retuning those already operational.

**Fast Energy and Orbit Lock**

To ultimately meet beam stability specifications for nuclear physics experiments, a fast feedback system has been developed [8]. Since the slow lock has a control bandwidth of only 0.2 Hz it cannot eliminate higher frequency noise signals. A fast feedback system is needed to correct for disturbances on beam position and energy at 60 and 180 Hz associated with AC line power harmonics. In addition noise components on beam energy have been observed at 4 and 10 Hz.

The fast feedback system has been based on the concepts of modern control theory using state space formalism [7]. Like the slow lock, BPMs in a high dispersion or orbit sensitive regions of the accelerator give a measurement of the beam's energy or betatron fluctuation. In the case of the energy lock the correction required is obtained by modulating the accelerating gradient in selected accelerating cavities upstream of the BPMs. The control input signal is calculated using the BPM measurements from the current sample and the state of the system from the previous sample. The controller design is based on a Linear Quadratic Gaussian controller/estimator and is optimized by using a system dynamics model, and process and noise statistics.

A prototype fast energy lock was installed in CEBAF’s injector where energy variations are measured using five BPMs. To implement this fast energy lock two I/O controllers (IOCs) were remotely linked through Ethernet [8]. The BPM receivers are located in a CAMAC crate controlled by one of the IOCs. The correction signals are computed on this IOC, and sent via Ethernet to the other IOC which controls the RF. A CAMAC DAC card that resides close to RF control modules then sends out a ± 5 V signal to correct for the energy variations. The RF system has feedback inputs exclusively designed for this purpose. This prototype system was run at a 60 Hz rate.

Tests using the prototype system have shown that the system works very well. Figure 3 shows the effect of closing the loop on
the energy lock in the injector [8]. An energy perturbation of 0.225 MeV was introduced upstream from the lock BPMs while the loop was open. The lock was then closed and the energy error was corrected. The system is very agile and can be operated using pulsed beam or with cw beam. In addition the system can also distinguish between betatron oscillations and energy variations. This prototype system has now been modified to perform measurement, computation of correction signal and actuation from a single IOC such that this system could be run at a 540 Hz rate.

A parasitic program that uses the LEM routine, “Kemcheck” calculates the headroom in each linac. It sums the requested cavity gradients and then compares them to the actual energy that is entering an arc. From this information an operator can not only determine headroom but also how well the cavities are phased. A large fudge factor and high gradient sum indicate poorly phased cavities.

**Cavity Phasing**

A novel use of the slow energy lock has been to phase (crest) all of the accelerating cavities in the two linacs. A program called Autokrest has been developed which uses the energy lock error signal to phase the cavities or crest the cavities for maximum acceleration [9]. The beam’s energy spread is greatly dependent on the ability to crest the accelerating cavities [10]. The specification for slow phase drifts is 2.9° rms for individual cavities. The energy locks do not differentiate between phase and amplitude drifts and do not take phase into account when compensating for energy loss. Therefore autokrest is needed to keep the cavities within phase specification to minimize the beam’s energy spread. The program is also useful during accelerator startups when the cavities tend to be dephased due to maintenance activities. The program can be configured in a variety of ways to phase a whole linac, a cryomodule (8 cavities) or individual cavities. The program runs in the background transparent to beam operations. Operators have found that once the cavities have been phased it is only necessary to phase the cryomodules for periods exceeding 4 weeks.

The program works by shifting the phase of a cavity, cryomodule or linac by a prescribed amount and then observing the error signal of the slow energy lock BPMs. Typically a cavity’s phase is shifted by ±10°, which corresponds to an energy shift of $1 \times 10^{-4}$. From the energy shift it is quite easy to determine distance off phase crest, and the cavity is adjusted accordingly. The error in determining the crested phase set point is approximately 2°. The crested phase resolution improves when the program is operated using groups of cavities like in a cryomodule.

Presently this program can be run continuously in the background even during experimental beam operations. The program is able to do this because energy lock is compensating for the phase shifts in the background. As long as the cavity is somewhat close to crest it will be adjusted. The program is not without its problems: other cavities can affect the measurement by perturbing the error signal while a cavity is being phased. Improvements to this are presently being implemented.

**Cavity Tuning**

A good example of a subsystem application is the automated frequency tuning of the superconducting cavities. An operational problem for the CEBAF accelerator is the detuning of the cavities after a helium liquifier crash or after an extended maintenance period. The resonant frequency is very sensitive to pressure...
variations within the helium bath and changes of only a few mbar will detune the cavity. A program known as Autotune has been written that can tune a cavity as much as 5 kHz off from 1497 MHz [11]. The application lives above the RF cavity controllers in the cluster of HP9000-7xx workstations that control the RF. The program itself has three steps in tuning a cavity: a coarse tuning known as burst mode, a fine tuning known as sweep mode and finally a tracking mode that keeps the cavity tuned.

Burst mode is used to coarsely tune the cavity to within 160 Hz of resonance. It uses a pseudo-random phase modulated noise burst from the RF control module to measure the transfer function of the cavity. The modulated signal is such that its power spectrum is a positive constant for frequencies within ±5 kHz and zero outside this range. By taking the Fourier transform of the cavity output, the resonance frequency can be determined. The bandwidth of the signal, ±5 kHz, is limited by the RF cavity control module’s microprocessor. For over 95% of the cavities this limited bandwidth has not been a problem. Cavities that are outside this range are initially tuned manually with a vector network analyzer.

Once the cavities are within 160 Hz they can be fine tuned with sweep mode. In this case the cavities are amplitude locked at a low gradient of 3 MV/m. A single sideband modulation is produced using the phase vector modulator. This modulation is then swept ±200 Hz. A detuning angle offset is generated by comparing the forward power and the output of the cavity. The program uses smoothing techniques and curve fitting to extract parameters such as detuning angle offset and loaded Q and also to minimize the effect of microphonics. If it does not fit within expected limits the process is terminated and an alarm is generated. The control system uses the offset angle to normalize the RF controls to a resonance condition.

Finally a program called Autotrack is used to correct any differences from the normalized angle. The program automatically turns itself on if the detuning angles are greater than ±10° and turns off when the angle is within ±3°. This program also minimizes the over and undershoot of the stepper motor tuner due to the backlash and hysteresis of the gear train. Autotune has been successfully working for almost two years with very few changes.

Summary

Any large process control whether, it is a petroleum refinery or a large particle accelerator, will depend on process and application specific programs. These programs are the real test of a control system. While all of the various subsystems - RF, beam instrumentation, magnets, etc.- have basically been tested for functionality and reliability, the control system is not tested until the commissioning and preliminary operations start. A control system must have the flexibility and speed to allow the multi-subsystem application programs to run. The high level programs at Jefferson Lab have been successful because the control system meets these basic criteria. EPICS is not without its detractors, it can be slow and new code upgrades have not always been bug free. This has been a handicap in some cases for the more complicated programs. The control system has been flexible enough so that solutions to these problems could be made with little or no impact on operations.

The success of CEBAF’s control system can also be attributed to the working culture. It involves the close communication between the hardware and the software designers. Software engineers were brought in early on in the hardware development to assist in the design of prototype controls. In some cases they have developed a better feel for the functionality of the hardware than the designer! In a similar manner the accelerator physicists and operators have formed strong bonds with the control system experts to assist them in making the machine more efficient and easier to turn on. This is not to say there were no frustrations; there have been many, but they are easier to deal with in an atmosphere of pervasive mutual respect.

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References

GROUND MOTION STUDIES WITH RESPECT TO LINAC PERFORMANCE

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Abstract

The future TeV linear collider should have extremely small beam emittance to achieve the required luminosity. Precise alignment of focusing and accelerating elements is necessary to prevent emittance dilution. Analysis of ground motion is therefore an essential problem. This paper reviews studies of ground motion, focusing on the effects of the main linac. After recalling results of measurements of ground motion collected at different places, the method based on spectral description of ground motion, which allows prediction of emittance dilution, in presence of orbit correction feedback as well, is discussed.

Introduction

The first study of ground motion with respect to linear collider was performed at SLAC by G. Fischer [1]. The intention to build TeV linear collider has inspired new studies started at Protvino [2] and since then in all laboratories developing linear collider projects [3]-[7].

The level of understanding of ground motion has been developed significantly in recent years. The correlation properties of high frequency motion have been investigated [2, 3, 7] in addition to simple spectral amplitude analysis. The slow motion investigations have resulted in discovering of the diffusive ground motion (‘ATL law’ [2]). Dependence of motion on the earth structure was studied [12, 6].

The mathematics, which allows prediction of the effect on the beam, was also being developed in parallel to measurements. The 2-D power spectrum $P(\omega, k)$, introduced for ground motion description [4, 8], makes the evaluation of the effect on the beam easy and natural — once this spectrum, the spectral response function of the focusing structure and the spectral properties of applied orbit correction feedbacks are known. The measured data were used to find an approximation of $P(\omega, k)$ [8] for typical seismic conditions.

This paper intends to show the complete way from measurements to the beam emittance growth. We start from general equations, then consider measured data, create approximation of the 2-D spectrum, and get results using spectral response functions and feedback properties. The misalignment generated beam offset and dispersion in the main regular linac governed by the ‘one to one’ orbit correction is used to illustrate our considerations.

Linac and Ground Motion

General equations

Misalignments of focusing quadrupoles of the linac produce offset of the beam trajectory and hence chromatic dilution of the beam, which can be expressed via an integral involving the power spectrum of the quadrupole displacements and a spectral response function of the considered linac.

Let $x_i(t) = x(t, s_i)$ be the transverse position of quadrupoles of the linac, relatively to a reference line, $s_i$, the longitudinal position. The incoming beam angle and position are zero, the reference line passes through some element, placed at the entrance. The beam offset at the exit, relative to the exit position $x_{\text{fin}}$, and the dispersion, linear term, are

$$x^*(t) = \sum_{i=1}^{N} c_i x_i(t) - x_{\text{fin}}$$
$$\eta(t) = \sum_{i=1}^{N} d_i x_i(t)$$

Here $c_i$ and $d_i$ are the first derivatives of the beam offset and dispersion at the exit of the linac with respect to the displacement of the $i$-th quadrupole.

While $(x^*(t))$ and $(\eta(t))$, averaged on realizations, are zero, the mean squared value gives the offset or dispersive error, for example

$$\langle \eta^2(t) \rangle = \sum_{i=1}^{N} \sum_{j=1}^{N} d_i d_j \langle x_i(t) x_j(t) \rangle$$

As we consider random process, one can express this through the corresponding power spectrum $P(t, k)$.

For initial misalignment or (and) ground motion all spatial harmonics are independent. We have then

$$\langle \eta^2(k) \rangle = \int_{-\infty}^{\infty} P(t, k) G_\eta(k) \frac{dk}{2\pi}$$

Here $G_\eta(k)$ is the so called spectral response function corresponding to dispersion. The expression for the offset is similar, with $G_{\text{off}}(k)$. The expression allows to obtain results for any spectrum, including the particular case of static gaussian misalignments studied in detail [9].

The spatial power spectrum $P(t, k)$ of displacements $x(t, s)$ can be easily found as far as initial misalignment or ground motion are concerned. Assuming that focusing elements are aligned at $t = 0$ and then are moved by ground motion, the evolution of the power spectrum is [4]:

$$P(t, k) = \int_{-\infty}^{\infty} P(\omega, k) 2 \left[ 1 - \cos(\omega t) \right] \frac{d\omega}{2\pi}$$

It is connected therefore to the 2-D power spectrum $P(\omega, k)$, which characterizes ground motion properties, including both spatial and temporal correlation information.

In a regular linac the correction procedures can also be correctly considered within the analytical spectral approach. Correction procedures, such as ‘one to one’ or ‘adaptive alignment’
[10] may introduce correlation of phases between harmonics \( k \) and \( k = k_{\text{max}} - k \) (where \( k_{\text{max}} = \pi / L \) is the quadrupole spacing). The rms dispersion \( \chi \) is then given by an expression, which takes the correlation into account [14].

In short, the spectral response functions \( G(k) \) describe the properties of the focusing channel, while the power spectrum \( P(t, k) \) depends on the applied method of correction, initial misalignment and ground motion.

**Ground motion properties**

The 2-D spectrum \( P(\omega, k) \) is hard to measure directly. But if one knows the power spectra of absolute motion and correlation information, or the power spectra of relative motion \( \rho(\omega, L) \), the 2-D spectrum can be found using

\[
\rho(\omega, L) = \int_{-\infty}^{\infty} P(\omega, k) 2 [1 - \cos(\omega L)] \frac{dk}{2\pi}
\]

and the reverse relation [4]. Naturally, \( \rho(\omega, \infty) = 2p(\omega) \).

The measurable correlation, defined via mutual spectrum as \( C(\omega, L) = p_{12}/\sqrt{p_{11}p_{22}} \), connected to the relative spectrum as \( C(\omega, L) = 1 - \rho(\omega, L)/(2p(\omega)) \).

The power spectrum \( p(\omega) \) of absolute ground motion (which contains contribution of all \( k \)) grows very fast with decreasing frequency. In quiet conditions it behaves approximately as \( p(\omega) \propto 1/\omega^4 \) in rather wide frequency band. The motion is unavoidable as it consists of seismic activity. At low frequency \( f < 1 \text{ Hz} \) the sources are also the atmospheric activity, water motion in the oceans, temperature variations etc. A famous example of the ocean influence is the peak in the band 0.1 – 0.2 Hz with a few micrometers amplitude (Fig.1). In general, motion in the low frequency band \( f < 1 \text{ Hz} \) depend not only on the local conditions, remote sources give significant contribution to the slow motion.

From the other side, in the band \( f > 1 \text{ Hz} \) the human produced noises are usually dominating over the natural noises and the power spectrum depends very much on the local conditions (location of sources, depth of tunnel etc.). Locally generated noises can be much bigger than remotely generated. For example the spectrum measured at the tunnel of operating accelerator (like HERA collider at DESY or SLC at SLAC) presents high amplitudes at \( f > 1 \text{ Hz} \) due to noises generated by different technical devices (Fig.2). These noises may have big amplitude and bad correlation. Technical devices therefore should be properly designed in order to pass as low vibration as possible to the tunnel floor.

It is known from correlation measurements [3, 7] that in quiet conditions the motion in the band \( f > 0.1 \text{ Hz} \) can be considered as wave-like, i.e. the frequency \( \omega \) and wave number \( k \) are connected via phase velocity \( v \). At \( f \approx 0.1 \text{ Hz} \) the value of \( v \) was found to be close to the velocity of sound in the surrounding media: about 3000 m/s at LEP and about 2000 m/s at SLC tunnel. At the cultural noise dominated band this value decreases rapidly — the fitted value of \( v \) determined from the measured at SLAC correlation behave as \( v \approx 450 + 1900 \exp(-f/2) \text{ m/s} \) (\( f > 0.1 \text{ Hz} \)) [7]. The SLAC measurements, which used the most accurate probes, have shown (at least at this place and these conditions) that contribution of non-wave motion, if there is any not resolved by probes, is negligible at \( f > 0.1 \text{ Hz} \).

![Figure 1](image1.png) Absolute power spectrum measured in a quiet place (CERN [3]) and the modeling spectrum. Modeling relative spectra \( \rho(\omega, L) \) for different \( L \).

![Figure 2](image2.png) Absolute power spectrum measured in a noisy place (HERA [5]) and the modeling spectrum. Modeling relative spectra for different \( L \).

The motion at \( f < 0.1 \text{ Hz} \) is different. The elastic motion (produced by the moon, for example) presents here too, but of much bigger relevance is the inelastic diffusive motion, probably fed by the elastic motion and caused by its dissipation. The motion is believed to be described by the ‘ATL law’ [2], which says that the relative rms displacement after a time \( T \) of the two points separated by a distance \( L \) is \( \Delta L^2 = AT \). The parameter \( A \) was found to be \( A \approx 10^{-5.1} \text{ m^2/s}^{-1} \text{m}^{-1} \) for different places. One can see that this displacement is proportional to the square root of the time and separation: this stresses the random, non wavelike, diffusion character of the slow relative motion and means that the number of step-like breaks that appear between two points is proportional to the distance between them and the elapsed time.

If this phenomenon is indeed connected with dissipation of the elastic motion, the parameter \( A \) should depend mainly on the earth properties, because the sources of elastic motion are the same for all places. One could expect that in the places with smaller dissipation the value \( A \) should be smaller and it should also depend on the level of the rock fragmentation. Indeed, the parameter \( A \) was observed to be smaller in tunnels built in solid rock. It also depends on the method of tunnel construction: in the tunnel bored in granite \( A \approx 10^{-6} \text{ m^2/s}^{-1} \text{m}^{-1} \) was observed, while in the similar tunnel, which was built by use of explosions, the parameter \( A \) is found to be 5 times larger probably because of the fragmentation, artificially increased during construction [6].
The parameter $A$ also depends on the tunnel depth, generally it is smaller in deeper tunnels [12].

The ranges of $T$ and $L$ where the 'ATL law' is valid are very wide. In [12] it was summarized that 'ATL' is confirmed by measurements of ground motion in different accelerator tunnels in the range from minutes to tens of years and from a few meters to tens of kilometers. The measured relative power spectra, presented in [6] and in [11], exhibit the 'ATL' behavior already for $f < 0.1$ Hz (for $L \approx 30$ m). These measurements indicate that the transition region from wave to diffusion motion is placed at rather short times (a few seconds). This can result in certain decreasing of correlation around $f \propto 0.01$ Hz.

Although the 'ATL law' was found from the direct analysis of measurements of ground motion, its most interesting confirmations come from the observations of beam motion in big accelerators produced by displacements of the focusing elements. An example is the measurements of the closed orbit motion in the HERA circular collider, which have shown that the power spectrum of this motion corresponds to the 'ATL law' in a wide frequency range, from $f \approx 0.1$ Hz down to $f \approx 10^{-6}$ Hz [11].

The very slow motion can be systematic (not described by power spectrum) as well. Such motion has been observed at LEP Point 1 and PEP [13] where some quadrupoles move unidirectionally during many years with rate about 0.1 - 1 mm/year. Quite close (a few tens of meters) points can move in opposite direction. Amplitude of the motion can be larger than the one of diffusive motion. The motion is probably due to geological peculiarities of the place or due to relaxation if the tunnel was bored in solid rock.

Ending with the ground motion one could note that the elements of the linac will be placed not on the floor, but on some girder, which could amplify some frequencies due to its own resonances. It is not only this amplification that is dangerous, more important is that the not identical girders will amplify or change the floor motion by different way, which can spoil correlation of the floor motion. It is therefore preferable to push the girder resonances to high frequencies where the correlation is poor anyway and floor amplitudes are smaller. This requires firm connection of the girder with the floor. The active systems [15], which can help in certain extend to isolate the quadrupoles from high frequency human induced floor motion, should be made insensitive to slow motion (say, below 1 Hz), otherwise long wavelength motion can create more dangerous short wavelength due to inequality of active supports.

**Ground motion model**

The approximation for $P(\omega, k)$ is built [8] in assumption that the low frequency part of motion is described by the 'ATL law', while the high frequency part is produced mainly by waves. The 2-D spectrum corresponded the 'ATL' motion is $P(\omega, k) = A/\omega^2 k^2$ (here $\omega$ and $k$ are defined on the entire axis). In order to be included into the model, this spectrum should be corrected because it overestimates fast motion — the corresponding spectrum of relative motion exceeds the one of absolute motion. The correction is made by the way that will overestimate the effect rather than underestimate it. Better model can be built once measured data on transition region are available. The elastic waves are assumed to be transverse, propagating at the surface of the ground with uniform distribution over azimuthal angle. Finally, the modeling spectrum is:

$$P(\omega, k) = \frac{A}{\omega^2 k^2} (1 - \cos(kB/A\omega^2)) + \sum D_i(\omega) U_i(\omega, k)$$

The function $U_i(\omega, k)$ describes the wave number distribution of the waves with frequency $\omega$. In our case $U_i(\omega, k) = 2/\sqrt{k_{cut}^2 - k^2}$ if $|k| \leq k_{cut}$ and zero otherwise. Here $k_{cut}(\omega) = \omega/\nu_i$ and $\nu_i$ the phase velocity of wave propagation. The cases $k = 0$ and $k = k_{cut}$ correspond to the waves propagating perpendicular and along the linear collider correspondingly. Since the integral over $dk/(2\pi)$ of $U(\omega, k)$ equals one, the function $D(\omega)$ describes contribution of these waves to the absolute spectrum $P(\omega)$. We write $D(\omega)$ as $D_i(\omega) = a_i/(1 + [d_i(\omega - \omega_i)/\omega_i]^3)$.

In order to model complex behavior of the spectrum, for example in presence of cultural noises, a few terms with waves added to $P(x, k)$, $i$ is the number of the peak.

We consider here two models. Parameters of the first model are the following: $A = 10^{-8}$ $\mu$m$^2$s$^{-1}$m$^{-1}$, $B = 10^{-6}$ $\mu$m$^2$s$^{-3}$. The single peak described by $\omega_i = 2\pi \cdot 0.14$ Hz for the frequency of the peak, $a_1 = 10^5$ $\mu$m$^2$/Hz for its amplitude, $d_1 = 5$ for its width, and $v_1 = 1000$ m/s for the velocity. It is the model of quiet place such as LEP tunnel during shutdown. The thick line on Fig.1 shows the spectrum of absolute motion, calculated from $P(\omega, k)$, corresponding to these parameters. The actual measured $P(\omega)$ can be bigger than the modeling one at $f < 0.1$ Hz, because slow long wavelength motion does not included into the model. The second model corresponds to seismic conditions with big contributions from cultural noises (as in the HERA tunnel in operating conditions). The parameters are the following: $A = 10^{-8}$ $\mu$m$^2$s$^{-1}$m$^{-1}$, $B = 10^{-5}$ $\mu$m$^2$s$^{-3}$ and three peaks: $f_1 = 0.14$, $f_2 = 2.5$, $f_3 = 50$ Hz; $a_1 = 10$, $a_2 = 10^{-5}$, $a_3 = 10^{-7}$ $\mu$m$^2$/Hz; $d_1 = 5$, $d_2 = 1.5$, $d_3 = 1.5$; $v_1 = 1000$, $v_2 = 400$, $v_3 = 400$ m/s. One can see (Fig.2) how the waves are faded by the 'ATL' in $P(t, k)$ when time increases. The parameters of these two models have been chosen taking into account correlation measurements in the LEP [3], HERA [5] and SLC [7] tunnels and measurements of the closed orbit motion in HERA [11].

The effect of the ground motion on the beam can be obtained both by analytical way via the integral of spectral function with the modeling power spectrum and also by simulations, when ground motion displacement $x(t, s)$ is modeled by summation of harmonics and the beam degradation determined by particle tracking. In the latter case we first analyze the modeling $P(\omega, k)$ spectrum to define the band of relevant $\omega$ and $k$, assuming that $T_{min} < T < T_{max}$ and $L_{min} < L < L_{max}$. Then we split this 2-D band by cells $(50 \times 50$ typically) equidistantly in logarithmic sense, find rms amplitude of each cell $a_{ij}$ and generate two sets of random phases $\phi_{ij}$ and $\psi_{ij}$. Positions of $\omega_i$ and $k_i$ withing each cells are chosen randomly so after many seeds all $(\omega, k)$ will be checked. The modeling displacement $x(t, s)$ is then

$$x(t, s) = \sum_i \sum_j a_{ij} \sin(\omega_i t) \sin(k_i s + \phi_{ij}) + (\cos(\omega_i t) - 1) \sin(k_i s + \psi_{ij})$$
This harmonics model was used in our simulations, eventually it will be used in the linear collider flight simulator 'MERLIN' [16], which is being developed to analyze performance of the beam delivery systems.

![Figure 3: Modeling power spectra $P(t, k)$ for the second noisy model and the spectra obtained in simulations using the harmonics model.](image)

**Spectral response function**

The spectral response function corresponded to dispersion of the beam is

$$ G_n(k) = \left( \sum_{i=1}^{N} d_i \cos(k s_i) \right)^2 + \left( \sum_{i=1}^{N} d_i \sin(k s_i) \right)^2 $$

Similar for the offset, with $c_i$, with the sum runs up to $N + 1$ and $c_{N+1} = -1$. In thin lens approximation, in linear order $c_i = -K_i r_{12}^i$ and $d_i = K_i r_{12}^i - t_{126}^i$, where $K_i$ is $r_{21}$ of the quadrupole matrix, $r_{12}^i$ and $t_{126}^i$ are the matrix elements from the $i$-th quadrupole to the exit.

At small $k$ one has $G_{off}(k) \approx k^2 P_{12}^2$ and $G_n(k) \approx k^2 T_{126}^2$. For the regular linac only the band $[0, k_{max}]$ is unique. In this band the spectral function has two resonances: $kL = \mu/2$ and $kL = \pi - \mu/2$. The values of spectral function at these resonances as well as their width can be found analytically.

![Figure 4: Spectral response functions.](image)

The examples in this paper are given for the modeling FODO linac: number of quadrupoles $N = 600$, spacing $L = 25$ m, phase advance $\mu = 60$ degrees, initial and final energy $\gamma_{fm} = 6000$, $\gamma_m = 5 \cdot 10^5$, beta functions at the even defocusing quadrupoles and at the exit are $\beta_{min} = 28.86$ m. The spectral functions for this linac are shown on Fig.4.

**Free evolution**

Fig.5 shows the rms beam offset relative to the linac exit versus time for quiet and noisy models of ground motion. The analytical results are shown in comparing with results of simulations, which use tracking and the model of harmonics to simulate beam line misalignment. To estimate the critical time scale, this offset should be compared with the beam size at the exit. If $\gamma \sigma_y = 2.5 \cdot 10^{-7}$ m, then at the exit $\sigma_y \approx 3.5 \cdot 10^{-6}$ m and the critical time is about one minute. For somewhat smaller emittance the cultural noise of the second model becomes important and the critical time decreases to a fraction of second.

One can see that the chosen $P(\omega, k)$ spectrum gives a linear dependence of the relative misalignment variance (and hence the rms beam offset as well) versus time for large $T$ (‘ATL’ behavior), while for small $T$ the variance is proportional to $T^2$. This square dependence at small time is the general property of the spectrum that drops fast enough with increasing frequency [17]. One can mention that if the systematic motion is significant, the $T^2$ behavior will appear at big $T$ too.

![Figure 5: Relative beam offset. Free evolution. Quiet and noisy models. Analytical results (lines) and simulations.](image)

**Feedback controlled evolution**

Many feedbacks will inevitably be used in linear collider. To study the equilibrium rms offset accurately, one need to put the feedback gain function into the integral, which will suppress frequencies smaller than $f_{rep}/6 - f_{rep}/20$.

To illustrate influence of an orbit correction feedback on the beam dispersion, let us consider the ‘one-to-one’ algorithm, which consists in zeroing the BPM measurements (assumed to be perfect). Here we assume that this is done by steering the beam by means of dipole correctors (equivalent to the quadrupole shift). This and other orbit correction or alignment methods are considered in more details (including BPM errors etc.) elsewhere [14].

If the $i$-th quadrupole is misaligned, three angles are needed to re-align the beam. The equivalent quadrupole displacements, to be subtracted from their initial positions, are (if acceleration is neglected):

$$ \Delta x_i = -2x_i/(LK_i), \quad \Delta x_{i-1} = \Delta x_{i-1} = -x_i/(LK_i) $$

After such a procedure the beam trajectory will pass through positions of quadrupoles before correction (Fig.6).

To find the beam dispersion one can notice that in spectral approach, in a regular FODO lattice with $K_i = -K_{i+1}$, a $k$-th harmonics of the initial misalignment produces two harmonics of quadrupole displacements after the correction: $k$-th and $(k_{max} - k)$-th with opposite phases. If this self correlation as
well as injection conditions are taken into account, the dispersion after correction can be found [14].

\[ \langle \eta_\perp^2(t) \rangle = 2 \int_0^{k_{\text{max}}} \hat{P}(t, k) \hat{G}_\eta(k) \frac{dk}{2\pi} \]  

(1)

where \( \hat{G}_\eta(k) \) and \( \hat{P}(t, k) \) are the effective spectral response function and the effective spectrum of quadrupole displacements before correction (which can include BPM offset and resolution errors also) respectively. The \( \hat{G}_\eta(k) \) is built with new coefficients (neglecting acceleration) [14]:

\[ \hat{d}_i = d_i + (2d_i + d_{i+1} + d_{i-1})/(LK_i) \]

It gives \( \hat{d}_i = -K_i r^2_{1,2} \). This follows from the algorithm of correction — the angle caused by displaced quadrupole is corrected, thus the term \( T_{12s} \) vanishes. The \( \hat{G}_\eta \) and \( G_{\text{off}} \) are practically the same therefore. The considered 'one-to-one' scheme reduce emittance growth by factor \( N^2 \) roughly, which increase significantly the time interval until a beam based alignment might be again required. The critical time (when \( \Delta p/p = 10^{-3} \)) for the beam with \( \Delta p/p = 10^{-3} \) is a few hours without and about one year with correction (Fig. 7).

Figure 6: Position of quadrupoles (symbols) before correction, beam trajectories (lines) and dispersion before and after correction. Quiet model at \( t = 100 \) s.

An alternative way to write the beam dispersion after 'one-to-one' correction is

Figure 7: Beam dispersion. Free (upper curves) and feedback controlled evolution (lower curves).

Fig.7 shows dispersion without and with 'one-to-one' correction. In the second case the dispersion is shown at the moment just after correction. This value does not depend on how many times the correction has been applied before. If the repetition rate of corrections is enough high, the values just after and just before correction are very close.

Conclusion

A future TeV linear collider, having extremely small emittance of beams, will suffer from the ground motion, which will spoil alignment of focusing and accelerating elements and result in offset and emittance growth.

The ground motion studies, performed by different laboratories, resulted in significant improvement of understanding of this phenomenon. Different types of motion have been investigated, many factors that the motion depends on are learned. The mathematical formalism allowing prediction of the beam behavior is developed.

Though many ground motion features are still to be carefully investigated, one may reasonably believe that the ground motion problem of the future linear collider can be overcome provided that stored knowledge will be used at each step of design and construction.

Acknowledgement

I am grateful to colleagues from Novosibirsk INP and Protvino Branch INP for being working together over many years and to colleagues from CERN, DESY, CEA Saclay and SLAC for numerous helpful discussions.

References

DARK CURRENTS

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Abstract

Dark current studies in the S-band structures and the DC electrodes have been primarily pointed at elucidating the causal relationships between the internally generated field emission currents and breakdown electric fields at high gradient. The experiment was focused to improve the material and fabrication method.

An S-band nose cone shape TM008 single standing-wave cavity was successfully operated surface electrical gradient up to 334 MV/m with 0.34 mA of peak dark current. A microscopic field enhancement factor of 37 obtain from the modified Fowler-Nordheim plots.

The DC electrodes using very clean SUS316L successfully obtained the maximum surface electrical field gradient of 34 MV/m with a 88 pA of very low dark currents at a gap width of 1 mm.

From these studies, it can mainly conclude that a magnitude of dark current is depend on a cleanliness of an inside of a structure, and the maximum electric field gradient is determined by shape of a structure geometry.

Introduction

This paper is an overall review of high gradient studies in the S-band structures and the DC electrodes carried out by author, some of our colleagues at KEK and T. Nakanishi group of Nagoya University. Also this work helped by G.A. Loew and J.W. Wang of SLAC and their colleagues.

A motivation of this work is to make clear an rf breakdown and a dark current phenomena at the breakdown surface electrical gradients as high as 200 MV/m; and determine the upper limit of the actual large scale accelerators.

For e+e- linear colliders with center of mass energies of 500 to 1000 GeV, the main linac will be operated with accelerating field gradients ranging from 40–100 MV/m. At this level, the corresponding peak surface electrical field gradient are in the range of 80–200 MV/m. At the present time however, most actual large electron accelerators run with accelerating gradients of around 10–17 MV/m. No laboratories have any experience yet with high gradient operations.

RF breakdown studies were started by SLAC and Varian to investigate the phenomena and to determine the upper limit of field gradients for rf structures [1, 2, 3].

In 1986, G.A. Loew and J.W. Wang of SLAC reported [1, 2, 4] their experimental results with a standing wave cavity that could produce an equivalent traveling-wave accelerating gradient as high as 147 MV/m and a peak surface field in excess of 300 MV/m. However, at this high a gradient, a considerable amount of field emission and x-ray radiation was observed.

From these studies, many factors have been found which must be discussed with regard to rf breakdown phenomenon and dark currents: such things as the surface finish, microscopic dust, electron multiplication, materials and the vacuum condition inside the structure. However, the fundamental mechanisms involved in rf breakdown are not yet clearly understood well enough for application not only to the accelerating structure but also to photo-cathode rf guns with peak surface electrical field gradients in excess of 200 MV/m.

In 1987, KEK started a high gradient study in connection with plans for linear collider R&D in Japan. The experiments were done on four traveling-wave disk loaded structures, four TM008 standing-wave single cavities and DC electrodes.

From those experiments, the main conclusions obtained about the relations between rf breakdown and dark currents are the following:

1. The magnitude of the dark current depends on the cleanliness inside the structure,
2. It was shown conclusively that the maximum electrical field gradient is determined by the shape of the structure especially that of the coupler cavity,
3. Further the existence of microscopic voids between crystal grains even in very high quality OFHC copper was demonstrated, and it was shown that these voids are one of the reasons for dark currents [5].

In the following, the author would like to show the relationships between rf breakdown phenomena and dark currents based on our experimental results.

High Gradient Experiments at KEK

The work started with conventional disk loaded traveling-wave type structures, operating as close as possible to actual accelerator conditions. The following test structures were machined from high quality OFHC (Oxide Free High Conductivity) copper blocks with purity of ~99.996% and having typical chemical compositions as listed in Table 1.

Table 1
Chemical compositions of OFHC copper (x10^-6%)

<table>
<thead>
<tr>
<th>Metal</th>
<th>Pb</th>
<th>Zn</th>
<th>Bi</th>
<th>Cl</th>
<th>Hg</th>
<th>O₂</th>
<th>P</th>
<th>S</th>
<th>Se</th>
<th>Te</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>&lt;1</td>
<td>1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>2</td>
<td>1</td>
<td>6</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Sb</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>&lt;1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Copper: HITACHI CLASS1 (>99.996%)

Test structures

All test structures were chosen to be of the 2n/3 phase shift per cell. They were designed so as to test peak axial and surface electrical field gradients of up to 100 and 200 MV/m,
respectively. The main parameters of the structures are listed in Table 2.

Table 2
Main specifications of high gradient structures.

<table>
<thead>
<tr>
<th></th>
<th>5 cell structure</th>
<th>17 Cell structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz):</td>
<td>2856</td>
<td>2856</td>
</tr>
<tr>
<td>Phase shift per cell:</td>
<td>2π/3, C.I.</td>
<td>2π/3, C.G.</td>
</tr>
<tr>
<td>Structure length (cm):</td>
<td>17.5</td>
<td>59.5</td>
</tr>
<tr>
<td>Iris diameter (cm):</td>
<td>1.6</td>
<td>1.8998-1.590</td>
</tr>
<tr>
<td>Factor of merit Q:</td>
<td>13330</td>
<td>11600</td>
</tr>
<tr>
<td>Attenuation constant (μsec):</td>
<td>0.702</td>
<td>0.48</td>
</tr>
<tr>
<td>Filling time (μsec)</td>
<td>0.19</td>
<td>0.475</td>
</tr>
<tr>
<td>Surface gradient Ep(MV/m):</td>
<td>18.84√P_n[MW]</td>
<td>14.32√P_n[MW]</td>
</tr>
<tr>
<td>Surface finish at irises (μm):</td>
<td>0.6</td>
<td>Conventional: 0.8</td>
</tr>
<tr>
<td>Clean: 0.8</td>
<td>Electroplated: 0.3</td>
<td></td>
</tr>
</tbody>
</table>

5 cell traveling-wave structure. For the first step, experiments were done on a small scale (five cells) traveling-wave, constant impedance (C.I.) type structure at S-band. It was manufactured by the usual methods and fabricated in the usual atmospheric environment (class 10000). The vacuum seal was made by an electroplated layer; no brazing process was necessary.

For this experiment, the maximum peak axial electrical field gradient and surface field gradient obtained was 104.5 and 209 MV/m, respectively. At this level, however, a large amount of dark current generated from the beam hole and rf breakdown was often observed coming from the structure.

From this experiment, it was found that reducing the dark current is more difficult than getting a high peak electrical field gradient on the conventional structure. However, as can be seen in Figure 1, the modified Fowler-Nordheim (F-N) plot gives us a hint towards the direction for the next step.

![Figure 1: Fowler-Nordheim plots at different times on the same day.](image)

Three fitted F-N plots lines in Figure 1 come from measurements at different times on the same day. From this we can see that the quantity of dark current emitted decreases with rf processing time; but the microscopic field enhancement factor (β) does not depend on the rf processing time. This data suggests that we may have to separate the dark current from the rf breakdown phenomena, because one can guess that the upper limit of the electrical field gradient mainly depends on the local β value; consider a simple geometry such as the electrical potential problem for two parallel plates.

17 cell traveling-wave structure. In the second step, the investigation was primarily aimed at elucidating the causal relationships between the internally generated dark currents and breakdown electrical field in high gradient accelerator structures.

Three structures were made to compare the maximum accelerating gradient and the amount of dark current emitted in the same experimental system [6].

Two structures were manufactured by a brazing method in a hydrogen furnace. The third was manufactured by the electroplating method. One of brazed structure was fabricated in the usual atmospheric environment (conventional structure); the other was carefully fabricated so as to be free from any contamination inside the structure (clean structure). The electroplated structure was fabricated in the usual atmospheric environment (electroplated structure).

During rf processing, the rf power (0.8 μs pulses at 50 pps) applied to the structure was controlled by a program to keep the vacuum pressure below 1 × 10^-5 Torr. The electrical field gradients were evaluated by measuring the energy spectrum of the dark currents generated by field emission from the structure. The performances achieved by the three structures are listed in Table 3.

Table 3
The performances achieved by the three structures.

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Clean</th>
<th>Electro-plated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum field gradient</td>
<td>MV/m</td>
<td>91</td>
<td>94</td>
</tr>
<tr>
<td>β</td>
<td></td>
<td>44</td>
<td>57</td>
</tr>
<tr>
<td>Processing time hours</td>
<td></td>
<td>800</td>
<td>200</td>
</tr>
</tbody>
</table>

The modified F-N plots for the three structures are shown in Figure 2.

![Figure 2: Modified Fowler-Nordheim plots for three 60 cm-long traveling-wave structures.](image)

As can be seen in Figure 2, the three F-N lines have almost same β values and the amount of dark current from the clean structure is an order of magnitude lower than that of the conventional and electroplated structures. The point to consider is that the only difference between the conventional and clean
structure is the amount of contamination on the structure surface. Thus, it can be concluded that a reduction in contamination could drastically reduce the dark current and that the upper limit to the electrical field gradient is determined by other factors.

In this experiment, both the input and output couplers of the clean structure had protruding areas (bumps) on the axis at each end cavity wall. These areas, with heights of a few mm and diameters of 1 cm, were caused by the rf tuning process. The effects can be seen in Figure 3, where in the energy spectrums of the emitted dark currents at each gradient, there is a narrow peak appearing in the energy range of 3 to 5 MeV and a broad peak appearing at around the maximum energy. Both of these features were caused by continuous rf breakdown at both bumps. After 200 hours of rf processing, the coupler cavities were examined and it was found that the top of the down-stream bump was melted by the continuous rf breakdown.

**Fig. 3.** Dark current energy spectrum of the clean structure.

This is the main reason why the clean structure did not achieve the highest electrical field gradient of the three structures. On the other hand, the Figure 4 shows that the electroplated structure did not have a clear peak in the dark current spectrum at any electrical field gradient. While even the electroplated structure has large amount of dark current, the maximum axial electrical field gradient achieved, up to 83.6 MV/m, is higher than the clean structure gradient of 73 M/m.

**Fig. 4.** Dark current energy spectrum of the electroplated structure.

**TM_{010} standing-wave single cavities.** After the first half of the second experimental stage, it was decided to try some experiments to make clear the rf breakdown and dark current phenomena in a high gradient structure.

Four TM_{010} single cavities were made to study the effects of fabrication methods such as using a pure water rinsing process and fabrication in a very high quality clean room (class 1), using low secondary electron emission coefficient Titanium (Ti) material and reducing the micro-pores of the OFHC copper by Hot Isostatic Pressing (HIP).

Three cavities with very simple pill box shapes all of the same dimension were designed so as to obtain surface electrical peak fields in excess of 100 MV/m at an input peak rf power of 5 MW. The main electrical parameters and cavity dimensions are listed in Table 4 and shown in Figure 5.

**Table 4** The specifications for the three TM_{010} cavities.

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Clean</th>
<th>Electroplated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz):</td>
<td>2854.5</td>
<td>2851.4</td>
<td>2853.3</td>
</tr>
<tr>
<td>Structure length (cm):</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Iris diameter (cm):</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Factor of merit Q:</td>
<td>13200</td>
<td>14090</td>
<td>8650</td>
</tr>
<tr>
<td>Surface gradient (MV/m):</td>
<td>149 P_{[MV]}</td>
<td>149 P_{[MV]}</td>
<td>123 P_{[MV]}</td>
</tr>
<tr>
<td>Surface finish at irises</td>
<td>0.1</td>
<td>0.1</td>
<td>Copper: 0.1</td>
</tr>
<tr>
<td>(µm):</td>
<td></td>
<td></td>
<td>Ti: 0.8</td>
</tr>
<tr>
<td>Clean room quality:</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
</tr>
<tr>
<td>Rinsing solvent:</td>
<td>Acetone</td>
<td>Acetone</td>
<td>UPW(2)</td>
</tr>
</tbody>
</table>

1) Particles per cubic feet (>0.1 µm)
2) UPW: Ultra Pure Water (>18.2 M-Ohm* cm)

**Fig. 5.** Three TM_{010} cavity dimensions. Only the Ti bounded cavity has Ti blocks around the beam holes.

A conventional cavity was fabricated by the usual methods in a class 10000 room and used as a reference to compare the quantity of dark current with the other two specially processed clean and Ti bounded HIP cavities.

The clean cavity was rinsed with ultra pure water (>18.3 M-Ohm*cm) at end of manufacture and fabricated very carefully in a class 1 clean room to avoid contamination during the final assembly.

The composite material cavity is composed of two materials, OFHC and Titanium (Ti). Ti blocks were attached around the beam holes by using a diffusion bond with HIP procedure as shown in Figure 5. This type of cavity is advantageous in reducing dark current, since the secondary field emission coefficient of Ti is less than unity (~0.9).
HIP is a thermomechanical forging method that makes using of a high gas pressure (~1200 kgf/cm²) at high temperature (~850°C). Even in very high quality forged OFHC copper, there generally are some number of micro-pores the size of a few μm each at grain boundaries. These pores will be one of main sites for contamination inside the structure because machine oils trapped in them will be carbonized after the brazing process. The micro-structures of forged OFHC copper and HIP processed OFHC copper samples are shown in Figure 6. The photographs clearly shows that forged OFHC copper has micro-pores between the gains and these micro-pores disappeared in the HIP processed OFHC copper [5].

High gradient experiments on the three cavities were done on a test stand to make relative comparisons in the amount of dark current.

Two simple Faraday cup detectors (FD) were used to measure the dark current. One FD mounted just to the left of the straight beam line was used for the F-N plots. The other was located on the right side with a 90 degree bending magnet and used to measure the dark current energy spectrum. The vacuum status is very important in ascertaining the surface cleanliness inside the cavity. The vacuum level was monitored with B-A and cold-cathode gauges. Partial vacuum pressure was measured with a residual gas analyzer. The total base pressure of the high gradient test stand reached ~1 × 10⁻¹⁰ Torr after baking at 200°C for 100 hours. It is necessary to observe the details of the residual gas mass spectrums for each of the cavities.

The conventional cavity, clean cavity and Ti bonded cavity produced maximum surface gradients of 134 MV/m, 146 MV/m and 156 MV/m, respectively. In this experiment the maximum surface electrical gradient of three cavities was limited by the available klystron peak rf power. Figure 7 shows the F-N plot of three cavities at the end of the rf processing time. As can be seen in Figure 7, the three F-N lines have almost the same slope (β = 50–59) and the amount of dark current from the clean and Ti bonded HIP processed cavities are one order of magnitude lower than that of the conventional cavity. From the results shown in Figure 6, it can be seen clearly that cleanliness is essential in reducing the dark current. The low secondary electron coefficient of Ti is also effective in reducing the dark current; this will be useful in rf gun applications.

Figure 8 and 9 shows the mass spectra of the residual gases from the conventional and clean cavities at each surface electrical gradient level. As can be seen in Figure 8, three high peaks appeared showing H₂, CO and CO₂ in the mass spectrums. CO and CO₂ molecules are typically caused by the impurities and contamination on the inner surface of the cavity. These two molecules are also very dangerous for a semiconductor photo-cathode material such as GaAs. On the other hand, the clean cavity in Figure 9 shows that the mass spectrum amplitudes do not depend on the surface electrical field gradient since only very small CO and CO₂ responses were observed. The total amount of residual gas in the clean cavity was smaller than that of the conventional cavity even at the highest 140 MV/m surface electrical gradient. These experimental results show again that the amount of dark current strongly depend on the cleanliness inside the cavity.

A nose cone shaped cavity was used to determine the upper limit of surface electrical field gradient on the S-band cavity for an rf gun. The maximum electrical surface gradient was designed so as to obtain up to 350 MV/m at a peak input rf power of 5 MW.
The cavity was rinsed with pure water at a pressure in the range of 10 to 30 kgf/cm². During this process, the specific resistance of the pure water was kept higher than 17 MΩ cm. All the processing and fabrication was done in a clean room of class 100. The cavity was filled with methanol until just prior to installation in the standard test stand [7]. Figure 10 shows the cavity rinsing procedure.

![Cavity rinsing procedure by high pressure ultra pure water.](image)

The high gradient test was started at a base vacuum pressure of $8 \times 10^{-11}$ Torr. In this experiment, the base vacuum pressure did not change greatly at rf processing at each power level except for an occasional rf breakdown. A maximum surface electrical field gradient of 334 MV/m was achieved which was limited by the klystron rf power available. Even at this level, the amount of peak dark current was 0.34 mA and a microscopic field enhancement factor of 37 was achieved.

**DC electrodes.** In the third experimental phase, the work went back to being a very basic study using DC electrodes to confirm the principles learned from the high gradient study and to prepare for the application of a very sensitive photo-cathode rf gun, such as a GaAs cathode. The electrode material was carefully chosen to be very high quality stainless steel SUS316L, because in general stainless is contaminated by oxide impurities such as dust particles during manufacture which is the main reason for dark current at high electrical surface gradients. Table 5 shows the specifications of clean (NK-clean-Z, SUS316L) and JIS standard SUS316L materials.

**Table 5**

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>NK-clean-Z</td>
<td>0.004</td>
<td>0.12</td>
<td>0.27</td>
<td>0.001</td>
<td>0.0006</td>
<td>14.96</td>
<td>16.8</td>
<td>2.36</td>
</tr>
<tr>
<td>JIS-SUS316L</td>
<td>&lt;0.03</td>
<td>&lt;1.0</td>
<td>&lt;2.0</td>
<td>&lt;0.04</td>
<td>&lt;0.03</td>
<td>12</td>
<td>16</td>
<td>18</td>
</tr>
</tbody>
</table>

The surface treatment and rinsing methods were also very important for obtaining a smooth and clean surface. Electro-mechanical polishing and warm pure water rinsing methods were selected. The surface roughness of the electrodes obtained from the lathe was less than 0.1 μm without pits on the surface. To avoid any contamination, the entire system of the DC high voltage test stand was fabricated in a class 1 clean room and pumped down to $\sim 4 \times 10^{-11}$ Torr after baking at 250°C for 1 week. In the experiments, no field emission current was observed from the 1 cm gap electrodes at the -120 kV operating voltage, which corresponds to a surface electric field gradient of 11 MV/m. The maximum surface electric field gradient obtained was 34 MV/m at 88 pA of dark current from the 1 mm gap electrodes. At this level, the microscopic enhancement factor obtained was 40 from the F-N plot [8].

**Conclusions**

It is concluded that the magnitude of dark current depends on the cleanliness of the structure, and the maximum electrical field gradient is determined by the shape of the structure. The general phenomena of dark current and breakdown are not strong frequency dependent from the DC and S-band frequency results. However, multiple long structures operating at high frequency will necessitate more study. This study should be useful for the realization of a semiconductor photo-cathode rf gun.

**References**

Invited Talk Session TH3

Chairman: H. Henke

Thursday, August 29, 1996
UPGRADE TO THE 8-GEV ELECTRON LINAC FOR KEKB

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Abstract

The KEK/PF 2.5-GeV linac is under reconstruction for KEKB (the B-Factory at KEK). The linac will be renewed in the autumn of 1998 as an 8-GeV electron linac, which can provide full-energy beams into the 8-GeV electron ring and 3.5-GeV positron ring of KEKB, while continuing the injection of 2.5-GeV beams for the synchrotron-radiation (SR) facilities. The main goal of the injector linac is to achieve an energy upgrade from 2.5 GeV to 8 GeV, as well as to increase the positron intensity. This report covers recent construction progress and the remarkable activities regarding the energy upgrade and positron beam improvements.

Introduction

KEKB includes an 8-GeV electron ring (HER: high-energy ring) and a 3.5-GeV positron ring (LER: low-energy ring), which is under construction in the same tunnel for TRISTAN (Fig.1). KEKB aims at a luminosity of 1×10^{34} cm^{-2}s^{-1} by establishing a crossing angle (±11 mrad) collision between 1.1-A electrons and 2.6-A positrons. In order to save injection time, KEKB requires full-energy injection from the linac for both electrons and positrons; furthermore, a positron beam intensity ten times as much as the present linac produces is required.

The present 2.5-GeV linac [1] was commissioned in early 1982 as an electron injector for the Photon Factory (PF) storage ring; a positron generator linac [2] was added during 1982-1985 for the TRISTAN project. Electron/positron beam injection was started in the autumn of 1986 to the TRISTAN accumulation ring (AR); the storage beam in the PF ring was changed from electrons to positrons in 1988 autumn, resulting in a stable long-life storage for SR experiments.

For KEKB, the linac will be reconstructed and expanded as shown in Fig.2. The linac will be renewed so as to deliver 8-GeV electron / 3.5-GeV positron single-bunch beams as well as 2.5-GeV multi-bunch beams for the SR rings. The energy upgrade is to be achieved by using 57 accelerator units with an acceleration gain of 160 MeV each: the linac building is being extended at the upstream end of the present linac in order to increase the number of accelerator units from 40 to 57; for increasing the rf peak power, the klystron modulator powers will be increased twice, the 30-MW klystrons replaced by the

Fig.1 Schematic plan-view of KEKB.

Fig. 2 Linac reconstruction from 2.5 GeV (upper) to 8 GeV (lower). The existing linac has 40 accelerator units which are divided into 5 sectors. The shadow areas are extension buildings to increase the number of accelerator units from 40 to 57.
50-MW klystrons, and rf pulse compressors used. These parameter changes are summarized in Table 1. The basic design details have been reported elsewhere [3]. The following section considers recent construction progress and the research and developments regarding the KEKB injector linac.

### Table 1 Change in the major parameters to the KEKB injector.

<table>
<thead>
<tr>
<th>(1) INJECTION BEAM</th>
<th>PRESENT</th>
<th>KEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>electron (GeV)</td>
<td>2.5</td>
<td>8.0</td>
</tr>
<tr>
<td>positron (GeV)</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>pulse length (ns)</td>
<td>&lt; 2</td>
<td>single bunch</td>
</tr>
<tr>
<td>bunch width (1σ) (ps)</td>
<td>~ 5</td>
<td>~ 5</td>
</tr>
<tr>
<td>particle/charge/pulse electron (nC)</td>
<td>2 x 10^9</td>
<td>8 x 10^9</td>
</tr>
<tr>
<td>positron (nC)</td>
<td>(0.32)</td>
<td>(1.28)</td>
</tr>
<tr>
<td>pulse repetition emittance (1σ) (m)</td>
<td>4 x 10^-8</td>
<td>6.4 x 10^-8</td>
</tr>
<tr>
<td>electron (m)</td>
<td>8 x 10^-7</td>
<td>8.8 x 10^-7</td>
</tr>
<tr>
<td>positron (m)</td>
<td>0.2%</td>
<td>0.125%</td>
</tr>
<tr>
<td>energy width (1σ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>electron</td>
<td>0.22%</td>
<td>0.125%</td>
</tr>
<tr>
<td>positron</td>
<td>0.22%</td>
<td>0.125%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(2) MAIN LINAC</th>
<th>PRESENT</th>
<th>KEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency (MHz)</td>
<td>2856</td>
<td></td>
</tr>
<tr>
<td>filling time (µs)</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>accelerator structure</td>
<td>T.W., 2p/3-mode, semi-C.G.</td>
<td></td>
</tr>
<tr>
<td>accelerator unit length (m)</td>
<td>9.6</td>
<td></td>
</tr>
<tr>
<td>accelerator unit number</td>
<td>40</td>
<td>57</td>
</tr>
<tr>
<td>before positron radiator</td>
<td>3</td>
<td>26</td>
</tr>
<tr>
<td>standby, energy tuning</td>
<td>~ 3+1</td>
<td>4+2</td>
</tr>
<tr>
<td>energy gain per unit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>with SLED (MeV)</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>without SLED (MeV)</td>
<td>62.5</td>
<td>90</td>
</tr>
<tr>
<td>input rf power / unit (MW)</td>
<td>20</td>
<td>40</td>
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<tr>
<td>energy multiplication</td>
<td>1.8</td>
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<table>
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<th>(3) PRE-INJECTOR</th>
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<th>KEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>type (cathode)</td>
<td></td>
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<tr>
<td>normalized emittance (m)</td>
<td>7 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>sub-harmonic buncher</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHB-1 frequency (MHz)</td>
<td>119.00</td>
<td>114.24</td>
</tr>
<tr>
<td>SHB-2 frequency (MHz)</td>
<td>571.20</td>
<td></td>
</tr>
<tr>
<td>Prebuncher / Buncher</td>
<td></td>
<td></td>
</tr>
<tr>
<td>frequency (MHz)</td>
<td>2856</td>
<td></td>
</tr>
<tr>
<td>phase velocity (Prebun.)</td>
<td>0.7 c</td>
<td></td>
</tr>
<tr>
<td>phase velocity (Bun.)</td>
<td>0.7 - 1 c</td>
<td></td>
</tr>
<tr>
<td>Output beam energy (MeV)</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>energy spread (1σ)</td>
<td>1.2%</td>
<td></td>
</tr>
<tr>
<td>normalized emittance (m)</td>
<td>~ 6 x 10^-5</td>
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</table>

<table>
<thead>
<tr>
<th>(4) POSITRON PRODUCTION</th>
<th>PRESENT</th>
<th>KEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator material</td>
<td>tantalum(Ta)</td>
<td>tungsten(W)</td>
</tr>
<tr>
<td>thickness (mm)</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>diameter (mm)</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Primary electron energy (GeV)</td>
<td>0.25</td>
<td>3.7</td>
</tr>
<tr>
<td>particle / pulse (1 x 10^11)</td>
<td>6 x 10^10</td>
<td></td>
</tr>
<tr>
<td>charge / pulse (nC)</td>
<td>(16)</td>
<td>(10)</td>
</tr>
<tr>
<td>positron production rate</td>
<td>&gt;6.5%</td>
<td>&gt;1.8%</td>
</tr>
<tr>
<td>after the DC solenoid (e^-/e/GeV)</td>
<td>1.8%</td>
<td>&gt;1.8%</td>
</tr>
<tr>
<td>final (e^-/e/GeV)</td>
<td>22.5</td>
<td>22.5</td>
</tr>
<tr>
<td>Focusing system type</td>
<td>quarter-wave transformer</td>
<td></td>
</tr>
<tr>
<td>normalized acceptance (m)</td>
<td>6 x 10^-3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(5) RF SOURCE</th>
<th>PRESENT</th>
<th>KEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulator</td>
<td>pulse transformer step-up ratio</td>
<td>1:12</td>
</tr>
<tr>
<td>core bias</td>
<td>no</td>
<td>use</td>
</tr>
<tr>
<td>Klystron</td>
<td>beam voltage (kV)</td>
<td>270</td>
</tr>
<tr>
<td>current (A)</td>
<td>295</td>
<td>354</td>
</tr>
<tr>
<td>output power max. (MW)</td>
<td>33</td>
<td>46.5</td>
</tr>
<tr>
<td>power ave (MW)</td>
<td>~ 27</td>
<td>~ 41</td>
</tr>
<tr>
<td>width (µs)</td>
<td>1.8</td>
<td>3.8</td>
</tr>
<tr>
<td>efficiency</td>
<td>44%</td>
<td>46%</td>
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<table>
<thead>
<tr>
<th>(6) SYNCHRONIZATION BETWEEN LINAC AND RING</th>
<th>PRESENT</th>
<th>KEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>synchronization</td>
<td>90:</td>
<td>(ns)</td>
</tr>
<tr>
<td>f0:</td>
<td>(MHz)</td>
<td>10.3854</td>
</tr>
<tr>
<td>Linac</td>
<td>f_Linac (2856MHz)</td>
<td>5x5x110</td>
</tr>
<tr>
<td>SHB-1</td>
<td>(MHz)</td>
<td>110(114)</td>
</tr>
<tr>
<td>SHB-2</td>
<td>(MHz)</td>
<td>5x110(571)</td>
</tr>
<tr>
<td>KEKB</td>
<td>f_Ring (MHz)</td>
<td>7x70(59)</td>
</tr>
<tr>
<td>harmonic number n</td>
<td>5120 (29x10)</td>
<td></td>
</tr>
</tbody>
</table>
from the tunnel. From late 1996, the first magnet for LER is

to be installed.

As for the linac, before the KEKB project was formally
approved, the linac group had discussed ways to upgrade the
energy, and conducted feasibility studies using the existing
linac [4,5]; consequently, the way mentioned above was
adopted as a reasonable one, because the linac must continue
injection for the SR experiments and the upgrade should be
performed only during annual shutdowns.

Since the project began, the upgrading of the existing 2.5-
GeV linac has gradually been performed. By the end of
FY1995, 32 high-power klystron pulse-modulators of 40
existing units had been upgraded; of 5 the sub-boosters, each
of which will drive 8 klystrons, 2 were replaced by new ones
for the SLED system [6]; 12 SLED’s and 50-MW klystrons
were installed (Fig.3), and the rf conditioning was finished in
10 units. These units were tested in order to prove the
acceleration gain and stability of the beam energy [7]. During
the rf conditioning, electric discharge, which causes a strong
vacuum degradation, was frequently observed in one unit. The
cause is now under investigation in connection with the rf rise
time and phase-switching time. The upgrading of the existing
linac will be almost completed by the end of FY1996.

In order to conduct a study regarding the production and
acceleration of a high-current, single-bunch primary electron
beam for positron production, two sub-harmonic bunchers
(SHBs) were inserted between the gun and the prebuncher.
The results obtained by a streak-camera system using optical-
transition radiation indicated that this system can produce a
bunch of about 12 ps FWHM at 10 nC [8].

The positron production target and the positron focusing
system have already been moved to a higher energy point
(Fig.4). The target was newly fabricated in order to be used at
higher beam powers; also, the layout was changed so as to
replace two 4-m accelerator structures by two 1-m ones and
two 2-m ones. A positron-production study was recently

begun; a preliminary result concerning the electron-to-positron
conversion rate is as follows: 5.4% $e^+e^\text{GeV}$ after the DC
solenoid with a 500 MeV and 3.2 nC single bunch.

The beam-transport system of the existing linac is being
replaced so as to accommodate higher-energy beams, adding
beam-position monitors accompanying the quadrupole
magnets.

Expansion buildings are being added to two areas: one is
the most upstream part; the other is the 180 degree-bend part
(“arc”) of the new linac layout, which forms a J-shape (see
Fig.2). These are under construction (Fig.5) and will be
completed by October and December, 1996, respectively.

Research and Developments

Compact high-power klystron

For KEKB, the 30-MW klystrons used for the PF 2.5-GeV
linac will be replaced by the 50-MW klystrons, which should
be operated at an average output of 41 MW, 4 μs, 50 pps. For
this purpose, the 30-MW klystron has been improved at KEK. The design concept is to increase the output power while keeping its original size, so that such equipment as the focusing magnet and pulse-transformer tank can be utilized, and that the height of output port is not changed.

In 50-MW klystrons, which were successfully developed at KEK [9], the overall size of the klystron assembly was not changed. However, the cathode insulator and the dimensions around the anode were improved so as to decrease the field strength at this part; the cathode diameter increased from 80 to 85 mm in order to decrease the current density; the distance between the anode and the input cavity was increased; the focusing field distribution was optimized so as to improve the efficiency on the basis of computer simulations. The applied voltage has been increased from 270 to 305 kV. At this voltage, it can output more than 50 MW pulses with an efficiency of more than 46%.

**RF compression system**

The 50-MW klystron with an rf compression system is to be used for the rf source of the KEKB injector linac. Three types of SLED systems were considered: the original SLED fabricated at SLAC [6], a modified SLED developed by the Japan Linear Collider group [10], and a resonant-ring type compression system (RRCS) developed by the injector linac group [11]. The former two use double TM_{015}-cylindrical cavities with a 3-dB power divider; on the contrary, the RRCS has a simple structure comprising a single resonant ring.

However, we decided to adopt the JLC-type SLED, which is improved in a low-gradient electric field around the cavity-waveguide coupling irises by using a two-hole coupling system. The RRCS was not adopted for two reasons: (1) the energy multiplication factor is 8% lower (this corresponds to 4 or 5 accelerator units against the total 57 units); (2) the radiation is higher (40 μSv/h at a 40-MW input), while not being detectable in JLC-type at more than 50 MW. These defects are due to the choice of the TE_{30}-like mode in a rectangular waveguide for the transverse cross section of resonant ring.

The detail structure of the JLC-type SLED was further modified in order to facilitate fabrication and handling in the existing linac: the processing precision and the welding structure/method were optimized so that they are sufficient for obtaining a Q-value of about 100,000 (theoretical value 107,000); the tuner function was improved so as to facilitate smooth adjustments with the necessary resolution (2 kHz in resonant frequency); the drive mechanism of the detuner needle was replaced by a solenoid type; the position of the needle was magnetically sensed while producing an electrical signal; and easily observable indicators were attached.

**Accelerator structure**

For the linac expansion, the number of regular accelerator section was increased from 160 to 228. The deficits are being newly fabricated. These are 2π/3-mode traveling-wave disk-loaded structures operated at 2856 MHz. In order to distribute the HEM-mode frequency, the structures have five sets of different disk-hole apertures, which have been decreased by 75 μm per cell from the input to the output, making an approximately flat field against wave attenuation through the structure. The input/output couplers are those of the cavity type, whose field asymmetry due to the coupling-iris is corrected by a dip on the opposite side of this iris.

The fabrication method used for the PF injector linac is unique compared to those widely used in other accelerators. The disk-loaded structure is made by an "electroplating method": disks and spacers, which were processed to a final dimension and inspected by measuring resonance frequency, are made one body by electroplating to a thickness of 5 mm. The motivation for developing this method was rather to facilitate mass production by eliminating any tuning after machining and welding. In a modern view of accelerator physics, it should be noticed that this method is only a "cool method" carried out at room temperature, thus eliminating any unexpected or uncontrollable HOM resulting from dimpling of the spacer surface.

![Fig. 6 Typical results of a nodal shift measurement: the standard deviation of phase error is about 0.9 degrees; the 2-m accelerator structures were fabricated by a "electroplating method" without any dimpling after machining.](image)

These basic design and fabrication method are also followed in the new structures. However, in the old positron generator, where two 4-m structures were used in a solenoidal magnetic field, the acceleration field in the accelerator structure installed immediately after the positron production target was not sufficient due to frequent electric breaking in the structure. Most marks due to arcing were found around the input coupler and the first disk. From this experience, in KEKB 1-m long structure was decided to be used after the positron production target; the coupler structure is being renewed in order to decrease the field strength when a higher input power is used. The coupler dimensions (2:inner diameter, W:iris aperture), were determined by a computer simulation [12]. These structures will be tested under higher input power this autumn.

**Positron beam increase**

One of the major target is to increase the positron intensity. The required intensity of 4 x 10^9 positrons (0.64 nC) per bunch was determined so that the injection time from
vacancy to 2.6 A would be ten–several minutes. In the case of a uniform fill into the 5120 ring rf buckets, the stored charge per bucket is 5 nC; about eight injections per bucket are therefore needed. This linac positron intensity is obtainable when a primary electron beam of 6 x 1010 electrons (10 nC) per bunch can be accelerated to the target, and the positron production rate still be kept at 1.8% e+/e– GeV, as in the old generator [13].

We have already experienced some difficulty concerning high-current beam acceleration at 2-ns, 16-nC beam up to 250 MeV. The investigation is still continuing using a combination of relevant fields: the first is how to produce an intense single-bunch beam by the pre-injector [14]; the second concerns theoretical studies regarding the wake-field [15]; the third involves beam monitoring [16]; the forth, an accelerator alignment [17]; and the fifth, a beam transport. Although beam studies regarding the pre-injector has been progressing, as mentioned before, the other studies are either under investigation on paper or are being qualitatively discussed.

Because of restrictions coming from the linac-ring beam transport line, the standard deviation of energy spread must be less than 0.125%. For the primary electron beam, the 180-degree bending "arc" in the expansion building was carefully designed so as to be achromatic and isochronous to the second-order optics [18]. The final design comprises 6 bends with quadrupoles and sextupoles, and satisfies less bunch and emittance growth for an energy spread of up to 1.2% σE/E. Further, a bunch-compression system (BCS) will be introduced before the radiator in order to suppress any debunching effect in the positron focusing system. For the produced positron beam, an energy compression system (ECS) will be used at the end of the linac.

![Fig. 7 Estimated bunch/energy width of the positrons after ECS.](image)

For increasing the positron yield, the focusing system behind the positron production target will be improved. Recently, a feasibility study was initiated regarding the use of a super-conducting magnet. According to a preliminary study, a tapered shape solenoid field (6T) would improve the yield by more than two-times as much as the present system [19].

Summary and future

The construction of the KEKB injector linac is successfully progressing. Reconstruction for the energy upgrade in the existing linac will be finished by the end of FY1996. The expansion buildings will be completed by the end of 1996, and the construction of the expanded part will start at the beginning of 1997. The pre-injector, including sub-harmonic bunchers, will be moved to the most upstream of the new building (before the construction is completed, injection for the PF ring will be made using a temporary pre-injection system). Then seventeen accelerator units will be installed sequentially. From the autumn of 1997, some of these units and "arc" will be tested by the local control system installed at the new sub-control station of the expansion building. Most of the construction will progress during FY1997, finished and connected to the existing linac by the summer 1998, and commissioned in the autumn of 1998.

References

Poster Session TH

Chairman: H. Henke

Thursday, August 29, 1996
STATUS AND RESULTS FROM THE NEXT LINEAR COLLIDER TEST ACCELERATOR

Stanford Linear Accelerator Center, Stanford, CA 94309

Abstract

The design for the Next Linear Collider (NLC) at SLAC is based on two 11.4 GHz linacs operating at an unloaded acceleration gradient of 50 MV/m increasing to 85 MV/m as the energy is increased from 1/2 TeV to 1 TeV in the center of mass[1]. During the past several years there has been tremendous progress on the development of 11.4 GHz (X-band) RF systems. These developments include klystrons which operate at the required power and pulse length, pulse compression systems that achieve a factor of four power multiplication and structures that are specially designed to reduce long-range wakefields. Together with these developments, we have constructed a 1/2 GeV test accelerator, the NLC Test Accelerator (NLCTA). The NLCTA will serve as a test bed as the design of the NLC is refined. In addition to testing the RF system, the NLCTA is designed to address many questions related to the dynamics of the beam during acceleration, in particular the study of multibunch beam loading compensation and transverse beam break-up. In this paper we present the status of the NLCTA and the results of initial commissioning.

Introduction

The Next Linear Collider Test Accelerator (NLCTA) is a 42-meter-long beam line consisting consecutively, of an injector, a chicane, a linac, and a spectrometer[2].

The injector consists of a 150-kV gridded thermionic-cathode gun, two prebuncher cavities and two 0.9 m detuned accelerator structures. The injector is surrounded by solenoids to provide the necessary focusing. Downstream from the injector we have a magnetic chicane for longitudinal phase-space manipulation, energy measurement and collimation. After the collimation, the average current injected into the linac is comparable to the NLC specification, 1.0 nC/1.4 ns.

The NLCTA linac which complete will consist of six 1.8-meter-long X-band accelerator sections which are designed to suppress the long-range transverse wakefield. These sections will be powered by three 50-MW klystrons whose peak power is quadrupled by SLED-II RF pulse compressors. This yields an unloaded acceleration gradient of 50 MV/m over 10.8 m so that the maximum energy gain in the linac is 540 MeV. The NLCTA RF system parameters are listed in Table 1.

Downstream from the linac we have a magnetic spectrometer that can horizontally momentum analyze the bunch train after acceleration. A vertical kicker magnet in the spectrometer will provide a method for separating the bunches vertically so that the energy and energy spread can be measured along the bunch train. We can also measure the emittance in the spectrometer and in the chicane.

In the future we plan to increase the linac gradient to 85 MV/m by installing six 75 MW klystrons as shown in Table 2. We also plan to upgrade the injector in order to increase the bunch spacing and intensity, each by a factor of 16. This will permit more detailed beam-dynamics studies on a train of bunches similar to that required for the NLC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Upgrade</th>
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<tbody>
<tr>
<td>Linac Energy</td>
<td>540 MeV</td>
<td>920 MeV</td>
</tr>
<tr>
<td>Active Length</td>
<td>10.8 m</td>
<td>10.8 m</td>
</tr>
<tr>
<td>Acc. Gradient</td>
<td>50 MeV</td>
<td>85 MeV</td>
</tr>
<tr>
<td>Inj. Energy</td>
<td>90 MeV</td>
<td>90 MeV</td>
</tr>
<tr>
<td>RF Freq.</td>
<td>11.4 GHz</td>
<td>11.4 GHz</td>
</tr>
<tr>
<td>No. of Klystrons</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Klystron Power</td>
<td>50 MW</td>
<td>75 MW</td>
</tr>
<tr>
<td>Klystron Pulse</td>
<td>1.5 μsec</td>
<td>1.5 μsec</td>
</tr>
<tr>
<td>RF Compression</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Structure Length</td>
<td>1.8 m</td>
<td>1.8 m</td>
</tr>
</tbody>
</table>

Klystron Status

The NLC (and NLC) specifications call for 50 MW klystrons operating with a 1.5 μsec pulse length (1.2 μsec for the NLC). Thus far, the klystron development effort at SLAC has produced four klystrons that meet or exceed the NLCTA specification[3]. Figure 2 shows the output power of the fourth in the series, XL-4. It is a very robust klystron with a very stable output power and can produce a 75 MW pulse 1.2 μsec long. Both XL-2 and XL-3 also produce more than the required 50 MW, and all of the three klystrons have the required bandwidth to work with the SLED-II compression system. The XL-4 klystron has been installed on the NLCTA injector modulator and is being used to power the initial commissioning of the injector.

* Work supported by Department of Energy contract DE-AC03-76SF00515.
Several more klystrons of the XL-4 type will be produced for the NLCTA. However, the development effort for NLC klystrons has been turned towards the development of a periodic permanent magnet (PPM) focused klystron[4]. This eliminates the focusing solenoid from the klystron, reducing the capital and operating cost significantly. The initial tests of the first PPM klystron have just been completed yielding up to 60 MW with about 60% efficiency. This klystron power exceeds the 50 MW required for the 1/2 TeV NLC.

![High-Power Test of XL-4](image)

**Figure 1. High-Power test of XL-4.**

**RF Pulse Compression Status**

In SLED-II RF pulse compression the klystron power flows through a 3-dB hybrid where it is split to resonantly charge two delay lines. After several round trip times, the klystron phase is flipped by 180 degrees, after which the power from the klystron adds to the power emitted from the delay lines to create a large compressed pulse of RF power. Figure 2 shows high-power tests of the SLED-II prototype for the NLCTA powered by the XL-2 klystron. The prototype exceeded the required output power of 200 MW, but with a shorter pulse of 150 nsec [5].

![High-Power Test of the SLED-II Prototype](image)

**Figure 2. High-power test of the SLED-II prototype.**

Three SLED-II systems have been installed in the NLCTA, one for the injector and two for the linac. Initial low-power tests of the injector SLED-II system have shown excellent performance with an overall efficiency that exceeded our expectations[6]. High-power processing of the injector SLED-II system is presently in progress. Thus far the system has been conditioned up to 135 MW output power with a 250 ns pulse.

**RF Structure Status**

The NLC design requires accelerator structures that operate reliably with an unloaded gradient of 50 MV/m for the 1/2 TeV collider and 85 MV/m for the 1 TeV upgrade. The NLCTA will serve as a model of this upgrade path in that we will begin at the lower acceleration gradient and eventually increase the gradient to the required 85 MV/m (see Table 1).

In addition to the gradient requirement, the NLC structures must be designed to substantially reduce the long-range transverse wakefields that can cause beam breakup. To achieve this reduction we have pursued two basic types of accelerator structures, a detuned structure and a damped-detuned structure. There are a total of eight structures in the NLCTA. The first two are one-half-length detuned structures. The second pair are full-length detuned structures. The third pair are damped-detuned structures; and finally, the last pair will initially be KEK detuned structures and later will be damped-detuned structures.

**Detuned Structures**

In a constant gradient traveling wave structure the irises are tapered to vary the group velocity in order to keep the gradient constant in spite of the losses in the structure. This tapering produces a variation of the frequency of the first dipole mode along the structure length that can be as much as 10%. The detuned structure takes advantage of this, but the profile of the iris taper is changed in order to create a smooth Gaussian-like distribution of higher-order modes. This leads to a Gaussian-like initial decay of the wake field behind the bunch[7]. We have successfully tested this concept using probe and witness beams in the Accelerator Structure Test Set-up (ASSET) facility in the SLC[8].

This technique has been used to manufacture four structures in the NLCTA. The first three are complete and the remaining structure will be brazed this fall.

**High-Power Tests of Structures**

During the past several years we have performed many high-power tests of different types of structures[9]. These tests indicate that surface fields up to 500 MV/m can be obtained in copper structures at 11.4 GHz. In power-limited tests, average acceleration gradients in short structures have reached 120 MV/m[10]. The first 1.8 m detuned structure has been high-power tested up to 67 MV/m[11]. These tests indicate that the conditioning up to the desired 50 MV/m will be straightforward.

**Damped-Detuned Structures**

In order to further reduce the wakefield and the tolerances, it is necessary to provide some moderate damping for the higher-order dipole modes. To accomplish this we have developed a damped-detuned structure that uses four symmetrically placed
manifolds to provide the damping [12]. The structure cells are
coupled to four waveguides that are formed when the cells are
diffusion bonded together. The dipole mode is coupled out to
the waveguide where is propagates to the end of the structure
to a load. This techniques should damp the first dipole modes
with Qs of about 1000. The signals from the manifold can be
used as a beam position to align the structure to the beam.

The first two damped-detuned structures are being
constructed in collaboration with KEK[13,14]. In addition, we
have just completed an experiment to measure the wakefield of
the damped-detuned structure[15]. The measured long-range
wakefield is reduced by more that two orders of magnitude
relative to the short-range wake and agrees well with the
theoretical predictions[14,15]. Finally, the modes that are
damped have now been shown to yield a sensitive position
measurement along the length of the structure[16].

**Beam Line Commissioning**

The entire NLCTA accelerator from the gun to the final
dump has been constructed and installed except for the
downstream 1.8 m accelerator structures. Spool pieces replace
these structures in the beam line, and the entire system from
the gun to the dump is evacuated. The current, position and
profile of the beam are monitored from the gun all the way to
the dump with monitors that are used to optimize and
characterize the beam.

![Figure 3. Torroid Current through the chicane](image)

The first 150 keV electron beam from the gun was achieved
in May. The gun and related electronics were characterized and
beams varying in intensity from 0.2 to 2 A and in pulse
length from 40 to 150 ns were transported to a Faraday cup
one meter downstream. The calibration of the gap current
monitor at the gun was verified against the Faraday cup.

In June and July 1996 the remainder of the injector system
was installed completing the beam line between the gun
and the chicane. In August, beam from the gun was accelerated
and transported all the way to the final dump of the NLCTA.

For the initial turn on a 150 kV, 0.5 A, 40 ns wide beam
from the gun was bunched into X-band buckets and accelerated
up to 60 MeV in the injector. We obtained 65% beam
transmission at the entrance to the chicane (0.32 A), and 55%
of the gun current reached the toriod at the end of the chicane
(0.27 A). The beam energy and energy spread were monitored
on a profile monitor in the middle of the chicane. While all
the phases of the bunching components and the accelerator
sections are not completely optimized yet, an energy spread of
0.6% for the core of the beam was achieved. Figure 3 shows
the signal from the various current monitors up to the end of
the chicane. Commissioning of the linac will commence this
fall as the remaining accelerator structures and klystrons are
installed.

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A DAMPED DETUNED STRUCTURE FOR THE NEXT LINEAR COLLIDER

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Abstract

An X-band Damped Detuned Structure (DDS) for NLC has been fabricated as part of a collaboration between KEK and SLAC. The individual cells were diamond point machined and microwave tested at KEK. The cells were diffusion bonded at SLAC. The structure has been cold tested. The time dependence of the beam induced dipole wakefields have been measured with the SLC beam in the test station ASSET. The structure is designed so that the dipole modes have an approximately gaussian density distribution in the frequency domain. This gives an approximately gaussian decrease of the wakefields for short times (about 10 ns), which is produced by the interference among the 206 modes in the lowest dipole mode band of the 206 cell structure. Without damping, the wakefields then rise back to a level which is approximately equal to the expected incoherent level from the 206 modes. The damping is accomplished by means of 4 rectangular slots or manifolds (approximately 5 mm by 10 mm) equally spaced in azimuth around the structure and running the full length of the structure. These manifolds act as single mode rectangular waveguides for the lowest band dipole modes, but are cut off for the accelerating modes. The manifolds are coupled to every cell in the structure, except for 3 at each end, by means of radial slots. Each of the four manifolds will have the dipole mode frequencies traveling in both directions and so are terminated on both ends. The structure will be installed in the NLC Test Accelerator this fall.

1. Introduction

Although the Damped Detuned Accelerator Structure, Fig 1, is being developed for the SLAC design of the Next Linear Collider, the concept is applicable to any long pulse, high pulse current accelerator. Indeed when linear collider designs go to many bunches to improve luminosity, they face the same problem which limits the performance of many industrial accelerators, linacs used for particle physics and linacs proposed for driving high power FEL's: long range dipole wakefields distort the particle orbits causing transverse emittance growth and eventually Beam Break Up. The structure discussed here achieves 2 orders of magnitude reduction in the transverse wakefields and may be capable with some modifications of as much as 3 orders of magnitude suppression. Thus the approach of detuning structures for short range wakefield suppression combined with light damping using manifolds may be an important innovation in the design of linacs.

Fig 1: Cutaway sketch of Damped Detuned Structure.

One of the important features of DDS's is that any dipole modes which the beam excites propagate through the manifolds to the end of the structure. Since the structure is detuned, there is a one to one relationship between the dipole frequency excited and the longitudinal position in the structure where the beam excited the mode. Thus, the spectrum of the dipole signals observed in the manifolds provides an internal monitor of the beam position relative to the structure, with a longitudinal resolution which can be a small fraction of the structure length. For the structure discussed here the resolution is of the order of 10 cells in the 206 cell structure.

The manifold damping used in the DDS works only because the structure is detuned. If the accelerator was a uniform (constant impedance) structure the beam would interact with a single velocity of light dipole mode which would not couple to a simple waveguide manifold where the phase velocity is necessarily greater than the velocity of light. A coaxial manifold would couple to the dipole mode, but it would be difficult, perhaps impossible, to keep it from coupling to, and therefore damping, the fundamental accelerating mode. In the detuned structure, all the dipole modes which interact with a velocity of light beam also have a region where the phase velocity is greater than c and equal to the phase velocity for their frequency in the damping.
manifold. In this region (different for each mode), where each dipole mode in the accelerator cells is synchronous with the mode in the manifold, the coupling takes place. A synchronous condition must be met because there is a coupling hole between each manifold and every cell in the accelerator. Thus, in effect, there is a multihole coupler between each manifold and the accelerator. Since each dipole mode has a different frequency, each mode is synchronous with the manifold and hence couples to it in a different longitudinal region of the accelerator. Since the manifolds are simple rectangular waveguides they are not synchronous with the fundamental accelerating mode anywhere, and, indeed, they are cut off for the accelerating frequency.

The pressure of the schedule for testing the structure for wakefield in the ASSET facility [1] in SLC and for installation in NLCTA forced the parameters of the first DDS to be frozen before an adequate theory existed to analyze its performance. As a consequence the performance of this first structure is degraded, but it can be significantly improved by some fine tuning of the design.

2. Design Issues

**Gaussian Detuning.** The goal of the gaussian detuning is to create a dipole impedance which is approximately a gaussian function of frequency, so that the wakefields will decay in an approximately gaussian manner. However, since it is a complicated calculation to get from the tapered structure parameters, or from equivalent circuit parameters to the functional dependence of the impedance on frequency, how does one get started? The solution is to make the quasi-uncoupled approximation: that after excitation by a velocity of light delta function bunch each cavity rings not at its resonant frequency, but at the velocity of light synchronous frequency of a periodic structure of that cavity. The justification for this approximation is that the boundary values for the fields in each cell are the fields in the adjacent cells which were excited by the same velocity of light bunch. Detailed equivalent circuit analysis by Bane and Gluckstern [2] indicates that this is a very good approximation. For the present structure the cells were picked to have gaussian density distribution of the synchronous frequencies. It would have been slightly better to have $K_n(\delta n/df)$ be a gaussian function of the synchronous frequency, where $K_n$ is the kick factor ($=1/4 \alpha R/Q$) of the nth cell. The gaussian width factor $\sigma=2.5\%$, and the gaussian is truncated at $+/2\sigma$.

**Single Mode Manifolds.** Although multimode manifolds were studied first, the final design utilizes single mode manifolds. Each design has advantages and disadvantages, and the choice is not clear cut. The multimode manifold was rejected for two reasons: concern about a fragile thin iris between the manifold and the cell and complexity of analysis of cell to manifold coupling in five modes. The single mode design chosen has no iris because the hole between the manifold and the cell is as wide as the manifold (the small dimension of the rectangular waveguide) and as long as the cell.

**Advantages of Single Mode Manifolds:**
1) Smaller, and well cut off for Accelerator frequency
2) Easier to couple out at ends since it is single mode
3) Simpler to fabricate - no thin iris
4) Perhaps easier to analyze - fewer modes
5) Negligible degradation of accelerator shunt impedance

**Disadvantages of Single Mode Manifolds:**
1) Match of terminations quite critical
2) Over coupling perturbs mode structures, frequencies and Q's introducing deleterious fluctuations in the gaussian impedance function
3) The single mode manifold chosen here couples only to the TE component in the dipole mode, which gets very small at the output (high dipole frequency) end of the structure. This makes it difficult to get adequate coupling. A narrow radial slot running from each manifold part way into the disk can raise the coupling and solve this problem.
4) Lower conductance for vacuum pumping

With careful design it should be possible to overcome satisfactorily the first 3 disadvantages, so the single mode design remains our design of choice.

**Choice of Q.** For the present structure Q of 1000 was chosen as the target value for all the lowest band dipole modes which interact strongly with the beam. This was chosen to attenuate the wakefields by a factor of e by 20 ns after the excitation, the time at which the wakefield envelope is rising again from the renewed constructive interference of the modes on the edges of the gaussian. However, the Q of 1000 corresponds to a resonance width, $\Delta f/Q$, twice as large as the mode separation at the peak of the mode spectrum, which produces mode distortion in the single mode design. In a multimode design, each waveguide mode would have weaker coupling and since each would couple power out of the mode at a somewhat different location, there would less mode distortion for the same loaded Q.

A better approach to the choice of Q and hence of the required coupling to the manifold, results from realizing that the motivation for the damping is to produce a dipole impedance which is a smooth, approximately gaussian, function of frequency. Thus we would like the width of the nth resonance to be $f/Q_n = k\delta f$, where k is a constant close to 1, and $\delta f$ is the mode spacing in the vicinity of the nth mode. The value of k should be chosen to give the smoothest impedance as a function of frequency. The optimum k would probably be higher for a multimode design.

The manifold coupling and hence the Q's are controlled in the present design primarily by varying the distance between the manifold and the accelerator cells and thus the length of the hole between them. The secondary method of varying the coupling is to vary the cutoff frequency, $f_c$, of the
manifolds. This affects the coupling because the dipole modes in the accelerator have a large TE component at small phase advance per cell and a small TE component at large phase advance. The manifolds couple only to the TE component of dipole modes because the narrow walls of the rectangular manifolds are adjacent to the outer surface the accelerator cells. In the TE10 mode the magnetic field along the narrow wall of the manifold is longitudinal and consequently does not couple to a TM mode in the cell. The higher the cutoff frequency of the manifold, the smaller the phase advance at the avoided crossing where the manifold couples to a particular cell, and hence the stronger the coupling. The cutoff frequency, $f_c$, varies from 12.5 GHz at the input end to 14.0 GHz at the output end in order to increase the coupling at the output end.

3. Equivalent Circuit Theory Results

Since the equivalent circuit analysis is the subject of another paper at this conference [3], only some of the most important results will be presented here. Fig 2 compares the wakefields for the Detuned structure (DT) with no damping but including the copper losses and the DDS with perfectly matched terminations each calculated with the equivalent circuit analysis. Fig 3 presents the calculation for the DDS structure with the existing terminations. The round dots are the preliminary data from the measurements of the wakefield of the DDS using the SLC beams in ASSET [4].

![Fig. 2: Calculated wakefield of structure without damping (upper curve) and with damping with perfectly matched terminations on manifolds.](image)

Prior to and during the design of the output structure for the manifolds, an equivalent circuit investigation of the effect of manifold mismatch on the wake function was carried out. It was found that while the wake function was relatively insensitive to small reflections at the input end, even very small reflections at the output end produced significant degradation. This asymmetry is presumed to be related to the fact that the field patterns of the exact damped eigenmodes with matched termination show a strong asymmetry in manifold excitation, favoring the output end. While this effect is not yet understood, it is absent in the manifold excitation patterns given by perturbation theory and hence must be a consequence of pattern distortion associated with strong coupling. The ASSET tests show nine times as much energy emerging from the output end of the manifolds as compared to their input end, a circumstance which is presumably a reflection of these phenomena. An equivalent circuit theory for these spectra had been worked out in anticipation of the ASSET tests, but it has not yet been implemented.

![Fig. 3: Calculated (curve) and measured (dots) wakefield of DDS structure with existing mismatched terminations.](image)

As is suggested by comparison of Figs. 2 and 3, the termination match at present is not very good: a VSWR of about 2 at the band edges at 14.2 and 15.8 GHz and dropping to about 1.2 at the center of the band, 15 GHz. At all 8 terminations (both ends of 4 manifolds) the dominant mismatch above 15 GHz is due to the windows, which are replaceable. Better windows are presently being developed, which we anticipate will be 1.1 or better over the full range. At 14.2 GHz the problem exists only at the output end, where we were unable to design a mitered bend from the manifold waveguide with a cutoff at 14.0 GHz which had a good match from 14.2 GHz to 15.8 GHz. Since the manifold and the mitered bend are integral parts of the accelerator, the remedy must await the next structure. We intend to adjust the taper of the manifold dimensions so that $f_c$ is about 13.5 GHz at the mitered bend.

There is an optimum coupling strength as a function of frequency which gives the smoothest impedance function. If the coupling is too strong it produces striking fluctuations in the amplitude of the kick factor, the Q's and in the mode density which all can give deleterious fluctuations in the impedance function.

4. Acknowledgments

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5. References

DESIGN OF THE NLC POSITRON SOURCE

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Abstract

The design of the positron source for the Next Linear Collider (NLC) is presented. The key features of this design include accelerating positrons at an L-band frequency (1428 MHz) and using a rotating positron target with multi-stage differential pumping. Positron yield simulations show that the L-band design yields at the source 2.5 times the beam intensity required at the interaction point and is easily upgradable to higher intensities required for the 1 TeV NLC upgrade. Multibunch beam loading compensation schemes in the positron capture and booster accelerators and the optics design of the positron booster accelerator are described. For improved source efficiency, the design boasts two parallel positron vaults adequately shielded from each other such that one serves as an on-line spare.

1 Introduction

The NLC is designed to collide a 90-bunch positron beam with an identical electron beam with a bunch intensity as high as $1.25 \times 10^{15}$ particles for each machine pulse [1,2]. The beam pulse intensity requirement for the NLC represents more than a 20-fold increase over its SLC counterpart! While the SLC positron source [3], by virtue of its relative design simplicity and its proven operational reliability, is used as a design basis for NLC, significant changes are made to greatly boost the positron beam intensity to meet the NLC needs. In this paper, we will first present a design overview, then concentrate on the important aspects of the design and report on the progress made in the design since the writing of our previous paper [4].

2 Design Overview

The NLC positron source is of a conventional type based on e+ e- pair production from an electromagnetic shower created in a thick, high-Z target upon bombardment by high energy electrons. Three subsystems comprise the NLC source: a drive beam electron accelerator, a positron production and collection system, and a positron booster linac. Table 1 summarizes the important parameters of the NLC positron source for both its phase-I design and its phase-II upgrade (500 GeV and 1 TeV center-of-mass energy, respectively).

The drive beam accelerator uses S-band (2856 MHz) RF for acceleration and has an injector consisting of a thermionic gun, two subharmonic and one S-band bunchers. The positrons are generated in a $W_{75}Re_{25}$ target, adiabatically phase-space transformed in a flux concentrator and a tapered-field solenoid, and captured in an L-band (1428 MHz) accelerator embedded inside a 0.5-T uniform-field solenoid.

Acceleration of the positron beam to 2 GeV for emittance damping occurs in an L-band booster accelerator with a dense array of quadrupole magnets providing transverse focusing.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>NLC-I</th>
<th>NLC-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy (GeV)</td>
<td>3.11</td>
<td>6.22</td>
</tr>
<tr>
<td>No. of bunches per pulse</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Bunch Intensity</td>
<td>$1.5 \times 10^{10}$</td>
<td>$1.5 \times 10^{10}$</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>180</td>
<td>120</td>
</tr>
<tr>
<td>Beam power (kW)</td>
<td>121</td>
<td>161</td>
</tr>
<tr>
<td>Beam σ on target (mm)</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Pulse Energy Density $\rho$ (GeV mm²)</td>
<td>$4.6 \times 10^{11}$</td>
<td>$5.2 \times 10^{11}$</td>
</tr>
</tbody>
</table>

**Positron Target:**

- Material: $W_{75}Re_{25}$
- Thickness (R.L.): 4
- Energy deposition (J/pulse): 126
- Power deposition (kW): 23

**Positron Collection:**

- Tapered field (T): 1.2
- Uniform field (T): 0.5
- Flux concentrator field (T): 5.8
- Flux concentrator minimum radius (mm): 4.5
- Accel. RF frequency (MHz): 1428
- Accel. gradient (MV/m): 25
- Minimum iris radius (mm): 20
- Edge Emittance (μrad): 0.06
- Collection efficiency (%): 19%
- Positron yield per electron: 1.4
- Positron bunch Intensity $2.1 \times 10^{10}$

The L-band design for the NLC positron capture and booster accelerators is the key to achieving the order of magnitude higher positron beam intensity over that of the SLC positron source. By quadrupling the transverse phase space admittance and boosting the longitudinal phase space admittance as well, it not only immediately provides a 4-fold increase in the positron capture efficiency, but ultimately ensures the upgradability of the source to NLC-II intensities, with a large intensity safety margin.

In operation, system reliability is always a critical issue. The reliability of the positron production and capture system is particularly important since the high radiation levels in these areas would prevent human access for prompt repair in case of hardware failure during a physics run. In addition to engineering the best possible reliability into each component, a most effective way to mitigate the reliability problem is to
build redundancy into the system. In our proposal, two side-
by-side positron vaults housing identical positron production
and capture systems that are adequately shielded from each
other will be built. If one system fails, we may immediately
switch over to the other to continue the run. In the meantime,
we may wait for the radiation level in the vault with failed
hardware to drop and then repair the failed component(s). As
long as the mean time to fail exceeds the mean time to repair,
which we hope will be the case based on the superior
reliability demonstrated by the SLC positron source, such a
redundancy design will ensure excellent reliability.

3 Target Engineering

By the nature of this design, the positron target that
serves the dual purposes of generating an electromagnetic
shower upon electron bombardment and inducing \( e^\pm \) pair
production must absorb a considerable amount of energy from
the drive beam. The drive beam energy density must be kept
below a critical threshold, which depends on the target
material, or excessive single pulse beam heating may cause
the target to fail. As in the SLC positron source, \( W_{75}\text{Re}_{25} \)
was chosen as the target material because of its high \( e^\pm \) pair
production efficiency and excellent thermo-mechanical
properties. Target R&D at SLAC using 20–25 GeV drive
electrons and 5–7 R.L. (radiation length) thick targets [5]
established a failure threshold for \( W_{75}\text{Re}_{25} \) due to single pulse
beam heating at

\[
\rho_{\text{max}} = \frac{N_\nu E_x}{2 \pi \sigma_x^2} = 1 \times 10^{12} \text{ GeV/m}^2,
\]

where \( N_\nu \) is the number of drive electrons per pulse, \( E_x \) the
energy of the electrons, and \( \sigma_x \) the rms radius of the electron
beam. Thus, the rms beam radius at the target has been
chosen to be 1.2 mm for NLC-I and 1.6 mm for NLC-II,
respectively, to keep the beam energy density per pulse about
50% below this threshold.

The \( W_{75}\text{Re}_{25} \) target, shaped into a ring with an outer
radius of 25 cm and a radial thickness of 0.7 cm, will be
rotated at a frequency of 2 Hz. In this way, areas of
successive beam pulse impacts on the target will be adequately
separated and the target will be heated uniformly. Unlike
other types of target motions such as trolley, the rotating
motion preserves the geometry of the target with respect to
the incident drive beam and the emerging \( e^\pm \) beams as well.
Therefore, it is expected to eliminate positron beam intensity
modulations that might be induced if the target motion is such
that its geometry with respect to the beam changes periodically,
as in the SLC source. The target will be cooled from the inner ring surface to which a silver or copper casting
containing stainless steel cooling tubes is brazed. With a
cooling water flow rate of ~2 l/s and a velocity of ~10 m/s, the
steady state temperature of the target is estimated to be
~400°C for the cases of both NLC-I and NLC-II, which is a
rather comfortable temperature for \( W_{75}\text{Re}_{25} \).

The rotating motion along with the necessity to cool the
target leads to a design in which the target is attached to a
rotating shaft that passes from vacuum where the target resides
to atmosphere where a driving motor is connected and cooling
water is coupled in and out. The high radiation levels near the
target precludes the use of conventional vacuum seals made of
organic materials such as viton. Instead of pursuing a
vacuum-tight seal, we propose to use multi-stage differential
pumping along the length of the shaft with radiation resistant
seals that limit conductance relying on tight clearances (~15
\( \mu \)m) between sealing surfaces and long path lengths.
Candidate seals include axial and radial face seals, axial and
radial labyrinth seals, and magnetic face seals.

Figure 1 depicts a conceptual design of the positron
target system with three stages of differential pumping. In
such a three-stage design, the first stage could use an oil-free
dry scroll pump, the second and third stages could each use a
turbomolecular pump backed by a dry scroll pump. If the
pressure drops by three orders of magnitude after each stage,
which we have reason to believe, then, such a design could
easily realize the desired 10−7 Torr vacuum in the target
chamber. A test two-stage differential pumping system with a
rotating shaft will be built and experimented to prove the
feasibility of this design and also to select the best seals.

4 Capture and Booster Accelerators

The capture accelerator is required to quickly accelerate
the positron beam to relativistic energies to minimize
debunching due to the initial huge energy spread. As electrons
are also accelerated along with positrons, it also must be able
to handle up to 14 A of multibunch beam loading current in the
case of NLC-II. In our design, two 5-m detuned L-band
(1428 MHz) structures with an average gradient of 25 MV/m
will be used for acceleration, and two 3-m L-band structures
sandwiched in between will be used for beam loading
compensation by operating off-frequency at 1428 ± 1428
MHz (i.e., the AF method). Each of the acceleration and
compensation structures will be driven by two 75-MW L-band
klystrons with SLED-I pulse compression. The beam will be
focused by a long DC uniform-field solenoid with a 0.5 T axial field that encloses all four structures.

The 250-MeV positron beam emerging from the capture accelerator will be injected into the booster linac after an achromatic and isochronous bend doublet, which also allows the electron beam to be separated from the positron beam and dumped. The booster linac, designed to accelerate the beam to 2 GeV, consists of 12 accelerating modules. Each module contains two 5-m detuned L-band structures with a minimum iris radius of 20 mm and will be powered by two 75-MW L-band klystrons feeding one SLED-I cavity. The unloaded gradient is about 20 MV/m. Beam loading in the booster linac, with a maximum loading current of 2.75 A, will be accomplished by using the ΔT method, i.e., injecting the beam before the structure is completely filled. In contrast to the ΔΦ method, the ΔT method offers the advantage of not introducing a large single-bunch energy spread, thus minimizing chromatic emittance growth. The booster linac has roughly a 15% energy headroom.

The lattice for the booster linac is designed using TRANSPORT up to second order. It consists of a dense array of FODO cells whose spacing is scaled approximately as $\sqrt{E}$ along the linac except for the first structure where the cell spacing is kept constant. Most of the quadrupole magnets have apertures large enough to surround the L-band structures, with one or two small-aperture quadrupoles in between successive structures to match the optics across the gaps. The strengths of the large-aperture quadrupoles are kept nearly the same. The phase advance per cell starts at 60° at the beginning of the lattice and gradually decreases to about 25° at the end. This design leads to a quasi-linear $E$ scaling of the maximum $\beta$ function. First-order TRANSPORT calculation shows that the positron beam size is shrunk to <15 mm after the first few structures.

Using the program LINACBBU [6], multibunch beam blow-up due to long-range transverse wake field has been calculated for the booster linac. It is concluded that such effects are negligible for structures with a 10% full-range Gaussian frequency detuning.

5 Yield Calculation

The yield for both positrons and electrons from $W_{75}\text{ReO}_5$ targets of thicknesses ranging from 3.5 to 6 R.L. (1 R.L. = 3.43 mm) are calculated using the program EGS [7] for both drive beam energies, i.e., 3.11 and 6.22 GeV. While it is desirable to maximize the positron yield, the volume density of pulse energy deposition in the target must be kept safely below the failure threshold. These considerations leads to the choice for the optimal target thickness to be 4 R.L.. The positron and electron yields per drive electron from such a target are, respectively, 7.2 and 9.0 for 3.11 GeV drive electrons, and 12.5 and 17.1 for 6.22 GeV drive electrons. About 18% and 14% of the drive beam energies are deposited in the target for 3.11 and 6.22 GeV beams, respectively.

The particle rays obtained from the EGS simulation are traced through the adiabatic phase space transformer and the capture accelerator, whose parameters are listed in Table 1, using the program ETRANS [8]. The best positron yield at the exit of the capture accelerator where the beam reaches an energy of about 250 MeV is found to be 1.4 and 2.1 per drive electron for NLC-I and NLC-II, respectively, after applying 6-dimensional phase space admittance cuts. Correspondingly, the positron beam intensities at the 250 MeV point are $2.1\times10^{10}$ /bunch and $3.2\times10^{10}$ /bunch, respectively, each exceeding the respective maximum desired bunch intensity at the IP (i.e., $0.85\times10^{10}$ and $1.25\times10^{10}$) by a factor of 2.5.

Using the program TURTLE, the positron rays are further traced through the booster linac, whose alignment is assumed to be perfect. After applying a 0.06 m-rad transverse emittance cut and a ±2% energy spread cut, it is found that beam transmission through the booster linac is about 95%. While structure and magnet misalignments are inevitable in a real machine, the transverse and energy admittances of the pre-damping ring with an energy compressor are 0.09 m-rad and ±3%, respectively, or 1.5 times greater than the cuts applied to the rays traced to the end of the linac. These two factors have offsetting effects on the beam transmission. Thus, the large intensity safety margins after the capture accelerator are almost fully preserved to the end of the booster linac.

Acknowledgments

We thank J. Clendenin, S. Ecklund, W. Nelson, K. Thompson, T. Umemoto, and M. Woodley for their valuable help. This work is supported by Department of Energy through contract DE-AC03-76SF00515.

References

[5]. S. Ecklund, "Positron target material tests", SLAC-CN-128, 1981. Note: the effective area for a Gaussian-shaped beam with a distribution width $\sigma$ is $2.7\sigma^2$, not $\pi\sigma^2$.
A SPECTRAL FUNCTION METHOD APPLIED TO THE
CALCULATION OF THE WAKE FUNCTION FOR THE NLCTA

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Abstract

The sum over damped modes, which provides the main contribution to the transverse wake of the DDS, is replaced by a Fourier-like integral of a spectral function over the propagation band of the manifolds. We present comparisons to previous calculations, assessment of appropriate domains of applicability, and applications to the SLAC structure with matched and mismatched manifold terminations.

1. Introduction

The recently completed prototype accelerating cavity for the NLCTA incorporates both damping and detuning (the DDS structure) of the higher order modes (HOM), with the objective of suppressing the transverse wakefield experienced by trailing bunches [1,2]. The current analysis of the structure is based upon an equivalent circuit model whose current form is described in [1]. We use the Bane-Gluckstern two band model [3], extended to include the damping manifold. The latter is represented by a rectangular TE\textsubscript{01} waveguide mode, periodically shunted with a series LC circuit, with the shunt capacitively coupled to the TE component of the two band model. Each section of the structure is described by nine circuit parameters defined and determined as described in [1] along with the beam coupling parameters (cell kick factors [3]). In the following sections we explain the spectral function method, and compare it to our previous methods. The spectral function method is then applied to compute the dependence of the wake function on the manifold terminations.

2. Review of the Fundamentals of the Wake Function Calculation

The TE and TM cell excitation amplitudes are related to the drive beam via the circuit equations. In matrix form and in the frequency domain this relation takes the form:

\[
\begin{pmatrix}
\hat{H} & \hat{H}_s \\
\hat{H}_s & H + GR^{-1}G
\end{pmatrix}
\begin{pmatrix}
\hat{a} \\
\hat{a}
\end{pmatrix}
- f^{-2}
\begin{pmatrix}
\hat{a} \\
\hat{a}
\end{pmatrix}
= f^{-2}
\begin{pmatrix}
B \\
0
\end{pmatrix}
\tag{1}
\]

where the quantities in the above expression are defined in [1]. The elements in the above 2 by 2 matrix are themselves N by N matrices, where N is the number of cells. \(\hat{H}\) and \(\hat{H}_s\) are tridiagonal matrices which describe the coupled chains of TM and TE resonant circuits, while \(H_s\) is the tridiagonal matrix with vanishing diagonal elements which describes the TE-TM coupling. \(R\), which describes the manifold, is also tridiagonal, while \(G\), which describes the coupling of the TE chain to the manifold, is diagonal. The diagonal elements of \(H\), \(G\), and \(R\) are frequency dependent. Corresponding to the above, each element of the column vectors are themselves N element vectors. To further compactify the notation we may also write Eq. (1) in 2N by 2N matrix form

\[
\vec{H}\vec{a} - f^{-2}\vec{a} = f^{-2}\vec{B}
\tag{2}
\]

The drive beam, represented by the N component vector \(\vec{B}\), couples only to the TM mode. We take it to be a point charge moving at velocity \(c\) and normalize it per unit charge per unit displacement. With this understanding it takes the form

\[
\vec{B}_s = \sqrt{(4\pi\varepsilon_0 / c)K_0^sL \exp[-(j2\pi f / c)n]}
\tag{3}
\]

where \(L\) is the periodicity length, \(K_0^s\) the Bane-Gluckstern kick factor evaluated at the synchronous mode and \(f_s\) the synchronous mode frequency, both evaluated for a uniform structure based upon the \(n^{th}\) cell [3]. The transverse wakefunction (ie wake potential per unit length) for a particle trailing a distance \(s\) behind a velocity \(c\) drive bunch (per unit drive bunch charge per unit drive bunch displacement) may be written

\[
W(s) = \int[Z(f - j\varepsilon)\exp((2\pi js / c)(f - j\varepsilon))]df
\tag{4}
\]

where \(\varepsilon\) is a positive infinitesimal quantity and the wake impedance \(Z\) is given by

\[
Z(f) = \pi^{-1}\sum_{n=0}^{N}\sqrt{K_0^sK_n^sL}f^s\exp((2\pi jL / c)f(f - n - m))\vec{H}_{mn}
\tag{5}
\]

with the 2N by 2N matrix \(\vec{H}\) given by

\[
\vec{H} = \vec{H}(1 - f^{-2}\vec{H})^{-1}
\tag{6}
\]

From causality \(Z(f)\) can be analytically extended to the LHP, and singularities on the real axis are avoided in Eq. (4) by integration over \(f\) just below the real axis as indicated in Eq. (4). Because \(W\) is real, we also have \(Z(f) = Z^*(f^*)\), for \(f\) in the LHP. Because \(Z\) is real for sufficiently low frequencies on the real axis, \(Z^*(f^*)\) provides an analytic extension of \(Z\) into the UHP. Since the \(Z\) so defined is discontinuous across the real axis where \(Z\) is complex, cuts are introduced there to
render Z single valued on what we call the "physical sheet" of its Riemann surface. It also satisfies \( Z(f) = Z(-f) \), that is, it is an even function of \( f \) in the complex plane. We note that \( Z \) is actually a four valued function arising from the sign ambiguity in \( \sin \delta \) and \( \sin \delta_{\text{r}} \), quantities which appear in \( R_{\text{r}} \) and \( R_{\text{m}} \) respectively [1]. (The \( \cos \delta \), defined by Eq. (4) of [1] are single valued analytic functions, but the corresponding sines are defined only by the trigonometric identity, \( \sin^2 \cos^2 = 1 \).) Damped modes appear as complex poles on sheets of the Riemann surface adjacent to the physical sheet.

3. The Spectral Function Method for Computing the Wake Function

Because the equivalent circuit wake function contains a small non-physical precursor on the [-NL,0] interval [3], it proves to be convenient to define a "causal" wake function by

\[
W_c(s) = \theta(s)[W(s) - W(-s)]
\]

(7)

\( W_c \) equals \( W \) for \( s > NL \) and vanishes for negative \( s \). In the interval \([0,NL]\) \( W(-s) \) would be zero in the absence of a precursor. Hence Eq. (7) represents a smooth way of suppressing the precursor, and \( W_c \) is more likely to portray the actual structure than the strict equivalent circuit model. From Eq. (4) and the symmetry properties of \( Z \) noted in the previous section we have

\[
W(-s) = \int \frac{Z(f + j\varepsilon)\exp([2\pi j s / c](f + j\varepsilon)) df}{f - f_0}
\]

(8)

which leads to

\[
W(s) - W(-s) = 2j\int \text{Im}[Z(f + j\varepsilon)]\exp([2\pi j s / c]f) df
\]

\[
= 4\int \text{Im}[Z(f + j\varepsilon)]\sin([2\pi j s / c]f) df
\]

(9)

(10)

To include the contribution of poles on the real axis (with real residue) in Eqs. (9) and (10) we interpret

\[
\text{Im}((f + j\varepsilon - f_0)^{-1}) = \mp\pi\delta(f - f_0)
\]

(11)

and define \( 4\text{Im}[Z(f + j\varepsilon)] \) as the spectral function \( S(f) \) of the wake function. Thus we have

\[
W_c(s) = \theta(s)\int_0^\infty S(f)\sin([2\pi j s / c]f) df
\]

(12)

We note further that the usually displayed wake envelope function \( \hat{W}(s) \) associated with \( W_c \) is given by

\[
W_c(s) = \theta(s)\int_0^\infty S(f)\exp([2\pi j s / c]f) df
\]

(13)

For the undamped case, which in the context of the NLCTA design is obtained by setting the coupling matrix \( G \) to zero, \( Z \) is real on the real axis and contains a set of poles on the real axis at the modal frequencies. The spectral function is then simply a sum of delta functions:

\[
S(f) = 2\sum_p K_p\delta(f - f_p) = 2K_n \delta n / df
\]

(14)

where the \( f_p \) are the modal frequencies, \( n(f) \) is the number of modes with frequency less than \( f \), and the \( K_p \) are called modal kick factors. The spectral function and the modal sum methods are thus formally identical. In the presence of damping, \( Z \) is complex on those portions of the real axis which lie in the propagation bands of the manifolds, and poles which would lie on that portion of the real axis in the absence of coupling to the manifold split into complex conjugate pairs on the non-physical sheets accessed by analytic continuation through the cuts. When the coupling is weak so that their position can be found by perturbation theory, their distance from the real axis is small compared to their separation, and the spectral function has sharp peaks in place of the delta functions of the undamped case. As the coupling strength increases these poles move further from the real axis, the peaks broaden, and while the peaks generally remain quite discernable, the behaviour is relatively smooth. The spectral function can be computed as a function of frequency by direct evaluation of Eq. (5). A combination of an \( N \) by \( N \) matrix inversion and the solution of a \( 2N \) system of linear equations is involved. In the weak coupling case it is relatively simple to determine the modal frequencies, eigenvectors and \( Q \) values and hence to compute the damped modal sum. In contrast a large number of frequency points is required to adequately delineate the narrow peaked spectral function. The situation is reversed in the strong coupling case. The process of determining the modes has proved to be quite difficult and computer time consuming [1], while on the other hand the number of frequency points required to adequately describe the more smoothly varying spectral function becomes more reasonable. The wake functions computed from the modal expansion and from the spectral function have been compared for the single example of the former which has been carried out and found to be in excellent agreement [4].

4. Applications of the Spectral Function Method

![Fig 1: Spectral Function and integral for Matched HOM Coupler and 2Kδn/df (Shown Dashed)](image)
The spectral function method has so far been employed principally to explore the effect of manifold mismatch on the DDS wake function. We begin with the spectral function for the matched manifold case, shown in Fig. 1. We have shown the smoothed spectral function, $2K_\delta n/\delta f$, for the undamped case (ie the G set equal to zero case) on the same curve. (The unsmoothed spectral function, $2K_\delta n/\delta f$, is a sum of delta functions as noted before.) One sees that the effect of the damping is to replace the delta functions by broadened peaks which produce an oscillation about the smoothed undamped spectral function. The wake envelope function for the matched DDS structure and, for comparison, the corresponding function for the NLCTA DT structure are shown in [5]. There the recoherence peak of the DT is seen to be strongly suppressed by the damping.

![Figure 2: Spectral Function For Fabricated DDS and its Integral](image)

A series of investigations demonstrated that the wake function was seriously degraded by small mismatches of the manifolds, especially on the output (hence downtapered) side. Accordingly a major effort was made to design mitered bend type structures to match the manifolds to standard waveguide (WR62 was used). The results achieved for both the input and output side are given in [4]. In order to test the structure in the ASSET experiment it is necessary to attach windows and loads. The available windows were unfortunately not well-matched in the 14 to 16 GHz band that is crucial to the damping. The window and manifold added in quadrature are also illustrated in [6]. The combined reflection coefficient for the output end of the manifold has a minimum of .09 at 15.05 GHz rising to .37 at 14.2 and .4 at 16. Ghz. At the input end the reflection coefficients are similar in the upper half of the frequency range but less than .09 for the lower half.

The effect of these reflections on the spectral function and wake envelope function are shown in Figs. 2 and 3. As compared to the matched case the oscillations of the spectral function show a large increase in amplitude, indicating significantly higher $Q$s for many of the modes, and the wake envelope function is substantially degraded. However, even with the degradation shown in Fig. 3, the results constitute a considerable improvement over the DT structure. Preliminary ASSET experimental results have already been obtained [7], and the experimental points have been superposed on the Fig. 3 curve. Matched windows over the required band are in preparation, and simulations already performed [4] indicate a two-fold improvement in the wake function over that of the present structure.

5. Conclusion

The DDS described here was designed with rather crude theoretical tools [2]. However, the well-founded theoretical analysis given here and in [1] were carried out after the design was complete (but prior to fabrication). While the agreement between the preliminary experimental results and the theoretical predictions is imperfect, given the differences (some planned, some inadvertant) between the theoretical design and the structure as fabricated, the comparison suggests that the present version of the theory provides both the physical insight and the quantitative analysis needed to design an improved structure, and a number of such improvements are under consideration [4].

6. Acknowledgements

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7. References

MICROWAVE ANALYSIS OF
THE DAMPED DETUNED ACCELERATOR STRUCTURE*

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Abstract

We report the first studies of beam-induced microwave signals in the Damped Detuned Structure (DDS). The DDS is a 206 cell, nearly constant gradient structure, employing Gaussian detuning, and four symmetrically placed waveguide manifolds to damp the first-band dipole modes. We describe the manifold and output coupler design, bench measurements, and measurements with beam during the ASSET experiment. Dipole mode signals have been used to steer the beam to the structure center and minimize the wakefield kick.

The fundamental and dipole mode features of the DDS depicted in Fig. 1 have been described by Miller, et al. [1]. In this work we report on the manifold coupler design and bench-measurements, as well as measurements with beam. Our primary concerns are good coupling of the dipole modes through the manifolds, and the use of the microwave signals from the manifold for measurement of the beam position.

![Diagram](image)

Fig. 1: Coupling of the HOM waveguide manifolds to WR62 waveguide for diagnostic measurements.

HOM Manifold Coupler Design and Measurement

To characterize the manifold-coupled higher-order modes (HOM) eleven Brillouin curves were determined from MAFIA frequency domain simulations, for the three lowest dipole modes, of strictly periodic structures having the dimensions of eleven representative cells [2]. The accuracy of the simulation for 5 such cells was tested by fabricating a short stack consisting of five cells and two half cells of like dimension and measuring the frequency of the various modes. Off axis E-field probes inserted into the cell portion of the end half cell were used to excite and detect dipole modes, while loop-type H-field probes in the manifolds were used to excite and detect manifold modes. Stacks were fabricated for cells 10, 70, 106, 156, and 196, and the measured frequencies were found to agree well with the simulations. Measurements for cell 106 are compared to the computer simulations in Fig. 2.

![Graph](image)

Fig. 2: Theoretical and measured Brillouin curve for cell 106.

Of concern next was the design of an output assembly matched to the manifold over a broadband. This assembly was constrained to the space made available by the absence of manifold coupling to the first three and last three cells in the structure. The coupling of the 14.2 - 15.8 GHz dipole modes in the manifold depends on the local cutoff frequency of the manifold, which tapers slowly from 12.5 GHz at the upstream end to 14.0 GHz at the downstream end of the 1.8 m structure. We assumed that the taper in cutoff wavelength was sufficiently gradual that an assembly matched to a uniform structure with all cells identical would be adequate. The downstream assembly presented a significantly greater design challenge than the upstream assembly because of the proximity of the lower end of the frequency band to the manifold cutoff frequency (14.0 GHz). Both waveguide and coaxial coupling were considered for the upstream and downstream ends. Earlier cold tests performed on a uniform structure of eleven #106 cells indicated that waveguide coupling had the most promise to achieve bandwidth and reproducibility.

Two different output assembly designs were modeled on MAFIA and cold tested. Coupler & bend configurations were designed matching the manifold output to rectangular waveguides with cutoff frequencies of 12.5 and 13.3 GHz. The reflections of the two designs were similar, but the design using the 12.5 GHz cutoff waveguide was chosen because it is better suited to a small radius H bend.

An 11 cell stack of #203 cells with a coupler at each end was machined for cold test. MAFIA was used to design a coupler that was reasonably well matched at the middle and upper part of the band of interest. It was not possible to get a good match at the lower end. The coupler cold test pieces were made so that a series of cut and measure steps could be made...
starting with more metal than MAFIA predicted would be optimum.

Measurement of the coupler assembly reflection coefficient $\Gamma_C$ relies on the fact that the match of a single unknown lossless network can be determined by measuring the complex reflection coefficient of a pair of identical unknown networks back-to-back separated by a variable length of transmission line. Thus a pair of coupler/mitre bend networks designed using MAFIA were separated by 8, 9, 10 and 11 identical #202 cells. The rf complex reflection measurements are made using an HP 8510C network analyser (NWA) in WR62 waveguide and tapers to the rectangular waveguide used in the coupler/mitre network.

At a given frequency, the locus of points in the complex reflection plane will lie on a circle. There will be four points, one from each measurement. A fifth point, located at the origin would always exist if the electrical spacing were such as to provide exact cancellation and thus a perfect match for this tandem configuration. The diameter of the resulting circle is the maximum possible reflection coefficient of the back-to-back networks. The magnitude of the reflection coefficient $\Gamma_C$ of one coupler network (by itself as though terminated by the waveguide manifold matched in its own impedance) is related to the circle diameter D by

$$|\Gamma_C| = \sqrt{\frac{1-\sqrt{1-D^2}}{1+\sqrt{1-D^2}}}.$$  \hspace{1cm} (1)

It is not necessary to plot a circle for each frequency of interest. In theory, three points define the circle, its diameter, and ultimately the individual coupler $\Gamma_C$. Thus two reflection measurements (each with a different number of cells separating the two couplers) together with the assumed match condition will determine D according to

$$D = \sqrt{|\Gamma_2|^2 + |\Gamma_1|^2 - 2|\Gamma_2||\Gamma_1| \cos(\phi_2 - \phi_1)} \frac{\sin(\phi_2 - \phi_1)}{|\Gamma_1|}$$ \hspace{1cm} (2)

where $\Gamma_{n1}$ and $\phi_n$ are the respective magnitude and phase angles for the nth reflection measurement. The NWA data are read into a computer where D and $\Gamma_C$ can be calculated for all frequency points from equations (1) and (2). The accuracy is reduced when the phase angle between the two vectors is less than 40° or greater than 120°. The optimum is 60°.

The completed DDS with windows mounted was made available for time-limited NWA cold test measurements. With the fundamental-mode coupler-cell waveguides shorted, the structure may be regarded as an eight port network, and the complete S matrix with its 36 independent complex matrix elements can in principal be determined from network analyzer measurements. For a structure actually possessing the nominal symmetry, the number of independent elements reduces to nine, three of which relate to the dipole components and hence directly to the equivalent circuit. A set of measurements sufficient to determine one of the two dipole components was carried out, but the reduction of the data has not yet been completed. It is however clear even at this stage that detailed comparison with the equivalent circuit will require the introduction of resistive losses in the model.

Fig. 3 Reflection coefficient $\Gamma_C$ of the manifold output assemblies looking from the manifold into the mitre bend and the vacuum window, as inferred from bench measurements.

**HOM Spectrum and Beam Position Measurement**

Next, the prototype structure was installed on the Stanford Linear Collider beam-line, as part of the ASSET (Accelerator Structure Setup) experiment [3], at girder 2a of sector 2, a location where electron and positron bunches are available, at an energy of 1.2 GeV, bunch charge of 1-5 nC, and variable orbit and bunch separation. The DDS output assemblies described above (ending in a vacuum window) were followed by WR62 terminated in a WR62 load with a 20dB (nominal) cross-guide coupler. In addition the fundamental mode input couplers were joined symmetrically via WR90 to a TEE, and tapered to WR62 followed by a 10dB side coupler and a WR62 load. The fundamental mode output ports were terminated in loads, with a 20dB cross-guide coupler on one load. Each of the ten output couplers fed a 17-meter length of 1/4” helical carrying the microwave signals out of the accelerator housing to an instrumentation bench in the klystron gallery.

Several circuits were available in different configurations for examining the microwave signals excited by the beam in the structure. For spectrum acquisition we employed an HP8560A 50GHz spectrum analyzer (SA) connected via HP1B extender to a VXI crate and thence to the SLC’s Solo Control Program (SCP). The SA acts as a receiver, using a two stage down-mixing scheme. In order to measure a spectrum the primary local oscillator frequency is swept continuously over the desired frequency range. We also operated the spectrum analyzer on a fixed frequency to analyze directly the down-mixed signal after the first mixer stage. Together with a phase reference signal from a BPM this configuration allowed determination of amplitude and phase of selected individual dipole modes. For power detection over the full bandwidth we employed a crystal detector with acquisition to a 1 GHz VXI scope. An assortment of filters was on-hand to block out non-dipole bands, including a WR75 19 GHz low-pass filter, and several WR51 waveguide high-pass filters.

Fig. 4 shows the dipole mode spectrum observed at one of the horizontal HOM output couplers for a 1 mm vertical beam offset. A detailed part of that spectrum around 15 GHz is shown in Fig. 5 together with the predicted spectrum. To employ this wakefield instrumentation to good effect we sought to locate the orbit of minimum wake-kick by steering the drive-bunch to a minimum of the induced 14-16 GHz microwave signals. We then checked the precision of this
alignment by measuring the size of the residual wakefield kick with the second bunch and inferring the remaining offset of the drive bunch from the kick. Since this could be done at close bunch distances, where the wakefield is very strong, residual offsets of μm size were observable.

The essential information of such a power scan is contained in the fit parameter $x_0(f, n)$, which is the offset of the structure as a function of cell number with respect to the nominal beam orbit. In Fig. 6 minimum power positions obtained by this method are compared to data from mechanical measurements on a coordinate measuring machine.

The second alignment technique was simple, allowing fast beam steering, but less precise. The dipole mode signal is high-pass filtered to avoid contributions from the fundamental mode or low frequency noise and fed into a crystal detector. The resulting signal is roughly proportional to the averaged quadratic offsets of the beam in the individual cells. For an ideally straight structure the trajectory yielding a minimum of the crystal detector signal should also result in a minimal wakefield kick. For a structure with internal misalignments, however, the answer will be different since the effective wakefield kick is proportional to the averaged linear beam offset.

Finally the most precise alignment method uses amplitude and phase detection of two different modes, where one was chosen at the upstream end and one at the downstream end of the structure. In this method, the spectrum analyzer was switched quickly back and forth between two fixed frequencies. When the beam passes the centre of the structure transversally the phase of the dipole mode signal flips by 180°. Since this phase switch occurs rather rapidly as a function of beam position the phase measurement provides a more precise position measurement than the mode amplitude. A detailed analysis of the residual wakefield kicks is in preparation and will be published in the near future.

Work supported by DOE DE-FG03-93ER40759 and DE-AC03-76SF00515.

References

[1] R.H. Miller et al., A Damped Detuned Structure for the Next Linear Collider (paper THPO2, these proceedings)
HIGH GRADIENT EXPERIMENTS ON NLCTA ACCELERATOR STRUCTURES

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Abstract

This paper presents new results of high-gradient studies performed on a 1.8 m traveling-wave section with detuned high-order deflecting modes. This structure was designed initially for studies of detuned structures and will be installed in the Next Linear Collider Test Accelerator (NLCTA). The paper describes the test set-up in the Accelerator Structure Test Area (ASTA) including electron gun, pre-buncher, pre-accelerator, spectrometer, Faraday cups, 200 MW SLED-II power compression system, Magic-T type phase shifters and attenuators. Rf processing, detailed dark current analysis, radiation problems, and beam acceleration measurements are discussed.

Experimental Setup and Accelerator Section

The Accelerator Structure Test Area (ASTA), where all tests were performed, has been described in a previous paper [1]. Figure 1 shows the layout of the setup for the high power test of the 1.8 m traveling-wave section. The accelerating mode of this detuned structure has a uniform phase velocity equal to the speed of light [2]. The electrons from an 80 kV thermionic gun are bunched and pre-accelerated in order to be captured in the accelerator section. Both pre-buncher and pre-accelerator use single cavities with nose-cones, in order to reduce the transient beam loading effect. The cavities are made of stainless steel to lower their Q value. The rf power for the pre-buncher and pre-accelerator is obtained via directional couplers from the feed waveguide for the accelerator section. Each feed includes a Magic-T type attenuator/phase shifter to adjust rf amplitude and phase. Two main arms are assigned to be input and output ports, and two side-arms are shorted without non-contacting plungers driven by stepping motors. Moving the shorts respectively toward the T-junction and away from it changes the phase at a constant amplitude, whereas moving the shorts synchronously in the same direction changes the amplitude at a constant phase.

Several scintillator detectors are installed alongside the accelerator structure for X-ray measurements. The detector heads are made from NaI crystals (0.38 in. in diameter x 1.0 in. in length) with lead collimation. The photons created by the X-rays are transmitted through a 3-5 ft. optical fiber to a Hamamatsu HC125 PMT based-detector, which includes a divider, high voltage power supply and signal processing circuitry. The whole system is calibrated by using a standard radioactive source.

The 1.8 m detuned structure is the first model for the NLC Test Accelerator at SLAC. It has 204 cavities plus input and output couplers. Its characteristics and main rf parameters are shown in the table.

<table>
<thead>
<tr>
<th>Section length</th>
<th>1.8 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase advance per cell</td>
<td>$2\pi/3$</td>
</tr>
<tr>
<td>Iris aperture diameter</td>
<td>1.134–0.786 cm</td>
</tr>
<tr>
<td>Cavity diameter</td>
<td>2.228–2.059 cm</td>
</tr>
<tr>
<td>Disk thickness</td>
<td>0.1–0.2 cm</td>
</tr>
<tr>
<td>Group velocity</td>
<td>0.12c–0.03c</td>
</tr>
<tr>
<td>Filling time</td>
<td>100 ns</td>
</tr>
<tr>
<td>Time constant</td>
<td>205–177 ns</td>
</tr>
<tr>
<td>Attenuation parameter</td>
<td>0.498 nepers</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>66.48–83.40 MΩ/m</td>
</tr>
<tr>
<td>Factor of merit, Q</td>
<td>7416–6674</td>
</tr>
<tr>
<td>Peak power for 50 MV/m</td>
<td>86.5 MW</td>
</tr>
<tr>
<td>RF pulse length</td>
<td>150 ns</td>
</tr>
<tr>
<td>Peak input power</td>
<td>150 MW</td>
</tr>
<tr>
<td>Maximum $E_{acc}$</td>
<td>80 MV/m</td>
</tr>
<tr>
<td>Average $E_{acc}$</td>
<td>67 MV/m</td>
</tr>
<tr>
<td>Maximum surface $E_s$</td>
<td>159 MV/m</td>
</tr>
<tr>
<td>$E_s/E_{acc}$</td>
<td>2.37</td>
</tr>
</tbody>
</table>

Experimental Results

RF processing was performed in two stages. The first stage took place in March of 1994, over a period of 30 hours in a two-day period, to reach an average accelerating gradient of 50 MV/m. The second stage took place in June of 1995 after the installation of a 50 MW peak power klystron. The improved SLED-II system was able to produce 200 MW, 150 ns rf pulses. The maximum power delivered to the accelerator structure was 150 MW, and the maximum accelerating gradient was limited by the klystron output power. Figure 2 shows the straight-ahead dark current as a function of accelerating gradient. Significantly higher power is needed to further reduce this dark current [3]. The dark current spectrum obtained so far was measured using the 45° spectrometer. In order to obtain more information on the origin of the captured dark current, two dipole magnets were installed alongside the accelerator section at a given z-position. They can create about 600 Gauss of transverse magnetic field in "x" and "y" to prevent any dark current originating upstream from reaching the spectrometer. Hence, each curve in Fig. 3 is a spectrum of the dark current transmitted and collected from that part of the accelerator section downstream of the magnets. Figure 4
Figure 1: Layout of Accelerator Structure Test Area.

Figure 2: Peak dark current measured by a straight-ahead Faraday cup as a function of average accelerating gradient for two stages of rf processing.

shows the total dark current collected at the straight-ahead Faraday cup as a function of the magnets position. From these plots we can conclude that most of the dark current is composed of low energy electrons. The total number of electrons captured at the end of the accelerator section no longer increases when the magnets are located upstream of cavity No. 90. This is probably because when the field emitted electrons are accelerated or decelerated by the rf fields, a majority of them strike the cavity walls. Secondary or back-scattered electrons are then created, which are also accompanied by X-ray radiation. During rf processing, the outputs of the scintillator-PMT system give strong bursts if there is sparking at nearby cells. Figure 5 gives the waveforms of four X-ray detectors at two different rf power levels. In the test, scintillators 1, 2, 3, and 4 are located respectively at the input region, one third, two third, and the output region of the accelerator section. Figure 6 shows the radiation dosage as a function of the position along the accelerator section at two different gradients.

Figure 3: Energy spectrum of dark current at average accelerating gradient of 58 MV/m for different positions of the dipole magnets.

A beam test was performed at an average accelerating gradient of 50 MV/m. The rf pulse length was 150 ns for the SLED-II system and the filling time of the structure was 100 ns. Because of radiation safety limitations, a pulsed beam of only 40 mA, 30 nsec was used. The maximum rf power available to the pre-accelerator was lower than expected because of the rf loss in the wave-guide system. The operating frequency was adjusted slightly higher to allow the captured electrons to drift in phase toward the rf peak in order to increase the net acceleration. The electron energy gain showed that for the particles on the rf peak, the average accelerating gradient for an input power of 90 MW reached 50 MV/m.

Work supported by the Department of Energy, contract DE-AC3-76SF00515.
Figure 4: Total dark current collected at the straight-ahead Faraday cup as a function of the position of the dipole magnets.

Figure 5: Waveforms for four X-Ray detectors at two different average accelerating gradients: (a) 50 MV/m, (b) 60 MV/m.

Figure 6: Radiation dosage along the accelerator section at two different average gradients.

References


A New Energy Recovering DeQing for Line-Type Pulse Modulators

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117312 Moscow, Russia

Abstract

In a typical line-type modulator the amplitude of the pulse forming network (PFN) voltage is controlled by a deQing circuit (resistor or resistor and capacitor in parallel, and SCR), connected to the secondary of the charging choke. The energy stored in the charging choke at the moment of deQing is usually dissipated in the deQing resistor. For the SLAC modulator, for instance, the typical value of average power dissipated in this resistor is 5-10 kW. At the moment there is only the SLAC energy recovering deQing system, which is based on accumulation of the deQing energy into a capacitor bank, from where it is then transferred by inverter to the main ac line.

This paper describes a new simple energy recovering deQing system. Other than the SLAC deQing system, the energy accumulated in the storage capacitor bank during a current PFN charging cycle is being transferred directly into the PFN capacitors, before the following charging cycle is started. The preliminary low-voltage model investigation shows that this scheme, besides reduction of the power consumption and elimination of the powerful deQing resistor along with its cooling system, allows to increase the level of deQing and insures a stable modulator output voltage over a wide range of the main ac voltage.

Introduction

A typical line-type pulse modulator consists of a pulse forming network (PFN), which is resonantly charged from a dc power supply through a charging choke, and discharging into a load using a thyatron or SCR as a switching element. The amplitude of the PFN voltage is controlled by a deQing circuit (resistor or resistor and capacitor in parallel, and SCR), connected to the secondary of the charging choke [1, 2]. The energy stored in the charging choke at the moment of deQing is usually dissipated in the deQing resistor. For the SLAC modulators [3] the typical value of average power dissipated in this resistor is 5-10 kW, for level of deQing 5-10 %, correspondingly. At the moment there is only the SLAC energy recovering deQing system, which is based on accumulation of the deQing energy into a capacitor bank, from where it is then transferred by inverter to the main ac line [3].

A new simple energy recovering deQing scheme has been proposed during the design of a line-type pulse modulator for the S-Band Test Facility at DESY [4]. Other than the SLAC energy recovery deQing system, the energy accumulated in the storage capacitor bank during a current PFN charging cycle is being transferred directly into the PFN capacitors, before the following charging cycle is started.

Principle of operation

A simplified schematic of the line-type pulse modulator with energy recovering deQing circuits is shown in Fig. 1.

Fig. 1 A simplified schematic of the line-type modulator with energy recovering deQing circuit

The traditional portion of the scheme consists of the dc power supply, charging choke with deQing switch SCR3, storage capacitor C_s and resistor R, main charging diode D1, pulse forming network PFN and main switch (thyatron or SCR). The recovery components of the scheme are charging switch SCR1, recovery switch SCR2 and recovery charging diode D2. When the switch S1 is closed, the resistor R is connected in parallel to the storage capacitor C_s and the scheme works in the usual dissipative mode. In this case SCR1, SCR2 and D2 can be excluded from the scheme. The idea of energy recovering deQing is to transfer the energy that has been stored in the capacitor C_s during the deQing process of the current charging cycle directly to the PFN capacitors, before the following main charging cycle starts.

Fig. 2 represents the waveforms along with the sequence of triggering pulses Tr1-Tr4 when the scheme runs at the energy recovering deQing mode. The main charging cycle begins at the moment t=t_s, when the charging switch SCR1 is fired. When PFN voltage reaches a predetermined level \( U_{PFN}\), the deQing switch SCR3 will automatically be fired thus providing the PFN voltage regulation. At the moment of deQing t=t_q, the energy accumulated in the charging choke will start to flow into the storage capacitor bank C_s. The deQing energy accumulation will be finished at t=t_s.

The deQing energy recovery cycle can be made at any moment within the time interval t1-t_s, after discharging the PFN to a load but before starting the following main charging cycle. The recovery cycle is started at t=t_s, when the recovery switch SCR2 is fired. During the recovery
process the energy accumulated in $C_a$ will be flowing into the PFN capacitors, finally charging them to the voltage $U_0$.

\[ I_0 = I_{PFN}(t_s) \]

where $I_0 = I_{PFN}(t_s)$ is the PFN capacitors charging current at the moment of deQing. For further calculations, it is convenient to write the operating level of regulated PFN voltage as

\[ U_{PFN_{reg}} = 2U_{DC} \alpha \]

where $U_{DC}$ is the output voltage of the dc power supply, and $\alpha$ is a parameter characterizing the level of deQing. Then the main parameters of the scheme can be expressed as presented below in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dissipative mode</th>
<th>Recovery mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{eff}$</td>
<td>$U_{DC}$</td>
<td>$U_{DC} - U_0$</td>
</tr>
<tr>
<td>$I_{max}$</td>
<td>$U_{DC}/\rho$</td>
<td>$2U_{DC}(1-2\alpha)(1-\alpha)$/$\rho$</td>
</tr>
<tr>
<td>$I_0$</td>
<td>$2U_{DC}\sqrt{\alpha(1-\alpha)}$/$\rho$</td>
<td>$2U_{DC}\alpha(1-\alpha)$/$\rho$</td>
</tr>
<tr>
<td>$\sin \alpha_s$</td>
<td>$2\sqrt{\alpha(1-\alpha)}$</td>
<td>$2\alpha(1-\alpha)$/$\rho$</td>
</tr>
<tr>
<td>$U_0$</td>
<td>0</td>
<td>$2U_{DC}\alpha(1-\alpha)$/$\rho$</td>
</tr>
<tr>
<td>$I_{av}$</td>
<td>$2U_{DC}C_{PFN}PRR\alpha$ or $U_{PFN_{reg}}C_{PFN}^{PRR}$</td>
<td>$2U_{DC}C_{PFN}^2\alpha^2$ or $U_{PFN_{reg}}^2C_{PFN}^{PRR}$</td>
</tr>
<tr>
<td>$W_{Lp}(t_s)$</td>
<td>$2U_{DC}^2C_{PFN}\alpha(1-\alpha)$/$\rho$</td>
<td>$\frac{1}{2}U_{DC}^2C_{PFN}\sin^2 \alpha_s$</td>
</tr>
</tbody>
</table>

$U_{eff}$: effective charging voltage

$I_{max}$: maximum PFN charging current

$I_0$: PFN capacitors current at the moment of deQing

$t_s$: moment of deQing

$U_0$: PFN capacitors recovery voltage

$I_{av}$: average current from dc power supply

$W_{Lp}(t_s)$: deQing energy (stored in the charging choke at $t_s$)

The maximum relative amount of energy which can be saved at 100% recovery efficiency, is equal to

\[ \gamma = \frac{W_{Lp}(t_s)}{PWR_{av}U_{DC}} = 1 - \alpha \]

where the numerator represents the deQing energy for dissipative mode, and the denominator equals to the amount of energy taken from the dc power supply over the entire charging period. An equivalent circuit describing the scheme during the processes of deQing and recovery (time intervals $t_5-t_4$ and $t_2-t_5$, correspondingly) is not finally clear up to now,

\[ U_0 = I_0\rho \]
so it was decided to build an experimental model of the scheme for investigation the idea of energy recovering deQing.

**Experimental model**

The Low Voltage Modulator Model (LVMM) parameters listed below

- Maximum dc voltage : 300 V
- Charging choke step-down ratio : 20 : 1
- Primary inductance : 10 H
- Secondary inductance : 25 mH
- Total PFN capacitance : 1.2 μF
- Storage capacitor bank : 300 μF

The LVMM total capacitance was chosen to obtain a characteristic charging impedance close to the one of real modulator. It provides an easy scaling of current flowing through the charging choke primary. LVMM has all the necessary electronics for firing the SCR switches as well as voltage dividers and current sensors for the most important signals.

**Experimental results**

Typical experimental pictures of the scheme's waveforms for dissipative and recovery modes are presented in Fig. 3a and 3b. Both pictures were made at $U_{DC} = 275$ V and constant level of PFN regulated voltage, $U_{PFNreg}$.

The value of $\alpha$ can be defined by comparing the amplitude of the modulator output pulse with and without deQing and by measuring time interval $t_3$-$t_4$ (see Fig. 2) and then calculating $\alpha$ using the formulas for $\sin(t)$ given in Table 1. For both pictures the values of $\alpha$ defined by these methods were found to be 0.91 for the amplitude method and 0.90 for the time interval one. An efficiency of the energy recovering deQing can be found by comparing the average currents taken from the dc power supply in the dissipative mode $I_{av,d}$ and recovery mode $I_{av,r}$, as

$$\varepsilon = \frac{I_{av,r} - I_{av,d}}{\eta_{av,d}}$$  \hfill (6)

The experimentally measured values of efficiency were between 0.86 and 0.91, depending on $\alpha$. For the real modulator a higher efficiency can be expected, due to the lower relative level of losses in switching devices.

**Conclusion**

The preliminary low-voltage investigation of the energy recovering deQing scheme shows that this scheme can be applied for any line-type pulse modulator with minimum additional expenses and efforts. Besides a reduction of the power consumption and elimination of the powerful deQing resistor along with it's air cooling system, it allows to increase the level of deQing and insures stable modulator output pulse over a wide range of the main ac voltage.

**Acknowledgment**

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**References**


A HIGH INTENSITY PROTON LINAC DEVELOPMENT FOR NEUTRON SCIENCE RESEARCH PROGRAM

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***Mitsubishi Heavy Industries Ltd., Oye-cho, Minato-ku, Nagoya, Japan

Abstract

The high-intensity proton linac with a beam energy of 1.5 GeV and a maximum current of 10 mA has been proposed for the Neutron Science Research Program (NSRP) in JAERI. The NSRP is aiming at exploring new basic researches and nuclear waste transmutation technology based on spallation neutron. The R&D work has been carried out for the components of a low energy part of the proton accelerator and conceptual design study on superconducting accelerating cavity as a main option for a high energy part (high β linac) above 100 MeV.

The proposed plan for accelerator design and construction will be composed of two consecutive stages. The first stage will be completed in about 7 years with the beam current of 1 mA. As the second stage, gradual upgrading of the beam current will be made up to the final maximum value of 10 mA.

Introduction

In 1980's, research activities have been made for high intensity proton linacs to be applied to the nuclear fuel breeding and high level radioactive waste transmutation. After the OMEGA (the partitioning and transmutation research) program was proposed by the Japan Atomic Energy Agency, JAERI started the work to study an accelerator-driven transmutation system of minor actinides. In addition to the development of the OMEGA program, new basic neutron researches on material science, neutron irradiation, neutron physics and many other potential applications for applying the intense linac have been also discussed. Those include meson/muon production and spallation RI beam (mainly for nuclear physics studies) and radio isotope production.

JAERI had originally planned to build the pulsed linac with an energy of 1.5 GeV and a peak current of 100 mA with 10% duty factor[1]. The design study has been intended to apply the accelerator to the engineering test for the transmutation system and obtain the technical validity to accelerate high peak current from the beam dynamics point of view. In this accelerator development, the R&D work has been continued on high brightness ion source, radio frequency quadrupole linac (RFQ), drift tube linac (DTL) and RF source, as well as the conceptual design of the whole accelerator components. In the beam test, the current of 70 mA with a duty factor of 10% has been accelerated from the RFQ at the energy of 2 MeV. A hot test model of the DTL for the high power operation with high duty factor was fabricated and tested[2]. The conceptual layout of the NSRP-LINAC is shown in Fig. 1.

High Intensity Linac Development

General Concept

Recently, JAERI has modified the original plan by proposing an option of superconducting (SC) linac to meet

![Diagram of the accelerator layout](image)

**Fig. 1 A conceptual Layout of the Accelerator for the Neutron Science Research Program**
requirements for a variety of basic researches mentioned above and an ultimate goal for waste transmutation. This SC linac will be operated in pulse as a first stage for the spallation neutron source and gradually upgraded toward CW by increasing duty factor. The SC linacs have several favorable characteristics as follows: the length of the linac can be reduced, which can meet the rather stringent requirement from the limited area of our laboratory site, and high duty operation can be made for simultaneous experiments. The possibility to inexpensive operation cost may be found in comparison with normal conducting (NC) option.

A preliminary specification for the NSRP LINAC is given in Table 1. The final value of the energy/current, accelerating frequency and pulse time structure etc. will be determined from further discussions based on the user requirement and the cost estimate. In particular, because the relationship between the energy and the current is complimentary, the reduction of the energy value can be compensated by increasing the beam current. Neutron scattering facility will require more strict pulse time structure. The beam chopping capability with about 400ns intermediate pulse length will be needed to compress the beam width by the storage ring. Three major R&D items are presently carried out. 1) the beam dynamic calculation including the high β linac. 2) the development of the negative ion source[3] and the fabrication of high power test models for CW-RFQ and CW-DTL. 3) the SC cavity development with the KEK electron SC group[4].

<table>
<thead>
<tr>
<th>Energy</th>
<th>1.5GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerated particle</td>
<td>Negative and positive hydrogen ion</td>
</tr>
<tr>
<td>Average current:</td>
<td>First stage: 1mA</td>
</tr>
<tr>
<td>Low energy part</td>
<td>Second stage: Maximum 10mA</td>
</tr>
<tr>
<td>High energy part</td>
<td>Normal-conducting linac: 200MHz</td>
</tr>
<tr>
<td>Pulse structure</td>
<td>Super-conducting linac: 600MHz</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>First stage: Pulse mode operation</td>
</tr>
<tr>
<td>Macropulse width</td>
<td>Second stage: CW/pulse mode operation</td>
</tr>
<tr>
<td>Intermediate pulse width</td>
<td>maximum 50Hz</td>
</tr>
<tr>
<td>Chopping factor: Peak current</td>
<td>2ns (at1mA operation) -&gt; maximum CW 400ns (interval 270ns)</td>
</tr>
<tr>
<td></td>
<td>60%: nominal 17mA</td>
</tr>
</tbody>
</table>

### Low Energy Accelerator Part

In the case of a high intensity accelerator, it is particularly important to maintain the good beam quality (low emittance; small beam size and divergence) and minimize beam losses to avoid damage and activation of the accelerator structures. The R&D work for the low energy portions has been made as a first step in the NSRP-LINAC development. Table 2.1 gives the preliminary specification of negative ion source which will be necessary for the injection into the storage ring.

Table 2.1 Preliminary Specification of Negative Ion Source

<table>
<thead>
<tr>
<th>Accelerated particle</th>
<th>H^-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>70keV</td>
</tr>
<tr>
<td>Current</td>
<td>30mA</td>
</tr>
<tr>
<td>Emittance(rms)</td>
<td>0.2mm.mrad</td>
</tr>
<tr>
<td>Type</td>
<td>Single /multi-aperture</td>
</tr>
<tr>
<td></td>
<td>Volume type</td>
</tr>
</tbody>
</table>

Because the superconducting accelerator has been selected for the high β linac, the low energy part should be capable for the CW mode operation. The design study has been started to develop the CW-RFQ (at 200MHz) cavity in the range of 20~30mA. From the experience of the pulse RFQ operation, the maximum electric field will be reduced to be 1.43 Ek (Kilpatrick Limit) compared to the previous value of 1.63Ek. The calculated transmission for the CW-RFQ is 97% for 20mA and more than 90% expected for the wider range of 0-60mA. Because the most important problem for the R&D-RFQ was the RF contact between vane and tank, the CW-RFQ will be made as integrated type by brazing without any RF contact between vane and tank. In 1996, the high power test model of the CW-RFQ of 50 cm in length is fabricated and tested in order to establish the manufacturing and assembling techniques. Table 2.2 gives the preliminary specification of the CW-RFQ.

<table>
<thead>
<tr>
<th>Energy</th>
<th>70keV - 2MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>nominal 17mA</td>
</tr>
<tr>
<td>Frequency</td>
<td>200MHz</td>
</tr>
<tr>
<td>Vane voltage</td>
<td>88kV</td>
</tr>
<tr>
<td>Length</td>
<td>3228mm</td>
</tr>
<tr>
<td>Number of cells</td>
<td>185</td>
</tr>
<tr>
<td>Bore radius</td>
<td>5.93mm</td>
</tr>
<tr>
<td>Synchronize phase</td>
<td>-30°</td>
</tr>
<tr>
<td>Total power</td>
<td>280kW(60%)</td>
</tr>
</tbody>
</table>

663
The parameters for the CW-DTL are also re-evaluated to match the CW operation for the new superconducting design concept. The frequency of the CW-DTL is chosen to be 200MHz. Accelerator gradient may be lowered to be 1.5MeV/m in order to reduce the RF consumption and the RF heating. The expected maximum magnetic field gradient for the focusing magnet is about 60.1T/m using the hollow conductor type Q-magnet. The end point energy for the DTL is 100MeV which will be determined from the beam dynamics and mechanical consideration of the high $\beta$ structure.

<table>
<thead>
<tr>
<th>Energy</th>
<th>2-100MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>nominal 17mA</td>
</tr>
<tr>
<td>Frequency</td>
<td>200MHz</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>1.5MV/m</td>
</tr>
<tr>
<td>Synchronize phase</td>
<td>-35° - -25°</td>
</tr>
<tr>
<td>Number of cells</td>
<td>239</td>
</tr>
<tr>
<td>Length</td>
<td>90.17m</td>
</tr>
<tr>
<td>Focus gradient</td>
<td>0.1T/m - 26.6T/m</td>
</tr>
<tr>
<td>Total wall loss</td>
<td>3.16MW (100%Q)</td>
</tr>
</tbody>
</table>

Table 2.3 Preliminary Specification of CW-DTL

### High Energy Accelerator Part

Superconducting cavity is selected as main candidate for high energy portion. In the CW electron accelerator, technologies of SC accelerators are established. Long design and operating experiences are accumulated and routinely used for the operation such as KEK-TRISTAN and other many accelerator laboratories. In the proton accelerators, however, the proton velocities $\beta$ gradually change from 0.43 to 0.92 corresponding to the energies for 100MeV and 1.5GeV. Accordingly, the length of the cavity also has change. Main concern is the strength of the cavity under the vacuum load for the low $\beta$ region. The mechanical structure calculations with the ABAQUS code have been made to determine the cavity shape parameters as well as electromagnetic ones with the SUPERFISH code[4].

In order to determine the layout of the SC accelerating structure, two typical cases of the SC linacs, which are composed of 4 different $\beta$ sections and 8 different $\beta$ sections, respectively, have been studied. The cavities in each $\beta$ section will be made identical with 4 cells and designed at the specific beam energy but also can be operated at slightly different beam energy with lower efficiency. The structure of the cryomodule, input/HOM couplers and tuning devices etc. are being designed based on the KEK-TRISTAN experiences. Using these parameters, preliminary calculation for the beam dynamics has been made with the modified PARMILA code. Preliminary data is given in Table. 3.

The test stand for a superconducting cavity development with the cryostat 80 cm dia. x 350 cm long and a clean room is under preparation and the first SC test cavity will be fabricated and tested within 1996.

<table>
<thead>
<tr>
<th>Case</th>
<th>4 sections $E_p=16MV/m$</th>
<th>8 sections $E_p=16MV/m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity configuration</td>
<td>4 cells</td>
<td>4 cells</td>
</tr>
<tr>
<td>Average synchronize phase</td>
<td>-30.1°</td>
<td>-29.4°</td>
</tr>
<tr>
<td>Accelerating length (m)</td>
<td>292</td>
<td>276</td>
</tr>
<tr>
<td>Total length (m)</td>
<td>769</td>
<td>719</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>408</td>
<td>378</td>
</tr>
<tr>
<td>Number of cells</td>
<td>1632</td>
<td>1512</td>
</tr>
<tr>
<td>Output emittance (50mA)</td>
<td>x:rcm.mrad (rms)</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>y:rcm.mrad (rms)</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>z:rad.deg,MeV (rms)</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>Total wall loss (kW)</td>
<td>23.3</td>
</tr>
</tbody>
</table>

### Summary

The R&D work for the prototype linac structures (ion source, RFQ, DTL and RF source) has been performed. The good performance of the components has been achieved.

Since 1995, the basic specification for the accelerator has been changed such as negative ion acceleration, SC cavity option and storage ring. The new design modification has been started. The test stand for the SC cavities is under preparation. For the injector of the SC cavities, continuous-beam or much longer duty operation will be required. The design work on the RFQ and DTL as well as SC cavities for the CW operation is being performed.

### Acknowledgment

The authors would like to thank Drs. S.Noguchi, K.Saito and E.Kako of KEK for discussion and help on the SC cavity development. They also thank Drs. T.Kato and Y.Yamazaki of KEK and Dr. R.A.Jameson of LANL for valuable suggestion about the beam dynamics calculations and accelerator system optimization. The PARMILA calculation carried out by Mr. Y.Honda of MHI is greatly appreciated.

### References

THE R&D STATUS ON THE FRONT END OF THE HIGH INTENSITY PROTON ACCELERATOR IN JAERI

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Abstract

The R&D for the high intensity and high duty factor proton linear accelerator has been carried out. A hydrogen ion source, an RFQ and an RF power source have been developed and 2 MeV proton beam tests have been conducted to study the front end of the accelerator. In the beam tests, an accelerated current of 70 mA with a duty factor of 7 - 10 % was achieved. To demonstrate the high duty factor operation of the DTL, a hot test model was fabricated and high power tests with a duty factor of 20 % have been carried out. In this report, present status of the R&D activities is described.

Introduction

A high intensity proton linear accelerator with 1.5 GeV and 10 mA has been proposed for basic research and to perform the various engineering tests for a nuclear waste transmutation system[1]. The low energy accelerator components have been developed since 1991 for the R&D, because the beam current and the quality are mainly determined by the low energy portion. Heat removal from the accelerator structures is one of the important issues for the high duty factor operation.

To study the front end of the accelerator, an ion source, an RFQ, and an RF source for 10 % duty factor operation were fabricated and 2 MeV beam tests have been performed. The characteristics of the RFQ such as beam current, energy spectra and emittance have been studied. To demonstrate the high duty factor operation and to study the cooling capabilities of the DTL, a hot model with 9 cells was fabricated and high power tests have been carried out.

Beam Test of the 2 MeV RFQ

The RFQ is a four-vane type and the frequency is 201.25 MHz. It is designed to accelerate 100 mA (peak) of protons to 2 MeV with a duty factor of 10 %[2]. The low power tuning, the high power conditioning and the first beam test were carried out at the test shop of the factory and the basic performance was obtained[3]. To study further properties, the beam tests have been made at JAERI since November, 1994.

A multicusp type ion source has been developed to obtain a high brightness proton beam. The ion source has been operated successfully with more than the designed current of 140 mA at 100 keV[4]. The proton beam from the ion source is focused by the two solenoids (solenoid-1 and -2) to match to the RFQ acceptance in the Low Energy Beam Transport (LEBT). The output beam current of the RFQ is measured by a Faraday cup. Figure 1 shows a contour plot of the RFQ output beam current with two solenoids currents. There are mainly two matching data sets; the lower set (I_{solen}=145A, I_{source}=200A) and the higher set (I_{solen}=275A, I_{source}=220A). The higher set has a sharp peak as a function of solenoid-2 current and is sensitive to the various conditions such as the ion source and the LEBT. The maximum RFQ output current was 80 mA at the ion source extraction current of 155 mA. The transmission rate through the RFQ was estimated to be 70 - 80 %, given the ion source proton fraction of 70 %. The precise proton fraction in the input beam, however, was not clear due to the mass separation effects of the solenoids. Moreover, we had meltdowns troubles with a Faraday cup just before the RFQ. To measure the input current and to evaluate the transmission rate, a current transformer system for 1 msec pulse width beam is now under test off-line and will be installed in the LEBT in a few months.

The energy of the proton beam from the RFQ was measured by a compact magnetic energy analyzer installed in the Medium Energy Beam Transport (MEBT). The pole radius, the gap length and the deflection angle are 40 mm, 6 mm and 25 deg, respectively. The energy resolution is assumed to be 5 % for 2 MeV proton beam. Figure 2 shows beam energy

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Fig. 1 Contour plot of the RFQ output beam current in mA as functions of the two solenoids currents in the LEBT.
spectra for five relative intervane voltages as well as the PARMTEQ simulated results. As the vane voltage is reduced, the energy spectrum shifts to the lower energy and many peaks are observed, which are in good agreement with the simulated results.

The RFQ emittance was measured by the conventional double-slit type monitor. The width of the front and rear slits and the distance between the slits were 0.4 mm, 0.1 mm and 380 mm, respectively. To prevent the meltdown of the front slit collimator, the repetition rate was limited to less than 2.3 Hz at 1 msec pulse width. Typical emittance diagram and the rms emittance as a function of the normalized vane voltage are shown in Fig. 3 and Fig. 4, respectively. The magnitude of the emittance has a minimum point at around $V_n = 1$, which corresponds to the designed vane voltage.

At the beginning of the beam test in JAERI, the maximum duty factor was limited less than 2% due to the partial burn out of the RF contact at the RFQ. A silver plated spiral type RF contact, which is made of beryllium copper alloy, was used between the tank and the vane. The diameter of the contact was 3.2 mm and the thickness of the base beryllium copper alloy and the silver plate were 100 μm and 30 μm, respectively. To improve the heat transfer properties, it was replaced by a 100 μm thickness silver-plated type. In addition to the contact replacement, copper blocks were installed to cover the open space between the vane and the tank to reduce the heat dissipation at the vane end region. As a result of these modifications, steady operations with 7% duty factor, and short-duration operation at 10% duty factor can be achieved at the beam current of 70 mA.

![Typical emittance diagram at 0.8 m downstream of the RFQ.](image)

![Normalized transverse rms emittance for the two matching cases (higher and lower) as a function of vane voltage.](image)

**Development of the 1 MW RF System**

A 201.25 MHz RF system was designed and manufactured for the RFQ beam tests and the DTL high power tests. A tetrode, 4CM2500KG (EIMAC), is used in a three-stage amplifier configuration[5].

Dummy load tests have been completed. An RF power output of 1 MW was achieved at a duty factor of 0.6%. The power efficiency was 60%, which is in good agreement with the designed value of 62%. At high duty operation of 12%, RF power of 830 kW was generated, which satisfied the requirement for the tests in the R&D.

The voltage and the phase stability during the beam acceleration should be controlled within +/-0.5% and +/-1 deg., respectively. To satisfy these specifications, the RF control system has a feedforward-circuit combined with a feedback-circuit. The performance of the feedback-circuit was examined in the RFQ beam tests. The amplitude and the phase errors were on the order of 0.5% and 5 deg., respectively, during 100 μs period after the beam injection when the beam loading was 110 kW. The feedforward-circuit will be examined to compensate these errors.
High Power Test of the DTL Model

A DTL hot test model with 9 cells, which is a mockup of the low energy portion of the DTL, has been fabricated to study the RF characteristics and the cooling requirements[6]. An electromagnetic quadrupole using a hollow conductor (5 mm x 5 mm) was designed for the focusing magnet, of which field is 80 T/m with 5.5 turns at 780 amperes. Two quadrupole magnets have been fabricated and installed in the model tank.

The high power tests have been carried out with the RF power source. Figure 5 shows the schematic layout of the test. Prior to the cooling requirement test, high power conditioning was done while monitoring the vacuum pressure and the RF signals from the pickup loop and the directional coupler. At first, the duty factor was limited to less than several percent due to the RF contact problem at the end plate. After covering the viton O-ring thoroughly to improve the RF contact, RF power with a duty factor of 20% was fed to the model without troubles to 128 kW, which corresponds to the average axial field of 2 MV/m. Bremsstrahlung X-ray spectra from the gap were measured to estimate the gap voltage. The measured gap voltage was 195 kV at an RF power of 128 kW, which was in good agreement with the calculated value of 197 kV by the SUPERFISH code.

The measured RF heat dissipation power in each drift tube and end plate was in good agreement with the SUPERFISH results. The frequency shift as a function of the #8 drift tube temperature also agrees well with the calculated values as shown in Fig. 6. The calculations were performed with the combination of the thermal deformation from the ABAQUFS FEM code and the frequency shift from the SUPERFISH code. These high power test results have confirmed the heat dissipation calculation and the cooling design of the DTL.

Summary

R&D with the design and the fabrication of the prototype accelerator structures (ion source, RFQ, RF source and DTL) have been carried out. The good performance of the components has been confirmed. In the RFQ beam tests, acceleration current of 70 mA with a duty factor of 7 - 10% has been achieved. The DTL high power test results have confirmed the heat dissipation calculations.

A superconducting (SC) cavity is one of the feasible candidates for the high-β structures and its R&D work has been started[7]. For the injector of the SC cavities, much longer duty factor or continuous-beam operation will be required. Design work on the RFQ and DTL for the CW operation are being performed.

References

DEVELOPMENT OF A NEGATIVE ION SOURCE FOR A HIGH INTENSITY LINAC

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Abstract

A negative hydrogen ion source has been developed for a high intensity proton linear accelerator. The ion source is a volume production type. Negative ion is generated in a magnetically filtered multi-cusp plasma generator. The negative ion production is enhanced by seeding a small amount of cesium in the plasma generator. It is demonstrated that negative ion beamlets extracted from multiple apertures can be focused by aperture displacement technique, which is useful to obtain higher ion beam current.

Introduction

At JAERI, construction of a 1.5 GeV/10 mA proton linear accelerator has been proposed for engineering tests of accelerator-based nuclear waste transmutation and for various basic science researches[1]. At the first stage of the ion source development for the accelerator, a positive hydrogen ion source was fabricated. The ion source has been successfully operated at the full design value of 100 keV and 140 mA peak [2]. At the second stage of the development, a negative hydrogen ion source has been newly designed and fabricated. Negative ion beam is required mainly for basic science researches to inject the beam into the storage ring which produces certain specific pulse duration and repetition rate at the high energy portion of the accelerator.

The basic performance of single aperture beam extraction system was investigated with the volume production type negative ion source which has been originally developed for a neutral beam injector for fusion application [3]. The plasma generator, whose dimensions are 340 mm in diameter and 340 mm in length, has a large semicylindrical volume. Figure 1 shows the negative ion current (density) as a function of the arc discharge power. The extracted ion beam current (density) of 36 mA (23 mA/cm²) was obtained at the arc discharge power of 45 kW with a low beam emittance [4]. In order to obtain higher beam current, the negative ion beam is extracted from multiple apertures and the beamlets are focused by aperture displacement technique. The positive ion source that was used for previous beam performance experiments [2] is modified to produce the negative ion beams in the present experiment.

Design of the Ion Source

Figure 2 shows a cross sectional view of the multi-aperture volume production type ion source. Negative ions are generated in a magnetically filtered multi-cusp plasma generator, whose dimensions are 200 mm in inner diameter and 170 mm in length. The dimension of the ion source is the same as the positive hydrogen ion source [2] except for the existence of the transverse magnetic field, which is created by changing the polarity of the cusp magnets near the plasma grid. The source plasma is produced by an arc discharge using four tungsten filaments, and confined by strong multicusp magnetic field. A magnetic filter, which is formed by Sm-Co permanent magnets, divides the generator into two regions and modifies electron energy distribution so as to produce negative ions. Negative ion production rate is enhanced by seeding a small amount of cesium [5] in the plasma generator.

The beam extractor consists of four grids such as a plasma grid, an extraction grid, an electron-suppression grid and a grounded grid. The plasma grid is made of molybdenum plate. There is a strong dependence of the negative ion production rate on the plasma grid temperature. This is because the cesium coverage is optimized by the temperature rise to give a minimum work function of the plasma grid surface. The plasma grid is heated up by pulsed arc discharge power. The extraction grid is made of a 10 mm thick copper plate with a water cooling channel and magnet grooves. In the extraction grid, Sm-Co permanent magnets are inserted so as to produce a dipole magnetic field. This field deflects the extracted electron and prevents the leakage of the electron to the acceleration gap. The electron-suppression grid is installed for trapping the leakage electron escaping from the extraction grid.

Fig. 1. Negative ion current (density) extracted from the large semicylindrical volume type source
Experimental Results

To measure the beam current and profile, a multichannel calorimeter was installed at 1.4 m downstream from the ion source in the beam diagnostics chamber, where we confirmed no electrons reached to the calorimeter. The calorimeter is made of copper buttons placed on a water cooled copper plate in two perpendicular directions. Temperature distribution of the buttons gives the beam profile and beam current.

Figure 4 shows the negative ion current as a function of the arc discharge power for the operations with and without cesium. The filling hydrogen gas pressure in the plasma chamber (Ps) was 0.8 Pa. In the pure volume operation, the ion current tended to saturate at high arc discharge power and was limited to 20 mA. In the cesium-seeded operation, on the other hand, the beam current was enhanced by about three times and increased linearly with the arc discharge power. The negative ion current (density) of more than 70 mA (16 mA/cm²) was obtained at 25 kW. The current density is defined by the beam current divided by the total beam extraction area of 4.45 cm².

![Graph showing negative ion current as a function of arc discharge power with and without cesium.]

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Fig. 2. Cross sectional view of the multi-aperture volume type negative ion source

In the present experiment, produced negative ions are extracted from seven apertures of 9mm in diameter. Figure 3 shows the cross sectional view of the extractor. The distance between the position of the central aperture and that of the peripheral ones are 13 mm on the PG and the EXG. The peripheral six apertures in the ESG and GG are displaced by 1mm to the direction of center axis. A strong electrostatic lens is formed by the electric field applied in the gap between the ESG and GG. The beamlets extracted from the peripheral apertures are steered by the electrostatic lens to merge into a single beam.

![Diagram showing cross sectional view of the extractor.]

Fig. 3. Cross sectional view of the beam extractor with the aperture displacement technique

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Fig. 4. Negative ion current (density) as a function of the arc discharge power for the operations with and without cesium

The single beam extraction test was also performed using the ion source by covering the peripheral apertures on the plasma grid with a thin molybdenum plate. Figure 5 shows the negative ion current and the beam divergence from a single aperture as a function of the beam energy. To prevent the beam from spreading by space charge expansion effect, the vacuum pressure in the beam diagnostics chamber was kept at 3.7 x 10⁻² Pa where the space charge of the negative ion beam was neutralized by the positive ions in the beam plasma. The small beam divergence θ_{1/e} of less than 6 mrad was obtained at a
beam energy of 40 keV. The beam current density was 12 mA/cm² at the arc discharge power of 20 kW.

![Graph](image)

Fig. 5. Negative ion current density and beam divergence extracted from a single aperture

In the multi-aperture extraction experiment, the emittance in vertical plane was measured using a double slits with a Faraday cup system at an acceleration voltage of 30 kV. The distance between the slits is 390 mm. The size of the first and second slits are 0.5 mm x 50 mm and 0.1 mm x 50 mm, respectively. Figure 6 shows the emittance diagrams at the ion source position. These three diagrams corresponding to those which were extracted from central aperture (closed triangles) and lower aperture (closed circles), upper aperture (closed squares), respectively. The normalized 90 % emittance of each beam was calculated to be about 0.8 mm.mrad. The beam steering angle is determined by comparing the angle of the peripheral beam axis with that of the central one. Because the beam from the lower (upper) aperture has the steering angle of + (-) 15 mrad, the beam trajectory was found to be deflected towards the center of the ion source. The focal point of the merged beamlets is estimated to be 800 mm downstream from the ion source. The beam trajectory measurement by observing the Balmer-alpha light emission from the negative hydrogen ion with CCD camera supported the result of the emittance measurement.

The R&D work is to be continued so as to investigate the dependence of the steering angle on the various type of the displacement. The steering angle is 1.5-2 times larger than the value predicted by the linear theory using thin lens approximation [6]. The experimental result is to be compared with the value calculated by the 3-D beam trajectory code, which is under preparation.

![Graph](image)

Fig. 6. Emittance diagrams from the multi apertures at the ion source position

**Conclusion**

The beam test of the negative hydrogen ion source has been performed. The negative hydrogen ion current extracted from seven apertures was about 70 mA with a current density of 16 mA/cm² at an arc discharge power of 25 kW. The measurement of the beam emittance and the Balmer-alpha light emission showed the beamlets from the multi aperture were successfully merged. The result proved that the aperture displacement technique has a possibility to produce the high brightness beam.

We are now preparing to perform the negative ion beam acceleration test by using the ion source and the 2 MeV RFQ which has been developed for the proton acceleration [7].

**References**

DEVELOPMENT OF A SUPERCONDUCTING CAVITY FOR THE HIGH INTENSITY PROTON LINAC IN JAERI

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Abstract

The R&D work of a superconducting (SC) cavity for the high intensity proton linac in JAERI has been started in collaboration with KEK. The RF field calculation and the structural analyses of the cavity have been made for the design in the proton energy range between 100 and 1500 MeV. The results indicate the feasibility of the SC proton linac, while more optimization is required. A vertical test stand with a cryostat, a clean room and a water rinsing system has been constructed. We present the preliminary cavity design and the overview of the test stand.

Introduction

The Neutron Science Research Program has been proposed in JAERI for the basic research and the engineering application[1]. This program requires a high intensity proton linac with an average current of several mA and an accelerating energy of 1 GeV class. The high energy section is the main part of the linac and has issues to be considered, i.e., beam loss, capital and/or operating cost, availability, reliability and the total linac length. A superconducting (SC) linac, which is considered to have capability to solve these problems, is selected as the first option of the high energy section. SC accelerators for electron and heavy ions have been operated successfully[2],[3], but an SC proton linac has not been realized yet. Therefore, the R&D work of the SC linac for the proton energy range between 100 and 1500 MeV has been started in collaboration with KEK.

SC cavity shape of the proton linac are flatter than those of the electron accelerators due to smaller β value (β=0.43–0.92 at the energy range mentioned above), that results in some difficulties with the RF characteristics and the structural strength. We have carried out these studies and defined preliminary cavity design. Parallel to those work, a test stand has been prepared for the vertical test of the cavity. In this paper, we present the results of the design work and the overview of the vertical test stand.

RF Characteristics

The cavity has been decided to be elliptical shape as used for the electron cavity. The resonant frequency has been chosen to be 600 MHz which is triple frequency jump of the low energy section frequency, 200 MHz.

The RF field calculations in the half cell geometry have been made by the SUPERFISH code. The schematic view of the cavity and the shape parameters are presented in Fig. 1. The shunt impedance (ZT), the ratios of the maximum surface electric and magnetic field to accelerating field (Ep/Eacc and Hp/Eacc) were obtained under the various shape parameters. The dependence of these characteristics on the shape parameters are summarized below.

Under the same β (=4L/λ) condition,
(1) smaller iris radius (a) makes larger ZT and lower Ep/Eacc,
(2) smaller wall slope angle (α) makes larger ZT but does not vary Ep/Eacc so much, and
(3) shorter semiaxis length of ellipse at iris (R1, R2) makes larger ZT and higher Ep/Eacc.

In comparison with different β cavities,
(4) lower β makes much smaller ZT,
(5) lower β makes higher Ep/Eacc, i.e., the Ep/Eacc values are 4–6 at β=0.43 and 1.5–3.5 at β=0.92, and
(6) lower β makes higher Hp/Eacc, however, the value (35–130 Oe/(MV/m)) will not limit the field strength.

Reduction of a and α is effective to obtain good RF characteristics but will make difficult to do surface treatments. In any case, it is difficult to obtain better RF characteristics at lower β cavities.

Fig. 1 Schematic view of the cavity and shape parameters
Structural Analysis

SC cavities are made from niobium sheets. The structural analyses have been made by the ABAQUS FEM code for the cavities at $\beta = 0.5, 0.7$ and 1.0 with the various shape parameters. The max. von MISES stress has been obtained under the vacuum load in the conditions of iris free or fixed. The cavity thickness is assumed to be 3 mm. The dependence of the max. von MISES on the shape parameters is listed below.

(1) Dependence on wall slope angle ($\alpha$);
   In the case of iris free, the max. von MISES is significantly decreased by increasing $\alpha$ and saturated at about 10–20 degree, where that values are $\sim 1/3$ of those at 0 degree.
   In the case of iris fixed, the max. von MISES does not depend on $\alpha$ so much.

(2) Dependence on semiaxis length of ellipse (R1, R2);
   The max. von MISES varies by 20–30%.

(3) Dependence on iris radius (a);
   The max. von MISES does not vary so much.

(4) Dependence on $\beta$;
   Lower $\beta$ makes much greater max. von MISES. In the case of iris free, the values are 80–190 MPa at $\beta = 0.5$ and 20–85 MPa at $\beta = 1.0$. In the case of iris fixed, the values are 40–65 MPa at $\beta = 0.5$ and 14–26 MPa at $\beta = 1.0$.
   From a viewpoint of structural analysis, $\alpha$ should be as large as about 10 degree. This competes with the RF characteristics. In any case, much greater strength is required for lower $\beta$ cavities against the vacuum load.
   The yield stress of niobium at room temperature depends on RRR, work hardening and heat treatment. Since the yield stress after the heat treatment at about 700 °C is considered to be 70–100 MPa, additional stiffening structure or more thickness of about 5 mm is required for $\beta < 0.6–0.7$ cavities. On the other hand, the yield stress of niobium used for the cavity fabrication should be confirmed experimentally.

Preliminary Design

The consideration about the RF and structural characteristics indicates the feasibility of the SC proton linac, while more estimation is required especially for lower $\beta$ cavities from standpoints of those considerations as well as the fabrication and surface treatment. The surface treatment is important to obtain designed performance of the cavity. We are considering electropolishing combined with barrel polishing[4] as the surface treatment.

For the preliminary design, we attach great importance on the surface treatment. Therefore, the iris radius (a) has been fixed to be 7.5 cm which is obtained by referring the shape of TRISTAN cavity[5]. Table 1 presents the preliminary design and calculated results for the RF and structural analysis. The design will be optimized from the results of the vertical tests.

Overview of Test Stand

To measure Q-value, surface resistance and maximum Ecc of the cavity, a vertical test stand for 600 MHz cavities has been prepared at JAERI Tokai site. The test stand consists of a cryostat for the tests, a clean room for cavity assembly, a high pressure water rinsing system and a data acquisition system. Figure 2 illustrates the overview of the system.

An SC cavity with the number of cells up to 4 can be installed in the cryostat with liquid helium (LHe) vessel of 0.8 m i.d. and 3.5 m long. The SC cavity can be cooled at about 2 K by evacuating LHe vessel. Therefore, the vertical tests will be performed at both 4.2 K and 2 K. The LHe vessel is covered with permalloy sheet to shield magnetic field. The field strength at room temperature has been measured to be $\sim 15$ G at the place where the cavity is located.

The clean room for cavity assembly is divided into class 10, 100 and 10000 areas. The cavity after rinsing is opened only in the class 10 area. In the class 10000 area, a cavity is evacuated by an oil-free vacuum pumping system. In the class 10 and 100 areas, any dusts above 0.5 $\mu$m were not detected by a particle counter under the condition without persons.

The high pressure water rinsing system consists of an ultra-pure water production system, a high pressure water pump of 8.5 MPa, a filter of 0.1 $\mu$m in mesh size and a cavity mount system. The ultra-pure water production system has a capability of 90 l/h, that makes an hour rinsing for the single cell cavity. The cavity mount system is placed in the class 100 area. Therefore, sequential works of rinsing, assembling and

Table 1 Preliminary design and their results of the RF and structural analysis

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<th>$\beta$</th>
<th>E (MeV)</th>
<th>a (cm)</th>
<th>b (cm)</th>
<th>R (cm)</th>
<th>R1xR2 (cm)</th>
<th>$\alpha$ (deg.)</th>
<th>L (cm)</th>
<th>$ZT^*$ (M$\Omega$/m)</th>
<th>$ZT^2$/Q (fΩ/m)</th>
<th>Ep/Eacc</th>
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*Calculated from the electric conductivity of Cu

L1 = L2 = 0.2 cm

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cavity evacuation are carried out in the clean room.

Conclusion

The RF characteristics and the structural analysis have been done for the SC proton linac with the energy range between 100 and 1500 MeV. The results indicate the feasibility of the SC proton linac, even more estimation is required. The preliminary design has been made based on these analyses and the considerations of the surface treatment.

The vertical test stand has been completed. The performance of each component; the cryostat, the clean room, the cavity evacuation pump and the high pressure water rinsing system, will be tested in collaboration with KEK.

According to the preliminary design, a SC cavity of $\beta=0.5$ with single cell is on fabrication now. The first vertical test is scheduled in this year. The vertical tests of the cavities with various shape parameters will be performed. Optimization of the cavity design will be made according to these test results.

RF field calculations with multi-cells are being made for optimization of the end cell shape and considerations of the higher order modes.

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References


Fig. 2 Overview of the test stand for the vertical test
SELF-CONSISTENT EFFECTS OF SPACE CHARGE COMPENSATION ON INTENSE ION BEAMS

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Abstract

It is usually assumed that beams are partially space charge compensated for the design of high intensity, low energy beam transport. Such continuous beams are confined in space by means of magnetostatic lenses, the transverse matching into the RFQ accelerator being achieved with solenoids. Along this low energy transport, beam neutralization is kept almost constant, but severe problems can appear at the entrance of the RFQ where longitudinal bunching takes place. The electric field pulls out the neutralizing electrons, leading to a redistribution of the charged particles. We analyze theoretical solutions of this phenomenon in a self-consistent approach in view of minimizing emittance growth and halo development that could result.

1. Introduction

High current proton beams are needed for industrial projects like TRISPAL.

In the low energy part of the accelerator machine the transport of such beams is critical up to kinetic energies of a few MeV, because the beams are space charge dominated. It was proposed for a long time to transport such proton beams in a charge compensated regime, where the protons are neutralized by trapped electrons.

This well known effect occurs naturally when the residual gas pressure is relatively high as it is the case after the ion source, even if the gas flowing from the source is pumped out efficiently.

The protons ionize the molecules of the residual gas and produce electrons which are trapped in the collective potential well of the beam.

As this was observed in many experiments [1–3], the beam tends to be partially neutralized, depending on characteristic parameters and vacuum pressure.

This is often a favorable situation since the transported beam current can be enhanced considerably, and this saves power for the external restoring forces which insure the confinement of the beam; the companion electrons screen the primary beam, diminishing the net defocusing force due to coulombian repulsion and participate to the confinement of the whole beam.

But these time dependent mechanisms of neutralization are not necessarily homogeneous in space: they can produce a cli or non-axisymmetric instabilities which contribute by non-linear effects to energy redistribution into the beam. This drives the density to a more or less steady profile [4].

Emittance degradation and particle losses in the low energy part of the machine are a real concern for machine designers, it is thus important to be able to predict the optical qualities of the beam and emittance growth. This is why transport must be simulated using a refined and a self-consistent description.

In this paper, we first describe the system from relevant parameters and time scales of the model that depend on physics: we then derive a set of self-consistent equations for a 1D1/2 model. After analyzing theoretical solutions, we draw conclusions for future studies.

2. Model and hypotheses

We consider a cylindrical DC beam with parameters:

\( T_0 = 100 \text{ keV}, \ I_0 = 100 \text{ mA}, \ S_0 = 1 \text{ cm}^2 \ (R_0 \sim 5 \times 10^3 \text{ m}) \).

The study is restricted to a region surrounding a waist where external confinement can be absent. Magnetic focusing is assumed ahead and behind this region; mechanical walls are absorbent and grounded.

- The primary beam \( \mathbf{p} \) is assumed cold, hence its phase space distribution function has the following expression:

\[
\mathbf{f}_p(r,v,t) = n_p \delta(\mathbf{v} - \mathbf{v}_p)
\]

where \( \mathbf{v} \) is reduced to the axial velocity \( v_z \); with our parameters \( n_p = 1.410^{12} \text{ m}^{-3} \).

- The residual gas \( \mathbf{g} \) mainly consists of hydrogen molecules \( \text{H}_2 \) at about \( 10^3 \text{ hPa} \) which are considered at rest compared to the other moving species. With these parameters \( n_g = 3.510^{19} \text{ m}^{-3} \).

Physical processes. We assume that the only source of secondary charges is the gas ionization:

\[
p + \text{H}_2 \rightarrow p + \text{H}_2^+ + \mathbf{e}
\]

and the generated plasma is composed of four species where 1, 2 are the primary species and 3, 4 are the secondary ones.

From the processes (2), we can estimate the electron density variation versus time:

\[
\frac{dn_e}{dt} = \sigma_n n_p n_g v_p
\]

and deduce an approximate neutralization time scale.

\( \tau_n = (\sigma_n n_p) \tau_p ^{-1} \) assuming that the density \( n_p \) and \( n_g \) are near constants [5]. With our parameters, \( \tau_n \sim 330 \text{ ns} \).

We consider that elastic scattering cross section at large energy transfer is small compared to the ionization one, it is thus assumed that residual gas depletion is inexistent ahead of the beam at any time scale of our study provided:

\[
n_i \leq n_p << n_g
\]

The radial potential \( \phi \) of a primary beam with a parabolic density profile \( \rho \) can be deduced from the Poisson equation:
\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \phi}{\partial r} \right) = -\frac{\rho(r)}{\varepsilon_0}
\]

(4)

Supposing that this potential vanishes on the wall of the vacuum chamber, we obtain the following expressions:

\[
\phi(r) = \frac{2\rho R_0^2}{16\varepsilon_0}(1 - \frac{4r^2}{3R_0^2} + \frac{4}{3} \ln(\frac{r}{R_0}))
\]

(5)

for \( R_0 \leq r \leq 0 \) and,

\[
\phi(r) = \frac{2\rho R_0^2}{4\varepsilon_0} \ln(\frac{r}{R_0})
\]

for \( R_0 \leq r \leq R \).

This global potential is attractive for the electrons as long as the total neutralization is not reached. In the same time the secondary ions are continuously expelled transversally.

At equilibrium, the ion radial flux balances their creation while electrons are confined in the potential well.

Since electrons are more mobile than ions, electron dynamics will govern this potential: a test electron gaining some energy will escape the well if the potential well is not deep enough. It is exactly as if it evaporates.

When evaporation balances creation a dynamic equilibrium seems to exist. To understand this balance, let us assume for instance that potential depth decreases for some reason; evaporation is then eased and the ions will be expelled slower to the wall, then the ion flux will start to decrease. While electron density decreases, ion density increases and the total potential will return to its previous value.

**Secondary particle dynamics.** In a first stage, the ionization of the residual gas by primary protons is only taken into account as the main inelastic process. But charge exchange, excitation and dissociation processes will be included in a second stage to interpret more refined experimental results.

**Potential of the electrons:** Once equilibrium is reached, the continuity equation applied to ions gives:

\[
n_i = \frac{R_0^2 \rho_{e} n_{e} n_{p}}{8 \Phi(R_0)}
\]

(7)

where \( \Phi(R_0) \) is the potential at the border of the beam, and is also the minimum energy of the electrons which evaporate. The relation (7) shows that the knowledge of the energy spectrum of the ions leads to the estimation of \( R_0 \) and \( \Phi(R_0) \).

For a partially neutralized beam, the typical value is \( \Phi(R_0) = 20 \) V.

**Screening effects:** To estimate the screening effects we assume that the beam is quasi-neutralized, \( n_e \# n_p \), so we can calculate the Debye length:

\[
\lambda_d = \frac{\varepsilon_0 T_e}{n_e e^2} \approx 10^{-3} \text{ m}.
\]

This estimation of the Debye length value shows that screening effects will not prevent an external electrostatic field from expelling rapidly the trapped electrons.

**Velocity distribution functions of the secondaries:**

Experimental data and theoretical calculations for the total and differential cross sections can be found in Refs. [6–9].

It comes out that:

- the primary protons have negligible deviation from incident trajectory and their velocity is almost unaffected,
- the secondary ions have a recoil energy less than 10 eV,
- the electrons created by ionization have energies picked at 0 eV but 50% of them have energies higher than 18 eV.

Usually, it is admitted that both ions and electrons are created at rest, this corresponds to the double differential cross section:

\[
\frac{d\sigma_i}{dE_e d\Omega} = \sigma_i \delta(P_e)
\]

(8)

where \( P_e \) represents the momentum of electrons created at energy \( E_e \) and with no energy transfer taken into account.

In our model, we take some more realistic initial condition: ions are still created at rest but electrons have a mean energy of about 10 eV. As mentioned before, the differential cross section is then:

\[
\frac{d\sigma_i}{dE_e} = \frac{\sigma_i \exp(-E_e/\Lambda)}{T_e}
\]

(9)

and their velocities are distributed as a maxwellian distribution function with a temperature \( T_e \). This temperature will be an adjustable physical parameter which can be checked by experiment.

**Relaxation time:** the velocity distribution function of the secondary particles is driven to thermodynamic equilibrium by the binary collisions: e-e collisions drive the distribution to a maxwellian, while e-i and e-g participate essentially to the isotropisation of the velocities. The relaxation time is then expressed by

\[
\tau_e^{i/e} = \frac{3.51 \times 10^{11}}{\Lambda n_e T_e^{3/2}}
\]

(10)

where \( \Lambda \) is the Coulomb logarithm.

With \( \tau_e^{i/e} = 3ms>>\tau_e \), one can conclude that neutralization equilibrium is reached well before electrons are thermalized.

**3. System of equations**

The system of equations for the different species can be resumed as follows:

- for the electrons

\[
\frac{df_e}{dt} = C_e^e(f_e)
\]

where \( C_e^e(f_e) \) is the collision operator and can be calculated from the continuity equation by:

\[
C_e^e(f_e(r,v_r,v_{th})) = n_e n_p(r) v_p \frac{d\sigma_i}{dv_r dv_{th}}
\]

(11)

This gives the number of electrons of velocity \( (v_r, v_{th}) \) created per unit volume in the phase space and per second.

From the relation (11) it is easy to derive the final form:

\[
\frac{d\sigma_i}{dv_r dv_{th}} = \frac{\sigma_i m_e}{2\pi T_e^{3/2}} \exp(-\frac{m_e v_r^2 + m_p v_{th}^2}{2T_e})
\]

(12)
For the ions
\[ \frac{df_i}{dt} = C^i_i(f_i) \]
where \( C^i_i \) is the collision operator and can be calculated by the same expression as (9) to give:
\[ \frac{d\sigma_i}{dv_r} = \sigma_i \delta(v_r) \tag{13} \]
We obtain finally at stationarity [12]:
\[ \nu_r \frac{df_r}{dr} + \frac{e}{m_e} \frac{d\phi}{dv} \frac{df_r}{dv} = \]
\[ n_g n_p(r) \nu_p \sigma_l \frac{m_e}{2 \pi T_e^{\mu}} \exp \left( -\frac{m_e (v_x^2 + v_y^2)}{2 T_e}\right) \tag{14} \]
\[ \nu_r \frac{df_i}{dv} = \frac{e}{2 m_p} \frac{d\phi}{dv} \frac{df_i}{dv} = n_g n_p(r) \nu_p \sigma_l \delta(v_r) \tag{15} \]
\[ \Delta\phi(r) = -\frac{e}{\varepsilon_0} (n_p(r) + n_i(r) - n_e(r)) \tag{16} \]
\[ \phi(r_c) = 0 \]
For the closure of the system, we suppose that \( f_i \) and \( f_r \) are not correlated, but the two kinetic equations are coupled by the Poisson equation. For the boundary conditions, we take absorbent walls. This complete set of equations is to be solved by numerical techniques.

**Conclusion**

A space charge neutralization may be needed to keep small the emittance degradation in a transport system made of magnetic lenses.

But this can be done only in a some dynamical equilibrium between the present charge species, where the degree of neutralization is kept near a constant value.

If this equilibrium cannot be maintained, a proton density redistribution will happen when the beam enters into the RFQ: the electrons participating to the self-confinement will be rapidly released by the electrostatic field.

In this case, the adiabatic matching and bunching into the RFQ might fail.

It is too early, at this stage of the study to draw definitive conclusions related to our concern.

But we saw that the study of the dynamics of the companion electrons is essential to understand the mechanisms of the equilibrium during the transport, and the rapid decompensation at the entrance of the RFQ.

We derived a 1D1/2 model close to reality since it represents a cylindrical beam which is transported in an axisymmetric magnetic system.

The assumed parameters like \( T_e \) and \( \phi(R_0) \) and the density profile will be measured experimentally to refine the initial conditions and hypothesis.

The numerical simulations that we are presently carrying out, will provide the density profile of the protons and electrons at equilibrium.

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**References**

Numerical simulation of ion production processes in EBIS

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Abstract

The numerical model of EBIS is presented. The calculation of Kr ionization by cooling with Ne ions was carried out taking into account charge exchange, ion heating by electrons, ion-ion energy exchange and ion escape processes. A good agreement with experimental data was observed. According to the model, the processes of Pb ionization in EBIS at close to ultimate parameters (the electron beam current is 10 A and the electron energy is 10 keV, the trap capacity is about 10^{12} e) by cooling with Ne ions were simulated.

Introduction

The electron-beam method of multicharge ion production was suggested by E.D.Donets in 1967 [1]. The first attempt to create an Electron-Beam Ion Source (EBIS) theory was undertaken by R.Becker [2] and M.C.Vella in 1981 [3]. A more complete theory of the electron-beam method of multicharge ionization in an ion trap was created by the Livermore EBIT group (M.Levine, M.Penetrante, R.Marrs et al.) [4,5]. Based on these results, we present a simpler numerical model of multicharge ionization in EBIS. Simplifications follow from our previous papers [6,7]. The computer codes describing the Kryon-S experimental data can be used to predict EBIS basic parameters: charge state spectrum, ion-beam current and even ion-beam position.

Physical processes in the trap

According to the Livermore papers, main processes in the EBIS trap are the following:

- electron-impact ionization of ions,
- radiative recombination of ions,
- charge exchange between ions and neutral atoms,
- ion heating by an electron beam,
- ion-ion energy exchange,
- ion confinement in the trap,
- ion escape from the trap.

The processes were considered in detail in previous papers [4,5,8,10].

Numerical model

We suppose that the ionization proceed by single steps:

\[
\begin{align*}
\frac{dN_0}{dt} &= -N_0 \lambda_0 + N_1 \lambda_{1,0}, \\
\frac{dN_1}{dt} &= N_1 \lambda_0 - N_1 (\lambda_{1,1} + \lambda_{1,0}) + N_2 \lambda_{2,1} - \left( \frac{dN_1}{dt} \right)^{\text{exch}} \\
\frac{dN_2}{dt} &= N_1 \lambda_{1,1} - N_1 (\lambda_{2,1} + \lambda_{1,1}) + N_3 \lambda_{3,1} - \left( \frac{dN_2}{dt} \right)^{\text{exch}} \\
\frac{dN_3}{dt} &= N_2 \lambda_{2,1} - N_3 \lambda_{3,1} - \left( \frac{dN_3}{dt} \right)^{\text{exch}}
\end{align*}
\]

where \( N_0, \ldots, N_Z \) are the ion and atom densities, \( \lambda_{0,1}, \lambda_{1,2}, \lambda_{i+1,i}, \lambda_{i+1,i+1}, \lambda_{Z-1,Z} \) are the ionization coefficients: \( \lambda_{i+1,i} = \sigma_{i+1,i} \lambda_\Phi \), \( \lambda_\Phi \) is the electron current density, \( \sigma_{i+1,i} \) the ionization cross-section, \( \lambda_{i+1,i} = \lambda_\Phi + \lambda_p \), where \( \lambda_p = \sigma_p \cdot J_e \), \( \alpha_i \) is the recombination and charge exchange cross-section, \( N_0 \) is the density of neutral atoms, \( <V> \) is the mean ion speed, \( \frac{dN_i}{dt}^{\text{exch}} \) is the rate of ion diffusion escape from the trap.

The corresponding energy evolution is described by:

\[
\frac{d(N_i kT_i)}{dt} = N_{i+1} kT_i \lambda_{i+1,i} - N_i kT_i (\lambda_{i+1,i} + \lambda_{i,i+1}) + N_{i+1} kT_i \lambda_{i+1,i} + \sum_j \frac{d(N_j kT_j)}{dt}^{\text{exch}} + \frac{d(N_j kT_j)}{dt}^{\text{heating}} + \frac{d(N_j kT_j)}{dt}^{\text{loss}}
\]

where \( kT_i \) is the ion temperature,

\[
\begin{align*}
\frac{d(N_i kT_i)}{dt}^{\text{heating}} & \text{ the rate of ion heating by the electron beam,} \\
\sum_j \frac{d(N_j kT_j)}{dt}^{\text{exch}} & \text{ the rate of ion-ion energy exchange due to Coulomb collision,} \\
\frac{d(N_i kT_i)}{dt}^{\text{loss}} & \text{ the rate of the energy loss due to escaping ions.}
\end{align*}
\]

Calculations and comparison with experimental results

The dependences of Kr ion densities, electron beam compensation values, Kr ion temperatures on time at taking into account ionization, charge exchange, ion heating by the electron beam, ion energy exchange and ion escape processes were calculated in [10].
The experimental data of the Kr current at the EBIS Krion-S exit measured over an ion extraction time of 100 μs and the calculated results obtained at \( j_c = 1.77 \times 10^{21} \text{ cm}^{-2} \text{s}^{-1} \), \( U_e = 7 \times 10^3 \text{ eV} \), \( N_{Kr}(0) = 6 \times 10^9 \text{ cm}^{-3} \), \( r_p = 0.015 \text{ cm} \), \( B = 1.2 \text{ T} \), by cooling Kr ions with Ne ones.

The next step was to consider ion cooling processes. The method of ion cooling in EBIS was suggested by E.D. Donets and G.D. Shirkov [8]. Equation systems for charge and energy evolution created for Kr and Ne were solved simultaneously. We supposed that the concentration of Ne atoms (NNe) in the electron beam is a constant [10].

The calculated results for Kr ionization by cooling with Ne ions were compared with the experimental data of Kr current measurements at the EBIS Krion-S exit. The experimental current dependence on time was measured over an ion extraction time of 100 μs. The best numerical approximation was obtained at the current density equals to \( j_c = 1.77 \times 10^{21} \text{ cm}^{-2} \text{s}^{-1} \), the electron energy \( U_e = 7 \times 10^3 \text{ eV} \), the start concentrations of Kr atoms \( N_{Kr}(0) = 6 \times 10^9 \text{ cm}^{-3} \), the electron beam radius \( r_p = 0.015 \text{ cm} \) and the magnetic field induction \( B = 1.2 \text{ T} \). The results for output current are shown in Fig. 1. The total numbers of ions, the values of beam compensation and the average ion temperatures corresponding to Fig. 1 are shown in Fig. 2, Fig. 3, Fig. 4.

The results were confirmed by an experimental observation of Kr higher charge state evolution at the LU-20 output when the EBIS Krion-S was installed on the linac pre-injector [9].

According to the model, the processes of Pb ionization in EBIS at close to ultimate parameters
(the electron beam current is 10 A and the electron energy is 10 keV) were simulated. The electron gun for the source with the perveance equals to 3 μA/V^3/2 at the cathode diameter of 3.4 mm, the cathode emission density of 111 A/cm^2, the first anode voltage of 22.3 kV and the second anode one of 10 kV can be produced in the firm "ISTOK" (Friasino, Moscow reg., Russia) [11]. After installation of the electron gun in the EBIS, the value of DC current power at the EBIS collector will be equal to 100 kW.

![Fig. 6](image)

Figs.6,7,8. The values of Pb ion currents at the EBIS output after 10, 50 and 100 ms ionization at U_e=10 keV, I_e=10 A, B=1.2 T, j_e=200 A/cm^2 and j_e=500 A/cm^2.

To avoid problems due to collector heating a pulse regime of ionization is suggested. At the pulse duration is about t=0.1 s the collector system can be cooled by water at the rate of flow is about Q=3 l/min. We suppose that the process of electron beam formation to reach the current density 200 ≤ j_e ≤ 500 A/cm^2 (as it takes place in Krion-S) won't be a very difficult problem. The time of ion extraction from the trap can be decreased from 100 μs to 10 μs. Therefore we carried out calculations of Pb atom ionization processes during 0.1 s at j_e=200 A/cm^2 and j_e=500 A/cm^2 by cooling the Pb ions with Ne ones and without one.

![Fig. 7](image)

The results for output ion currents at the ion extraction time of 10 μs for different ionization periods are shown in Fig. 6, Fig. 7, Fig. 8. In the calculations, the values of Pb ion currents for calculations with cooling are very close in amplitude to ones without cooling at the same ionization period. Therefore we present the ion currents for calculations with cooling only. The electron beam compensation values f and the average ion temperatures presented for both calculation types (with cooling- fT11 and without one- fT12) are shown above the currents.

![Fig. 8](image)

**Fig. 8**

**Conclusion**

The workable numerical model of EBIS has been created. The calculated results for Krion_S are close to the experimental ones. The model made more understandable the influence of different processes in the trap on the EBIS output parameters. It allows us to undertake some attempts to predict future results.

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**References**

FRONT-END PHYSICS DESIGN OF APT LINAC*

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Abstract

The accelerator for the Accelerator based Production of Tritium (APT), uses a radio-frequency quadrupole (RFQ), followed by the newly developed [1] coupled-cavity drift-tube linac (CCDTL) and a coupled-cavity linac (CCL). The production target requires the APT linac to deliver a 100-mA proton beam with an energy of 1.3 GeV to 1.7 GeV. The main challenge in the design comes from the requirement to minimize beam loss. Hands-on maintenance of the entire linac requires very little beam loss.

Introduction

Recent studies indicate that mismatch is the single most important factor leading to beam-halo formation. Beam-halo can lead to beam loss and activation of the linac. A mismatch causes the beam size to oscillate about the equilibrium value. In practice, a mismatch usually occurs at transitions in the transport lattice such as the transition between an RFQ and a CCDTL or drift-tube linac (DTL). Traditionally, “matching sections” match the beam from one to the next structure. However, since matching is never very adiabatic, it can introduce emittance growth at abrupt lattice transition. Low energies especially enhance these effects. Here, we describe the front end of the linac and show the performance of this design. Figure 1 shows virtually no emittance growth of the beam as it moves through the current-independent transition between the RFQ and the CCDTL.

Linac Front End

In this paper we define the ‘front end’ of the APT linac as the RFQ and a portion of the CCDTL. This portion provides a 100-mA proton beam with an energy of 20 MeV. As noted earlier, there is no matching section between the RFQ and the CCDTL. The transverse focusing lattice beyond the RFQ is a FODO with a constant focusing period of $8\beta_0$, where $\beta$ is the proton velocity relative to the speed of light and $\lambda$ is the free-space wavelength at the CCDTL resonant frequency of 700 MHz.

The RFQ for APT, designed to accelerate a 100-mA proton beam to 6.7 MeV, will be the highest energy RFQ ever built. References [2,3] describe the detailed conceptual design. The 350-MHz RFQ operates at a subharmonic of the 700-MHz CCDTL. It is an 8-m-long rf structure consisting of four resonantly-coupled sections. In the high-energy part of the RFQ, we specially tailor the vane-tip modulation to reduce the phase width of the exit beam. The CCDTL can directly capture this RFQ output beam and does not require a separate matching section.

The CCDTL accelerator up to 20 MeV uses two types of cavity configurations. The first part has 2 gaps per cavity with one cavity between quadrupole focusing magnets. At about 8 MeV the configuration changes to three gaps per cavity. Figure 2 shows the cavity configurations at this interface. The change from two to three accelerating gaps per cavity in the CCDTL mainly increases the acceleration efficiency. From a beam-dynamics point of view, these structures are indistinguishable. The entire accelerator beyond the RFQ consisting of CCDTL and CCL maintains the 8$\beta_0$ FODO transverse focusing lattice. Thus, the only transition the beam encounters is the one shown in Fig. 3 between the RFQ and the CCDTL at 6.7 MeV.

![Figure 1. Longitudinal and transverse emittance versus energy. The transition from the RFQ to the CCDTL occurs at 6.7 MeV.](image)

The first two gaps, which are in the first CCDTL cavity following the RFQ, provide no acceleration. This first cavity provides only longitudinal focusing and takes the place of a buncher cavity. Unlike conventional buncher cavities, this cavity is an integral part of the CCDTL structure. The resonantly coupled structure locks the phase and amplitude of each cavity to the phase and amplitude of its neighboring cavities through side coupling cavities. The relative longitudinal spacing between cavities sets the synchronous phase. The third cavity starts a quasi-adiabatic ramp in both the synchronous phase and the field amplitude. The synchronous phase starts at $-60^\circ$ and provides the large longitudinal acceptance needed in the early part of the CCDTL. The doubling of the frequency at this transition requires the large longitudinal acceptance. The chosen amplitude gives the same zero-current phase advance per unit length as at the end of the RFQ.

![Figure 2. Interface between the single and the double-drift tube CCDTL cavity configuration at 8 MeV.](image)

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RFQ-CCDTL Transition

An earlier design of the APT [2] accelerator used a 350-MHz DTL with electromagnetic quadrupoles after the RFQ. The DTL required a relatively high-energy beam (7 MeV) from the RFQ to make room for the quadrupoles inside the drift tubes. The CCDTL structure has replaced the DTL in the present design of APT. The CCDTL structure does not constrain the quadrupoles to fit inside drift tubes. Therefore, it could accept beam from the RFQ at a comparatively lower energy. However, a lower energy would mean the loss of a major benefit, the current-independent transition from the RFQ to the CCDTL.

In the design of the APT accelerator we have reduced the transverse focusing strength in the high-energy end of the RFQ and increased the longitudinal focusing strength. In typical RFQs the accelerating gradient and the longitudinal focusing strength fall off rapidly at higher energies. Increasing the vane gap and the gap voltage in the high energy region of the RFQ maintains both the accelerating gradient and the longitudinal focusing strength. Smoothly varying the synchronous phase from $-33^\circ$ at 3.0 MeV to $-40^\circ$ at 6.5 MeV also helps maintain the longitudinal focusing strength. Varying the synchronous phase quickly to $-65^\circ$ in the region from 6.5 MeV to 6.7 MeV helps compensate for the loss of longitudinal focusing in the drift between the RFQ and CCDTL.

Figure 4 shows the zero-current phase advance per unit length, which is a measure of the focusing strength, in the RFQ and the first section of the CCDTL up to 8 MeV. Note that the transverse and longitudinal focusing strengths are nearly the same before and after the transition between the RFQ and CCDTL. This is the feature that makes the transition current independent. The focusing period is in the RFQ is 1.0 $\lambda$ at 350 MHz while in the CCDTL the focusing period is 8 $\lambda$ at 700 MHz. Therefore, the focusing period in the CCDTL is 4 times the length of the focusing period in the RFQ. The zero-current transverse phase advance at the high energy end of the RFQ is 20$^\circ$ per period. Early designs of the RFQ had stronger transverse focusing at the high energy end. Increasing the aperture radius at the high energy end of the RFQ reduced the transverse focusing. This change costs in terms of rf dissipated power. The rf power dissipated on the cavity walls increased from 12 to 13 watts/cm$^2$. However, this change made the transverse focusing strength per unit length nearly continuous at the transition from the RFQ to the CCDTL. It would be difficult, if not impossible, to reduce the transverse focusing strength to this level at lower transition energies. An alternating-gradient quadrupole channel (FODO) provides the transverse focusing in the CCDTL. The transverse focusing strength of this channel in the CCDTL is $-80^\circ$ per period which is the same phase advance per unit length as in the RFQ. The optimum focusing strength for the smallest beam size is about $80^\circ$ per period.

The last cell in the RFQ is a transition cell [4] that reduces the vane modulation to zero from its value in the next to last cell. The vane tips end with an exit-fringe-field region [5]. Adjusting the length of the fringe-field region provided Twiss, or Courant-Snyder, beam parameters that matched the beam to the quadrupole focusing channel of the CCDTL. This eliminated the need for a transverse matching section between the RFQ and the CCDTL. It is possible to adjust the match because the quadrupoles in the CCDTL are electromagnets. The difficulty will be detecting a mismatch with the beam diagnostics. PARMILA simulations show that a small mismatch will be extremely hard to detect.

This design has no separate longitudinal matching section. The longitudinal focusing strength in the RFQ is the same at the end of the RFQ and beginning of the CCDTL. However, between the end of the RFQ transition cell and the beginning of the CCDTL, there is no longitudinal focusing. Compensation for this loss in the longitudinal focusing is necessary. A slight increase in the longitudinal focusing in the last few cells of the RFQ provides part of the needed compensation. However, the CCDTL provides most of the compensation. Increasing the amplitude of the first CCDTL cavity and operating it in the buncher mode ($\psi_s = -90^\circ$) provides most of the compensation. Reducing the longitudinal focusing in the second cavity balances the increased longitudinal focusing in the first cavity. This reduction comes from changing the synchronous phase of the second cavity to $-30^\circ$ from the nominal $-60^\circ$. The codes PARMILX [6] and PARMTEQM [7] provided the information to make adjustments of the field amplitude in first cavity and the synchronous phase of the second cavity. Adjustment of the cavity-to-cavity coupling in the CCDTL will provide the correct relative field amplitudes. The longitudinal match relies
completely on these simulations because no beam diagnostics exist that could provide the necessary information about the actual beam to adjust the match.

**Simulation Results**

The computer code PARMILX designs the cavity lengths and performs the particle-dynamics simulation for the entire linac beyond the RFQ. Figure 5 (a-c) shows the x beam profiles (top) and beam phase profiles (bottom) from multiparticle simulations for full current (100 mA), ~ half current (55 mA) and zero current. There were no adjustments to the transition region for the different cases. No profile oscillation’s indicative of mismatch conditions attests to current independence matching between the RFQ and the CCDTL. Figure 5 (d) shows the profile and phase plot for the case when the RFQ vane voltage is 5% above the nominal design value. In this case, there is a slight mismatch in the phase centroid. The higher voltage changes the phase of the exit beam slightly. The oscillations of the phase centroid are visible in the phase profile of Fig. 5 (d).

Figure 6 shows the equipartitioning ratio for the front end.

Figure 5. Shows the profile plots for the 6.7- to 8-MeV CCDTL. The x coordinate profiles are at the top and the phase coordinate are below for: (a) full-beam current of 100 mA, (b) 55 mA beam current, (c) zero-beam current, (d) the case with full-beam current and the RFQ operating at 5% above nominal designed vane voltage.

Equipartitioning [8] implies: \( \xi_x^2 / x_{rms} = \xi_y^2 / y_{rms} = \xi_z^2 / z_{rms} \), where \( \xi_x \) and \( \xi_y \) are the normalized emittances for the transverse coordinates and \( \xi_z \) is the longitudinal emittance. The respective rms beam sizes are \( x_{rms} \), \( y_{rms} \), and \( z_{rms} \). Both the RFQ and the CCDTL have alternating gradient quadrupole focusing channels. This type of focusing causes the \( x_{rms} \) and \( y_{rms} \) values to oscillate about the equilibrium value \( \sqrt{x_{rms} \cdot y_{rms}} \). Therefore, averaging over these oscillations the equi-partitioning ratios \( Ax \) and \( Ay \) plotted in Fig. 6 are defined as:

\[
Ax = \frac{\xi_x^2}{x_{rms} \cdot y_{rms}} \cdot \frac{x_{rms}}{\xi_z^2} \\
Ay = \frac{\xi_y^2}{x_{rms} \cdot y_{rms}} \cdot \frac{y_{rms}}{\xi_z^2}
\]

Although it is desirable to have these ratios near unity, they are extremely sensitive to mismatch. A slight mismatch at the entrance to the RFQ causes the oscillations of \( Ax \) and \( Ay \) in Fig. 6. The equipartitioning ratios are greater than 1.0 in most

![Figure 6. Shows the equipartitioning ratio (Ax and Ay) for the APT front end of the RFQ because strong transverse focusing with respect to the longitudinal focusing minimizes the beam loss but increases the equipartitioning ratios. The smaller longitudinal acceptance of the 700-MHz CCDTL compared to the 350-MHz RFQ required relatively stronger longitudinal focusing. This bias in designing the APT front end resulted in equipartitioning ratios less then 1.0 near the end of the RFQ and in this portion of the CCDTL. The longitudinal focusing weakens as the beam energy increases. Thus the equipartitioning ratios tend to grow at high energy unless there is a corresponding reduction in the transverse focusing.]

**Conclusion**

We have outlined the approach for a current independent design of the front end of a high current APT linac. The use of the hybrid CCDTL structure in combination with a high-energy RFQ eliminates all but one transition in focusing period throughout the accelerator. In addition, the RFQ and CCDTL perform the matching at this transition without a separate conventional matching section.

**References**

LINAC DESIGN ALGORITHM WITH SYMMETRIC SEGMENTS

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Abstract

The cell lengths in linacs of conventional design are typically graded as a function of particle velocity. Use of symmetric cells in short segments of both the coupled-cavity drift-tube linac (CCDTL) and coupled-cavity linac (CCL) simplifies the cavity design. Mechanical design and fabrication are also simpler without compromising the performance. We have implemented a design algorithm in the PARMILA code for symmetric cells and symmetric multicavity segments. This feature significantly reduces the number of unique components. We have compared the performance of a symmetric-segment linac with a more conventional graded-cell-length linac.

Elements in a Symmetric Unit

Figure 1 defines a cell as an acceleration unit that includes a single rf accelerating gap. A cavity contains one or more accelerating cells and may be resonantly coupled to other cavities.

CCDTL [1] cavities may contain two types of cells. One type extends from the center of one drift tube to the center of the next. The other type starts from the upstream face of a cavity and extends to the center of the first drift tube. The reverse of this later type occurs in the last cell of a CCDTL cavity. In a graded-β design, each cell in a CCDTL would have a unique length and the resulting cavities would be asymmetric. In a CCL, cells and cavities are synonymous and are typically symmetric.

We define a symmetric unit or segment as a series of coupled cavities all of which by themselves are symmetric and all of which have identical geometry. In symmetric units the rf fields in each cavity are equal. In the CCDTL, the field amplitude in each cell may be different but is fixed relative to the other cells within the cavity. In a symmetric unit, symmetrically placed cells have equal fields.

Symmetric units may include space between cavities for focusing elements. Symmetry does not constrain the placement of the focusing elements. Ignoring the quadrupole lenses, a symmetric unit is non-directional. It will perform correctly with either end located up-stream. The quadrupoles position is independent of the cavity position so long as it fits within the space between the cavities.

Algorithm of Linac Design

In a graded-β linac design (β = relativistic particle velocity) a synchronous particle determines the cell length by requiring it to arrive at the center of the accelerating gap when the rf fields are at the "synchronous" phase. Any phase programming along the linac is folded into the increasing cell lengths which are otherwise proportional to βa (λ = the rf wavelength.) In PARMILA [2] the thin-lens approximation determines the acceleration across a gap [3]. Longitudinally, the Prome term [4] corrects the phase advance across the gap ensuring that thin-lens approximation conserves emittance.

PARMILA divides the gap at its electrical center zc. In a multiple-drift-tube CCDTL cavity, the fields in the end cells are asymmetric and the geometrical and electrical centers do not coincide. Therefore, we use the code CDTFISH [5] to design the CCDTL cavities so that the electrical center of the gap coincides with the center of the gap as defined by PARMILA. The value of zc, can be found by satisfying the equation:

$$\int_{zc}^{∞} E_z(z) \cdot \sin(kz) dz = -\int_{zc}^{∞} E_z(z) \cdot \sin(kz) dz . \quad (1)$$

CDTFISH adjusts the length of the cavity noses until the electric field integrals in equation (1) are equal for a given value of zc. It does this while maintaining its resonant frequency. For each geometrical velocity βs SUPERFISH [6] then calculates the transit time factors and other relevant cavity parameters. This procedure is now used by PARMILA to determine the cell lengths of a graded-β linac. In principle, a linac designed by a graded-β method accelerates slightly more efficiently than one designed by the symmetric method.

To maintain an average phase synchronism over a symmetric unit, PARMILA sets the entry phase to the symmetric unit so that average phase equals the design phase. The average phase is the phase, averaged over all gaps in the symmetric unit, of the reference particle when it arrives at the gap centers. In conventional graded-β designs, the reference particle sees cells of increasing length. However, imposing
equal cell lengths, optimized near the mid section of the symmetric unit, inevitably results in cells that are the incorrect length at both ends of the symmetric unit. A reference particle sees a longer cell length than preferred in the earlier cells, and a shorter cell length in the later cells. This results in a phase slip, shown in Fig. 2 through the symmetric unit. We determine $\beta_g$ so that the reference particle phase increases at successive gaps until the mid section, then, decreases from above the design phase until the end of a symmetric unit.

Figure 2. PARMILA adjusts the symmetric unit length and the entry phase until the design phase equals the average reference particle phase.

**Determining the Geometrical $\beta_g$**

In designing a symmetric linac, we define a "design particle" and a "reference particle." We no longer use a "synchronous particle" that arrives at the center of cells at the synchronous phase. The purpose of the loosely-defined design particle is to keep track of the phase programming. The design phase may not correspond to phase at any particular gap for multiple-gap symmetric unit.

The reference particle is a sample particle that obeys the particle dynamics. PARMILA chooses the length of the symmetric unit such that all the phases seen by the reference particle at the gap centers are close to the design phase. We determine the geometrical velocity $\beta_g$ from the requirement that the time required for the reference particle to traverse a symmetric unit is equal to a time that should lapse to maintain synchronism at both ends of the unit. We impose no restrictions on the phase or energy of the particle at the gaps within the unit. The total length of a symmetric unit must be $n_s\beta_g\lambda/2$ ($n_s$ is an integer). The geometrically determined velocity $\beta_g$ is constant over the symmetric unit. We have investigated alternate approaches for determining $\beta_g$ such as choosing its value corresponding to half the energy gain in the segment, or to half the velocity gain in the segment. These schemes were unsatisfactory, particularly when the number of cells in a symmetric unit was small.

In our calculation of $\beta_g$, we include the Prome-phase correction [4] as an extra time contribution in a gap transformation. Previously PARMILA used this only in the particle-dynamics portion of the calculation. The effect of a positive Prome value is a reduction in the cell lengths. For example, for the 2-drift-tube CCDTL in Fig. 1, The following expression determines $\beta_g$:

$$
\frac{1}{4} \beta_g \frac{\lambda}{c} + \frac{1}{2} \beta_g \frac{\lambda}{c} + P_1 + \frac{1}{4} \beta_g \frac{\lambda}{c} + \frac{1}{2} \beta_g \frac{\lambda}{c} + P_2
$$

where $T$ is the rf period ($\lambda/c$). $\beta_\mu$ and $\beta_\nu$ are the relativistic velocities of entry to and exit from the gap $j$. Terms $P_j$ ($j=1,2,3$) are the time delays derived from the Prome phase corrections for each gap ($P_j = \lambda/(2\pi c) \ast$ (phase correction)$_j$.)

With this correction, the cell lengths and the particle dynamics through the symmetric unit become consistent. An error the order of 0.1 degrees per cell accumulates during the cell generation process when the Prome correction is neglected.

After determining the symmetric unit length, PARMILA adjusts its longitudinal position so that the reference particle arrives at the entrance to the symmetric unit at the correct phase. The exit phase of the reference particle traversing a symmetric unit differs from its entrance phase to the next symmetric unit. Also the exit phase of a reference particle through a symmetric unit does not necessarily equal its entrance phase. PARMILA adjusts the entry phase to minimize this phase difference using simple particle dynamics through each symmetric unit. After determining the entry phase, the code calculates the length of the drift space between the units to provide the exit to entry phase difference. If the design requires a ramp in the phase, adjusting the drift-space length provides the ramp. If external-quadrupole magnets require additional space, it is added in units of $\beta/2$ to maintain the correct reference particle phasing.

If the linac design requires a ramp in the accelerating field gradient, we step $E_0$, the average axial electric field, from unit to unit while maintaining $E_0$ constant within the unit. For a given ramp in $E_0$, the value of $\beta_g$ is required to calculate the needed value of $E_0$. Therefore, we iterate about 5 cycles through each symmetric unit until the correct $\beta_g$ is found for the $E_0$ calculation.

**The Entry Phase into a Symmetric Unit**

The average phase of reference particle must bear some relation with the design particle phase. Because the design particle is simply a programmed phase angle, there are a number of ways to approach this problem. Using a reference particle that follows the correct beam dynamics, one can constrain the entry and exit phases of the reference particle through the symmetric unit to be equal. However, if the number of cells in a symmetric unit is small (2 or 3), we often encounter a difficulty. The extreme phases (phase at gap 1 through 4 in Fig. 2) do not bracket the design phase. Another approach requires the equal phase angles at the center of first and the last gap in the unit as seen by the reference particle. This approach also suffers from the same problem.
We therefore require that the average of reference particle phases at gap centers in a symmetric unit equal the design phase. This approach ensures the extreme phases in the symmetric unit bracket the design phase. The entry and exit phases are not necessarily equal. In the PARMILA code, we employ Brent's zero-crossing technique [7] in determining the entry phase angle. For each iteration, a single particle is propagated through the symmetric unit. This method converges quickly and accurately.

When the number of gaps becomes large in a symmetric unit, $\beta_g$ is appreciably different from the actual particle $\beta$ near both ends of the segment. This situation requires a correction in the transit time factors for the reference particle. We use CDTFISH to design the cavity for specified $\beta_g$. Then SUPERFISH calculates the transit time factors (T, T', S, S', etc.) assuming that the reference particle velocity $\beta = \beta_g$. When the reference particle $\beta$ is not equal to $\beta_g$, we expand the transit time factors around $\beta_g$ with respect to the wave number $k$ (k is 2n/$\beta_0$). PARMILA uses this expansion in both the single-particle-dynamics calculations in the linac design and in the multiple-particle simulation sections of the code.

After determining the entry phase, PARMILA stores the phases at the entrance, center and exit of each cell as well as the energy at the exit of the unit. Normally, the exit phase of one unit is not equal to the entry phase of the next one. The source of this can be partly a ramp in the phase, and partly the phase slip through the multiple cells in the unit. Adding extra space between units corrects this small phase discontinuity. The PARMILA code generates one additional symmetric unit beyond the end of linac. It uses this additional unit to calculate the correct spacing between the end of this section of linac and the next section if more follows. The design of the next unit uses the exit energy of this unit as its starting energy. The linac is designed by repeating this process until the required energy is achieved. All of the pertinent design information is stored in memory for the multiple-particle beam-dynamics simulation.

In a more general CCDTL structure (see Fig. 1, CCDTL with 2 drift tubes), the cell lengths within a cavity may differ according to their position in the cavity. Multiple cavities that are completely interchangeable may comprise symmetric units. In a symmetric unit, if there are no external quadrupoles between cavities, either end can be placed to the beam up-stream. If there are multiple drifts within a symmetric unit for quadrupoles, the unit may not be reversible because the drift lengths may be different. Each symmetrically designed unit has a unique $\beta_g$ and all of the cell lengths within the segment are proportional to $\beta_0 \lambda$.

**Example: Design of 2-Drift-Tube CCDTL**

We designed a 2-drift-tube CCDTL that accelerates a 100-mA proton beam from 8 to 20 MeV in two ways: The conventional graded-$\beta$ approach and the symmetric unit approach. Table 1 compares the two of designs at the end of 59 cavities.

<table>
<thead>
<tr>
<th></th>
<th>Length (cm)</th>
<th>Energy (MeV)</th>
<th># of cavities</th>
<th># of cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graded-$\beta$</td>
<td>1639.9</td>
<td>20.274</td>
<td>59</td>
<td>177</td>
</tr>
<tr>
<td>Symmetric</td>
<td>1637.9</td>
<td>20.215</td>
<td>59</td>
<td>177</td>
</tr>
</tbody>
</table>

These designs use a ramp in both the cavity field amplitude and the synchronous phase. The cavity phase varies from -54° to -40° and the field E0 varies from 1.56 MV/m to 2.26 MV/m. The two designs differ by 0.06 MeV and about 2 cm in length.

**Summary**

The new version of PARMILA can design symmetric cavities and symmetric linac sections. It does this for both CCDTLs and CCLs. Then it calculates the beam dynamics through the linac. The symmetric design process simplifies the engineering and eases the fabrication. The difference in performance of the graded $\beta$ design and the symmetric design of a CCDTL is small.

**Acknowledgment**

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**References**

ALIGNMENT AND STEERING SCENARIOS FOR THE APT LINAC*  
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Abstract  
The Accelerator for the Production of Tritium (APT) requires a very high proton beam current (100 mA cw). The requirement for hands-on maintenance limits the beam spill to less than 0.2 nA/m along most of the linac. To achieve this goal, it is important to understand the effects of fabrication, installation and operational errors, establish realistic tolerances, and develop techniques for mitigating their consequences.  
A new code, PARTREX, statistically evaluates the effects of alignment, quadrupole field, and rf phase and amplitude errors in the linac. In this paper we review the effects of quadrupole misalignments and present two steering algorithms that minimize the potential for particle loss from the beam halo. We tested these algorithms on the 8-to-20-MeV portion of the APT linac.  

Introduction  
To meet the beam loss criteria, the APT design [1] incorporates a very strong magnetic focusing lattice that maintains a small well defined beam in transverse space. The apertures of the accelerating structures are sized, with consideration to power, to give maximum clearance to the beam. We expect beam halo to be the main source of particle loss. The linac design avoids known causes of halo growth, such as lattice discontinuities, beam mismatch and large beams. Opportunities for beam excursions both longitudinally and transversely have been minimized.  
Following the RFQ, a coupled-cavity drift-tube linac (CCDTL) accelerates the beam from 6.7 to 100 MeV and a coupled-cavity linac (CCL) accelerates it to a final energy of 1.3 GeV. The resonant rf structure is integrated with a FODO electromagnetic-quadrupole (EMQ) focusing lattice having a constant period of 8λ (λ=relativistic particle velocity, λ=freespace rf wavelength at 700 MHz). The EMQs are approximately centered in the spaces between cavities as shown in Fig. 1.  

Alignment  
Beam spill can result from beam halo and transverse beam excursions. Mismatches between the beam and the focusing lattice cause the beam halo to grow. Misalignments of the EMQs cause beam excursions. Besides the EMQs, the beam-position monitors (BPMs) that detect the trajectories of errant beams have tight tolerances. The lenses are very strong to maintain a small beam size and as a consequence of their strength, the beam trajectory is very sensitive to their alignment. It is even more important to accurately align the BPMs to avoid unknowingly misteering the beam, which would compound the effect of the EMQ misalignments.  
Two effects relax the alignment tolerance on the accelerating structure itself. The rf fields have a very small influence on the beam's transverse motion so cavity misalignments primarily reduce the clear aperture. Because the beam is largest in the EMQs, spill is more likely there than in the rf structure even with a reduced aperture.  

Figure 1. CCDTL at 8 MeV.  

We have evaluated three effects that influence the alignment. Beam steering and repositioning of EMQs correct for static misalignments. We do not actively correct for dynamic misalignments. We will minimize vibrational errors through careful design of the support stand and by decoupling all driving forces such as coolant manifolds. We will correct long term misalignments, arising from settling and ground movement, manually by using a laser based reference line and alignment scheme.  

Quadrupole doublets in the LAMPF CCL vibrate with a measured amplitude of ±0.0003 in. at harmonics of 30 Hz. [2] The driving force comes from a shaft imbalance in the pumps and motors. The accelerator support stand holding both the accelerator and manifolds has a natural mechanical frequency that is a subharmonic of the pump frequency. Based on this study, we have set the dynamic alignment tolerance at ±0.0001 for the APT linac EMQs.  
The EMQs are of conventional design and are mounted independently of the accelerating structure in the inter-cavity spaces as shown in Fig. 1. Their integrated field of 2.625 T for the 8λ lattice period produces a zero-current transverse phase advance of about 80°/period. The steering coils, shown in Fig. 2, on the magnet yolk produce a dipole field superimposed on the quadrupole field. Saturation in the yoke tips and undesirable sextapole field components limit the useful steering. All EMQs will include steering windings for both axes. We will connect power supplies to these windings as required.  

The beam centroid will be located in the linac using 4-lobe microstrip transmission-line detectors (BPMs) that measure the image currents of the beam traveling along the wall of the beam tube. Figure 3 shows a BPM that will be located inside a quadrupole between two cavity segments.  
We will put the magnetic center of each EMQ and the electrical center of each BPM on a common line within a given tolerance. The bore of the EMQs will be inaccessible after installation. Therefore before installation we will align the
magnetic center of each EMQ to its mounting fixture. Each lens will then be mounted kinematically, independent of the linac, on rails attached to the support stand which have been aligned to a smooth and continuous reference line extending the length of the accelerator. Table 1 lists four operations whose tolerances contribute to the final accuracy in locating the lenses.

Figure 2. APT EMQ.  
Figure 3. APT BPM.

Table 1. Local EMQ Alignment Budget

<table>
<thead>
<tr>
<th>Alignment Operation</th>
<th>Tolerance (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic center to mounting fixture</td>
<td>0.002</td>
</tr>
<tr>
<td>Magnet mount to support rail</td>
<td>0.002</td>
</tr>
<tr>
<td>Support rails to reference line</td>
<td>0.002</td>
</tr>
<tr>
<td>Reproducibility of the reference line</td>
<td>0.002</td>
</tr>
<tr>
<td>Cumulative tolerance (quadrature sum)</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Reliably reestablishing a reference line running the length of the accelerator may be the most challenging of these to achieve. Techniques to achieve this alignment are under investigation. The expected long term motion of the tunnel, renders fiducials useless so we plan to use a laser beam to establish the reference line.

Like the lenses, the electrical axis of each BPM must be referenced to its mounting flange before installation. Conventional techniques determine its installed position, relative to the reference line. The measured offsets are entered in the control system data base. Table 2 lists four operations whose tolerances contribute to the final accuracy in locating the BPMs.

Table 2. Local BPM Alignment Budget

<table>
<thead>
<tr>
<th>Alignment Operation</th>
<th>Tolerance (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric center to mounting flange</td>
<td>0.001</td>
</tr>
<tr>
<td>Location of flange relative to support rails</td>
<td>0.004</td>
</tr>
<tr>
<td>Support rails to reference line</td>
<td>0.002</td>
</tr>
<tr>
<td>Reproducibility of the reference line</td>
<td>0.002</td>
</tr>
<tr>
<td>Cumulative tolerance (quadrature sum)</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Particle Distributions

The beam emerging from the RFQ is small and very well defined. Careful matching and strong focusing preserve its quality for a very long distance in the APT linac. Figure 4 shows the transverse profile of a 100 mA beam from a PARMILA simulation using 100k particles and a 2-D (r-z) space charge routine. The total beam size in both planes remains within 3σ through 20 MeV.

Figure 4. 100 mA beam profile at 8 and 20 MeV.

PARTREX

We have written a new version of PARMILA (PARMILX [3]) that generates three types of linac structures: DTLs, CCDDTLs and CCLs and simulates their performance. For error studies, beam steering and matching algorithms, and linac commissioning methods, we have developed a companion code PARTREX (similar to PARTRAC [4]). PARTREX generates the same linac and follows the beam center in exactly the same way that PARMILX does but represents the beam by an ellipsoid. PARTREX can carry out multiple simulations rapidly, and the effects of various errors such as quadrupole misalignments are quantized by probability distributions.

To study the effect of quadrupole displacements, PARTREX applies random displacements, within a specified tolerance, to the position of each EMQ. It then records the maximum displacement of the beam center and the maximum beam radius. With multiple runs (=100), each using a different set of random errors, we analyze the probability that the maximum beam displacement or beam radius might exceed acceptable limits. Studies with different tolerances can reveal the probability that a specified tolerance will result in beam spill, or alternatively, can indicate how often corrective action (i.e., steering) must be taken.

PARTREX represents the beam in transverse space by an ellipse. The semi-axis are a function of the beam emittance and the total beam size which is specified by the user in units of μm (σ) beam size. A value of 3 (typical) means that the edge of the beam (for purposes of this study) is assumed to be at 3σ. As the beam traverses a sequence of misaligned lenses, its centroid is displaced from and oscillates about the linac axis. The beam radius R₀ is defined to be the maximum distance from the linac axis to the outer edge of the beam ellipse. The aperture radius is Rₐ, and we define a filling factor F = R₀/Rₐ. At some point F will reach a maximum value, Fmax, which is recorded for each run. Fmax=1 means that the edge of the beam is just scraping the aperture.

Steering with Dipole Pairs

Using PARTREX we investigated several steering schemes for the APT linac. We tested these algorithms in the 8-to-20-MeV section that includes 177 cells and 60 EMQs. The simplest scheme is to steer at one focusing EMQ to put the beam on-axis at the BPM located in the next focusing EMQ. We then steer in this second EMQ to put the beam on axis again at the BPM in third focusing EMQ. Because the phase advance between the steering magnets and BPMs is 80° nom., this procedure does a good job of restoring errant beams.
However, BPMs can be costly, and we would like to minimize their number and still assure minimum beam spill.

We have investigated a number of variants on this scheme. We present a representative scenario in which this steering set, comprised of two dipoles and two BPMs in 5 EMQs, is repeated every 4.5-lattice periods. The diagram below shows this schematically. We steer in both planes of each steering EMQ.

EMQ

                        ++++++++++++++++++++++
Steering x y s.s.s.s.s.s.s.s.s.s.s.s
BPM                       .b.b. .b.b. .b.b.

Figure 5 shows the result of 100 PARTREX runs in which we have assumed a 3r beam and an alignment tolerance of 0.005 in. for both EMQs and BPMs. The left-hand plot shows the probability distribution for the maximum horizontal excursion of the beam centroid (Xbar max) from the linac axis. The dashed curve represents a misaligned linac with no steering while the solid curve corresponds to the application of the steering algorithm described above. Without steering we expect a maximum excursion of 2 mm on the average (0.5 on the ordinate). In the worst case it would reach 4.5 mm. Steering reduces these values to 1 and 2 mm respectively.

\[
\begin{array}{c}
\text{Fraction > Xbar max} \\
\text{0.0} \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \\
\text{Fraction > Fmax} \\
\text{0.0} \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1.0
\end{array}
\]

Figure 5. Probability distributions for maximum beam centroid excursions and maximum filling factor with and without steering with dipole pairs.

The right-hand plot shows the corresponding probability distributions of Fmax. Without steering, the beam will fill 70% of the bore on the average and just scrape in the worst case. A steered beam will fill 57% of the bore on the average or 65% in the worst case.

This steering scheme does a good job using few BPMs but at the cost of unacceptably large dipole fields. The left-hand plot in Fig. 7 shows the frequency distribution of the expected dipole strengths. Integrated steering fields as high as 1000 G-cm, which are required in some cases, exceed the practical limit of our EMQ design.

Least-Squares Steering

A second steering scheme uses multiple steering magnets (10-20 nom.) followed by a pair of BPMs. Since there are many more variables (steering magnets) than constraints (2), there is an infinite number of solutions. However, there is a unique solution that also minimizes the steering required in each magnet, which is the one we want. We find a least-squares solution with constraints by minimizing the sum of the squares of the steering fields while constraining the beam center to the axis at the two BPMs. This scheme works extremely well, in that few position monitors are required and the magnitude of the steering fields are well within practical limits.

We have investigated a number of variants on this scheme. We present a representative scenario, shown schematically below, in which BPM pairs are located in quads of the same sign every 7.5-lattice periods. We steer in the focusing plane only of each EMQ.

EMQ

                        ++++++++++++++++++++++
X steer s.s.s.s.s.s.s.s.s.s.s.s.s.s
BPM                       .b.b. .b.b. .b.b. .b.b.
Y steer s.s.s.s.s.s.s.s.s.s.s.s.s.s

Figure 6 shows the results of 100 PARTREX runs assuming the same conditions and conventions described in the previous section. In this case the steered beam (solid curves) experience slightly smaller excursions than in the previous example. Figure 7 shows that the expected dipole strengths, using the least-squares steering method, are all within 300 G-cm.

\[
\begin{array}{c}
\text{Fraction > Xbar max (cm)} \\
\text{0.0} \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \\
\text{Fraction > Fmax} \\
\text{0.0} \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1.0
\end{array}
\]

Figure 6. Probability distributions for maximum beam centroid excursions and maximum filling factor with and without least-squares steering.

\[
\begin{array}{c}
\text{Frequency (Bunch)} \\
\text{-1000} \quad -500 \quad 0 \quad 500 \quad 1000
\end{array}
\]

Figure 7. Frequency distribution for expected dipole strengths steering with dipole pairs and least-squares steering.

Conclusion

We have discussed two alignment algorithms for the APT linac. Simulations show that for the expected alignment tolerances both do a good job of preventing excursions leading to beam spill. Least-squares steering, although requiring more dipoles, keeps the fields in all magnets within an acceptable range because the task is shared by many magnets.

References

[2] Los Alamos National Laboratory Internal Memorandum ESA-M7C931
PHYSICS DESIGN OF APT LINAC WITH NORMAL CONDUCTING RF CAVITIES*

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Abstract

The accelerator based production of tritium calls for a high-power, cw proton linac. Previous designs for such a linac use a radio-frequency quadrupole (RFQ), followed by a drift-tube linac (DTL) to an intermediate energy and a coupled-cavity linac (CCL) to the final energy. The Los Alamos design uses a high-energy (6.7-MeV) RFQ followed by the newly developed [1] coupled-cavity drift-tube linac (CCDTL) and a CCL. This design accommodates external electromagnetic quadrupole lenses which provide a strong uniform focusing lattice from the RFQ to the end of the CCL.

The cell lengths in linacs of traditional design are typically graded as a function of the particle velocity. By making groups of cells symmetric in both the CCDTL and CCL, the cavity design as well as the mechanical design and fabrication is simplified without compromising the performance. At higher energies, there are some advantages of using superconducting rf cavities. Currently, such schemes are under vigorous study [2]. Here, we describe the linac design based on normal conducting cavities and present the simulation results.

Introduction

The linac for the production of tritium calls for 100 mA of cw proton beam to be delivered onto a production target. The main challenge in the design comes from the hands-on maintenance requirement of the entire linac by way of permissible beam loss along its length. Thus, elimination of known causes of beam-loss and control of transverse emittance growth (implying larger transverse spread of beam particles) are of utmost concern in the design of such a linac. In the room temperature design, we minimized the number of transitions between accelerating structures. In contrast to earlier designs [3], the only transition we have is between the RFQ and the CCDTL. In addition to eliminating all but one transition, we do not have a separate matching-section between the RFQ and the CCDTL. Instead, the transport properties in both the transverse and longitudinal motion are tailored to be continuous at the end of the RFQ and the beginning of the CCDTL, thus avoiding a discontinuity in the restoring forces experienced by the beam.

A schematic of the linac is shown in Fig. 1. It consists of an RFQ followed by a CCDTL and a CCL. The RFQ accelerates the beam from 75 keV to 6.7 MeV and the CCDTL takes the beam to 100 MeV. A CCL accelerates the beam to a final energy of 1.3 GeV.

RFQ Accelerator

The cw RFQ for the APT linac produces a 100-mA beam of protons with an output energy of 6.7 MeV. An engineering drawing of the RFQ is contained in Ref. 3. The conceptual design is described in complete detail elsewhere [3-4]. This is an 8-m long rf structure consisting of four 2-m-long segments that are resonantly coupled together. Each segment is a resonant structure assembled from two 1-m-long brazed sections.

The RFQ design uses an improved beam-dynamics code [5] that includes multipole field effects. It has been benchmarked successfully against other codes [6]. The transverse current limit is greater than 240 mA throughout the length of the structure. The longitudinal current limit exceeds 150 mA beyond the 1-MeV point. The peak surface field along the length of the vane-tips does not exceed 1.8 times the Kilpatrick limit.

In the high-energy part of the RFQ, we specially tailor the vane-tip modulation to increase the longitudinal focusing strength thereby reducing the phase width of the exit beam.

Post-RFQ Acceleration

Figure 2 summarizes the configuration of the accelerating scheme beyond the RFQ. The transverse focusing lattice is FODO with a constant focusing period of 8βλ. We define the length of 4βλ between two consecutive electromagnetic quadrupoles (EMQ) of opposite polarity as a “segment.” Between 6.7 and 8 MeV, there are only two accelerating gaps per segment. At low energy, a minimum length of 2.5βλ is needed for the EMQs. In the remaining length of 1.5βλ only one cavity containing two gaps can be placed. As β increases, we can use more gaps per cavity. Between 8 and 20 MeV, we have 3 gaps per segment provided by two drift tubes in one cavity. The structure has 4 accelerating gaps per segment between 20 to 100 MeV, which increases the packing fraction (ratio of the active accelerating length to the total length of a segment) to 0.75. The conventional CCL starts at 100 MeV. Both CCDTL and the CCL are coupled cavity structures. Hence, from beam-dynamics point of view, it is not a transition in structure. At this energy, β is large enough for six 0.5 βλ coupled-cavity cells (accelerating gaps) with 1βλ space available for EMQs. The packing fraction remains 0.75. At 155 MeV, where we add a seventh cell to each segment, the

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packing fraction increases to 0.875. The pattern continues to the final energy of 1300 MeV.

<table>
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<tr>
<th>Structure Type</th>
<th>Accel. Gaps per Segment</th>
<th>Energy (MeV)</th>
<th>Cavity Range (βZ)</th>
<th>Quad Range (βx)</th>
<th>Cavity Space Packing Fraction</th>
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<td>6-7-8-0</td>
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<td>5/2</td>
<td>3/8</td>
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<td>6</td>
<td>155-1,200</td>
<td>1/2</td>
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<td>3/8</td>
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<td>7</td>
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</table>

Fig. 2. Schematic for five different types of cavity configurations in the linac beyond the RFQ.

Effective shunt impedance for cavities as a function of β are calculated by the 2-D code SUPERFISH. Except for the very beginning of the coupled cavity structure (<10 MeV), we keep the real-estate shunt impedance ZT² above 35 MΩ/m. Consistent with this choice, we open up the bore radius as quickly as practicable. Figure 3 shows the average real estate shunt impedance as a function of energy while the variation of the bore radius along the length of the linac is shown in Fig. 8.

For power partitioning, each supermodule (chains of up to 160 coupled-accelerating cells driven in common by multiple klystrons) is fed by 4 to 6 klystrons. This concept permits the addition of an extra klystron to each supermodule i.e., operate each supermodule with 5 to 7 klystrons, thus providing redundancy in the system.

The design of the transition region involves tailoring the end of the RFQ as well as first few periods of the CCDTL. General design philosophy of this region is described in Ref. 8 while the detail is contained in Ref. 7. Following this capture section, there is a quasi-adiabatic ramp in both the synchronous phase φ and the field accelerating gradient E₀T. Both are initially ramped adiabatically up to 11.4 MeV. We start at φ₀ = -60° to assure capture of the beam in the “bucket”. We then ramp down φ₀ and ramp up E₀T adiabatically while maintaining a large ratio between the bucket and the beam size. The structure E₀, real estate E₀, real-estate E₀T, and acceleration-rate variation as a function of energy are shown in Fig. 4. The design goal was to obtain a smooth variation in the real-estate E₀T until a predetermined value of real-estate E₀T is reached. ZT² values dictate the bore radius which does not vary smoothly with energy. Since transit time factor is also dependent on the radius, the structure E₀ does not show a continuous variation as seen in Fig. 4. At 155 MeV, we achieve a real-estate E₀T of 1.3 MV/m which is held constant thereafter to conserve power. The design parameters of the entire linac are given in Table 1.

![Fig. 3. Average real estate shunt impedance ZT² vs. energy.](image)

![Fig. 4. Various field gradient measures vs. energy.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RFQ</th>
<th>CCDTL</th>
<th>CCL</th>
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<tr>
<td>Energy (MeV)</td>
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<td>6.7-99.6</td>
<td>99.6-1300</td>
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<td>Frequency (MHz)</td>
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<td>700</td>
<td>700</td>
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<tr>
<td>Beam Current (mA)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Aperture Radius (mm)</td>
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<td>10.0-17.5</td>
<td>17.5-25.0</td>
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<td>Cavity E₀T (MV/m)</td>
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<td>1.095-1.574</td>
<td>1.574-1.485</td>
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<tr>
<td>Real Estate E₀T (MV/m)</td>
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<td>0.410-1.180</td>
<td>1.180-1.300</td>
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<td>Synchronous Phase (deg)</td>
<td>-90 to -60</td>
<td>-60 to -30</td>
<td>-30</td>
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<td>Real Estate ZT² (MΩ/m)</td>
<td>-</td>
<td>18-33</td>
<td>33-47</td>
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<tr>
<td>Quad Lattice</td>
<td>-</td>
<td>FODO</td>
<td>FODO</td>
</tr>
<tr>
<td>Quad Length (mm)</td>
<td>-</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Quad Gradient (T/m)</td>
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<td>87.5</td>
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<td>Trans. Emit. (π cm. mrad)</td>
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<td>0.023</td>
<td>0.023</td>
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<tr>
<td>Long. Emit. (π deg. MeV)</td>
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<td>0.450**</td>
<td>0.482**</td>
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<td>Aper. rad. / rms beam-size</td>
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<td>13-26</td>
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</table>

+ emittances are rms, normalized; * @ 350 MHz; ** @700 MHz

**Simulation**

The computer code PARMILX [9], a modified version of PARMILA, was used to both generate and simulate the performance of the linac beyond the RFQ. An end-to-end simulation was performed with 100,000 macro-particles at the entrance to the RFQ. A 4-D waterbag distribution was assumed at the input.

Transverse phase space distributions at 1.3 GeV for full current of 105 mA are shown in Fig. 5. Beam profile plots for full current from 155 MeV to 1.3 GeV are shown in Fig. 6. No
profile oscillations indicate a good match in the transition region. Longitudinal and transverse emittances vs. energy are

![Graphs showing phase space distribution and beam profile plots.](image)

Fig. 5. Phase space distribution at 1.3 GeV for 105 mA.

![Graph showing longitudinal and transverse emittance vs. energy.](image)

Fig. 6. Beam profile plots from 155 MeV to 1.3 GeV for 105 mA.

luminosity requirements are not important for this application. Figure 8 shows the relationship between beam-size (rms), aperture-size, and maximum radius of a particle as a function of energy. This particle is the outermost one in the distribution, outside the core distribution and constitutes a particle in the halo. Even at higher energies, this particle does not occupy more than ~25% of the bore.

![Graph showing beam-size (rms), aperture-size, and maximum radius of the outermost particle vs. energy.](image)

Fig. 8. Beam-size (rms), aperture-size, and maximum radius of the outermost particle vs. energy.

**Conclusion**

We have described the conceptual design for a high-current normal-conducting linac specifically designed to deliver a high-power proton beam on an extended target. A very high bore-to-beam-size ratio was achieved at higher energies where beam-loss is of concern. Simulations show zero transverse emittance growth for the entire linac.

**References**


The RF System for the Accelerator Production of Tritium (APT)
Low Energy Demonstration Accelerator (LEDA) at Los Alamos*

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Abstract
To develop and demonstrate the crucial front end of the APT accelerator and some of the critical components for APT, Los Alamos is building a CW proton accelerator (LEDA) to provide 100 mA at up to 40 MeV. LEDA will be installed where the SDI-sponsored Ground Test Accelerator (GTA) was located. The first accelerating structure for LEDA is a 7-MeV RFQ operating at 350-MHz. This is then followed by several stages of a coupled-cavity Drift Tube Linac (CCDTL) operating at 700-MHz. The first stage of LEDA will go to 12-MeV. Higher energies up to 40-MeV, come later in the program. Three 1.2-MW CW RF systems will be used to provide power to the RFQ. This paper describes the RF systems being assembled for LEDA, including the 350 and 700-MeV klystrons, the high voltage power supplies, the transmitters, the RF transport, the window coupler assemblies, and the controls. Some of the limitations imposed by the schedule and the building itself will be addressed.

APT System Overview
The accelerator for APT is nominally configured at 1300 MeV, 100 mA, CW [1]. The accelerator layout uses an RFQ to accelerate to 7 MeV and a coupled-cavity, drift-tube linac (CCDTL) [2] to accelerate from 7 to 100 MeV. Above 100 MeV, a Coupled Cavity Linac (CCL) is the baseline structure, but consideration is also being given to a superconducting structure. In the room temperature configuration now planned, over 225 1-MW klystrons are required for the entire accelerator.

LEDA Overview
LEDA is being accomplished in several stages. Stage 1 includes the H- injector only and is in operation now. Stages 2 through 4 all have 100 mA of accelerated beam. Stage 2 adds the RFQ. Two klystrons are required for the RFQ, but it will be configured with 3 as a first test of the supermodule concept. Stage 3A adds the first section of CCDTL and requires 1 klystron. Stage 3B goes to 20 MeV and requires 2 klystrons. Stage 3A has an output energy of 10.7 MeV, and stage 3B has an output energy of 16.7 MeV. The building configuration as it now stands cannot power more than 5 klystrons total, so phase 3B does not allow testing of the supermodule (with the 'on-line' spare) on the CCDTL. Phase 4 adds significant modifications to the building and enough CCDTL to go to 40 MeV. In addition, a complete supermodule will be tested. The complete CCDTL from the output of the RFQ to 40 MeV will be resonantly coupled. Six klystrons will be needed to power it, and 7 will be installed. In the final phase of LEDA (phase 5) funneling will be tested, with a total 'funneled' current of 134 mA. A second leg will be added to 16.7 MeV, a funnel will be installed to combine the two beams at that point, and additional acceleration will take the complete beam to approximately 28 MeV. In phase 5, no additional klystrons will be used compared to that used for phase 4. In order to maximize the final energy, there will be no 'on-line' spares.

RF System Architecture
A uniform RF system architecture is adopted for all APT RF systems. The RF system is made up of the klystron subsystem, the transmitter subsystem, the high voltage power supply subsystem, and the cavity field control subsystem. A block diagram of the RF system is shown below in Fig. 2.

Fig. 1: APT accelerator schematic.

The end portion of the accelerator is considered the key to success of the system, and therefore a demonstration accelerator (LEDA) is being developed at LANL.

One concept which is being investigated for use on APT is the supermodule. This is an assembly of accelerator modules which are resonantly coupled together. In theory, these supermodules could be extremely long, but we have chosen units which use 7 RF generators or less. In all supermodules, the design uses 1 large RF generator or less. This provides a type of on-line spare. Its operation allows any RF generator to fail, and the remaining generators can take over and provide the necessary power. This concept is one that we plan to test on LEDA.

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This includes the waveguide from the klystron to the RF vacuum windows on the accelerating structures, including circulators, power splitters, waveguide switch, and RF loads. WR 2300 waveguide will be used for the 350 MHz RF system and WR 1500 waveguide for the 700 MHz RF systems. The klystron generators will be protected by a y-junction circulator from reflected power. After the circulator the power from a single klystron is divided into four equal parts using magic tees or hybrid waveguide power splitters. It is necessary to divide the power from the klystron to minimize the stress on the RF vacuum windows on the accelerating structures.

Each of the power splitters, the waveguide switch, and the circulator require an RF load. With the exception of the waveguide switch these loads only absorb significant power in fault conditions. Therefore, in order to minimize load cost we will use 200 kW CW loads protected by instrumented directional couplers. The philosophy is that unless the system is in a fault condition the load power will not exceed the 200 kW, and if the system is in a fault condition we would not want to operate and would bring the system off line for repair. The directional couplers will be used to verify the quality of the load match and the absolute power being absorbed by the load. This information will be used to rapidly disable the drive for the RF system if the power exceeds the load capabilities or the load match degrades.

The cavity field control subsystem is described in detail in another paper at this conference (refer to “APT LLRF Control System Functionality and Architecture”, by Regan and Rohley). The control system contains the circuitry to ensure stable RF fields in the accelerating cavities, as well as some system interlock and interface circuitry. The low-level RF control system will perform a number of different the accelerating cavities. 2) The resonance condition of each functions: 1) Feedback and possibly feedforward techniques will be utilized to control the RF fields inside cavity will be detected and control signals provided to the cooling water system used to maintain the cavities on resonance during normal operation. 3) A frequency agile drive signal will be provided to the klystron when the RF to the cavity has been off, as in the case of start up or failure recovery. In these situations the cavity resonance will be far from the fundamental operating frequency, so the frequency agile drive signal will allow faster recovery to the correct operating frequency. 4) The LLRF control system will develop the reference system for the entire accelerator. This work entails providing phase stable, coherent signals not only to every LLRF control system but also to other subsystems such as the Beam Diagnostics. The reference signal is both a time reference signal as well as the RF reference signal. 5) The LLRF control system will provide logic circuitry that can shut down the drive to high power amplifiers should a number of fault conditions exist, e.g., arcs, high reflected power.

**Key Issues**

**RF Vacuum windows**

RF vacuum windows for CW accelerators are in service in the 200 - 300 kW range in the frequency spectrum of interest.

The window requirements for the RFQ are listed below in Table 1. Four cases need to be evaluated to determine the most stressing case for the RF vacuum windows for the RFQ. The conditions include: whether or not beam is present and whether or not all klystrons are available or 1 klystron is off-line. The number of windows is based on using four windows per klystron (power divided four ways). The effective forward power per window (last column) is the forward power which would generate the same voltage as that of the combined forward and reflected powers.

A similar analysis has been performed on the CCL and CCDDTL windows and their required power capacity is illustrated in Table 2 for four windows per klystron. The worst case in both situations is beam on with 1 klystron off-line. However the effective forward power level is consistent with the demonstrated technology at accelerator facilities.

**Super Module**

The top level RF system design of a super module is illustrated below in Figure 3. The super module provides for on-line redundancy in the RF systems. In the figure, only six of the seven klystrons illustrated are required to meet the RF power requirements of the accelerating structure. With an individual power supply and transmitter per klystron, the super module redundancy is also applicable to the high voltage system and klystron support electronics. Not shown is the complete splitting of the RF power. Only the first level of splitting is shown.

**Table 1**

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<th>Condition</th>
<th>VSWR:1</th>
<th>P fwd</th>
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<th>Pwr Cavity</th>
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<td>232</td>
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</table>

Table 2: CCL/CCDTL RF Window Requirement.

During operation, and with no faults in any of the RF systems, all klystrons are operated at 6/7 of their maximum output power. When a fault is detected, the RF systems for the super module are disabled and the waveguide switch is activated on the faulted unit. The waveguide switch serves two purposes. It connects the faulted unit to an RF load for evaluation, repair, and test. It also reflects a short circuit at the appropriate phase back to the accelerating structure so as not to perturb the accelerating fields. Once the failed system has been taken off-line, the remaining systems are returned to service.

![Waveguide Switch Diagram](image)

Fig. 3. Typical RF Super Module

The super module concept allows for rapid service restoration (5 minutes) in the event of an RF system fault. The failed component is then repaired off-line and restored to service when convenient. It allows the RF system to meet its availability allocation of 95%. The additional cost for this configuration is seen in two ways. The number of installed klystrons is increased 17% (7 divided 6), and the klystrons are not operating as efficiently as possible. Klystrons are designed to provide their maximum efficiency when operating saturated at a specific power level. We must operate below saturation to allow the accelerator field control circuits to operate properly. This reduces the operating efficiency from the maximum capable by the klystron. In addition, when 7 klystrons are operated to satisfy the needs of 6 they are operated below their nominal maximum output power. An additional efficiency penalty results. By variation of the klystron beam voltage and current the efficiency penalty can be minimized to a 1 - 2% absolute reduction in efficiency. The adjustment of the klystron cathode voltage has additional impacts to the high voltage power supply in terms of increased ripple, line harmonics, and reduced power factor as it is operated below its nominal design point.

While there is an operational efficiency penalty that results from operating a klystron below its maximum power there is also a corresponding increase in klystron operating life. Experience at accelerator facilities world wide indicate that high average power klystrons operate more reliably if in their typical service environment they are utilized below their maximum capacity. Also, experience on LAMPF indicates that if the klystrons are typically operated under ratings the operating life of the klystron can be dramatically increased. Several klystrons at LAMPF have over 100,000 hours of operating life. The super module architecture also allows for the repair and test of klystrons and their associated electronics in situ and validation of performance before the RF system is returned to service. This greatly simplifies maintenance activities and minimizes mean time to repair.

**Capital and Operating Cost**

In such a large system (>200 MW of CW RF power), cost is an important issue. While klystrons are the baseline choice for the RF generator, we are considering other types of sources. These include advanced klystrons of several varieties (depressed collector, high efficiency designs using multiple second harmonic cavities, multi-beam klystrons), and inductive output tube types which operate class B and consequently have very high ‘operating’ efficiency. The high operating efficiency is due to the slow rolloff in efficiency over the upper 25% of output power range (Figure 4). Another area of investigation is the HVPS. We are investigating the use of both 6-pulse and 12-pulse SCR-type supplies, and we are looking into solid state switching power supply technology based on IGBT’s, to achieve enhanced power factor and efficiency.

![High Voltage Power Supply (HVPS) Diagram](image)

Fig. 4. Inductive Output Tube (IOT), Efficiency vs. Output Power

**References**

LANSCE LINAC RF PERFORMANCE FOR A LONG PULSE SPALLATION SOURCE

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Abstract

The proposed Los Alamos National Laboratory Long Pulse Spallation Source (LPSS) design consists of a 1 MW neutron spallation target fed by a pulsed proton beam from the Los Alamos Neutron Science Center (LANSCE, formerly LAMPF) accelerator. This proton beam would have a repetition rate of 60 Hz and a pulse length of 1 ms for a duty factor (DF) of 6%. An average/peak current of 1.25 mA/21 mA would be required for an 800 MeV beam to provide this power at this duty factor. The spallation target would reside in what is now called Area A and would use the H+ beam. The LANSCE accelerator would also be required to simultaneously deliver H- beams to the Manuel Lujan Jr. Neutron Scattering Center (MLNSC) and the Weapons Neutron Research (WNR) facility at the requisite duty factors and currents. LANSCE currently delivers 16.5 mA peak of H+ beam at 120 Hertz, with a 625 μS beam pulse length. H- beams are accelerated for use in MLNSC and WNR.

In November of 1995, operation of the linac shifted to the LPSS pulse parameters, except for the peak current which remained at the 16.5 mA production level. In addition to delivering 800 kW of H+ proton beam to physics production targets, H- beams were simultaneously delivered to customers for the proton storage ring feeding MLNSC, and to researchers using the WNR facility. Performance of the RF powerplants for the 201.25 MHz drift tube linac (DTL), the 805 MHz side-coupled linac (SCL), and the associated electronics is described [1].

The conclusion of the experiment is that the LANSCE linac can be upgraded through modest improvements to drive a 1 MW LPSS.

LPSS Demonstration Conditions

The objective of this experiment was to simultaneously deliver an evenly spaced 60 Hz x 1 ms, 1 mA average, 800 MeV beam to Area A (800 kW beam, 80% of LPSS design), an evenly spaced 20 Hz x 600 ms, 70 mA H- beam to the PSR/MLNSC, and 60 Hz x 625 ms, 1 μA H- beam to WNR. These criteria were chosen because they represent the present beam parameters. Also, it represents an H+ peak current which is a large fraction of the LPSS design. The WNR and Area A beams (both at 60 Hz) were accelerated in the same RF pulses. The 20 Hz PSR beam was interleaved with those 60 Hz pulses. The parameters used during the test are shown in Table 1.

To achieve the above beam parameters, we operated the RF at 80 Hz, spaced irregularly in a three on, space, one on, space pulse sequence. Refer to Figure 1. Peak power was maintained near the normal operation values, as peak beam current did not increase.

The 805 MHz RF systems required a pulse length of 1185 μs, and therefore operated at a duty factor of 9.5%. The 201.25 MHz RF systems required more time at the start of each pulse to fill the cavities and stabilize the fields (1235 μs pulse length). The 201.25 MHz duty factor was 9.9%

201.25 MHz DTL RF Systems

A description of the 201.25 MHz RF systems is given in a companion paper [2]. The RF power amplifiers (PA) driving DTL tanks 2 through 4 are operating close to their maximum average power ratings. DTL tank 1 uses the same PA tube for compatibility, operating at one-sixth of the power.

We measured the waveform of the voltage on the HVDC capacitor bank for Modules 2 - 4, the highest power systems. Module 2 was the only system requiring increased HV for adequate headroom. This module was operating at the highest peak power, so it also had the highest plate current. With H+ beam on, the peak power for modules 2, 3 and 4 was 3.05, 2.54, and 2.71 MW, respectively. Because of the higher plate current, the plate modulator of module 2 had a large voltage drop across the pass tube components. This is seen in the comparative modulator voltage drops in the oscilloscope traces in Figure 2.

The ripple on the capacitor banks was observed (Module 2 shown in figure 3). Note that the step for each pulse starts at a different voltage, repeating after 50 milliseconds.
Each klystron is capable of supplying 1.25 MW of RF power. RF drive is modulated for field amplitude control. They are spaced over 731 meters of linac and increase the proton beam energy from 100 to 800 MeV. Six to seven klystrons are clustered with a HVDC capacitor bank.

In a series of tests in 1993, the cluster of klystron amplifiers at modules 18 through 24 was operated at 12% DF and 60 Hz repetition rate. These tests were performed without beam, with extreme (2 ms) pulse length. It was determined that the practical DF limit comes from the maximum current from the high voltage power supplies. Browman [3] reported that the maximum peak beam current of 25 to 30 mA was limited by the available peak power from the klystrons. During the 1995 LPSS experiment, we measured the peak power of module 48, with calibrated couplers and instrumentation, for the 16.5 mA H+ beam of the LPSS test. Close attention was given to the low level RF controls and the amount of work to adjust them for this test.

Due to the increased demands on the RF powerplant by the high current, long pulse H+ beam, in addition to the 20 Hz H-beam, the 805 MHz RF capacitor banks experienced significant voltage droop. This droop problem was exacerbated by the irregular pattern of pulses. Figure 4 depicts the droop and pattern of klystron cathode current for Module 48. The relationship of cathode current, \( I \), to capacitor bank voltage, \( V_c \), is \( I = kV_c^{0.5} \). A reduction in capacitor bank voltage results in reduced klystron cathode current and overall gain. Reduced gain in the klystron results in reduced loop gain and causes the control system to increase its drive power. This requires the control system to operate over a larger dynamic range than in past operational modes.

805 MHz SCL RF Systems

The 805 MHz RF systems for the SCL (also called coupled cavity linac or CCL) are comprised of forty-four Varian and Litton klystron amplifiers operating with a pulsed mod anode.
The controls for the SCL RF powerplant required considerable hands-on tuning, which was made more difficult by the length of the accelerator. The asymmetric pulse train of the RF made the capacitor bank voltages vary from pulse to pulse. To compensate, the capacitor banks were operated at higher levels. For certain modules, it took adjustment of the klystron focus magnet currents to move tube gain irregularities out of the nominal control range of the system. Otherwise these anomalies would perturb the control loops, causing instability.

In order to project the requirements for 21 mA beam operation, the power signals were carefully measured at 16.5 mA of peak beam current. The output power for the Module 48 klystron is representative of Sector H, which traditionally has a high power load as a result of the beam loading. The directional coupler and the diode detectors were calibrated to back out the actual power consumptions during the beam operation:

**Predicted beam loading at 16.5 mA peak current**

<table>
<thead>
<tr>
<th>Description</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.5 mA X 16.81 MV (tank 48)</td>
<td>277 kW</td>
</tr>
<tr>
<td>Measured incident power without beam (Resistive Losses only)</td>
<td>607 kW</td>
</tr>
<tr>
<td>Measured incident power with 16.5 mA peak current (Resistive losses plus beam loading)</td>
<td>872 kW</td>
</tr>
<tr>
<td>Measured beam loading with 16.5 mA peak current (872 kW - 607 kW)</td>
<td>265 kW</td>
</tr>
<tr>
<td>Predicted beam loading at 21 mA peak current (21 mA X 16.81 MV)</td>
<td>353 kW</td>
</tr>
<tr>
<td>Predicted power required for 21 mA LPSS beam</td>
<td>~1000 kW</td>
</tr>
</tbody>
</table>

The measured power is within a 4% agreement with the design code estimated resistive copper losses including corrections for bridge coupler losses and the SCL measured Q [4].

**Corrected design code estimate**

<table>
<thead>
<tr>
<th>Description</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>631 kW</td>
</tr>
<tr>
<td></td>
<td>607 kW</td>
</tr>
</tbody>
</table>

In comparing with the measured values, we must allow for some small difference introduced in fine tuning the beamline optics by adjusting the beam output energy with Module 48 power.

The 805 MHz klystrons are rated at 1.25 MW peak power and are consistently tuned to that power level into a matched load. Driving into the mismatched load of the accelerating cavity does effect the klystron output, depending on the phase and magnitude of the reflection. The expected 1 MW peak power requirement for 21 mA of beam leaves 250 kW for control margin for closed-loop control and for the mismatch. It is felt that the 805 MHz RF powerplant will be able to supply the needed power without needing significant upgrading.

**Future Direction for RF Systems at LANSCE**

Additional tests in coming months will examine operation at 21 mA peak H+ beam current while delivering beams to the other users. This will, of course, require a reduction of the DF for the present 201.25 MHz system. A project to eliminate the IPA plate modulators, and operate the tubes from standalone DC power supplies has been funded to improve reliability, simplify the RF power system, and reduce the amount of droop in the IPA RF output power. An adaptive feedforward controller is proposed to be added to the low level amplitude/phase controllers to improve response to repetitive beam transients, temporal and cyclic drifts in tune, and component changes or gain drifts inside the controlled loop. These improvements are offered to improve the LANSCE DTL RF system for the present beams and for the proposed LPSS beam.

For 21 mA LPSS operation, we have proposed a new RF amplifier chain. The new PA systems would not require high-level plate modulation for amplitude control but would operate with DC from the capacitor bank. Without the modulators, the plate voltage drop would disappear, raising the peak power capacity of modules 2 through 4 while maintaining low capacitor bank voltages. Duty factor would not be a limitation. The tank window will be examined with improvements to handle the higher peak voltages and currents. RF circulators are proposed to eliminate troublesome reflected power [2].

Due to the large number of systems in the SCL RF powerplant, any proposed modification must be analyzed for benefit versus the individual unit cost. This has limited the overall upgradability of the SCL RF systems in the past to minor improvements. Upgrades must be reviewed in light of this philosophy. Work is underway to improve the controllability, the power monitoring instrumentation, the uniformity of klystron parameters, and the inventory of spare klystrons. There is much more room for significant modification in the 201 MHz DTL powerplant, with only four modules.

**Acknowledgments**

The LPSS experiment was carried out through the combined efforts of the AOT-6 Beam Delivery and Physics Teams and the AOT-5 RF Team. They were instrumental in making the adjustments and changes in a timely and coordinated manner, over a continuous period encompassing 48 hours.

**References**

LANSCE 201.25 MHz DRIFT TUBE LINAC RF POWER STATUS

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Abstract

The Los Alamos Neutron Science Center (LANSCE) linac provides high power proton beams for neutron science, Tritium target development, nuclear physics, material science, isotope production, and weapons research. The number of simultaneous beam users places heavy demands on the RF powerplant, especially the 201.25 MHz power amplifiers (PA) driving four drift tube linac (DTL) tanks. Designed nearly 30 years ago, these amplifiers have operated at up to 3 Megawatts with duty factors of 12%. The large number of power tubes in the PA and Intermediate Power Amplifier (IPA) plate modulators, the age of the cooling and control subsystems, tube manufacturing problems, and operation near maximum PA tube ratings have all affected the system reliability.

By monitoring final power amplifier plate dissipation and tube vacuum, improved operating procedures have raised RF system reliability above 95% for operation periods in 1993-95. Other recent modifications and upgrades to the 201.25 MHz RF powerplant have significantly improved the operation. Higher beam current for a proposed Long Pulse Spallation Source (LPSS) cannot be delivered simultaneously with other beams at high duty factor, however. Plans are underway to develop a new final power amplifier which can use low-level RF modulation for amplitude control. With only a few power tubes, the system will deliver high peak power and duty factor, with improved DC to RF efficiency, and a simplified cooling system.

Overview of Original 201.25 MHz RF Systems

A block diagram of the original 201.25 MHz RF system is shown in Figure 1. The maximum duty factor is 12% where the plate dissipation of the final amplifier tube (Burle Industries 7835 triode) is approximately 250 kW. A selection of the 7835 parameters is given in Table 1. The peak power out of the final cavity amplifier is over 3.0 MW in some cases. The amplifier chain used a solid state preamplifier and a dual tube driver to provide 4 kW output. This output drives the IPA, a Burle 4616 tetrode, to achieve 130 kW. Finally the 7835 PA can deliver over 3 MW.

The 7835 cavity amplifier is unstable if operated with B+ but no RF drive, so the input high voltage is modulated by the amplitude control electronics in order to adjust the saturated output and thereby provide the amplitude control. This high voltage modulation technique requires four power tubes. The modulator has an internal voltage drop of 8 to 12 kV, so the high voltage capacitor bank must be maintained with that head room above the level needed by the 7835. At the present peak powers, the 7835's require 19 to 21 kV, and the capacitor bank operates at approximately 30 kV. Operation above this level not only stresses the capacitor bank and power supply, but stresses the modulator tubes.

The IPA high voltage is derived from the same high voltage as the PA. The IPA operates as a linear amplifier, so the high voltage is only switched on and off. Its level is not modulated as in the case of the final amplifier. A tube-based modulator is used to switch the high voltage on the 4616, requiring 3 power tubes (fig. 1).

*Work supported by the US Department of Energy.
Modifications and Upgrades to 201.25 MHz RF Systems

In the original configuration, the entire 201.25 MHz amplifier system required thirteen power tubes per module times four modules, or fifty-two power tubes. Recent modifications have reduced that number to nine per module [1,2]. These included the 1994 installation of a solid-state driver and a solid-state screen grid (G_s) pulser for the IPA stage. These are included in fig. 2. An upgrade is planned for the near future in which the IPA will have its own high voltage power supply (HVPS). This will eliminate the three-tube HV modulator and bring the total tube count per module to six. When the IPA HVPS is installed the 201.25 MHz system will be arranged as in Figure 2. This upgrade is just beginning with the purchase of a prototype HVPS, due for arrival in late 1996.

![Upgrade Diagram](image)

Fig. 2. ‘Upgraded’ 201 MHz Amplifier System.

Plate Power Dissipation Monitors

The original specification for the 7835 super power triode lists the average plate dissipation limit of 300 kW (Table 1). LANSCOE has operating experience which suggests that for safe operation, dissipation should be below 250 kW. Real time monitoring of the average plate power dissipation of the FPA was installed in 1993 [3]. Using the temperature difference in the plate coolant manifold and the flow from a sensor, the power wasted in the plate coolant (plus a factor for filament and drive power) is computed with an embedded controller and used for readout and interlock of the HV. We implemented administrative controls to limit the operation to plate dissipations of less than 250 kW. Catastrophic failures have been significantly reduced. This is especially effective during beam tuning and transient start-up conditions when the RF power level is fluctuating and the resonance controller is moving the DTL tuning slugs.

Peak Power Monitors

Another significant improvement was the addition of peak power monitors (PPM) to indicate RF power levels in Watts for the entire amplifier chain. The PPM replaced original uncalibrated detector diodes and directional couplers which were only useful for indicating that a signal was present. We purchased commercial directional couplers in 5 kW, 150 kW, and 3 MW “sizes”, for the driver, IPA, and PA outputs, respectively. Lowpass filters eliminate harmonics from the power signals. A PPM timing gate allows sample/hold of the peak anywhere in the RF waveforms. These signals are fed to large LED displays, and to the central control room for logging. Both forward and reflected power are monitored, using custom versions of the Narda 481 diode power monitors. Linearity is ±0.25dB over a 10dB dynamic range.

Filament Power Regulator

The original 7835 PA filament supply was an unregulated, variac-controlled supply. As noted in table 1 above, this supply delivers over 30 kW of DC power. A modern SCR supply was purchased for our test stand to see the benefits of filament current regulation. The regulation has been shown to be effective in stabilizing the 7835 operation, since the cathode current in the grounded-grid triode is proportional to emission from the filament. However, because of the cost of the filament supply and the desire to replace the 7835 amplifier stages in the near future (see below), we have chosen to modify our existing supplies rather than make new purchases. The modification consists of adding a control circuit to the power supply which adjusts the variacs as the supply output current varies. In order to avoid excessive brush wear in the variacs, the control circuit is designed with an adjustable dead band. We have found that 50A is a suitable band. The regulation is sufficient, and the brush movement is not excessive. The regulator is isolated and filtered to ignore the pulsed cathode bias voltage which is common to both filament connections.

Modifications to the PA Plate Modulators

In 1992, analysis of the PA plate modulator output waveforms showed an undershoot of about 5 kV after pulse shutoff. The cutoff 7835 triode was acting as a rectifier for the returning RF power spike from the DTL tanks during decay. A high power clamp diode was connected from the floating deck to ground, eliminating the negative transient which was charging the deck. This modification dramatically reduced nuisance crowbars due to modulator tube faults. Current transformers were also added to monitor screen current and the plate current in each 4CW250,000B tetrode. These diagnostics have allowed us to predict when a driver or modulator tube is weakening and plan a changeout in advance [1,2].

The modulator driver tetrode (4CX3000A) filament and screen power supplies were modified with the addition of ferroresonant (constant voltage) transformers. This stabilized the overall modulator loop gain for line voltage fluctuations, and has doubled driver tube lifetime by allowing us to hold closer tolerance to optimal filament temperature. Because of
the screen voltage regulation, linac fill time is improved when the driver tetrode operates saturated.

We have installed new bias power supplies for the 4CW250,000B tetrode modulator tubes which allow a higher control grid bias: 500 versus 350 volts negative. This cuts off the tubes more completely during the beam-off time, to minimize cutting of the anode of the tube from the electron beam, which is focused in this condition. The new bias supplies are modular units which are very easy to replace compared to the original hard-wired supplies. Safety is enhanced with the new bias power supplies, and modulator tube life is extended.

Solid State Amplifier

The second stage of solid state amplification in Figure 2 was a recent upgrade which replaced a dual-tube amplifier [1]. The original Burle 7651 tetrode driver tubes had a short lifetime due to a cooling design limitation. They were adequate at low duty factor, but the present duty-factor raised the ceramic seals in some units to near 250°C. New water-cooled solid state amplifiers, using thirty-two Motorola MRF141G MOSFETs combined to deliver up to 5500 W, were installed in 1993 and 1994. Reliability is now excellent with these units. In addition, an entire rack of power supplies, blowers, and amplifier cavities has been eliminated for each 201.25 MHz amplifier system.

Capacitor Room and Crowbar Upgrade

The first level of arc protection for the FPA and IPA RF tubes is provided by a modulator blocking circuit. That is, in the event of an RF tube arc, the modulator switch tubes are shut off as rapidly as possible. In addition, the crowbar trigger circuit waits on the order of 10 μs for the modulator to extinguish the fault current before commanding the crowbar to fire. This long delay time forces a requirement for a 10Ω fault limiting resistor which must dissipate about 70 kW in normal operation. The resistor is immersed in an oil tank, and the oil is cooled by a heat exchanger external to the capacitor room. Maintenance costs plus environment and safety concerns have pushed us to consider an air-cooled resistor. Toward that end, we developed a 3μs crowbar, with an amplitude threshold of about 3 kA to work in conjunction with the existing crowbar in module two. The fault limiting resistor is reduced to 3Ω, dissipates 21 kW, and is air cooled. In addition to the crowbar and limiting resistor improvements, we fitted each capacitor with a spring loaded fuse to isolate the capacitor in the event of an internal short. The new crowbar circuit will protect a 30 gauge wire; after 3 months of full operation, there has been no increase in the number of crowbar faults in Module-two. The remaining three modules are scheduled for similar upgrades in late 1997.

Proposed 201.25 MHz Amplifier Replacement

LANSCE is beginning to look into options for replacement of the 7835 PA stage. The primary goal would be to install a new cavity amplifier which will operate as a linear amplifier and eliminate the need for modulation of the high voltage. Modulation of the output power will be done with the RF drive to the preamplifier stage. This will eliminate four more tubes in the system, leaving only two RF amplifier tubes per module. In addition, the voltage overhead of the high voltage modulator will disappear (about 10 kV), so the capacitor bank and HVPS can operate at reduced voltage levels. We hope to be able to replace the 7835 with a single tube amplifier, but we are also considering the use of two tubes which are summed together in a hybrid combiner.

Cathode-driven tetrodes initially designed for fusion heating are the likely choice. There are very few other super-power VHF tubes capable of high duty factor like the 7835. With this power source, we expect to be able to deliver up to 3.8 MW of peak RF power at a duty factor of 15%. This would provide enough RF for long pulse operation of the H+ beam at 21 mA, interleaved with the H- beam for our proton storage ring. This work is in the early stages of design.

Conclusions

Through continuous improvements, the LANSCE 201.25 MHz RF powerplant has reduced from using fifty-two power tubes in 1992 to thirty-six in 1996. Planned upgrades to the IPA and PA stages to remove both plate modulators will reduce this number to only the RF amplifiers themselves, with a total of eight tubes being the optimal design for the high duty-factor requirements of neutron science. Along with the reduction in power tubes, improvements in operational procedures with new diagnostics, stabilization, and protection circuitry have enabled the RF systems to function with exceptional reliability in the past three years.

References


700
Development of a 110-mA, 75-keV Proton Injector for High-Current, CW Linacs*

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Abstract

A dc proton injector is being developed for a 6.7-MeV CW RFQ at Los Alamos. The RFQ input beam requirements are 75-keV energy, 110-mA dc proton current, and 0.20 nm-mrad rms normalized emittance. The injector has now produced a 75-keV, 117-mA dc proton beam (130-mA total current) with the required emittance. The emittance has been measured after a 2.1-m-long two-solenoid beam transport system. The measured emittance can be explained in terms of the ion source emittance and beam transport through the focusing elements. Measured proton fractions are 90 - 92% of the beam current. The engineering of the accelerating column high-voltage design is being improved to increase the injector reliability. Injector design details and status will be presented.

Table 1.

Summary of the LEDA injector requirements and present status.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Req.</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (keV)</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Proton current (mA)</td>
<td>110</td>
<td>117</td>
</tr>
<tr>
<td>Duty factor (%)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>H₂ Gas flow (T-l/s)</td>
<td>0.04 - 0.1</td>
<td>0.04 - 0.09</td>
</tr>
<tr>
<td>Proton fraction (%)</td>
<td>&gt;70</td>
<td>91</td>
</tr>
<tr>
<td>Reliability (%)</td>
<td>98</td>
<td>To do</td>
</tr>
<tr>
<td>Lifetime (hr)</td>
<td>&gt;168</td>
<td>To do</td>
</tr>
<tr>
<td>Beam noise (%)</td>
<td>±1</td>
<td>±1</td>
</tr>
<tr>
<td>LEDT exit emit. (n-mm-mrad)</td>
<td>0.20</td>
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</table>

Introduction

High-current (100 mA), high-energy (1 GeV) linacs are being designed for accelerator-driven transmutation technology (ADTT) applications [1]. A CW radio frequency quadrupole (RFQ) has been designed to accept a 75-keV, 110-mA proton beam from a dc injector to produce a CW 100-mA, 6.7-MeV final beam [2]. The dc proton injector and the CW RFQ are being developed for the low-energy demonstration accelerator (LEDA) project at Los Alamos [3].

This dc proton injector development began at Los Alamos with a collaborative program with Chalk River Laboratories (CRL) [4]. The microwave-driven proton source [5] developed at CRL has now been extended to meet most of the LEDA beam requirements as shown in Table 1. Beam diagnostic measurements and interpretation are described in the following sections. Other injector details may be found in a recent review [6].

Injector and Beam Diagnostics

Figure 1 shows the injector configuration which has been used in these initial 75-keV beam tests. It is a prototype to check the conceptual design before building the final

*Work supported by the U. S. Department of Energy.
measuring unit (EMU) entrance slit. The magnetic focusing system consists of two joined solenoids. The injector is designed to operate in the dc mode at 10-kW beam power, and all of the diagnostics (excepting the EMU) are of the non-interceptive type. The diagnostics with their distance (z) from the ion source extractor are: (1) Bergoz dc beam current monitor (0.30 m), (2) four-grid energy analyzer (FGA) beam space-charge neutralization monitor (0.41 m), (3) x,y video profile CCD imaging (0.42 m), (4) ac current toroid for measuring beam current fluctuations (0.53 m), and (5) the EMU (2.1 m).

Figure 2 shows a set of measurements for the total beam current (Bergoz dc monitor) and beam fluctuations plotted versus the ion source axial magnetic field. Accuracy of the measured axial magnetic field is estimated to be 3 - 5%. Two maxima in the total current data (left scale) are seen: the first at 0.0875 T which satisfies the electron-cyclotron resonance (ECR) condition at 2.45 GHz, and the second sharper beam current resonance at 0.0935 T. This type of resonant behavior is typical [5].

The ac toroid is a Supermalloy transformer with a $T_i = 1(A/V)$ transfer ratio with a flat bandwidth response from 1 kHz to 10 MHz. The rms beam noise ($i_{rms}$) data reported in Fig. 2 (right scale) is obtained from the integrated power $P_i$ and the relation $i_{rms}(A) = (P_i * R)^{1/2} T$, where $R$ = spectrum analyzer input impedance = 50$^\Omega$. The power sum is done over the beam noise frequency, from 12.5 kHz to 1 MHz. Measured beam noise is maximum at low frequencies, and decreases to background for $f > 1$ MHz. The beam is generally tuned to minimum noise at each magnetic field setting by minimizing the reflected power from the ion source by adjustment of the three-sub tuner in the 2.45 GHz waveguide. Quiescent beams are obtained over the lower field broad resonance, whereas it is somewhat more difficult to maintain a quiet beam at the higher magnetic field.

The FGA [7] has been used to measure the degree of beam space-charge neutralization $f_n$ within the LEBT. An energy distribution of the radially-flowing beam-plasma ions measured with this diagnostic is shown in Fig. 3 for $i_n = 100$-mA, 75-keV hydrogen ion beam [8]. The derivative of the FGA Faraday cup current vs. the discriminating grid voltage (grid 3) is shown. The base width of this distribution is $\Delta E = 4 V$, and this leads to $f_n(%) = (1 - \Delta E/\Delta E_0) * 100 = 98\%$ where $\Delta E_0 = 240$ V, the radial potential drop across an unneutralized uniform beam. The $H_2$ LEBT gas density $= n_0 = 1.5 * 10^{12}$ (cm)$^{-3}$.

The measured phase-space distribution of a 130-mA, 75-keV hydrogen-ion beam is shown in Fig. 4. The proton fraction is 90%, thus the proton current is 117 mA. The focusing solenoids were both excited to 0.17 T, which gives a 7-cm diam. beam (10% contour) at the EMU. This focusing strength gives an average power loading of 0.25 kW/cm$^2$ at the EMU slits. The measurement is made by a two-slit technique using a dc emittance-measuring device [9]. The contaminant $H_2^+$ beam is focused less and is visible in Fig. 4. A Gaussian extrapolation procedure [6] is used to extract the proton rms normalized beam emittance of 0.20 (mm-mrad) which is the design RFQ input emittance.
Discussion

The measured emittance may be partially understood by examining possible emittance growth mechanisms in the LEBT. Estimates can be made for (1) solenoid aberrations, (2) nonlinear space charge, (3) beam fluctuations, and (4) power supply regulation. The effects of (1) and (2) are estimated with the code SCHAR [10], which calculates beam trajectories through the measured solenoidal magnetic fields and takes into account the residual beam space charge. The influence of effects (3) and (4) on the measured beam emittance may be estimated by applying the mismatch factor concept to beam emittance growth in LEBTs [11].

Figure 5 shows the higher-order SCHAR code prediction for 999 macroparticles traced from the ion source extractor to the EMU superimposed on the measured 10% contour from Fig. 4. The SCHAR starting beam distribution (phase-space orientation, emittance) is deduced from drifting the measured beam parameters at the 10% threshold backwards through the LEBT with the first-order transport code TRACE [12]. The measured magnetic fields and a residual beam space charge corresponding to a current of 3.5 mA are included in the simulation. Onset of a third-order aberration is observed in Fig. 5 in both the measurement and prediction. The SCHAR code predicts an 18% emittance growth for the beam transport through this 2.1 m long LEBT.

Soloshenko [13] has shown that dynamic decompensation of space-charge neutralized beams will occur when \( n_0 \gamma \sigma_b \sigma_\theta / 2f < c m \sqrt{\alpha} \) where \( n_0 \) is the beam density, \( v_b \) is the beam velocity, \( \sigma_\theta = 2 \times 10^{-16} \text{ cm}^2 \) is the electron production cross section, and \( \alpha \) is the beam noise amplitude. The inequality is satisfied when the electron density produced in the beam by ionization is much less than the beam current density fluctuations. This effect would be important for this injector operating at \( \alpha = 1\% \) when \( f > 1 \text{ MHz} \), but beam noise from the microwave source has typically reached background at \( f = 1 \text{ MHz} \). An effective emittance growth of <10% from beam current and voltage fluctuations is estimated using the TRACE code and the beam ellipse mismatch concept [11].

A maximum 30% emittance growth estimate from known beam-transport effects has been made. The optimum ion source only emittance is estimated to be 0.13 (mm-mrad) by extrapolation of the published emittance vs. emission aperture radius to the 4.2 mm value used in these measurements [5]. It may thus be possible to reduce the injector emittance performance below the measured 0.20 (mm-mrad) by optimizing the ion extraction system. Injector work has shifted to increasing extraction voltage stability in order to meet the 98% reliability requirement.

References

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[8] R. Ferdinand, private communication and to be published.
RECENT OPERATING EXPERIENCE WITH THE
H+ ION INJECTOR AT LAMPF/LANSCE

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Abstract
A cusp-field, cesium conversion ion source has provided H+ beams at LAMPF/LANSCE since 1984. Three interchangeable sources are now used during beam production cycles to minimize down-time during scheduled source change-outs. Ion source change-outs are scheduled to prevent unscheduled loss of beam time due to finite filament lifetime. Ion source operating parameters and filament lifetime data are presented.

Introduction
A surface conversion H+ ion source has been in use at LAMPF (now the Los Alamos Neutron Science Center, LANSCE) since 1984. References [1] and [2] describe the development of this ion source; the recent operation of the ion source is described below. From 1984 to 1993 two sources were used during production cycles. One source was used for beam production while the other source was made ready for operation. In 1991 an off-line processing stand came into use to shorten time required to bring a fresh source into production capable condition. In 1993, a third ion source was assembled and added to the rotating inventory of sources used during LANSCE production cycles in 1994. We have found that having three ion sources available during production cycles allows not only for a smooth transition during a scheduled maintenance period but also offers the additional advantage of having a back-up source available should something unforeseen occur, either during the recycle or at some time during production.

Ion Source Operation
During normal operation for production the H+ Ion Injector is expected to continuously deliver approximately 16 mA of quiescent (≤ 1% noise) 750 kV beam with an emittance (phase space area) of 4 μcm-mrad (for 98% beam fraction) to ground level where it is then transported to the linac for final acceleration to 800 MeV. The 750 kV beam is produced by operating the ion source on an 80 keV transport system located inside the equipment dome of a 670 kV Cockcroft-Walton. The transport system inside the dome consists of an 80 keV accelerating column mounted on a two-solenoid transport. The transport also has provision for beam steering[1]. A beam deflector between the two solenoids permits changing the length and repetition rate of the beam pulse delivered to ground while the ion source operates at a continuous duty factor of almost 10%.

The ion source duty factor is determined by the rate and length of time at which the hydrogen discharge is pulsed by modulating the arc voltage with a solid-state switch. During recent years the discharge has operated at a length of 815 μsec at a repetition rate of 120 Hz. All other power supplies for source operation run continuously d.c. Recent ion source operating parameters are given in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Normal Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc Voltage</td>
<td>V</td>
<td>190 to 200</td>
</tr>
<tr>
<td>Arc Current</td>
<td>A</td>
<td>35 to 45</td>
</tr>
<tr>
<td>Pulse Repetition Rate</td>
<td>Hz</td>
<td>120</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>μsec</td>
<td>815</td>
</tr>
<tr>
<td>Filament Voltage</td>
<td>V</td>
<td>11 to 13</td>
</tr>
<tr>
<td>Filament Current</td>
<td>A</td>
<td>86 to 96</td>
</tr>
<tr>
<td>Converter Voltage</td>
<td>V</td>
<td>250</td>
</tr>
<tr>
<td>Converter Current</td>
<td>A</td>
<td>0.4 to 0.8</td>
</tr>
<tr>
<td>Hydrogen Flow</td>
<td>sccm</td>
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</tr>
<tr>
<td>Cesium Temperature</td>
<td>ºC</td>
<td>165 to 185</td>
</tr>
<tr>
<td>Repeller Voltage</td>
<td>V</td>
<td>0</td>
</tr>
<tr>
<td>Accelerating Voltage</td>
<td>kV</td>
<td>80</td>
</tr>
<tr>
<td>Drain Current @ 80 kV</td>
<td>mA</td>
<td>5 to 7</td>
</tr>
<tr>
<td>Beam Current</td>
<td>mA</td>
<td>18 to 20</td>
</tr>
<tr>
<td>Electron Component</td>
<td>mA</td>
<td>2 to 3</td>
</tr>
<tr>
<td>a. Power Supply</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. Measured at approximate midpoint of two-solenoid transport</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Refurbished ion sources are pre-conditioned and stored under vacuum on a processing stand dedicated to this purpose. The ion source processing (see below) requires running a pure hydrogen discharge, with no cesium added to the discharge. An ion source thus prepared is installed in the injector high voltage dome at scheduled intervals of four weeks. The time scheduled for removing the used source and return to production quality beam with the new one is two days. Linac development experiments are often performed at the end of the scheduled source change-out, however, so it is desirable to return to production quality beam as quickly as possible.

The determining factor for the length of time required for the change-out is most often the relative ease of which is called the cesium transfer. The transfer of cesium from the external reservoir (by ohmic heating) is started only after the discharge reaches a minimum pulsed current of 25 to 30 amps. In the first several hours of operation it is often necessary to raise the filament currents above their eventual operating points to attain this initial discharge current. In this ion source cesium...
is continuously deposited on the converter to enhance the \( \text{H}^+ \) ion production from plasma-generated \( \text{H}^+ \) ions striking the converter surface. The attainment of the proper rate of cesium evolution to both coat the converter for production of the \( \text{H}^+ \) ions and maintain the coating as the source conditions is a somewhat unpredictable process. It is an equilibrium process that depends not only on the temperature of the cesium reservoir, but also on other parameters such as discharge and filament power, hydrogen flow rate, and converter voltage. It is possible to over-cesiate the source and thus have problems with sparking or to under-cesiate and not produce sufficient \( \text{H}^+ \) beam current. When the cesium transfer has gone very smoothly, it has been possible for the linac to be delivering beam to target in as little as nine to twelve hours from the start of the change-out. A more realistic expectation for the length of time required to return to production-quality beam is twenty-four hours.

Other than unexpected difficulties, the arc down rate of the 80 kV accelerating column is usually the only factor that can cause delays in the return to quality beam production. Prior to the advent of the processing stand mentioned below, the 80 kV column arc-down rate was a problem that often took many hours to overcome by conditioning of the three column gaps.

The column conditioning procedure, when necessary, now takes approximately three hours to complete. During the most recent LANSCE extended maintenance period we disassembled and cleaned all elements of the column. We have not had to condition it since it was re-installed on the dome transport and have thus saved three hours of time during the change-over.

**Processing Stand**

An off-line, cryopumped processing stand is used to pre-condition and store under vacuum the two ion sources that are not in use for production. The processing stand has all the power supplies and equipment necessary to run a discharge in an ion source.

When a source is removed from production service it is refurbished before being placed on the processing stand. The cesium accumulated during the four weeks of continuous operation is removed from all surfaces, new filaments are installed, and the cesium reservoir is cleaned and refilled with fresh cesium.

The source is then mounted on the stand and tested for both vacuum leaks and water leaks. It is then operated to produce an un-cesiated discharge of 25 to 30 amps. This process removes undesirable residues that may remain from the cleaning and re-assembly procedures. It is this initial source operation that caused voltage-holding problems with the 80 kV column in the \( \text{H}^+ \) injector dome prior to the use of the processing stand.

The filament side-plates are then carefully removed and cleaned of tungsten deposited during the first operation and the source body is wiped out. The ion source is then operated again. The last step of this processing procedure is to briefly open the valve on the cesium reservoir to pump out any residual argon from the filling procedure. The ion source is then left under vacuum on the processing stand until it is needed for production service in the injector dome. The approximately 16 hours of filament usage during processing is not included in the lifetime prediction calculations mentioned below.

**Filament Lifetime**

The ion source is scheduled to continuously deliver beam for four weeks between scheduled change-outs. The determining factor for the interval between change-outs is the finite lifetime of the 0.15 cm diameter tungsten wire filaments. Daily filament current measurements at a specified voltage provide a resistance measurement of each filament that is compared to its resistance at the beginning of the change-out. This yields an evaporation rate for each filament. The remaining filament lifetime is then estimated by comparing the least-squares fit of the last five days of data with the assumption that the filament will break open once it attains 12% evaporation. The graphical presentation of such data for a well-behaved filament pair is shown below in Figure 1.

Filaments do not always behave as well as those shown in the figure. If a hot spot develops because of a weak point somewhere along the filament length then the evaporation curve will often begin to take on a strongly quadratic, if not exponential character. Such behavior generally means that the filament will fail in only a day or two. The daily acquisition of filament evaporation data thus serves to provide an indication of impending premature failure and we can be prepared to perform an unscheduled change-out.

![Fig. 1. Filament lifetime data. The number of days of remaining lifetime is based on the assumption of filament failure at 12% evaporation.](image)

Filaments are formed on a mandrel designed to produce filaments of the desired shape. The mandrel consists of circular brass pegs of different diameters arrayed in an arc on an aluminum plate. The 0.15 cm diameter, 29 cm long tungsten filament wire is bent around the pegs to produce a filament. Figure 2 depicts the way in which the brass pegs are arrayed and also shows the shape of the filament that is produced. Not shown are the tag ends of the filament which are bent at 30° to attach the filament to the filament posts. The bending of the stiff tungsten welding rod used for the filaments is made somewhat easier by using a 2000 watt heat-
gun to locally heat the tungsten rod as it is passed around the forming pegs.

Fig. 2. Filament mandrel and filament. The figure shows how the tungsten wire is bent around the mandrel pegs to form the filament, as described in the text.

Bending of the straight tungsten wire welding rod used to form the desired filament shape can introduce stress points that are prone to forming hot spots, the suspected cause of premature filament failure. We have recently been using the forming mandrel in a different way to reduce the amount of induced stress when filaments are formed. The forming pegs are inserted into the mandrel sequentially as the filament wire is bent around them. This removes the stress induced by lifting the straight wire out of the plane of the mandrel base to pass over pegs not yet used in the bending process. Filaments formed in this manner have not failed because of hot spot formation.

Summary

Three ion sources used in rotation allow us to smoothly change out a source with limited remaining lifetime and replace it with a fresh one.

An off-line processing stand is maintained for the pre-conditioning of ion sources after they have been cleaned and supplied with new filaments. Its use diminishes voltage-holding difficulties that used to occur when ion sources were changed.

At least one potential cause of premature filament failure due to hot spot formation has been mitigated by using the filament forming mandrel in a different way.

References

A DESIGN APPROACH FOR SUPERconducting HIGH-CURRENT ION LINACS

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Abstract

An approach for designing superconducting high-current ion linacs is described. This approach takes advantage of the large velocity acceptance of high-gradient cavities with a small number of cells. It is well known that this feature leads to a linac design with great operational flexibility. Algorithms which have been incorporated into a design code and a beam dynamics code are discussed. Simulation results using these algorithms are also presented.

Introduction

The work presented here is part of an ongoing effort [1] to design reliable, low-loss, high-current, cw superconducting ion linacs for applications such as accelerator transmutation of waste, the next generation spallation neutron sources, and accelerator production of tritium. We have limited our effort to the design and simulation of a 100-1000 MeV, 100mA, cw linac which uses independently-phased elliptical multicell superconducting rf cavities to accelerate a proton beam. However, our approach should be more generally applicable. The expressions presented below can be used to determine the linac cavity parameters such as the number of cells/cavity, the velocity range over which a cavity can efficiently accelerate beam, and the required cavity gradient.

Our approach takes advantage of the large velocity acceptance of high-gradient superconducting cavities. An analytic model of multi-cell elliptical cavities excited in a π-mode was used to determine the initial cavity parameters. A simple cavity field distribution was assumed where the fields are uniform in the gaps and fall to zero immediately outside the gaps. With this assumption, an approximate expression for the transit-time factor $T$ can be given as a product of two separate factors $T = T_G T_S$. The gap factor $T_G$ is the transit time for a gap of length $g$ and is given by the expression $T_G = \sin(\pi g / \beta \lambda) / (\pi g / \beta \lambda)$. The synchronism factor $T_S$, is a function of the number of cells per cavity $N$ and of the ratio of the reference-particle velocity, $\beta$, to the cavity geometric velocity, $\beta_G$. The synchronism factor is given by:

$$T_S(N, \beta / \beta_G) = \begin{cases} \frac{(\pi g)^{N-1} \sin(\pi g / \beta G)}{\beta G / 2} / N \cos(\pi g / \beta G) / 2 \beta, \quad N \text{ odd} \\ \frac{(\pi g)^{N+1} \sin(\pi g / \beta G)}{\beta G / 2} / N \cos(\pi g / \beta G) / 2 \beta, \quad N \text{ even} \end{cases}$$  (1)

where $g = \beta_G \lambda / 2$. Figure 1 shows the model predictions for the transit-time factor $T$ for various numbers of cells/cavity as a function of the ratio $\beta / \beta_G$. In order to choose the number of cells per cavity, a compromise must be made between many competing effects. As can be seen in the figure, a small number of cells/cavity provides a large velocity acceptance. Additionally, the power-coupler levels, for a given beam current and field, are lower and the cavity field uniformity is easier to maintain. Using a larger number of cells has the advantage of reducing the overall number of system components, system size, and system complexity. In our design example, we have chosen 4 cells/cavity.

![Fig. 1. Transit-time factor from the model versus $\beta / \beta_G$.](image)

The rf power required to accelerate the beam can be expressed as the product of the beam current times the energy gain per cavity:

$$P_C = I \Delta W = IE_o T(\beta) \cos(\phi) N \beta_G \lambda / 2.$$  (2)

Here, $I$ is the average beam current and $E_o$ is defined in terms of the spatial average of the axial accelerating field $E_o$ and the transit-time factor for the design velocity $T(\beta_D)$ as $E_o = E_o T(\beta_D)$; $T(\beta)$ is the transit-time factor at the reference-particle velocity $\beta$; $\phi$ is the phase of the field when the design particle is at the center of a cavity; and $N$ is the number of cells/cavity. The cell length equals $\beta_G \lambda / 2$, where $\lambda$ is the free-space wavelength. The design velocity $\beta_G$ is defined as the velocity that gives the maximum transit-time factor. The velocities, $\beta_D$ and $\beta_G$, are nearly, but not exactly, the same due to the gap factor, which increases with increasing particle velocity. This can be seen in Fig. 1. A higher velocity particle spends less time in the gap, experiencing a smaller transit-time reduction. The relation between $\beta_D$ and $\beta_G$.

*Work supported by the U. S. Department of Energy
depends on the number of cells/cavity. For a 4-cell cavity, \( \beta_D = 1.05 \beta_G \).

The transit-time factor decreases as the reference-particle velocity \( \beta \) varies from \( \beta_D \). In order to efficiently accelerate the beam, we have arbitrarily allowed the transit-time factor to decrease no more than 20% of the maximum value for a given cavity of \( N \) cells. Equation 1 can be used to determine the velocity limits for a given constant-\( \beta \) section (all identical cavities) if the number of cells/cavity has been chosen. For a 4-cell cavity, it is found that \( T(\beta)/T(\beta_D) = 0.8 \) at \( \beta/\beta_G = 0.879 \) and 1.283. If the beam velocity is specified at either end of the section, \( \beta_G \), \( \beta_D \), and the \( \beta \) at the other end of the section can be calculated from these ratios. For our design example with a starting \( \beta_{\text{min}} = 0.425 \) (98.3 MeV) and using the \( \beta/\beta_G \) ratios above, \( \beta_G = 0.484 \), \( \beta_D = 0.506 \), and \( \beta_{\text{max}} = 0.620 \) (261 MeV). Iteration for the next section gave \( \beta_G = 0.706 \) and \( \beta_{\text{max}} = 0.906 \) (1276 MeV). Therefore, for our example only two cavity regimes are required (2 sections). We will call the 100-261 MeV section the medium-\( \beta \) section and the 261-1000 MeV section the high-\( \beta \) section.

The amount of power per cavity available to accelerate the beam is limited by rf power coupler capacity. We have assumed a conservative maximum capacity of 105 kW per coupler and two couplers per cavity (210 kW maximum per cavity). To obtain good power efficiency, it is desirable to have all rf power couplers deliver power at their maximum capacity. Therefore, all cavities in a section will have an identical energy-gain per cavity if \( E_a \) is allowed to vary over the section. A 20% variation in \( E_a \) over the section will be required to maintain a constant value of \( E_a T(\beta) \) over the entire velocity range due to the constraint \( T(\beta)/T(\beta_D) \geq 0.8 \).

We have used the energy gain per cavity of the high-\( \beta \) section, since it contains the largest number of cavities, to constrain the accelerating gradient throughout the linac. The energy gain per cavity can be calculated using Eqn. 2. For \( I = 100 \) mA and \( P_C = 210 \) kW, the energy gain per cavity is 2.10 MeV. For our design example, we have chosen \( \phi = -35^\circ \), \( N = 4 \), and \( \lambda = 0.428 \) (700 MHz) which results in a value of \( E_a T(\beta)/T(\beta_D) = E_a T(\beta) = 4.24 \) MV/m. This is a relatively conservative accelerating gradient for superconducting cavities and will be used for both sections of the linac in our example. The energy gain/cavity for the medium-\( \beta \) section is reduced by the ratio of the medium-\( \beta \) to high-\( \beta \) cell lengths and is 1.44 MeV.

**Design Algorithm**

In order to generate a linac design, a computer design program was written which uses an iterative procedure to determine the required rf field amplitude and injection phase for each cavity such that the desired energy gain per cavity, \( \Delta W \), and average synchronous phase is achieved. In order to achieve this, the cavity rf amplitudes must vary as a function of beam energy to compensate for the variation in the transit-time factor.

The algorithm we have used is an iteration procedure which can be used to generate a linac cavity-by-cavity. It assumes that \( \Delta W \), \( \beta_G \), and \( \phi \) are specified, and that \( T(\beta) \) can be calculated. A polynomial fit obtained from actual elliptical cavity shapes, developed using the MAFIA codes, was used to specify \( T(\beta) \). Initial guesses for the injection phase(\( \phi_{\text{in}} \)), at the center of the first gap, and cavity field (\( E_a \)) are calculated using the expressions:

\[
E_a = \frac{\Delta W}{(N \beta_G/2) T_{\text{ave}} \cos \phi},
\]

\[
\phi_{\text{in}} = \phi - \frac{\pi}{2} (N - 1) \left( \frac{\beta_G}{\beta_{\text{ave}}} - 1 \right)
\]

where \( \phi \) is the phase of the field when the design particle is at the center of a cavity (average phase) and \( \beta_{\text{ave}} \) is the average velocity calculated using the average beam energy in the cavity, \( \sqrt{W_{\text{ave}} = W_{\text{in}} + 1/2 \Delta W} \). The average of the transit-time factors for the inner and end cells of a cavity, \( T_{\text{ave}} \), seen in Eqn. 3, is given by \( T_{\text{ave}}(\beta) = 1/N (2T_{\text{out}} + (N - 2)T_{\text{inner}}) \). These transit-time factors differ because of the field leakage at the end cells into the beam pipe due to the large cavity bore. Equation 4 is merely a phase shift from the physical center of the multi-cell cavity back to the center of the first gap seen by the beam.

Next, an integration over all \( N \)-cells in the cavity is performed to determine the beam output energy (\( W_{\text{out}} \)) and phase (\( \phi_{\text{out}} \)) using:

\[
W_{\text{out}} = W_{\text{in}} + \sum_{k=1}^{N} E_a T_k (\beta_k) \frac{\beta_G \lambda}{2} \cos \phi_k
\]

and

\[
\phi_{\text{out}} = \phi_{\text{in}} - \sum_{k=1}^{N} \pi \left( 1 - \frac{\beta_{\text{ave}}}{\beta_k} \right)
\]

The average cavity phase is then calculated from \( \phi_{\text{in}} \) and \( \phi_{\text{out}} \), and is compared to the desired average phase. We have required that these two average phases agree to within 0.05°. If not, a new guess for the injection phase is made using \( \phi_{\text{in,new}} = \phi - 1/2(\phi_{\text{out}} - \phi_{\text{in}}) \), and a new iteration is begun. Once an injection phase for the cavity has been determined, a comparison is also made between the calculated energy gain and the desired energy gain. If the difference in energy gain is greater than 1 keV, a new guess for the cavity field is determined using \( E_{a,\text{new}} = E_a \frac{\Delta W_{\text{desired}}}{\Delta W} \), and a new iteration is begun. We have found this algorithm to converge rapidly.

**Simulation Results**

In order to perform simulations using the results of the design code, a beam dynamics simulation code to model
elliptical superconducting cavities was written. This code is not discussed here, only the simulation results. It should be noted that the linac example presented here is unoptimized. We have chosen conservative requirements for the various system components, most of which have already been demonstrated in existing accelerators or laboratory tests.

Table 1 gives some of the accelerator parameters. The linac consists of two sections (medium-β and high-β). Each section is composed of identical 4-cell elliptical cavities, with cell lengths equal to \( \beta_G \lambda / 2 \). The \( \beta_G \) values for the two sections are \( \beta_G = 0.48 \) and \( \beta_G = 0.71 \), as discussed earlier. A cryostat containing two cavities forms a cryomodule. In this example, transverse focusing is provided by quadrupole doublets between each cryomodule. The power from each klystron would be split among four cavities and fed to each cavity using two antenna-type power couplers, each capable of handling 105 kW.

Table 1 - High-Energy Superconducting Accelerator Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>100 - 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range (MeV)</td>
<td>100 - 1000</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>700</td>
</tr>
<tr>
<td>Beam Current (mA)</td>
<td>100</td>
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<tr>
<td>No. of β Sections</td>
<td>2</td>
</tr>
<tr>
<td>No. of Cavities</td>
<td>488</td>
</tr>
<tr>
<td>No. of Cryostats</td>
<td>244</td>
</tr>
<tr>
<td>No. of klystrons</td>
<td>122</td>
</tr>
<tr>
<td>Cavities/Cryostat</td>
<td>2</td>
</tr>
<tr>
<td>Cavities/Klystron</td>
<td>4</td>
</tr>
<tr>
<td>Cells/Cavity</td>
<td>4</td>
</tr>
<tr>
<td>RF Couplers/Cavity</td>
<td>2</td>
</tr>
<tr>
<td>RF Power/Klystron (MW)</td>
<td>0.67 (med.-β), 1.0 (high-β)</td>
</tr>
<tr>
<td>RF Power/Coupler (kW)</td>
<td>72 (med.-β), 105 (high-β)</td>
</tr>
<tr>
<td>Accelerating Field, ( E_a ) (MV/m)</td>
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</tr>
<tr>
<td>Average Phase (deg)</td>
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</tr>
<tr>
<td>Aperture Radius (cm)</td>
<td>5.0 (med.-β), 7.2 (high-β)</td>
</tr>
</tbody>
</table>

Simulation results for the ideal linac show emittance growths from 100-1000 MeV of 25% and 8%, respectively, for the transverse and longitudinal degrees of freedom. We have used the ratio of transverse aperture radius to rms beam size as a figure of merit in our designs. For this example, our simulation results show this ratio ranges from 19 to 26, which is comparable to past results for room-temperature designs.

The large velocity acceptance of these cavities allows operational flexibility. In normal operation, the multi-cell cavities will be operated for a specific energy gain per cavity (medium-β \( \Delta W = 1.44 \) MeV, high-β \( \Delta W = 2.1 \) MeV) with an average synchronous phase of -35°. To investigate alternative operating schemes that use the inherent flexibility of a linac built from independently-phased resonators, three examples were simulated. The simulation results are given in Table 2, below. Case 1 assumes that all cavities will be operated at a constant accelerating field of \( E_a = 5.3 \) MV/m. This is the maximum field under normal operating conditions. In this scheme, the energy gain per cavity is no longer fixed. We have assumed a cavity average synchronous phase of -35°. As can be seen, the beam output energy is raised by 99 MeV. The changes in output beam emittances and ratio of transverse aperture to rms beam size are small. Also shown in Table 2 is the minimum required beam current to produce 100-MW output beam power at 1099 MeV. This example demonstrates an alternative operating scheme which could be used in the event of source output current degradation. In Case 2, the average synchronous phase has been reduced to -25°. As is expected, the output energy is further increased to 1179 MeV. In Case 3, the cavity fields have been increased by 33%. This scheme demonstrates a possible upgrade path, which would require significantly increased power-coupler capabilities and klystron output to produce 130 MW of beam power, without requiring additional accelerating cavities. In the last two schemes, there is a slight degradation in the ratio of transverse aperture to rms beam size. Transverse emittance growth is observed in all cases, which is comparable to the 25% observed for the nominal operating mode. The effects of emittance growth on beam uniformity at a neutron production target have not been studied.

Table 2 - Alternative operating schemes for the high-energy superconducting option. Required beam current is the beam current required to produce a 100-MW beam power.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1</td>
<td>1099</td>
<td>17%</td>
<td>-5%</td>
<td>91 mA</td>
<td>18.21</td>
</tr>
<tr>
<td>2</td>
<td>1179</td>
<td>32%</td>
<td>98%</td>
<td>85 mA</td>
<td>18.20</td>
</tr>
<tr>
<td>3</td>
<td>1297</td>
<td>19%</td>
<td>-4%</td>
<td>77 mA</td>
<td>17.20</td>
</tr>
</tbody>
</table>

Experience at operating superconducting accelerator facilities has shown that often there is a large variation in the maximum accelerating gradients achieved in identical multi-cell accelerating cavities. Typically these are \( \beta_G = 1 \) cavities used to accelerate electron beams. If cavities fail or perform at lower than expected accelerating gradients, the gradients and rf phases in the other cavities are adjusted to compensate and provide the required additional energy gain. A possible solution to increase machine availability is to provide additional accelerating cavities, thus anticipating some fraction of cavity failures. We simulated a case where 5% of the total cavities were failed (every 20th cavity off) with 5% additional cavities added to the high-β section. Simulation results, using a simple algorithm for setting the cavity phases, showed a transmission of 100% with a reduced output beam energy of 993.4 MeV for this case. Small adjustments of the phases should restore the correct final beam energy. The transverse and longitudinal emittances were observed to grow by factors of 2.9 and 6.8, respectively; however, only small reductions in the aperture to rms values were observed.

References

CONVENTIONAL AND SUPERCONDUCTING RF LINAC DESIGNS FOR THE APT PROJECT

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Abstract

The proton linac for the APT (Accelerator Production of Tritium) project will produce a nominal CW beam power of 130 MW at 1300 MeV. Two designs are currently under consideration. The reference design is composed entirely of normal-conducting (NC) copper accelerating structures, while an advanced-technology design employs superconducting (SC) niobium cavities above 217 MeV. The front-end accelerator for both concepts is a 100-mA NC linac. In this paper, the two APT linac designs are described and compared in terms of key factors, including power efficiency, beam loss control, machine availability and flexibility, and construction and operating costs.

Introduction

The overall design of the APT linac, which has a very high beam power, is driven strongly by the large amount of rf power required. Efficient conversion is needed at each stage in the power train to minimize system capital and operating costs. The selection range for basic accelerator parameters [1] (current, energy, accelerating gradient) is determined by the plant production capacity, using a cost-performance model that is based on the energy-dependence of spallation neutron production in high-Z targets, and which includes unit cost estimates for major components and consumables (electricity). Superimposed on this model are technical constraints, including injector current limits and the relationships between peak current, frequency, and beam emittance in low-beta structures.

Normal-Conducting Linac Design

The reference APT linac design is based on copper water-cooled accelerating cavities, and has evolved significantly since it was first presented [2-4]. The NC linac architecture is illustrated in Fig. 1, with additional parameters listed in Table 1. A 75-kV injector housing a microwave-driven ion source [5] generates a continuous 110-mA proton beam. From this input, a 350-MHz, 8-m-long RFQ produces a CW 100-mA beam at 6.7 MeV. The RFQ is built in four segments that are resonantly coupled. RF drive is provided by three 1.2-MW CW klystrons through 250-kW windows.

The RFQ output beam is matched to a 700-MHz CCDTL that accelerates it to 100 MeV. The CCDTL [6] is made up of short sequences of 2-gap and 3-gap accelerating structures embedded within a FODO focusing lattice; quadrupoles are external. Acceleration to the final energy of 1300 MeV is in a 700-MHz side-coupled π/2-mode linac that continues the same (8-βA) focusing period. Fig. 2, shows the transition between CCDTL and CCL. The average accelerating gradient (EaT) is ramped up in the CCDTL and in the first 55 MeV of the CCL to reach 1.3 MV/m, and is held constant thereafter. In general, the linac accelerating and focusing parameters change very smoothly as beta increases [7].

Fig. 1. Architecture of normal-conducting linac design.

Table 1. NC Linac Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RFQ</th>
<th>CCDTL</th>
<th>CCL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure gradient (MV/m)</td>
<td>1.38</td>
<td>1.10-1.57</td>
<td>1.57-1.49</td>
</tr>
<tr>
<td>Avg. gradient (MV/m)</td>
<td>1.38</td>
<td>0.41-1.18</td>
<td>1.18-1.30</td>
</tr>
<tr>
<td>Length (m)</td>
<td>8.0</td>
<td>113.0</td>
<td>1166.3</td>
</tr>
<tr>
<td>Synchronous phase (deg)</td>
<td>-90 to -60</td>
<td>-60 to -30</td>
<td>-30</td>
</tr>
<tr>
<td>Avg. shunt. impedance (MΩ/m)</td>
<td>–</td>
<td>18-33</td>
<td>33-47</td>
</tr>
<tr>
<td>Phase advance (deg)</td>
<td>–</td>
<td>80</td>
<td>80-35</td>
</tr>
<tr>
<td>Quadrupole lattice period</td>
<td>–</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>No. of quadrupoles</td>
<td>–</td>
<td>234</td>
<td>826</td>
</tr>
<tr>
<td>Quadrupole gradient (T/m)</td>
<td>–</td>
<td>87.5</td>
<td>87.5</td>
</tr>
<tr>
<td>Trans. emittance (π mm-mrad)*</td>
<td>0.22</td>
<td>0.23</td>
<td>0.23</td>
</tr>
<tr>
<td>Long. emittance (π deg-MeV)*</td>
<td>0.214</td>
<td>0.450</td>
<td>0.482</td>
</tr>
<tr>
<td>Aperture radius (cm)</td>
<td>0.23-0.34</td>
<td>1.0-1.75</td>
<td>1.75-2.50</td>
</tr>
<tr>
<td>Aperture-radius/rms-beam-size</td>
<td>–</td>
<td>5-13</td>
<td>13-26</td>
</tr>
<tr>
<td>Copper power losses (MW)</td>
<td>1.26</td>
<td>5.0</td>
<td>54.9</td>
</tr>
<tr>
<td>Number of klystrons</td>
<td>3</td>
<td>21</td>
<td>249</td>
</tr>
</tbody>
</table>

* Normalized rms values.

The result is an accelerator design that has strong focusing at low beam energy and is free from phase-space transitions after the RFQ. Beam dynamics analyses and simulations [8,9] have shown these factors to be important in terms of minimizing core emittance growth and the growth of beam halo. As shown in Table 1, the transverse emittance growth is negligible after 20 MeV and longitudinal emittance grows only slightly.

Fig. 2. Transition from CCDTL structure to CCL at 100 MeV

Another design feature is that the cavity and quadrupole aperture dimension increases in steps to 5 cm in the high-energy part of the linac, while the rms beam size shrinks gradually. Fig. 3 shows the dependence of these parameters on beam energy. Also plotted is the transverse position of the proton furthest from the beam core in a typical 100,000 particle simulation. At full energy, the aperture ratio (aper-
ture-to-rms-beam-size) is 25, and at 100 MeV it is 13. The average gradient of 1.3 MV/m in the CCL is high enough to allow a relatively short linac, without producing excessive rf power losses in the copper cavities. Total cavity wall losses in the CCDDTL and CCL are 5.0 MW and 54.9 MW respectively. Power deposition per unit length in the CCL is 50-60 kW/m. Both the CCDDTL and CCL are driven by 1-MW 700-MHz klystrons through 250-kW windows (tested to > 500 kW).

Fig. 3. Aperture radius, rms beam size, radius of outermost particle.

In order to meet the high availability goal for the APT linac (> 85%), a redundancy scheme is employed for the rf stations, using the accelerating structure itself as a power combiner. The linac is sectioned into "supermodules", each consisting of 100-150 side-coupled accelerating cells, and each provided with n+1 klystrons (typically 5 to 7), where only n units are needed for operation. When an rf station fails, it is isolated by a waveguide switch, and the supermodule continues to provide the full energy gain needed in that section.

Assuming an average plant availability of 75%, the reference APT linac is capable of producing tritium at the rate of 2 kg/yr, with a target design that includes a 10% performance margin. Therefore, the beam power needed to increase plant production capacity to 3 kg/yr (with zero margin) is 174 MW at 1300 MeV. The upgrade path would be to increase the proton current to 134 mA, which would be accomplished by adding a second low energy linac and funneling the two 350-MHz beams at 20 MeV [10]. About 1/3 more rf stations would be added in the high-energy part of the linac to provide the increased beam power.

Superconducting RF Linac Design

A superconducting rf (SC) linac made up of niobium cavities is currently being evaluated as a replacement for the high-energy portion of the APT linac. A feasibility study [11] showed that a SC high-energy linac would reduce the plant electric power demand by 20-25%, and could also offer important technical and operational advantages, including lower beam loss, current/energy flexibility, and improved availability. Fig. 4 shows the architecture for a hybrid SC/NC accelerator design now being developed for the APT project. It consists of a 100-mA NC linac injecting into a SC linac at an energy of 217 MeV. Output energy of the SC linac is 1300 MeV for 2-kg/yr production. The low-energy linac is nearly identical to the front end of the reference NC linac described earlier. The SC linac is composed of cryomodules that contain three or four 5-cell 700-MHz accelerating cavities, alternating with SC quadrupoles in a FODO focusing lattice. There are two kinds of cryomodules; each designed for efficient acceleration in a different energy/velocity range. Cavities in the medium-energy section (from 217 MeV to 469 MeV) are optimized at $\beta = 0.64$, and in the high-energy section at $\beta = 0.82$. Cavity shapes are modeled on the well-established elliptical designs for electron machines, but are compressed along the longitudinal axis in proportion to beta.

Fig. 4. Architecture of SC/NC hybrid linac design.

Fig. 5 shows a $\beta = 0.82$ cryomodule, which holds four 5-cell cavities, and five quads. Each cavity is fed by two coaxial rf power couplers, and each cavity pair is supplied by a single 1-MW klystron. The magnets have SC coils and iron poles, and are similar in design to the RHIC trim quads. The medium-beta ($\beta = 0.64$) cryomodules contain three 5-cell cavities, which are powered by one 1-MW klystron, and four quads. Because of the short independently-driven cavities, each section of the SC linac has a very broad velocity bandwidth, which allows the gradient profile of the linac and its output energy to be adjusted over a wide range. About 5% of the accelerating cavities and rf stations are in an operational reserve distributed along the linac to compensate for failed units.

Fig. 5. High-beta cryomodule ($\beta = 0.82$) for SC linac.

The production upgrade to 3 kg/yr for the SC linac is to raise the gradient in the high-beta section, increasing the beam energy to 1700 MeV and increasing the beam power to 170 MW. Initial structure gradients for this section have been set at a rather low value (4.1 MV/m), so that a 50% increase can be accommodated at the higher production level.

Because of the high beam current in the APT linac, a major design issue is the power coupler capability. Adjustable antenna-type coaxial couplers are envisioned, with rf windows in the warm region. Since coupler performance with beam has been demonstrated at about 150 kW, and the technology is advancing rapidly, an initial rating of 140 kW per coupler has been specified, with an upgrade to 210 kW in the high-beta section for operation at 3 kg/yr. Table 2. lists key parameters of the two sections of the SC linac ($\beta = 0.64$, $\beta = 0.82$), as well as the last section of the NC linac (100-217 MeV CCL).

The SC-cavity linac can have much larger apertures than the NC linac without incurring significant power penalties. Initial beam simulations show that emittance values are
somewhat larger than in the NC linac, but the resulting aperture ratios are nevertheless much greater, ranging from 35 (at 217 MeV) to 45 (at 1300 MeV).

Table 2. SC Linac Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CCL</th>
<th>β=0.64</th>
<th>β=0.82</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure gradient (MV/m)</td>
<td>1.57-1.49</td>
<td>5.5</td>
<td>4.1 (6.4)</td>
</tr>
<tr>
<td>Avg. gradient (MV/m)</td>
<td>1.18-1.30</td>
<td>1.54</td>
<td>1.26 (1.89)</td>
</tr>
<tr>
<td>Peak surface field (MV/m)</td>
<td>–</td>
<td>19.1</td>
<td>12.7 (19.1)</td>
</tr>
<tr>
<td>Section length (m)</td>
<td>100.7</td>
<td>204</td>
<td>792</td>
</tr>
<tr>
<td>No. of (5-cell) SC cavities</td>
<td>–</td>
<td>90</td>
<td>312</td>
</tr>
<tr>
<td>No. of klystrons (1-MW)</td>
<td>34</td>
<td>30</td>
<td>156</td>
</tr>
<tr>
<td>Synchronous phase (deg)</td>
<td>-30</td>
<td>-38 to -35</td>
<td>-29</td>
</tr>
<tr>
<td>Coupler power (kW)</td>
<td>–</td>
<td>140</td>
<td>140 (210)</td>
</tr>
<tr>
<td>Power per klystron (kW)</td>
<td>850</td>
<td>840</td>
<td>560 (840)</td>
</tr>
<tr>
<td>Trans. phase adv./period (deg)</td>
<td>80-35</td>
<td>81.5-66.7</td>
<td>81.2-79.0</td>
</tr>
<tr>
<td>Quadrupole length (cm)</td>
<td>5.4</td>
<td>30.5</td>
<td>45.9</td>
</tr>
<tr>
<td>No. of quadrupoles</td>
<td>125</td>
<td>120</td>
<td>390</td>
</tr>
<tr>
<td>Quadrupole gradient (T/m)</td>
<td>87.5</td>
<td>6.4-8.1</td>
<td>5.4 - 12.6</td>
</tr>
<tr>
<td>Trans. emittance (x mm-mrad)</td>
<td>0.23-0.29</td>
<td>0.29</td>
<td>0.33</td>
</tr>
<tr>
<td>Long. emittance (x deg-MeV)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Aperture radius (cm)</td>
<td>1.75-2.5</td>
<td>6.5</td>
<td>8.0</td>
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<tr>
<td>Aperture-radii/beam-size</td>
<td>13-17</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>Thermal load @ 1.9k (kW)</td>
<td>–</td>
<td>2.0</td>
<td>6.1 (9.2)</td>
</tr>
</tbody>
</table>

* 100-217 MeV section. Numbers in parentheses are for 3-kg/yr.

Design Issues and Comparisons

The NC and SC linac point designs developed for APT have matured to the point that comparisons can be made with respect to major criteria, including 1) construction and operating cost, 2) power efficiency, 3) beam loss, 4) availability, and 5) operational flexibility.

Preliminary estimates show that construction costs would be similar, with a modest (5-10%) advantage to the SC linac. Greater unit costs for the accelerating structures are offset by the smaller rf power installation. Refrigeration system costs are nearly balanced by reduced water cooling system costs. Annual operating costs for a SC-based APT plant will be significantly lower (15%) than for a NC-based plant due to reduced electric power requirements.

Electrical efficiency of the SC linac design is clearly greater than the NC design, (0.40 vs 0.33) because 48 MW of cavity rf losses are eliminated. The 8 MW needed to run the cryopant system is offset by reduced water-cooling pumping power and elimination of quadrupole magnet power in the SC linac.

The aperture ratio is much greater in the SC linac than in the NC linac, greatly reducing halo interception, and dramatically relaxing alignment and steering requirements. In terms of acceleration drive to the accelerator, the transition to a large aperture at about 200 MeV is advantageous, since neutron production ratios increase in this energy region.

The major source of unavailability for either of the linac designs lies in the large number of rf power stations and their critical components (klystrons, power supplies, etc.). In the NC linac, the supermodule architecture provides for many redundant station units, with each 25-MeV segment of the linac, allowing failures to occur without interrupting operation for more than a few minutes. In the SC linac, high availability is provided by the 5% reserve cavities and klystrons. After a failure, one of the reserve units is energized, and phases and amplitudes of the downstream linac are reset to maintain an optimum acceleration profile. Small changes in output energy that may result after retuning are tolerable because of the wide momentum acceptance of the HEBT and target system.

In the NC linac, the accelerating gradient and maximum beam energy are fixed by the beta profile of the long coupled chains of cavities, although operation at reduced energies is possible by turning off the highest-energy rf stations. In the SC linac, operational flexibility is enhanced by the retunability of the accelerator and the adjustability of the cavity gradients. It is practical to increase proton energy to compensate for reduced current to provide a given beam power. In both designs, electrical efficiency is highest when using the full capacity of the klystrons, so schemes for power-grid load leveling would be best implemented by turning off the final section of the linac.

We believe that either linac design is a practical approach to APT, but the SC linac would be superior in terms of operating cost, beam loss, availability risk, and operational flexibility. With respect to ED&D (engineering development and demonstration), the LEDA program [12] is prototyping the low-energy linac at full CW power. The high-energy NC linac needs little further ED&D. For the SC linac, cavity prototyping is needed, since the medium-beta cavity shapes differ from the (β=1) shapes used for electron accelerators. Confirmation of insensitivity to proton irradiation is another task. Finally, complete pre-production prototypes of the SC cryomodules must be built and tested; these are structurally different than existing units at CEBAF, CERN, DESY and KEK, because of the high density of quadrupole magnets. Programs to provide the needed tests and demonstrations are underway.

References

MEASUREMENTS AND NUMERICAL CALCULATIONS ON HIGHER-ORDER-MODE-DAMPERS WITHIN A STACK OF 36 DETUNED S-BAND-CELLS

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U. v. Rienen and T. Weiland, TH-Darmstadt, Germany
M. Dohls, DESY, Hamburg, Germany

Abstract

The wake field effects in accelerator sections for future linear colliders will be reduced either by damping, by detuning or a combination of both. In the case of the DESY S-band test linac it is foreseen to employ two HOM damped cells within a detuned stack of undamped ones. In order to obtain optimal performance by use of single cell dampers a design was derived by applying numerical tools. To understand the behaviour of such a damper cell in a detuned structure, a damper cell was build and inserted in a strongly detuned 36-cell S-band structure. This structure was investigated experimentally by perturbation measurements.

Introduction

The S-Band 500GeV Linear Collider Study SBLC foresees about 5000 constant-gradient (cg) acceleration structures of 180 cells with a loaded gradient of 17 MV/m. It considers a bunch train of 333 bunches with a spacing of 6ns from bunch to bunch. To achieve a high luminosity any cumulative beam break-up along the bunch train has to be avoided. Wakefield effects driven by HOMs are one of the primary sources of emittance growth. Consequently, the suppression of these HOMs is a very crucial point in all actual linear collider designs. The major interest of calculations was focussed on the modes of the first dipole band since they cause the severest deflecting effects, but also the 3rd and 6th dipole passband need to be studied.

Calculations for the SBLC structure were carried out with ORTHO [1] for a somewhat simplified 180–cell structure with 30 landings. One of the main results was that not only the first \( \pi \)-like dipole modes influence the beam dynamics but about 140 modes! A major part of these deflecting modes is trapped inside the cg structure, that is without contact to the end cells.

Since the phenomenon of trapped HOMs in tapered waveguides was neither theoretically nor experimentally well known and has a strong influence on the design of damping schemes further HOM investigations have been started: A test structure was designed with the goal to have a structure which is easy to measure, easy to manufacture, which is computable with different numerical methods (MAFIA, URME-L-T, ORTHO, COM) without geometric approximations, and which shows the clear appearance of trapped modes.

Performing RF-measurements on long structures is severely limited by the appearance of mode overlap. Therefore a relatively short structure had to be chosen. In order to get a both mechanically and thermally stable structure a massive design was chosen. For low mechanical tolerances a simple geometry was designed. The structure has a very strong linear tapering of the iris, constant outer radius and twice as thick irisses as the original SBLC structure. Comparisons of numerical calculations and measurements [2] gave a good agreement in resonance frequencies and the field distribution. Further the clear appearance of trapped modes was found for several modes.

The Test Setup

The structure, made of standard OFHC copper, consists of 36 cells clamped together by truss rods. Overall length is 1450mm, cut-off pipes of 100mm length are attached to each end of the structure. The cell geometry is similar to the one chosen for the SBLC, except for the iris thickness which is 10mm instead of 5mm. The iris openings were evenly tapered from 40mm diameter at the beginning to 20mm at the end.

Fig. 1: 36-cell-structure with damping-ring in cell #18

IAP-Frm

Fig. 2: Measurement setup with 36-cell structure

For the measurements of the damped structure we have inserted a sheet of paper covered with graphite in cell #18 (see Fig. 1). This damping material could be inserted without demounting of the structure. It is only a model for test purpose that represents a damping unit like a wall slotted cell with four rectangular waveguides attached. This method avoids the influence of changed electrical contacts due to the reassembling on the
measured Q-values. Proper alignment is ensured by laying the structure on top of an optical bench. The field measurements were performed using a modified nonresonant bead pull technique [3], [4], [5]. Data is taken by a HP8719c network analyser for 801 discrete positions along several paths parallel to the cavity axis. In Fig. 2 a picture of the test setup is shown.

The Measurement Method

The method applied is a variant of the nonresonant bead pull technique as described elsewhere [6]. In the measurements we are only interested in the longitudinal component of the electric field, because it is sufficient to indicate the effect of the damper cell. Thus we used a dielectric needle (Al₂O₃, εᵣ=9.2) as bead. This ceramic bead was 6mm long and 1mm in diameter. A lumped circuit representation of the resonator combined with Slater’s formula [7] leads to the electric field:

$$ E^2 = \frac{P_{loss}}{\alpha} \cdot \frac{(1 + k_1 + k_2)^2}{2 \omega \cdot \sqrt{k_1 k_2}} \cdot |\Delta z_2| $$  (1)

Results

For the measurements the bead was calibrated in a TM₀₁₀-pitchbox for the longitudinal perturbation constant ($\alpha$=9.34E-20 As/m²/V). Since the measured modes were of dipole type the bead pull measurements were performed off-axis with a distance of 7mm to the structure axis. For the measurements we have chosen several modes of the first dipole passband which have significant field strength at the damper position (cell #18) since a considerable damping effect could only be expected in this case.

In a tapered structure trapped modes always change their phase shift from cell to cell from 0 to π. To investigate the influence of the damper position, we have chosen mode A with the π-end, mode B with the π/2-part and mode C with the 0-end at the damper position.

As mentioned above, the damper was realized by a sheet of paper covered with graphite (thickness 1.5μm, conductance of graphite = 1.25E5 1/Ωm). First the sheet was pressed to the inner wall of cell #18 in order to have a symmetric damper and relatively weak damping effect (damper on surface). Additionally the damping effect was increased by moving the sheet some mm towards the iris, since the electrical field increases in this direction (damper in cell).

The following pictures (see Fig. 3, Fig. 4 and Fig. 5) show the measured mode geometry without damping, weak damping and strong damping.

Fig. 4: Mode B, bead pull measurement, 7mm off axis

Fig. 5: Mode C, bead pull measurement, 7mm off axis
The following table contains the results of the measurements in detail:

<table>
<thead>
<tr>
<th>Measurement results</th>
<th>without damper</th>
<th>damper on surface</th>
<th>damper in cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [GHz]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode A</td>
<td>4.143,83</td>
<td>4.143,83</td>
<td>4.142,33</td>
</tr>
<tr>
<td>unloaded Q₀</td>
<td>10,400</td>
<td>8,900</td>
<td>1,500</td>
</tr>
<tr>
<td>damping effect</td>
<td>1.000</td>
<td>0.778</td>
<td>0.045</td>
</tr>
<tr>
<td>long.shuntimp. [MΩ]</td>
<td>6.43</td>
<td>5.00</td>
<td>0.92</td>
</tr>
<tr>
<td>Frequency [GHz]</td>
<td>4.173,97</td>
<td>4.174,01</td>
<td>4.172,94</td>
</tr>
<tr>
<td>unloaded Q₀</td>
<td>10,500</td>
<td>9,000</td>
<td>3,200</td>
</tr>
<tr>
<td>damping effect</td>
<td>1.000</td>
<td>0.815</td>
<td>0.172</td>
</tr>
<tr>
<td>long.shuntimp. [MΩ]</td>
<td>11.32</td>
<td>10.74</td>
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<tr>
<td>Frequency [GHz]</td>
<td>4.324,61</td>
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<td>4.323,87</td>
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<tr>
<td>unloaded Q₀</td>
<td>12,100</td>
<td>10,800</td>
<td>4,400</td>
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<tr>
<td>damping effect</td>
<td>1.000</td>
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<td>0.183</td>
</tr>
<tr>
<td>long.shuntimp. [MΩ]</td>
<td>11.73</td>
<td>7.63</td>
<td>3.26</td>
</tr>
</tbody>
</table>

The next Picture (see Fig. 6) shows that the damping effect is evenly distributed over all phases of the modes.

![Diagram showing damping effect with weak and strong damping](image)

Fig. 6: Damping effect with weak and strong damping

**Conclusion**

From former measurements a strong influence on mode geometry was expected [8]. But as can be seen in Fig. 6 weak damping as well as strong damping has not changed the mode geometry significantly. The damping effect is even distributed over all phase shifts.

Here we have to mention, that no damping effect could be expected, if the mode has no energy at the location of the damper. Further investigations concerning the interaction between mode energy in the damped cell and damping effect are planned. Additionally we intend to investigate the effect of several damper cells grouped together or distributed over the structure.

Numerical calculations with the program MAFIA concerning the damped 36-cell structure are in preparation.

**References**


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MEASUREMENT OF HOM-PROPAGATION THROUGH CAVITY CHAINS IN TERMS OF S-PARAMETERS

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Abstract

The propagation of HOM-energy along an accelerator channel can be described in terms of frequency dependent scattering (S-) parameters of the individual elements of the channel. These S-parameters can be measured for each element (cavities, couplers, etc.) separately. Once they are known, it is possible to predict the behaviour of any arbitrary combination of elements. As long as only one waveguide mode propagates in the connecting pipes, standard RF calibration schemes are applicable methods to measure the three S-parameters of the representing two-port. In the presence of additional modes - corresponding to higher frequencies - S-matrices of higher dimensions have to be determined. Therefore we have been developing an experimental method which allows for determination of S-parameters in the regime of waveguide ports with several propagating modes. The principles of the method as well as results from measurements of normal conducting TESLA cavity models are presented.

Introduction

The TESLA HOM-damping scheme consists of two couplers attached to either side of each cavity and a single absorbing element in a 8-cavity module [1]. The latter is intended to dissipate HOM-power propagating through the accelerator. This leads to the question of how to measure RF power transmission in a complicated structure at frequencies that may allow for the appearance of more than only the fundamental waveguide mode. Therefore the problem exceeds the capabilities of the usual two-port S-parameter measurement, which is only appropriate for a single propagating mode. Even then the question of de-embedding the test devices properties from the measurement results, being modified by the necessary coaxial line-waveguide- adaptors, remains, but it is similar to calibration problems in pure coaxial setups. If more modes are present in the waveguides there was to our knowledge no practicable method available to measure a multidimensional S-matrix at an arbitrary (for a given number of modes) fixed frequency (or a spectrum of them).

We performed measurements in the frequency range with only the fundamental mode propagating (2.25 GHz to 2.95 GHz for 78 mm diameter TESLA beam pipe) using a standard Through-Short-Delay-calibration method (eg. [3]). For higher frequencies we have been developing an alternate method that has been tested now with two waveguide modes for a device measurement and with three modes for a calibration of an adaptor at single frequency points (see [4] for details).

Measurements with one mode

Fig. 1 shows results from single mode S-parameter measurements of two 9-cell cavities (compare [2] for details) using a TSD-method for the adaptor calibration. With the knowledge of the individual S-matrices one can calculate the result expected for two cavities chained together. This calculation is plotted in Fig. 1 together with the measured transmission of the chain.

In Fig. 2 the calculated transmission through four identical cavities is plotted. One observes a behaviour well known from filter cascades: The slopes increase with the length of the chain.

Fig. 1 Transmission through a chain of two TESLA 9-cell copper cavities: Calculated from single cavity measurements and measured directly (two curves)

Fig. 2 Transmission through a chain of four TESLA 9-cell copper cavities, calculated from single cavity measurement

Measurements with more than one mode

In the case of more than one propagating mode the S-matrix of an adaptor with one coaxial line (index 0) and n waveguide ports may be written as:

$$\bar{A} = \begin{pmatrix} A_{00} & A_{01} & \cdots & A_{0n} \\ A_{10} & A_{11} & \cdots & A_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{n0} & A_{n1} & \cdots & A_{nn} \end{pmatrix} = \begin{pmatrix} A_{00} & A^T \end{pmatrix} \bar{A}$$

(1)

Herein the scalar $A_0$ describes the reflection at the coaxial port, the vector the coupling from the coaxial line to each waveguide mode and the submatrix the reflection at the waveguide flange, that may couple every mode to each other. The matrix is symmetric due to the reciprocity of the device. Like in the single mode case, the problem of determining the properties of a device splits into the calibration step - i.e. determination of the adaptors - and the measurement once the adaptors are known. Considering the number of unknowns (10 in the case of two modes at two waveguide ports) it becomes clear, that a single measurement with two completely known adaptors, which gives three numbers (two reflection, one transmission quantity), is not able to provide a sufficient
amount of information. Thus one has to use different pairs of known adaptors for a number of subsequent device measurements. To keep the calibration effort as small as possible we take only two fixed adaptors and combine them with various delay line lengths (see Fig. 3). In the same manner we use a short (which is one of the very few reliable broadband standards in waveguide technique) and different delay line lengths to calibrate the two adaptors.

![Fig. 3 Schematic drawing of setups used for adaptor calibration with delayed shorts and for measurement. Small letters denote the signals at all connection planes, index 0 corresponds to the coaxial line.](image)

**Geometric Series Expansion**

Equation (6) can be rewritten using

$$ (1 - M)^{-1} = (1 + M + M^2 + M^3 + ...) $$

(7)

(we skip the discussion of the mathematical conditions)

$$
\begin{bmatrix}
\Gamma_1 & T \\
T & \Gamma_2
\end{bmatrix} =
\begin{bmatrix}
A_{00} & 0 \\
0 & B_{00}
\end{bmatrix}
\begin{bmatrix}
\delta_0 & 0 \\
0 & \delta_2
\end{bmatrix}
\begin{bmatrix}
H_1 & H_{12} \\
H_{12} & \delta_1 + H_{12}
\end{bmatrix}
\begin{bmatrix}
\delta_0 & 0 \\
0 & \delta_2
\end{bmatrix}
\begin{bmatrix}
H_1 & H_{12} \\
H_{12} & \delta_1 + H_{12}
\end{bmatrix}
=\begin{bmatrix}
\delta_0 & \delta_2 \\
\delta_2 & \delta_0
\end{bmatrix}
\begin{bmatrix}
H_1 & H_{12} \\
H_{12} & \delta_1 + H_{12}
\end{bmatrix}
\begin{bmatrix}
\delta_0 & 0 \\
0 & \delta_2
\end{bmatrix}
\begin{bmatrix}
H_1 & H_{12} \\
H_{12} & \delta_1 + H_{12}
\end{bmatrix}
+ \begin{bmatrix}
\delta_0 & \delta_2 \\
\delta_2 & \delta_0
\end{bmatrix}
\begin{bmatrix}
H_1 & H_{12} \\
H_{12} & \delta_1 + H_{12}
\end{bmatrix}
\begin{bmatrix}
\delta_0 & 0 \\
0 & \delta_2
\end{bmatrix}
\begin{bmatrix}
H_1 & H_{12} \\
H_{12} & \delta_1 + H_{12}
\end{bmatrix}
\ldots
\end{bmatrix}
(8)

as a geometric matrix series. This expansion is useful as well as an approach for the numerical solution of (6) with a set of measurement data and for its physical interpretation. We denote (8) as the "reduced model". To simplify discussion, we restrict ourselves to the calibration problem, which is a special case of (6) (set all elements of C to 0 except the upper left block which is the negative identity). Then the complete model is

$$
\begin{align*}
\Gamma_1(L_1) &= A_{00} - A^2 T E(L_1) A \big(1 + \Delta E(L_1)^{-1} A\big) \\
\text{and its reduced version reads like:}
\Gamma_1(L_1) &= A_{00} - A^2 T E(L_1) A + A^2 \Delta E(L_1) A E(L_1) A
\end{align*}
(9)

(10)

Evaluating this in the case of two modes

$$
\begin{align*}
\Gamma_1(L_1) &= A_{00} - A^2 T e^{-2\tau_1 L_1} A + A_{02} e^{-2\tau_2 L_1} + \\
&+ \big( A_{11} e^{-4\tau_1 L_1} + 2 A_{02} A_{21} e^{-4\tau_2 L_1} + \\
&+ 2 A_{01} A_{22} e^{-2(\tau_1 L_1 + \tau_2 L_2)} \big) \ldots
\end{align*}
(11)

shows that each term describes a possible signal path from initial incidence to final detection. The same holds for (8) but the expressions are much more complicated. With the arithmetic derivation of (6) we just did a summation over all signal paths, written in a very compact way. To solve a set of equations (6) with measurement data, we fit the data depending on L_1, L_2 in the reduced model using the set of oscillations with wave numbers, given by the combinations of the known phase advances. The amplitudes of the lowest and therefore dominant frequencies are functions easy to be solved for the S-parameters (compare (11)) (due to some quadratic expressions some of the signs remain ambiguous). This procedure works as well for an adaptor calibration as for a complete measurement; in the latter case we have to fit with respect to two parameters.

**Measurement setup**

The main effort in the setup had to be spent in the realization of the various delay line lengths. This has been done by building two adaptor systems sliding in two fixed waveguides. They are driven by stepping motors with spindles that allow for a nominal position resolution of 6.25 μm. The RF equipment consists of a HP8753C-Si GHz-network analyzer. The components are computer controlled using LabVIEW™, the data evaluation is done with Mathematica™.

**Calibration results with three modes**

One of the adaptors has been measured at 4.5 GHz with three propagating modes (TE_{11}, TM_{02}, TE_{22}). The results are:

\[ \Delta = \begin{bmatrix}
-0.145 & 0.562 & 0.003 & -0.001 & 0.022 & 0.103 & -0.025 & 0.0031 \\
0.001 & -0.001 & 0.005 & -0.001 & 0.001 & -0.001 & 0.0011 & -0.0011 \\
-0.036 & -0.012 & 0.001 & 0.001 & -0.016 & 0.147 & 0.050 & 0.751
\end{bmatrix} \]

We insert these parameters into the reduced and the complete model (Fig. 4) plotted against L_1 and add the measurement
points. We observe a sufficient agreement of the reduced model and a very good one of the complete model. This may be explained by the limited amount of wave numbers contributing in the reduced model, whereas the complete model covers all of them up to an infinite degree of multiple reflection.

Introducing a normalized error function

$$E = \frac{1}{N} \sum_{\tau = 1}^{N} \left| \frac{m_{\tau}(L_i) - \Gamma_{\tau}(L_i)}{m_{\tau}} \right|^2$$

(12)

we studied the error-sensitivity of the result by adding some random offset within a certain part of each parameter value. Fig. 5 shows the result of 100 attempts together with the error function of the unperturbed S-parameters. We found the majority of attempts revealing an increased error, confirming that the unperturbed S-parameters are a very good (but not optimal) approximation to the real values.

![Fig. 4](image)

**Fig. 4** Value of input reflection factor of adaptor A at 4.5 GHz against $L_i$: measured points (dots) together with reduced (upper curve) and complete model.

![Fig. 5](image)

**Fig. 5** Normalized error function (12) of adaptor S-parameters (normal line) with homogeneously distributed random offset of 3% for 100 attempts (dots); dashed line: average of all attempts.

**Measurement results with two modes**

The S-matrix of the TESLA 9-cell copper cavity has been measured at 3.0968 GHz. At this frequency the TE$_{01}$ and the TM$_{01}$-mode propagate. After the calibration runs of the adaptors (we skip these results) we find from (8):

$$C = \begin{pmatrix}
0.399 + 0.2871 & 0.000 - 0.0491 & 0.310 - 0.7331 & -0.034 - 0.0516 \\
0.009 - 0.0011 & 0.086 - 0.0281 & -0.000 + 0.0231 & 0.004 - 0.0041 \\
0.310 - 0.7331 & 0.009 + 0.0391 & 0.400 + 0.3561 & -0.076 - 0.0471 \\
-0.034 - 0.0161 & 0.004 - 0.0041 & 0.004 - 0.0471 & -0.395 - 1.0301
\end{pmatrix}
$$

The reason of the value of $C_{11}$ being about 20% greater 1 is not yet clear. Probable causes might be the small number of measurement points (13 for $L_1$ and $L_2$ leading to an 13x13-array) or a temperature drift, that has been observed during the measurement time of about 1 hour. Again, we tested the complete model and found a sufficient though not extremely good agreement (Fig. 6, 7).

![Fig. 6](image)

**Fig. 6** Typical plot of the transmission of the complete setup for fixed $L_2$ against $L_1$: value (left) and argument (right curve).

![Fig. 7](image)

**Fig. 7** Typical plot of the input reflection at port B of the complete setup for fixed $L_1$ against $L_2$ (comp. Fig. 6).

**Conclusion and Outlook**

The TSD-calibration technique is a useful tool to calibrate coax-waveguide-transitions if only one mode is propagating. To expand measurements in the frequency range of several waveguide modes we have been developing a new method for multimode S-parameter measurements showing encouraging results in first tests. These evaluations will continue to specify the capabilities of the method. In further investigations we shall try to resolve additionally degenerated modes, especially different polarisations.

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**References**

THE ACCELERATION OF DIFFERENT SPECIFIC CHARGE IONS IN THE HEAVY IONS RFQ LINAC.

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Abstract

The acceleration of ions with different specific charge in the heavy ions RFQ linac has enabled to determine both several linacs experimental characteristics and the ion beam parameters at the injector output which is undetermined by the another technique. They are: the dependence of the capture efficiency on specific charge of ion; the magnitude of the limit current for the linac and its dependence on the ion specific charge. In particular there is the possibility to find non-linear disturbance in RF field distribution. The technique is acceptable to test any RFQ accelerator in action.

Introduction.

The first section of the accelerator TIPr-1, working on frequency 6,19 MHz, has been intended for acceleration of twice charged bismuth ions under the inertial thermonuclear fusion program [1]. It has been designed for energy 36 keV/u. Its start and the first researches of a regime of ion acceleration were made with twice charged xenon ions produced by a duoplasmatron ion source. Now a vacuum arc source of metal ions (MEVVA) is used for the accelerator TIPr-1. It has enabled to produce and accelerate in TIPr-1 a set of ions of different metals, in particular, ions of copper (Cu⁺, Cu²⁺, Cu³⁺), tantalum (Xe⁺, Xe²⁺, Xe³⁺), tungsten (W⁺, W²⁺, W³⁺), lead (Pb⁺, Pb²⁺) and uranium (U⁺, U²⁺) [2]. The measurements of ion charge state distribution (CSD) and the research of acceleration regimes in TIPr-1 were made by time-of-flight method. The whole length of the RFQ structure (13 m) was used as drift channel for CSD measurements. In addition to further study of the already mastered (on ions Xe²⁺) acceleration mode of ions with specific charge about 1/60, the possibility of acceleration of ions with other specific charges was investigated. Below we consider features of acceleration of ions with various specific charges in RFQ structure and experimental results obtained on TIPr-1.

Results and Discussion.

The basic purpose of work is to obtain data about dependence of capture efficiency for transversal movement and maximum current at the output of the accelerator from magnitude of ions specific charge. At first, in order to exclude the influence of a non-resonance (non-accelerated) ions flow at the output of the accelerator to the basic measurements results, we consider the passage of non-resonance ions through the channel with RFQ. For non-resonance ions the RFQ structure represents the channel with an RFQ focusing without acceleration. (Their average longitudinal speed does not vary, <β> = const). It is possible to assert that longitudinal component of the RF field keeping the average longitudinal speed of non-resonance ions can increase the spread of their longitudinal speeds in the beam. For short (about 2 μs) pulses of a beam current which are used for the time-of-flight technique, the expansion of longitudinal ions speed spread leads to the increase of the beam current pulse duration.

![Image]

Fig.1. The diagram Smith-Gluckstern.
A - a working point for TIPr-1

On Fig.1. the Smith-Gluckstern diagram of a transversal movement stability. is shown. Where μ is a phase advance per focusing period for transversal oscillations, K - rigidity of the channel, γ - factor of defocusing.

\[ \cos \mu = \cos \mu_0 + \gamma f(K), \]

where \( \cos \mu_0 \) characterizes the focusing channel without acceleration, i.e. at \( \gamma = 0 \). If in the accelerator with RFQ the average value of the defocusing factor for non-resonance particles is equal to zero the non-resonance particles are kept in the channel while an amplitude of the RF field increases (i.e. the increase of the value of K on the diagram S-G, Fig.1) up to the value corresponding to \( K_{\text{m}0} \) (while \( \cos \mu | < 1 \)). At larger K the transversal movement becomes unstable, the focusing in the channel stops and the beam current at the output of the channel disappears.

The phenomena described above has been observed on the experiment at the accelerator TIPr-1. Experimental dependence of a beam current of non-resonance ions (single charged xenon (Xe⁺) and ions W²⁺, U²⁺) from amplitude of the RF field is shown on Fig.2.
Fig. 2. Dependence of a nonaccelerated ions current from amplitude of RF field

We have to note that the critical value of RF amplitude for Xe\(^+\) ions has not achieved (beam current has not fallen down to zero), because during measurements the electrical strength of RF system has been insufficiently high. For ions W\(^{2+}\), U\(^{5+}\) the data Fig. 2 enable to determine value \(K_m\) for ions with reverse specific charge 90 and 119.

Measurements have shown that the beam current pulse length of the non-accelerated ions is increased from 2 μs at \(U_r=0\) up to 6 μs at the maximum amplitude of a RF field. It means that the spread of longitudinal speeds accordingly grows. Thus in contrary to the influence of a RF field accelerating component on the resonant particle (for which the point A representing a synchronous particle on the diagram on Fig. 1 moves to the right while an RF field amplitude grows), from experimental data it follows that for non-resonance particles of beam the average value of the defocusing factor remains practically constant, \(<\gamma> = 0\). It means that the location of peak corresponding to the current of non-resonance ions in time-of-flight spectrum at the output of the accelerator remains constant in time for all levels of RF field changing its duration only. That allows easily to distinguish it from peaks corresponding to resonant, accelerated ions.

It is necessary to consider a behavior of resonant ions beam current while the amplitude of a RF field in RFQ structure increases. For resonant particles the increase of a RF field on the one hand leads to the increase of an equilibrium phase, i.e. to the increase of separatrix scope both on a phase and on a momentum, and on the other hand increases the rigidity of the focusing channel. The stability in a transversal movement and, hence, a focusing of the ion beam disappears when the RF amplitude reaches \(U_m\) (\(K = K_m\), Fig. 1.). On the diagram of the dependence of the ion beam current with the given relation \(Zm/A\) on amplitude of the RF field in the accelerator the beam current should at first grows (from the threshold level of a RF field) up to a maximum, and then falls practically to zero when the amplitude of a field equals to critical value \(U_m\). Such experimental dependencies were obtained for copper (Fig. 3.) and for the ions Ta\(^{3+}, 4+\), W\(^{5+}, 6+\), U\(^{5+}, 6+\). On Fig. 4 the dependence of relative capture efficiency for a transversal movement (divided to capture efficiency for \(Ze/M = 1/60\)) on specific charge of ions is shown.

Fig. 3. Acceleration of a copper ions

Data from Fig. 3. and data for ions of tantalum, tungsten and uranium were used. The question of optimum tuning of the accelerator is essential to reach the greatest possible current of the accelerated beam at the output of the accelerator, and hence for measurement of transversal capture factor. Therefore for measurement of each points for dependence Fig. 4. the special work to optimize the operation regime of the accelerator was required.

Fig. 4. Dependence of capture efficiency from specific mass.

From the diagram Fig. 4. one can see, that for the greatest achieved beam current, the capture efficiency on a transversal movement in RFQ structure of the accelerator TIPr-1 decreases with the specific charge growth.

Fig. 5. Dependence of a Ta and Cu ion beam current greatest achieved on experience from M/Ze

The result for a beam current, which is lower than calculated value of the limiting current, is unexpected and requires an explanation, because the \(K\) and \(\gamma\) depend on parameter \(UZe/M\), which for each points on the diagram Fig. 4. remains constant. Therefore, the working point on the diagram S-G does not leave the place while \(Ze/M\) changes. A number of processes can cause these results.
1) The influence of a beam space charge can cause a reduction of the capture efficiency with the specific charge growth.

A limiting current \( I_1 \sim I_0 \) where

\[
I_0 = 4\pi e_0 c^3 M_0 / Ze
\]

and \( M_0 \) is a rest mass, so \( I_1 \) linearly depends from \( M/Ze \). It means the higher \( Ze/M \), the less limit current. The experimental dependence, which is shown on Fig.5, gives linear dependence of the greatest achieved current on size \( M/Ze \), as well as the dependence \( I_1 = f(M/Ze) \). It probably means that for data Fig.5 the greatest achieved beam current is close to its limit value.

2) The emittance of a beam with the given \( Ze/M \) at the output of the injector is not exactly equal to the emittance of beam with other \( Ze/M \) values. Therefore the losses of particles are probably resulted by the worse matching of the ion beam with a specific charge larger, than 1/60. The direct measurements of the matching quality for each beam components can give the answer to this question.

3) The decrease of capture efficiency can be caused by a dependence from a RF field quality. Nonlinear distortions in the focusing RF field or in the its distribution along the axis of structure (and also other differences from the calculated distribution) can result the loss of particles by an excitation of a coherent oscillation of particles. If other factors of decrease of capture are excluded, the nonlinear distortions in the distribution of the RF field along the structure axis can be detected by the reduction of transversal capture factor. Distortions in the distribution of the RF field take place in TIPr-1 at a joint point of two parts of structure and have caused decrease of capture efficiency when a small beam current is accelerated, at that moment the space charge restriction of a current could not influence on a capture efficiency.

**Conclusion.**

The study of acceleration of ions with various specific charge in the linear accelerator with RFQ enables to determine a number of the characteristics both of the accelerator and beam of ions at the injector output, which can not be determined by other methods. Such as: dependence of capture efficiency from specific charge of ions; experimental value of limiting (maximum) current in TIPr-1 and dependence it from specific charge of ions. Also this study enables to detect presence of essential nonlinear distortions in the distribution of the RF field along the axis of structure and their influence on an ion beam passage.

The results of this work allow to state the following assumptions:

The space charge limit for the accelerated beam current is defined by space charge of a total unseparated beam instead of space charge for only the resonant component of a beam as it is assumed for calculated limit current. Apparently it is the main reason of difference between the maximal achieved current in our measurements and the calculated one.

To overcome this limiting, it is useful to accelerate simultaneously beams of particles with different polarity. It eliminates space charge restriction of a beam current at the beginning of RFQ structure (where beam is bunched) and allows to obtain at the accelerator output the extreme permissible beam current.

As mentioned above the presence of ion beam components with lower specific charge than accelerated ion beam components leads to the increase of beam space charge and limits accelerated beam current. The RFQ structure focuses only this component but not accelerates it. On other hand if this nonaccelerated component would have an opposite sign (for example W\(^{99}\) is accelerated ions and Bi\(^{183}\) is nonaccelerated ions), the limit current should increase. In this case the space charge compensation should take place in any point and at every moment of ion beam acceleration. Probably it is useful to inject into structure such nonaccelerated ions with opposite sign simultaneously with accelerated ions. It should result to the increase of the accelerated beam intensity.

**References**

MULTIPLE-BEAM RFQ STRUCTURE WITH A MATRIX-ARRAY OF BEAMLETS

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Abstract

There is an interest in using multiple-beam RFQ (MB-RFQ) with a high packing of beamlets for a variety of purposes. The principle of the MB-RFQ arranged as a matrix array of longitudinal rod-electrodes is known for a long time. It allows to reach a packing factor up to 40%. The unsolved problem is to define such configuration of resonator, which preserves a high packing without disturbing RFQ fields and correctly excites electrodes surrounding every channel.

According to the usual design principle, which is extended from a single-channel 4-rod RFQ to MB-RFQ resonators, every electrode of MB-RFQ must be discretely connected with tank by coupling elements, while adjacent RFQ electrodes having different potentials cannot be interconnected by short-circuited couplers and the couplers may interconnect only next adjacent electrodes "in a chess order", avoiding adjacent electrodes. The principle reduces a packing factor considerably from the above value.

A new principle for MB-RFQ is suggested. A high packing factor is preserved, because of discrete connections of adjacent electrodes are allowed. The beam dynamics in RFQ-channels is modified. Beams perform "slalom" motions, utilizing intrinsic transverse oscillations. Essential design issues are discussed.

Introduction

In recent years, many ion sources with a broad-beams have been developed [1-3]. The broad-beams are formed as multiple-beams consisting of an array of identical single-beams (or beamlets). The beamlets are packed very closely. The packing factor defined as a ratio between the sum of areas occupied by beamlets and a total area of broad-beam can reach 40-50 %. The number of beamlets may achieve several hundreds (or even thousands). Transverse size of broad-beam can be up to one meter or more.

There are applications, which require MeV-range broad-beams, e.g. heating of plasmas in magnetic confinement devices [3]. Existing broad-beam accelerators use the electrostatic method of acceleration. Because of technical problems due to the voltage breakdown, an attainable level of beam energy is restricted. Perhaps, some RF-acceleration method adapted to a multiple-beam accelerator may be applied for MeV-range broad-beam accelerators. Many RF multiple-beam accelerating structures had been already presented in the past years [4-13].

MB-RFQ arranged as an array of longitudinal rod-electrodes (see Fig. 1) is known for a long time [4, 7, 9]. It is required to realize a high packing factor without disturbing RFQ fields and excite correctly electrodes surrounding every channel. In this paper, we try to find out possible configurations of the MB-RFQ structures satisfying the above requirements.

MB-RFQ based on a usual 4-rod RFQ

Resonators with coupling stems

Known MB-RFQ structures [4, 7, 8-12] are designed using a periodical multiplication of an single-channel 4-rod RFQ in the transverse direction. RFQ-electrodes in a matrix array should be discretely supported by some transverse stems or coupling elements. Adjacent electrodes have different potentials along the whole structure. They can not be interconnected by short-circuited couplers. Only next adjacent electrodes may be interconnected "in a chess order".

Two possible configurations of couplers consisting of ideal thin conductors are shown in Fig. 2. In the first (left) configuration, coupling conductors bypass the RFQ-channels. Only a quarter of RFQ-channels is used. The second (right) configuration allows the penetration of the coupling elements inside RFQ-channels. The couplers have aperture-holes. The original RFQ-fields are distorted in this configuration.

Fig. 2. Two possible configurations of coupling elements.

In order to prevent voltage breakdown, the realistic configurations should be composed of thick conductors. The curvature radii of all conductors could not be less than the curvature of RFQ-electrodes. We tried to design such couplers. However, the packing factor is reduced to 5% and 10% for the left and right configurations, respectively.
A quarter-wave short resators

To preserve the packing factor, MB-RFQ resonators can be designed without coupling elements. The RFQ-electrodes are only connected to the tank bottoms, and the length of MB-RFQ resonator, $l$ is about a quarter of the wavelength $\lambda$. The MB-RFQ accelerator is composed of several short resonators.

Two types of such resonators are known [7,8,10]. In the first type, all RFQ-electrodes are connected to the one bottom of the tank and have open ends at the another bottom. In the second type, all electrodes are divided into two groups in a chess order. The electrodes of two groups are connected to the tank in opposed manner. Figure 3 shows the example of the second type of the resonator.

![Fig. 3. The second type of MB-RFQ resonator.](image)

The resonators with $4 \times 4$ matrix arrays of RFQ-electrodes have been studied with MAFIA code [14]. The first type provides correct quadrupole excitation of electrodes when the tank cross-section is a square with the side $4d$, where $d$ is the distance between axes of adjacent electrodes. This resonator can be used as an RFQ matching section, because RFQ voltage increases along the resonator as a sine function.

The second type of the resonator does not provide correct quadrupole excitation of the electrodes. The voltage amplitudes at the middle of the resonator are shown in the Fig. 3. The voltages on the electrodes surrounding RFQ-channels deviate from quadrupole symmetry. It is difficult to adapt this type of resonator to MB-RFQ-acceleration.

**MB-RFQ based on a new 4-rod RFQ**

Let us find out a type of a resonator, which allows a short-circuited connections between adjacent electrodes. Figure 4 shows a unit module of such resonator.

To provide RFQ-acceleration, the field at the resonator axis should be the same as in a conventional RFQ-channel. It is described by the following lowest-order electric-field potential function [15,16]:

$$U(r, \psi, z) = \left( V/2 \right) \left[ \left( \kappa r/a \right)^2 \cos 2\psi - A l_0(kr) \sin kz \right]$$  \hspace{1cm} (1)

where $A = \frac{(m^2 - 1)}{m^2 l_0(ka) + l_0(mka)}$, $\kappa = 1 - A l_0(ka)$, $k = \frac{2\pi}{\beta \lambda}$.

At every cross-section of the resonator, its conductors have some definite voltages $U_1$, $U_2$, $U_3$, and $U_4$. To provide the RFQ fields described by Eqs. (1), surfaces of the RFQ pole tips for every conductor is defined by equation:

$$U(r, \psi, z) = U_i, \hspace{1cm} i = 1, \ldots, 4.$$  \hspace{1cm} (2)

Figure 4 shows pole tips at the ends and the middle of the resonator. The RFQ-channel has a zero optical transparency, and could not provide a conventional RFQ acceleration. The beam dynamics must be modified in this case.

![Fig. 4. Unit module of new 4-rod RFQ resonator, voltage distributions on its conductors, and pole tips at different cross-sections of the resonator.](image)

We have revealed a possible way to provide RFQ acceleration in this accelerating channel. It is based on the fact that parts of beam coherently oscillate around the axis during transverse oscillations in a strong-focusing quadrupole channel. Figure 5 shows particle motion calculated by PARMTEQ code [16] in transverse plane, X0Y. Part of beam injected in the first quadrant of the X0Y-plane performs periodical excursions between the first and the third quadrants of X0Y-plane. This part of the beam can be transported in the accelerating channel of the new resonator, if space period of transverse beam oscillations $L_y$ is equal to $L_y = 2\pi/(2n + 1)$,

![Fig. 5. Beam structure in the transverse plane X0Y at different cells of a conventional RFQ-channel.](image)

To test this principle, numerical simulations have been done. Figure 6 shows the resonator of the simulated accelerating structure. It consists of a quarter-wave matching resonator and two sections of the new resonator.

![Fig. 6. The cross-sections of the resonator and the voltage distributions on the electrodes.](image)
Eqs. (2). The beam dynamics had been calculated using beam dynamics code DYN1 written by V. Kapin. Figure 8 shows the example of the beam-structure and the electrode profiles in the XOZ-plane. Similar picture exists for XOY-plane. Beam performs "slalom" motions, avoiding pole tips. Acceptances of the RFQ-channel are presented in Fig. 9. The results of the test calculations show principal possibility of beam acceleration in the new RFQ-channel. The MB-RFQ resonator designed by a multiplication of the new 4-cell RFQ in the transverse direction is shown in the Fig. 10. The MAFIA calculations have shown the existence of the necessary mode of field oscillations in this structure.

Fig. 8. The XOZ cross-section of the RFQ-channel showing the beam structure and the electrode profiles.

Fig. 9. Acceptances of the RFQ-channel.

Fig. 10. MB-RFQ resonator with 6x6 matrix array of the RFQ-electrodes.

References

2 MV, 0.8A, K⁺ INJECTOR FOR HEAVY ION FUSION

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Abstract

A driver-scale injector for the Heavy Ion Fusion Accelerator program has been built at LBNL. The injector has exceeded the design goals of high voltage (> 2 MV), high current (> 0.8 A of potassium ions) and low normalized edge emittance (< 1 π mm-mr). The injector consists of a 750 keV pre-injector diode followed by an electrostatic quadrupole accelerator (ESQ) which provides strong (alternating gradient) focusing for the space-charge dominated beam and simultaneously accelerates the ions to 2 MeV. The ESQ is followed by a six-quadrupole section to match the beam into the main accelerator. 3-D PIC simulations, confirmed by comparing with scaled experiments, were used to generate a physics design with minimal emittance growth. Detailed measurements of ion current, emittance, and beam energy, and comparison with code predictions are reported.

Introduction

The driver accelerator required in a Heavy Ion Fusion power plant scenario [1] must deliver several megajoules of heavy ions with particle energy of a few GeV, onto a target of 2 to 3 mm radius in 10-15 nanoseconds. The linear induction accelerator approach to the fusion driver consists of multiple beams, each confined to a quadrupole focusing channel, which is electrostatic at the low energies, and magnetic at high energies, and sharing a common induction acceleration core. A driver-scale one-beam heavy ion injector was constructed and operates at Lawrence Berkeley National Laboratory. The injector has as design goals a particle energy of 2 MeV, line charge density of 0.25 μC/m (800 mA of singly charged potassium) and a normalized edge emittance of less than 1 π mm-mr. These design parameters are the same as in the front end of a full-scale driver. The low emittance is essential for final focusing onto a small target. The line charge density corresponds to the optimal transportable charge in a full-scale electrostatic quadrupole channel, and the high injector energy has a significant cost advantage in a fusion-driver.

The design of the injector was based on calculations using the three-dimensional PIC (Particle-in-cell) codes WARP3d [2] and ARGUS [3] running in steady state mode. A full 3D PIC simulation code was required to incorporate the beam space-charge-field as well as the self consistent fields from the accelerating quadrupoles. The parameters of the design represent optimal choices to have a proper balance between breakdown risks and emittance growth.

The Injector System

The injector is based on an electrostatic quadrupole (ESQ) configuration [4]. Fig. 1 shows the layout of the injector system. The ion beam, after extraction from an axisymmetric diode, is injected into a set of electrostatic quadrupoles arranged to provide simultaneous acceleration and strong focusing. The ESQ configuration was chosen over the more conventional electrostatic aperture column primarily because of high voltage breakdown considerations. The accelerating gradient of an ESQ can be made quite low, and the strong transverse fields sweep out secondary electrons, features which may avoid the initiation of breakdown processes. However, the ESQ configuration must be carefully controlled to minimize emittance degradation. The injector is composed of 5 ceramic columns. The first column consists of a brazed structure with 16 alumina rings, each 1.5" in width, and separated by thin niobium rings enclosing the alumino silicate source and the 750 kV diode front end. The subsequent 4 columns consist of similarly brazed structures with 3" alumina rings, each containing a set of 4 electrodes arranged in a quadrupolar configuration designed to provide strong beam focusing and acceleration from 750 keV to 2 MeV. The quadrupole electrodes are shaped to minimize surface fields without introducing unwanted higher order multipoles. The ceramic column is contained in a pressure vessel under 80 psig of SF6 gas. Water resistors around the column provide graded voltages to the diode and each of the 4 quadrupoles.

Fig. 1. The Injector System layout showing from left to right the source, the four-quadrupole ESQ accelerator, and the six-quadrupole matching section assemblies.
The source is a 6.7" diameter curved hot alumino-silicate source emitting potassium ions. These sources have been shown to produce beams with temperature-limited emittances, and have long life-time and high reliability [5]. The source assembly is coupled to an extraction pulser which is at -80 kV relative to the high voltage dome at all times except during beam extraction when the pulser is switched to +80 kV in about 300 nanoseconds. This extraction pulser configuration allows ion extraction without the need for grids which tend to be unreliable and beam-quality degrading.

The injector is powered by a 2 MV Marx [6] which consists of 38 trays with parallel LC and RC networks to produce a 4 µs flat-top pulse to accommodate the entire ion beam plus the transit time across the injector.

A 3 meter long, six-quadrupole matching section is being constructed and tested in stages at the end of the injector ESQ section. The matching section performs a dual function of focusing and steering of the ion beam. In a multiple beam accelerator design, the matching section is needed to focus beams which are 4 cm in radius at injector exit to 1 cm in radius into the electrostatic channels in close proximity.

**Injector performance**

On the first day of operation (November 92) a K⁺ beam in excess of the design parameters of 2 MeV and 800 mA was produced (Fig. 2).

![Fig. 2. Measured Marx voltage waveform (2 MV at flat top) and beam current waveform (800 mA at flat top).](image)

The measurement of the current was made with a Faraday cup and a Rogowski loop at the exit of the injector. The current was measured for a range of Marx and source gate pulser voltages, and the agreement with code predictions was excellent (Fig. 3). The highest energy and current achieved thus far is 2.3 MeV and 950 mA of potassium, 15% above the design goals.

The emittance was measured with a double slit scanner in both the horizontal and vertical directions. Over a broad range of parameters the measured normalized edge emittance was less than the required 1 π mm-mr. The measured emittance, beam radius, divergence, and beam centroid displacement were found to be reasonably constant over the entire pulse.

Precision measurement of the beam energy from head-to-tail, were performed using a modified 1 MeV electrostatic spectrometer. The spectrometer energy range was extended to above 5 MeV by placing a gas stripper in front of the 1 MeV spectrometer thus changing the singly ionized potassium ions to multiply charged ions up to the charge state 5. With this sensitive energy measuring device we were able to fine tune the extraction pulse to the point where the beam is flat to less then 0.2% over a 1 µs pulse length.

![Fig. 4. Time profile of measured head-to-tail beam energy.](image)

The transport of the injector ion beam through the matching section is being studied in stages. Displacements of a single quad by 1.5 cm in a 3-quadrupole experiment led to the bending of the beam by nearly 2 cm, in very good agreement with simulation predictions. Preliminary beam profile measurements resulted in profile variations along the matching section that can be connected to the beam profile measured at the injector exit. Further investigations, experimental as well as theoretical, will continue.

**Numerical simulations**

Measurements of the transverse phase space distribution has shown excellent agreement with WARP3d calculations[7]. Fig. 5 shows a comparison of measured and calculated phase space distribution in the horizontal plane.
The transient longitudinal dynamics of the beam in the ESQ was simulated by running WARP3d in a time dependent mode. During beam turn-on the voltage at the source is biased from a negative potential, enough to reverse the electric field on the emitting surface and avoid emission, to a positive potential to start extracting the beam; it stays constant for about 1 μs, and is reversed to turn-off the emission. Since the Marx voltage applied on the accelerating quadrupoles and the main pre-injector gap is a long, constant pulse (several μs), the transient behavior is dominated by the extraction pulser voltage time profile. The extraction pulser voltage profile has, in general, a 0.5 μs rise time, a 1 μs flat top and a 0.5 μs fall-off.

![Graph showing phase space](image)

Fig. 5. Horizontal phase space at the end of the injector as calculated and as measured.

![Graph showing current waveform](image)

Figure 6: Current waveform at the end of the ESQ as calculated by WARP3d. Compare with Fig. 2. Horizontal scale at 1μs per division.

The results of the simulations showed a significant spike in current and energy at the head of the beam. A similar spike appeared in the experimental results. Fig. 6 shows the current profile at the end of the ESQ as calculated by WARP3d. The current waveform from the experiment shows a similar profile. The height of the initial spike is dependent on the rise time of the pulser. Simulations of the pre-injector with varying rise time showed that the minimal spike height was obtained with a 500 ns rise time. In an ideal, one-dimensional injector, with a rise time equal to the transit time, the Lampel-Tiefenback relation would result in no spike being formed [8]. Another feature seen in the simulations is the shortening of the current rise time with respect to the pulser rise time. With the pulser rise time of 500 ns, the current rise time produced is 200 ns, which agrees with the experiment. After the initial rise and spike, a stable flat top was maintained for a time comparable to the flat top of the pulser voltage. The tail of the current waveform showed a long fall-off as expected.

Acknowledgements

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References

SIMULATIONS AND COLD TEST OF AN INDUCTIVELY DETUNED RF CAVITY FOR THE RELATIVISTIC KLYSTRON TWO BEAM ACCELERATOR

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Abstract

Electromagnetic and particle-in-cell codes in two and three dimensions were used to design inductively detuned traveling wave cavities for the Relativistic Klystron Two Beam Accelerator (RKTBA) expected to extract high RF power at 11.424 GHz for an energy upgrade (TBNLC) to the Next Linear Collider, as well as for the prototype (RTA) being built at LBNL. Previous design was based mainly on 2D calculations. We will present full 3D simulations of a three-cell traveling wave structure in two configurations (with and without a choke structure), as well as preliminary cold-test results of a model cavity assembly.

Introduction

A preliminary point design study for an rf power source based on the Relativistic Klystron Two Beam Accelerator (RKTBA) concept to extract high power at 11.424 GHz for the 1 TeV center of mass Next Linear Collider design has been presented recently by a LBNL-LLNL team [1]. The point design requires that the bunched drive beam delivers 360 MW of rf power with an rf current of 1.15 kA (600 A DC) in each of the 150 rf extraction cavities in a 300 m long RK-TBA. To achieve this goal, and to maintain longitudinal beam stability over long distances, the extraction cavity must be inductively detuned. To maintain low surface fields to avoid breakdowns, we consider traveling-wave output structures. The frequency-domain and time-domain computations were performed using the three-dimensional electromagnetic code MAFIA [2]. Based on the simulations results an experimental, cold test, extraction cavity was fabricated and tested. Initial S-parameter measurements show good agreement with numerical calculations.

Numerical Simulations

The numerical effort for the physics design of the rf extraction cavity is based on calculations that are fully three-dimensional electromagnetic simulations of the complete cavity geometry including the output structures and the driving beam.

The favored type of simulations that we have been performing are the so-called "stiff-beam" calculations, where the beam excites the cavity to generate electromagnetic fields, but the fields do not act upon the beam. From this type of simulation we can calculate the electromagnetic fields and the wake potentials. The output power can be calculated as a function of time. The beam dynamics can be analyzed from the wakes potentials by beam dynamics code simulations [3,4,5].

The mesh size used is under one millimeter to accurately represent the cavity geometry. This type of mesh translates into a calculation involving about one million nodes. Furthermore, time steps of under 1 picosecond (dictated by the Courant condition for stable simulation) require running the calculation for several tens of thousands of time steps to simulate several tens of nanoseconds in order to have a smooth filling of the cavity and reach steady-state condition.

The beam is represented as a train of micro-pulses at the driving frequency. Each micro-pulse line-charge density shape is represented as the superposition of a constant term and three harmonics of the train frequency; this improves the numerical stability of the simulation.

The fully electromagnetic, three-dimensional code MAFIA has been the code of choice to perform all calculations. We have been using the frequency-domain as well as the time-domain modules. The alternate fully electromagnetic, three-dimensional Particle-In-Cell code ARGUS [6] has been used to cross-check the MAFIA calculations.

Traveling Wave Extraction Cavities

To avoid electrical breakdown, traveling-wave cavities are preferred over standing wave cavities since they generate lower surface electric fields for a given output power.

Present designs for the TBNLC extraction cavities evolve around traveling wave structures (TWS) with 3 cells of 8 mm inner radius; 180 MW of rf power is extracted through each of 2 separate ports in the third cell and transported via waveguides.

Fig. 1 shows a schematic of the 3-cell traveling wave output structure. A beam pipe length of 3.0 cm on each side is required to confine the electromagnetic field inside the cavity. The rf power is extracted through two WR90 waveguides attached to the last cell of the cavity.

Fig. 1. Schematic of the 3-Cell TWS. The structure is cylindrically symmetric with the exception of the two WR90 waveguides.
For this type of structure we have found a cavity design that delivers the right amount of power for the design parameters of the beam. Fig. 2 shows the calculated power as a function of time out of each WR90.

Transverse beam dynamics require low shunt impedances to avoid the beam break-up instability (BBU). Even when the 3-Cell TWS has low enough transverse impedance to avoid BBU [7], further damping of the high order modes is desirable to increase the confidence for the success of the accelerator as well as to relax tolerances on other parameters.

The addition of a cylindrically symmetric choke structure [8] to the 3-cell TWS, that confines the fundamental mode of the cavity while allowing high order modes to propagate out of the structure has been evaluated numerically.

Figure 4. shows a schematic of the 3-Cell TWS with choke used in the simulation. The dimensions of the 3 cells are changed slightly to compensate for the effect of the choke structures in the resonant frequency; the output waveguides are the same as in the previous case.

It was found numerically that by a small change in the cavity dimensions, to keep the resonant frequency constant, the cavity could extract the same amount of power from the beam while maintaining the inductive detuning. Even when this design was not optimized the transverse impedance calculated decreased appreciably by the introduction of the choke.

Cold tests of the rf cavity structure

An experimental 3-cell traveling wave extraction cavity was designed and fabricated. The design is based on the results of the 3D computer simulations. Since cold tests do not present any break down or vacuum requirements the cavity mechanical design is rather simple, allowing a quick and flexible assembly of the cavity. The cavity assembly shown in Fig. 5 consists of from 1 to 5 cells and two 30 mm long end beam pipes. One of the cells contains the two extraction apertures connecting to the WR90 waveguides. The test cavity is made from brass to reduce manufacturing costs.

Cold test measurements can be used to validate the results of the electromagnetic computer calculations by measuring the frequency-dependent S-parameters of the extraction cavity. Furthermore the measurements may allow the optimization of the extraction cavity geometry by evaluating the loaded Q of the cavity.
The cavity S-parameters are measured for cases when the second extraction aperture is terminated with a short, open, and a matched load. Fig. 7 shows an example of a frequency dependent S11 measurement in agreement with MAFIA calculations. The frequency shift, and the difference in the loaded Q, between the calculated and measured S11 behavior is probably due to the resolution of the calculation. The final tuning of the system can be done by readjusting the dimensions of the cavity using the above measuring procedure.

Future plans include the extension of the measurement system to frequency perturbation techniques using moveable dielectric rods or beads inside the cavity structure to evaluate the R/Q and the electric field variation along the cavity.

References

PUSH-PULL LINAC PAIRS TO GENERATE TWO DRIVE BEAMS FOR CLIC MULTIBUNCH OPERATION

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Abstract

This note describes an RF power generation scheme for multibunch operation at 1 TeV CM and luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. The scheme is upgraded to use acceleration with 250 MHz SC cavities (instead of 352 MHz ones) in order to have available the increased stored RF energy necessary to accelerate to 3 GeV the newly required charge of 30 $\mu$C/drive beam.

Introduction

The drive beam energy increase (to 90 KJ/drive beam) is a consequence of the recently specified CLIC main linac acceleration field of 100 MV/m (instead of 80 MV/m, to reduce transverse beam blow-ups) and the introduction of damped acceleration structures [1] for multibunch operation (having degraded R/Q and Q values, see next column).

Independent push–pull linac pairs

These are foreseen, see Fig. 1, mainly for the following 2 reasons:
a) Twice as many drive bunchlets (60 instead of 30) per 250 MHz period halves the required charge per bunchlet (from 100 to 50 nC in our case).
b) Good drive beam to RF efficiencies are obtained through matching of the train energy profile to the decelerating wake pattern in the drive linac. With two trains of 30 bunchlets per period (instead of one) the bunchlet deceleration variation inside one train is reduced (from $\pm$76% to $\pm$23%, see Fig. 2).

As shown by Fig. 3, the reduced wake variation makes it feasible to preshape the train energy profile to the deceleration ramp by simple phase shifting of the 250 MHz voltages in the SC cavities in conjunction with a small H = 4 correction.

One drive beam consists of 11 bunchlet train pairs, obtained with two switch-yards (each combining bunchlets from 10 short parallel S-band linacs [2]) followed by the push–pull (antiphase) accelerations shown in Fig. 1.

Fig. 2. Computer optimized bunchlet numbers, relative intensities, normalized 30 GHz CTS wake amplitudes (dashed, linear variations of $\pm$23%) and the normalized CTS output amplitude.

Fig. 3. Acceleration ramp synthesis.

The purpose of each drive beam is to produce, via 7813 Clic Transfer Structures (CTSSs), 30 GHz output pulses to power 15626 CLIC Accelerating Sections (CAS) [1] of the main linac with the provisional parameters:
R/Q = 3920 $\Omega$/structure,
(circuit convention)
length $\ell = 0.32$ m
Q = 2800
$\nu_{gr} = 0.066$ c
$E_{acc} = 100$ MV/m (loaded)
Spacing of multibunches = 1 ns
Multibunch charge = 1.28 nC

Fig. 1. Generation of one drive beam upstream of one drive linac.
To deliver two flat-top 102 MW CAS input power pulses (2 CASs are fed by one CTS) the main CTS parameters can be chosen as follows:

\[ R/Q = 1.4 \ \Omega/\text{structure}, \]
\[ \text{length } \ell = 0.71 \ \text{cm} \]
\[ \text{drain time } d = 4 \ \text{ns} = 1/250 \ \text{MHz} \]
\[ v_{gr} = 0.37 \ \text{c} \]
\[ \text{CTS internal power losses } = 5\% \]

with CTS to CAS transmission losses of 10% and for a bunchlet length of 0.6 mm rms. The flat-top bunchlet intensity is 50 nC.

**Bunchlet trains**

Following a suggestion by K.A. Thompson and R.D. Ruth [3], almost constant multibunch energies (±0.2%, necessary to pass the CLIC final focus sections) are obtained by a specially shaped CTS output power pulse: the time shape is such that, prior to the passage of the multibunches, first the steady state of the CAS (with beam-loading) is established (with the first 5 drive train pairs) and then, during the passage of the multibunches, this state is maintained with a constant input power level (102 MW/CAS).

To obtain both the necessary multibunch acceleration precision and drive beam excitation of the fourth harmonic correction structures (explained later), the 5 prefill train pairs have increasing numbers of bunchlets (18, 22, 26, 28 and 30 bunchlets/train) [4], combined with small variations of bunchlet intensities [5].

The energy spread of the accelerated 26 multibunches of the main beam is 0.1% rms.

To guarantee good mains to RF efficiency it is necessary to accelerate the drive beam bunchlets inside each train according to the above decelerating wake curve, such that at the end of the CLIC drive linac, the bunchlets are dumped at an almost equal and low average energy, e.g. 0.3 GeV, but above 0.2 GeV to avoid electron losses.

We focus the acceleration optimization on the flat-top trains (which have the most severe deceleration), in particular on the compensation optimization of the beam-loading they cause in the 250 MHz SC structures.

Figure 3 indicates the specified acceleration ramp (matching the flat-top wake of one train) for any train of the flat-top and the synthesized one obtained with the fundamental and the fourth harmonic.

**Beam-loading compensation**

The voltage decrease of the fundamental frequency cavities \( R/Q = 96.6 \ \Omega/m, \text{ circuit convention} \) has been compensated by two groups of cavities with slightly different frequencies (243 and 257 MHz); they produce a fractional beat during the passage of the drive beam, yielding low deceleration for the first prefill trains and high acceleration for the flat-top ones [5]. During the compensation optimization a beneficial (for drive beam to RF efficiency) voltage increase pattern for the prefilling trains resulted (see Fig. 4, curve D).

![Fig. 4. Decrease of normalized(with respect to the sum of all installed cavity peak voltages) accelerating H = 1 voltage due to beam-loading over 11 trains of bunchlets (upper full trace A). Curve B shows the compensating voltage obtained as a fast beat between the 2 groups of compensating cavities with 29% of the total installed voltage and frequencies of 243 and 257 MHz. Curve D is the sum of A and B. Curve E is the error with respect to constant amplitude during the flat top. Only the successive short phase intervals (of 90°) populated by the bunchlets of each train are shown, whereas the remaining unpopulated 270° in each of the 11 periods have been cut out. The error with respect to the ideal H = 1 oscillation is 0.01 rms.](image)

**Fourth harmonic cavities**

Figure 5 shows their energizing by the first 4 prefilling train pairs (excitation occurs when the trains last less than one oscillation period), as calculated using R/Q of 386 Ω/m at 1 GHz. The flat-top trains lasting exactly one period cause no net excitation. The resulting field amplitude is 6.1 MV/m and the total active length 67 m. The geometry is scaled from the H = 1 structures.

**Cryogenics**

The harmonic synthesis of Fig. 4 shows that 3.5 GV are needed per linac. Beam-loading compensation, as can be seen from Fig. 4, requires an additional installed voltage in the fundamental frequency range of 33%. Thus, a total fundamental installed SC voltage of 18.5 GV is needed. We follow investigations by K. Huebler [6] and I. Wilson [7] for LEP2 structures at 6 MV/m, 352 MHz and Q = 4 \times 10^9 with static losses of 29.5 W/m and dynamic losses of 32.3 W/m. For the 250 MHz structures static losses are estimated to be 15% [8] and the Q-value to be 75% [9] higher than for the 352 MHz ones. Taking into account by a factor of 3/4 the yo-yo stored RF energy level between pulses (the cavities yielding half their energy to the passing drive beam), the dynamic losses are 19.7 W/m. Applying a cryo-factor of 250 the total cryogenics mains power becomes 41.4 MW for the 2 push-pull linac pairs.
Fig. 5. H = 4 excitation by the prefill train pairs (upper trace). The drive train pairs (bottom trace) are also shown. Only a small fraction (600J, 0.7%) of one drive beam energy (90 kJ) is used for energizing. Furthermore it is taken from the first trains which are underdecelerated in the drive line. The voltage obtained is 6.1 MV/m.

The most important assumptions, leading to an overall (wall plug to main beam) efficiency of 10.5%, are illustrated in Fig. 6. RF and mains power level indications are for both main beams.

703 Hz pulsed rate, luminosity 10^{34} cm^{-2} s^{-1} at 1 TeV CM

- 222.4 MW (wall plug)
- 181.2 MW
- 41.4 MW
- Power supplies and CW klystron (depressed anode) efficiency = 69%
- Cryogenics
- 125.8 MW
- 156.6 kW at 4.2 deg. K
- Drive beam accel. efficiency = 99.8%
- 125.8 MW
- Drive beam to 30 GHz efficiency (incl. 5% int. loss and form factor 0.93, damping drive beam at 3 GHz) ~ 73%
- 91.2 MW
- 10% CTS to CAS transfer loss = 90%
- 82.1 MW (30 GHz from drive linac)
- CAS to main beam efficiency = 28.5%
- 23.4 MW (kinetic main beam power)

Overall efficiency = 10.5% 

Fig. 6. Wall plug to main beam efficiency.

Figure 7 indicates for a variable number of drive beam train pairs the drive beam to RF and the RF to main beam efficiencies. Unfortunately, because of beam-loading in the 250 MHz SC cavities, it is difficult to accelerate more than 11 drive train pairs corresponding to 26 multibunches.

Conclusions

In this compact double push--pull linac proposal most of the capital investment would be for 250 MHz cavities (with their klystrons and cryostats at 4.2K) providing usable stored energy for acceleration.

The main disadvantages of the scheme seem to be:

a) a significant amount of RF and cryogenics hardware for the complete drive-beam generation complex, corresponding to about 8 times the LEP2 upgrade [10].

b) a high bunchlet charge of 50 nC.

c) an overall efficiency of only 10.5%, essentially because of the limited stored RF energy in the 250 MHz structures, which limits the number of drive bunchlets per pulse.

Fig. 7. Efficiencies

The main advantages appear to be:

a) simplicity: no long drive-beam transport lines, no 180° and 90° arcs and no fast kickers as in previous concepts. The drive-beam generation process thus occurs over a limited and almost straight length of about 1.4 km (including SC cavities, magnets and straight sections).

b) acceleration in largely large aperture (33 cm) 250 MHz SC structures causing low wakes.

c) only 41 kW/m input power for the SC cavities.

The forty 3-GHz linacs, upstream of the switchyards delivering up to 33 bunchlets of 50 nC per pulse, seem a difficult challenge; the development work can however be attempted within the modest framework of the CTF. Dark currents in the 250 MHz SC cavities should be investigated. Cavity tune changes due to ponderomotive forces, periodic with the 703 Hz pulsing, may be acceptable thanks to the shortness (< 50 ns) of the drive pulse [11].

References


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CLIC WAVEGUIDE DAMPED ACCELERATING STRUCTURE STUDIES

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Abstract

Studies of waveguide damped 30 GHz accelerating structures for multibunching in CLIC are described. Frequency discriminated damping using waveguides with a lowest cutoff frequency above the fundamental but below the higher order modes was considered. The wakefield behavior was investigated using time domain MAFIA computations over up to 20 cells and for frequencies up to 150 GHz. A configuration consisting of four T-cross-sectioned waveguides per cell reduces the transverse wake below 1% at typical CLIC bunch spacings.

Introduction

Extension of the CLIC scheme to allow operation with trains of 10-30 bunches (30 cm spacing and 8x10^7 particle population) is being studied in an attempt to increase overall efficiency. Such an extension requires a new accelerating structure design that produces suppressed long range wakefields. Preliminary tracking results indicate that the accelerating structure must have a reduction of the transverse wake by a factor of approximately 100 by the time of arrival of a following bunch [1] - including the cumulative effects of all higher order modes. After the time of the following bunch the wake should continue to decrease such that the wake from many bunches does not accumulate.

Wakefield reduction based on detuning has been studied [2], however it does not appear that this scheme provides a sufficient level of performance. The conclusion has persisted even though proposed multibunching parameters have changed significantly since the study was made.

The scheme of wakefield reduction considered here is based on frequency discriminated waveguide damping. Damping waveguides, connected to the outer cavity wall, are chosen to have a cut-off frequency above the fundamental but below all higher order modes - higher order mode energy can propagate out of the accelerating section but the fundamental mode energy cannot.

A number of damping waveguide configurations have been studied using MAFIA. Time domain MAFIA computations were used to determine the transverse and longitudinal wakefields because this direct calculation involves a minimum of assumptions and gives a more or less complete wakefield in a single calculation. In all cases the simplifying assumption of a constant impedance structure has been made. The suitability of a structure design is to be confirmed by beam dynamics simulations that use a computed wakefield.

Computation method

The first step in the study of a candidate geometry was to determine the dimensions needed for a correct fundamental mode frequency by making frequency domain computations. This also gave the fundamental mode Q and R/Q.

Initial time domain calculations over one or two cells followed. If the results looked promising, more accurate calculations of up to 20 cells followed, the number being limited by computer size and speed. The larger number cells gives a more accurate wakefield because it more accurately captures the correct R/Q and phase advance - the discrete set of modes given by a finite cell model does not in general include the synchronous mode of the passband.

The four lowest modes of the damping waveguides were ideally terminated. Thus the assumption that the damping waveguides are nearly perfectly terminated underlies all of the results presented here. The beam pipes were terminated with electrical boundary conditions in order not to overestimate the damping of the structures.

Design considerations

The transverse wakefield of the CLIC constant impedance geometry is dominated by the lowest, TM_{10}, transverse passband with a number of higher bands contributing at the 5-10% level. The criterion for an acceptable design has been that modes in a wide frequency band, up to about 150 GHz, must be damped.

The basic design features that were used to produce adequate transverse wake damping include: the placement of the waveguides in the cells, the number of waveguides per cell, the waveguide cutoff frequency, waveguide coupling strength and the waveguide cross section.

CLIC disk loaded waveguide is assembled from elements each containing a full iris and a full cell. The waveguides studied here have been restricted to those which could in principle be milled into the top of the element on the cell side. This limitation was imposed to limit the mechanical complexity of the design but it does restrict damping waveguides to being longitudinally off-center in the cells and adjacent to the iris.

A configuration with four waveguides per cell has the advantage of coupling to both polarizations of transverse modes in each cell, and of maintaining a high order of symmetry in the fundamental mode. However the cells become mechanically simpler if the number of waveguides per cell can be reduced. Three waveguides spaced by 120° per cell [3] were considered. This solution damps both
polarizations of the dipole mode and maintains an acceptable symmetry of the fundamental mode. However the symmetry of the structure does not match that of the quadrupole modes and results in a shift of the center of the field pattern (Fig. 1). Near the origin this gives the quadrupole modes a dipole mode characteristic thus increasing the number of dipole modes contributing to the transverse wake. Subsequently only two and four waveguides were considered - the choice being largely determined by the strength of coupling needed.

![Figure 1: Quadrupole mode in 3-fold symmetric cavity.](image)

The cutoff frequency of the damping waveguide is bounded by an excessive fundamental mode field penetration into the waveguide and consequent loss of R/Q and Q the low side and by the persistent wake [4] on the high side. The persistent wake is a result of the resonance associated with the cutoff frequency of the waveguide - at the cutoff frequency the group velocity goes to zero and the waveguide acts like a resonator. The transverse wakefield has an initial exponential drop-off followed by a wave decreasing with $t^{-3}$ as the persistent wake becomes dominant. Lowering the cutoff frequency contributes to suppressing the persistent wake.

The coupling strength of the waveguide to the lowest transverse mode of the accelerating structure also plays a role in the level of the persistent wake. An increased coupling can quicken the initial exponential drop-off but at the expense of increased coupling to the persistent wake and consequently a higher value of the wake for longer times. The coupling can be adjusted by changes in the damping waveguide height (the cutoff frequency remains unchanged) or by adding an iris at the cell-waveguide connection.

The waveguide resonance makes incorporating detuning into the design more difficult as the waveguide cutoff frequency partially determines the frequency of the transverse wake. In addition the varying frequency split between the dipole mode and the fundamental mode along the length of a constant gradient or detuned structure implies varying damping characteristics.

The waveguide (and iris) cross section at the connection point to the cavity wall is the primary means to ensure adequate coupling to the forest of higher order transverse modes including the lowest hybrid TE mode (which itself contributes roughly 0.5 % to the amplitude of the undamped wake). For the class of waveguides considered here the primary difficulty is that the $\text{TE}_{21}$ cutoff frequency in rectangular waveguide is too high to couple to the $\text{TE}_{21}$ mode of the cavity. This has been resolved by using a "T" cross-sectioned waveguide (Fig. 2). This results in two waveguide modes of relatively low cutoff frequency, one of which couples to the $\text{TE}_{21}$ cavity mode.

![Figure 2: Magnetic field patterns in a T cross-sectioned waveguide.](image)

**Design results**

The application of the design considerations has lead to two waveguide damped disk loaded waveguide designs. One cell and iris of the disk loaded waveguide of each of the designs are shown in Figs. 3 and 4. Successive cells of the two waveguide geometry are rotated by 90° in order to couple to both polarizations of the transverse modes. The wakefield from the structure is shown in Fig. 5.

![Figure 3: Two waveguide damping.](image)

The primary defect of the design is a substantially reduced Q, 2800 rather than 4400 for the undamped geometry. The Q is lost by the current density concentration around the edges of the top part of the "T". Closing of this part of the "T" off with an iris, as in the geometry shown in
figure 4, reestablishes the Q. However four waveguides must be used in each cell in order to maintain an adequate coupling. The wake from this geometry is shown in Fig. 6.

Another perspective on the damping can be seen by comparing the Fourier transforms of the wake from a damped and an undamped (CLIC constant impedance) structure geometry, Fig. 7.

Figure 4: Four waveguide damping with iris.

Figure 5: Transverse wakefield from two waveguide geometry computed over 20 cells.

Figure 6: Transverse wakefield from four waveguide geometry computed over 13 cells.

Figure 7: Fourier transform of the transverse wake of the 2 waveguide damped (Fig. 5) geometry and corresponding wake of the undamped geometry.

Conclusions

MAFIA computations have been used to design an accelerating structure geometry with four damping waveguides per cell and to demonstrate that the geometry can produce a reduction of the transverse wake by a factor 100. Beam tracking simulations using the computed wake are now being made to demonstrate that this damping is adequate.

A number of further issues must now be addressed. The effects of imperfect waveguide terminations, the design of a highly compact load effective near the waveguide cutoff frequency, the beneficial effects of adding detuning to the damping and the complications of producing a constant gradient structure must all be considered.

Finally, however, a number of mechanical and fabrication issues have lead to the conclusion that the designs presented here are probably not buildable. An assessment, that includes consideration of mechanical feasibility, of the direction that the study will now take is being made.

References

A CODE FOR MULTIBUNCHEO BEAMS WITH WAKEFIELDS, GROUP VELOCITIES AND SPACE CHARGE

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Abstract

Tracking multiparticle bunches with PIC codes is possible, but limited to very short distances. Using the model description these codes provide, PARMTRACK can calculate detailed intra bunch dynamics, and bunch to bunch dynamics for travelling in relatively long beam lines. Macro-particle simulation allows for permanent redistribution in longitudinal as well as in transverse space, without any limiting approximations. Care is taken of group velocities associated with each frequency of the wakefield description. Applications are shown for the part of the CLIC two-beam test facility producing the 30 GHz power.

Introduction

A Two Beam Linear Collider (CLIC) is studied at CERN for a main linac powered at 30 GHz by a drive linac. To support the study, a CLIC Test Facility has been developed over the last few years. At the entry of the energy transfer line of the CTF drive linac, the nominal parameters are now 13.4 nC per bunch of 0.6 mm rms length, for 48 bunches separated by 10 cm. Total energy dispersion per bunch is 7%. Bunch energy is distributed on a parabola with dispersion also equal to 7%, and an average at 62 MeV [1]. A new code was developed for calculating the effects of the wakes in the 30-GHz power production part, built on the PARABELA code scheme [2], keeping the space charge calculations alive. First results obtained with PARMTRACK [3] for preliminary parameters of transfer structures and of the beam, led to a new design of the structures [4], with high damping of the transverse wake, and new plans for CTF2 such that the beam can be constrained in the apertures in the part which is studied, as demonstrated by PARMTRACK and now other codes [5,6]. A version of the code has been worked out for parallel computing in the space charge and wakefields routines [7].

Limits Due to Group Velocities

Group velocities are very important parameters for calculating wakefields and their effects [8, 9]. In the modal description of the delta wake potentials,

\[ w_{\text{d}}(t) = -2 \sum k_{\nu_1} \cos(\omega_{\nu_1} t) \]

\[ w_{\phi}(t) = 2 \left( \frac{c}{a^2} \right) \sum k_{\nu_1} \sin(\omega_{\nu_1} t)/\omega_{\nu_1}, \]

where \( t \) is the time between the passage of the leading and the test particle, \( \omega_{\nu_1} \) is the angular frequency for the longitudinal mode, \( k_{\nu_1} \) the corresponding loss factor, and \( a \) the iris radius. The wake on the test particle is obtained by summing over all particles having an effect on this particle. Attenuation is accounted for by multiplying by an exponential term. If the group velocity \( \nu_1 \) for mode \( n \) is zero, all particles in front of the test particle contribute to the wake seen by it for this mode. If \( \nu_1 \) is not zero, it is represented by an angle in the longitudinal position versus time graph (Figs. 1 and 2). Test particle \( M_1 \), influenced by particles in front, such as \( M_n \), but the energy flowed from position \( M_n' \) of \( M_1 \). All particles influencing \( M_1 \) at its position were on segment \( M_1 M_n' \). The limit is given by the intersection of \( M_1 M_n' \) with the structure entry face (\( \nu_1 > 0 \)) or with the structure exit face (\( \nu_1 < 0 \)). Designating the structure length by \( l \),

\[ \nu_1 > 0: \quad 0 < z < \nu_1 (z_n - z_t)/(c - \nu_1) \]

\[ \nu_1 < 0: \quad 1 - \nu_1 (z_n - z_t)/(c + \nu_1) < z < l \]

Fig. 1. Forward wake
Fig. 2. Backward wake

Frequencies and the Loss Factors

Code MAFIA has been used to calculate the wake potentials resulting from crossing through a small number of cells of the structures by a truncated Gaussian distribution of charge travelling along the structure axis or at 1 mm distance from it [10], in parallel with measurements [4]. These potentials are given as functions of distance \( S \) to bunch head. One can try to get mode frequencies and loss factors by minimizing the differences between these results and those of the convolution of the delta wake potentials \( W(s) \) with the distribution. For longitudinal wake,

\[ W(S) = \int_{-\infty}^{\infty} dz \int_{-\infty}^{\infty} w(s) \exp(-(s-Sn \sigma)/v \sqrt{2} \sigma)^2) ds, \]

where \( \sigma \) is the bunch half width, \( z \) is the distance of the test particle from the structure entry, \( s \) is the distance to the particle in the bunch. Limits are functions of \( S \) and \( \nu_1 \). The loss factor obtained for mode \( n = 2 \) is at least a factor of 100 smaller than for \( n = 1 \). A comparison of the input resulting from MAFIA with the wake reconstructed by the convolution is shown for 12 cells of a structure similar to the CTF ones. Transverse potential decreases because of \( \nu_1 \) (Fig. 3).
Main Features of the Calculating Procedures

Code PARMTRACK follows each of the particles of a beam through a given series of elements such as drifts, focusing devices, dipoles, accelerating cavities. For calculating wakefields, as for calculating space charge, it is necessary to know the particle distribution at as many time steps as required by the precision. After each step, the resulting changes in the momenta are superimposed on the momenta due to the other fields. For the space charge, the coordinates of all the particles at a given time are used. For the wakefields, the coordinates of the particles at the time they were sources of the energy flow are also important, as shown above. Coordinates are reconstructed from a series of tables corresponding to selected transverse planes, such as structure entry faces.

Main Features of Beam Input Data

Accounting for multibunches and wakefields effects makes the calculations complex and limitation of the total number of particles, and therefore also of the number of particles per bunch, is necessary. The distribution is a truncated Gaussian one. A random choice in a Gaussian distribution would require too many samples. So, instead, positions of the particles are taken at centres of equally populated intervals of this Gaussian, giving as many particles as intervals. The series of positions (or phases) in a bunch is the series of increasing values thus obtained and normalized with the rms bunch length. Random permutations in the same series give, after having normalized with corresponding rms values, the initial coordinates $x$, $dx/ds$, $y$, $dy/ds$, $dE/E$ for each particle. Coupling between initial $x$, $dx/ds$ or initial $y$, $dy/ds$ is possible.

For each of these particles, three other particles are derived with same longitudinal position but inverse signs on pairs $(x, dx/ds)$ or $(y, dy/ds)$, or both. The beam transverse symmetry imposed by the procedure suppresses a source of artificial wakefields.

By default, the distribution in successive bunches is the same as the one in the first bunch. A variation of the energy from bunch to bunch and a variation of the bunch centre transverse position can be specified.

Application to CTF2 Drive Beam

A series of a maximum of 6 transfer structures, each of 0.6 m, is installed in the drive beam line after acceleration and compression devices. In longitudinal and in dipole modes, the loss factors are negligible for frequencies higher than the first one. Damping of the transverse mode is vital to restrain the beam in the apertures (r = 7.5 mm for structures, 12 mm for quadrupoles). The difference between the fundamental frequency and the dipole one is also important.

<table>
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<td>29.9625</td>
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<td>1.63 $10^4$</td>
</tr>
<tr>
<td>$v_g$</td>
<td>$c/2$</td>
<td>$c/2$</td>
</tr>
<tr>
<td>damping factor (0.1 m)</td>
<td>no</td>
<td>0.5</td>
</tr>
</tbody>
</table>

By the effects of group velocity, structure length and bunch separation, steady state is reached after 12 bunches. The energy variation with $z$ is shown (Fig. 4), with the position of the structures.

Fig. 4. Minimum, average, maximum energies in bunch 12.

Focusing is provided by triplets in intervals between structures, with identical forces (0.904 T, 0.494 T). The input emittance is 1000 π mm rad in each plane. Transverse effects are caused by the following displacements:

<table>
<thead>
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</tr>
</thead>
<tbody>
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<td>50</td>
</tr>
<tr>
<td>structures</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>quadrupoles</td>
<td>0</td>
<td>20</td>
</tr>
</tbody>
</table>

The envelope is shown for a calculation made with 17 bunches and 84 particles per bunch (Fig. 5). Alphanumeric digits indicate to which bunch the particle at the limit is related.

Positions of the centres of each bunch cross over but with a similar variation with $z$ (Fig. 6).

The correlation between the variation of the maxima of the envelopes and the variation of the central positions of the bunches may be used for displacing the triplets in a one to one correction scheme. The chosen BPMs allow averaging on the transverse position of the 5 successive bunches whose energies are close to the overall average. Results (Fig. 7) show the good transmission of the beam.
In another study, the parameters were more severe: 21 nC for 1 mm rms bunch length, 43 MeV input energy, damping of 0.3 between bunches.

In this case, the lowest energy at the end is 20 MeV. Focusing was varied from (749 T, 441 T) to (663 T, 390 T) from triplets 1 to 6, by more than required by the energy drop, but avoiding over-focusing. The beam is lost on structure 5. With correction, the amplitude of the average position of the bunches is brought from ±3 mm to ±2 mm: the beam is lost in the middle of structure 6 (Fig. 8). More damping is needed if 6 structures are used.

Acknowledgments

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References

TRAJECTORY CORRECTION ALGORITHMS ON THE LATEST MODEL OF THE CLIC MAIN LINAC

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Abstract

Control of beam emittance is a key issue in the design of future linear colliders. Results depend closely on the assumptions made for the alignment tolerances of the various linac components. Processes involving several correctors and beam position monitors help either to reduce the emittance blow-up or to increase the tolerances beyond the values provided by simpler ‘one-to-one’ schemes. ‘Dispersion-Free’ or ‘Wake-Free’ algorithms require a simulation of the effects to be corrected, by lattice quadrupole detuning. Wakefield effects can also be measured, for example by current modulation as in the ‘Measured-Wakefield’ and ‘dispersive-Wakefield’ processes.

For the Compact Linear Collider (CLIC) these algorithms, so far tested in the thin-lens approximation and assuming continuous scaling with energy of quadrupole strength and RF section length, are now applied on a more realistic structure of the main linac. Their implementation is described and the performances achieved in terms of the alignment tolerances are presented. Special emphasis is placed on the merits of the most powerful ‘Dispersive Wakefield’ process.

Introduction

The virtues of trajectory correction processes involving several correctors and beam position monitors to control the transverse beam emittance in future linear colliders or to increase the alignment tolerances of the accelerator components have already been demonstrated. These processes are based on the minimization of an algorithm. This algorithm contains a term related to the nominal trajectory — measured with nominal beam and lattice parameters, in particular at the nominal momentum $p_0$ and bunch population $N_p$ — and other terms dealing with trajectories taken under perturbed conditions, in order to evaluate the undesirable effects which need to be corrected. When only the term related to the basic trajectory is considered, the correction is named ‘few-to-few’. Methods involving other terms have been presented several times; therefore, only their fundamental principles are recalled.

The undesirable effects can be simulated as in a ‘Dispersion-Free’ (DF) or ‘Wake-Free’ (WF) algorithm [1]. In a DF correction, the beam trajectory is measured for given beam-energy exciters $\delta p$ (typically $\delta p = \pm 0.035$ $p_0$) is adopted when applying the method on the CLIC linac model) and the differences between these and the nominal trajectory are corrected. A WF algorithm tries to evaluate the effects of the self-transverse wakefields within a bunch by the application of antisymmetrical perturbations on the lattice quadrupoles: when QFs are detuned by $+\delta, -\delta$ is applied on QDs and vice versa. Again the differences with respect to the beam trajectory measured under normal conditions are minimized.

Instead of simulating these effects by quadrupole detuning, another possibility is to measure them. One needs to reproduce conditions which are free of the effects to be corrected and compare them to the nominal situation. There are various ways to evaluate the effects of transverse wakefields. In CLIC it has been shown [2] that on a beam trajectory measured with a bunch charge at least ten times smaller than the nominal one, transverse wakefields effects can be neglected. One can evaluate and correct the trajectory differences measured at these various currents. The method is called ‘Measured Wakefields’ (MW) correction [2]. In CLIC the method efficiency is improved by also incorporating a dispersive term in the algorithm (differences at low current between a bunch trajectory at nominal momentum and trajectories taken with energy excitations $\pm \delta p$). The measured wakefield effects and the dispersion effects can be further combined in a single term in the algorithm. This correction is named ‘Dispersive Wakefields’ (DW) [2].

These methods were applied on a model of the main linac based on the following assumptions: the thin-lens model for quadrupoles and continuous scaling with energy of quadrupole strength and of RF section length to ensure stability. With alignment tolerances increased to 10 $\mu$m rms on pickups and cavities, DF and WF algorithms allow the normalized vertical emittance $\gamma \varepsilon_y$ to reach values around $25 \times 10^{-8}$ rad.m at 250 GeV for an initial emittance of $5 \times 10^{-8}$ rad.m [3]. MW and DW corrections reduce this figure to $\gamma \varepsilon_y = 10 \times 10^{-8}$ rad.m. A more realistic model of the main linac was developed [4] with finite cavity and quadrupole lengths, and divided into 6 sectors (for the 0.5 TeV CM energy option) with constant quadrupole length and correction within each. The various corrections have been adapted to this model; implementation and results are reported.

Code Description and Characteristics

Initially, the implementation of the different corrections required three different programs.

- Program 1 processes the transfer coefficients needed in the algorithm [2, 3], applying a kick unity and looking at the response on the subsequent pickups. Kicks are located at quadrupoles and the number of position monitors is a parameter; usually one monitor is placed on every other RF girdder (2.8 metres). The whole linac model comprises 530 quadrupoles (kicks) and 1700 position monitors. For each kick, the

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response at 50 subsequent pickups is computed. This is performed for nominal conditions and for each perturbed situation required by the method; a minimum of three different machines is required for either correction.

- Program 2 tracks the bunch, measures its trajectory under each appropriate condition (quadrupole strength, bunch charge) and can apply the kicks calculated by program 3. It generates alignment errors, applies corrections and stores trajectories. Both programs 1 and 2 derive from MTRACK [5, 6].
- Program 3 actually applies the desired correction algorithm using the transfer coefficients from program 1 and the trajectories from program 2; different weights can also be applied to the various terms. Program 3 generates kicks which are then read by program 2 to measure the corrected trajectories. Programs 2 and 3 iterate along the whole linac.

The same architecture was kept for the new model with a few modifications because of the new linac structure. Some improvements were also implemented. Owing to the thin-lens treatment, it was necessary to consider quadrupole strength and cell length rather than phase advance and betatron wavelength. Matching between two consecutive sectors is required [4]; each matching section is precalculated (with MAD) for a given quadrupole gradient configuration. The three programs had to be adapted to the physical sectorization of the linac and overlapping between sectors was made possible. In program 1 the size of coefficient tables is reduced. For corrections, program 2 deals with quadrupole displacement during prealignment phases and with kicks, applied at quadrupole entrances during the application of more sophisticated processes. Program 3 was modified to deal with the new coefficient-table structure. During phases 1 and 2 only the relevant piece of linac is considered for a given kick or iteration. The procedure now works simultaneously in both the x and y planes; transverse coupling and quadrupole tilt are possible with a 4 x 4 matrix formalism.

Once tested, the three programs were merged as subroutines of a single manager called CALICO (Correction Algorithms for Linear Colliders). The overall process efficiency is greatly improved in terms of simplicity and speed. The transmission of parameters between routines is easier, hence the procedure is simpler. A huge time saving has been achieved for transfer coefficient processing and correction application. CALICO is currently installed on the SP platform. The processing of the transfer coefficients for three different machine conditions requires 5 min and the application of an algorithm along the whole linac takes 10 to 15 min. Several corrections can now be tested in a short time.

Results

DF and WF corrections

The application of DW or WF corrections requires, as observed for the thin-lens model, several passes, varying the linac section length considered during an iteration and the relative weight of each term in the algorithm until an acceptable solution is reached. With the new linac model, the application of DF or WF algorithms hardly results in a significant reduction of the emittance values obtained after prealignment. This was already stated in Ref. [7].

Figure 1 shows a typical result after a DF correction, requiring a total number of 90 iterations on linac sections of 12 quadrupoles; the trajectory term carries 10 times more weight than the dispersion. The final normalized vertical emittance is reduced from 6.0 x 10^-7 rad.m (after prealignment) to 4.3 x 10^-7 rad.m. The benefit of the DF correction is dependent on the position considered along the linac.

Fig. 1. Evolution of the vertical emittance along the linac with alignment errors of 10 μm rms after: 'one-to-few' correction (dotted line) and DF correction (continuous line).

MW and DW corrections

As in the case of the thin-lens model, it was verified that a trajectory taken when the bunch charge is 12 times smaller than the nominal value is not affected by wakefields in the thick-lens model.

With rms alignment errors of 10 μm on pickups and cavities, on a machine which is prealigned by the application of a 'one-to-few' correction, one pass (50 iterations) of the DW process leads to a reduction in the normalized emittance at the linac exit from 50 x 10^-7 rad.m to 15 x 10^-7 rad.m in the horizontal plane (see Fig. 2) and from 6 x 10^-7 rad.m to 0.7 x 10^-7 rad.m in the vertical plane (Fig. 3), starting from 14.5 x 10^-7 rad.m and 0.5 x 10^-7 rad.m at injection. The dispersive term carries 100 times more weight than the trajectory.

Fig. 2. Evolution of the horizontal emittance along the linac with alignment errors of 10 μm rms: (a) after 'one-to-few' correction; (b) after DW correction.

When alignment errors are reduced from 10 μm to 5 μm rms a final vertical emittance of 0.56 x 10^-7 rad.m is obtained

741
(less than 12% of blow-up) (see Fig. 3c). The better efficiency of a DW algorithm compared to a MW correction (which considers only the contribution of measured wakes without the dispersive term) is shown in Fig. 4. The efficiency of the DW method has been verified on five different machines (all having alignment errors of 10 μm rms but different seeds). The average final vertical emittance value is $0.8 \times 10^{-7}$ rad.m starting from $0.5 \times 10^{-7}$ rad.m; the blow-up rate is 60%.

Fig. 3. Evolution of the vertical emittance along the linac: (a) after 'one-to-few' correction and alignment errors of 10 μm rms; (b) after DW correction and alignment errors of 10 μm rms; (c) after DW correction and alignment errors of 5 μm rms.

Fig. 4. Evolution of the vertical emittance along the linac: (a) after MW correction; (b) after DW correction on the same machine. Alignment errors are of 10 μm rms.

The DW method efficiency is also illustrated in Fig. 5, where the term describing wakefield effects (trajectory difference between a bunch with nominal charge and a bunch twelve times less populated) and the dispersive terms (trajectory difference between a bunch with nominal energy and a bunch with energy excursion) are represented. The correction is only applied on the first 800 pickups (2 km).

**Conclusion**

The same conclusions apply as in the case of the thin-lens model. The application of DF or WF algorithms requires difficult and time-consuming optimization of the various parameters (relative weights between terms, linac section length considered, microwave quadrupole setting) through several consecutive passes. It therefore relies strongly on the presence of diagnostics facilities. On the contrary, a single pass with the DW method allows direct convergence to final vertical emittance values lower by a factor of 2–3 without requiring special optimization of these various parameters. Hence the power of the method can probably still be improved if one considers the various possible sophistications. The single-bunch vertical emittance blow-up rate in CLIC has now been pushed down to 50% for alignment tolerance values of 10 μm rms which is a big achievement and could perhaps allow tolerances to be further increased.

Fig. 5. Effect of a DW correction on: (a) the term describing wakefield effects (b) the terms describing the effects of energy dispersion. Correction is applied over 800 pickups.

**Acknowledgements**

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Status of the High Current Injector Project

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1 Abstract
Many experiments at the Test Storage Ring TSR are limited by weak ion beam intensities [1], delivered from a tandem-postaccelerator combination. A new high current injector, consisting of a CHORDIS ion source, 2 RFQ and 8 seven-gap resonators, will deliver 1–3 orders of magnitude higher intensities of singly charged ions. The final energy of 1.8 MeV/u is well adapted to the acceptance of the postaccelerator. By adding an ECR-source in a second phase the system will be able to deliver heavy ion beams up to uranium with energies above the coulomb barrier of the heaviest elements. The CHORDIS is already operating in cw-mode, in sputter mode the pulsed intensity has still to be optimized. By means of an optimizing algorithm it was possible to lower the electrode voltage of the RFQ-accelerator from 71 kV to 60 kV maintaining a particle transmission of about 80% with ion currents of 10 mA. All of the 8 seven-gap resonators have been power tested successfully and performed as expected. This paper describes the status of the project.

2 Introduction
In its first phase the high current injector consists of a commercial CHORDIS ion source [4], 2 RFQ-accelerators [3] and eight 7-gap resonators [2] delivering $^4\text{He}^+$ or $^9\text{Be}^+$ ion beams with 1–3 order of magnitude higher intensities. In a second phase an ECR- or EBIS-source will be added to increase the currents for highly charged heavy ions because some experiments are frequently limited by low beam currents due to stripping losses. In fig. 1 the schematic layout of the new injector is shown. The accelerator will be placed parallel to the Tandem. The $^7\text{Li}^+$ or a $^9\text{Be}^+$-beam will be injected directly into the postaccelerator acting as a transfer line. For a second phase stripping will be used behind the last seven gap resonator and the proper charge state will be selected by an achromatic separator consisting of four 60°-magnets. Like the existing post accelerator the new injector operates at 108.48 MHz. The ion velocity of $\beta = v/c = 5\%$ after the high current injector is well adapted to the post accelerator and final energies higher than 5 MeV/u can be reached for all ion species in a pulsed mode operation with up to 25% duty cycle.

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</table>

Table 1: List of ion species and current intensities already produced with the CHORDIS source.

Figure 1: Schematic layout of the new high current injector. A, M, Dou, Tri: magn. dipoles and lenses, Re: rebuncher, D: beam diagnosis.

3 The ion source
For the production of high currents of $\text{Li}^+$ and $\text{Be}^+$ with low duty factor (5 Hz, 500µs) the commercial ion source CHORDIS [4] is used. The construction of the ion source section consisting of the source on a platform, a 60°-magnet for isotope selection and a quadrupole triplet to match the beam to the RFQ section has been finished. The CHORDIS ion source has been in operation on its testbench for several hundred hours [see Table 1]. The design value of 2 mA was achieved with $\text{Li}^+$ in stable operating conditions. Higher currents were reached and could be stably produced by using an additional cooling equipment of the sputter cathodes. For the $\text{Be}^+$-source an alloy with...
a Beryllium contents of only 2% was used with which an intensity of 0.2 mA was satisfactory for all tests. Higher currents can then be achieved with cathodes made from pure Beryllium. Improvements were made with respect to diagnostic methods for source operation and particle beam optimization. The pulsed mode operation has been established for the gas version, however, some improvements are still necessary in the sputter mode. The emittance of the CHORDIS of 35 mm mrad has been measured to be within specifications.

4 The RFQ–Resonators

The second section of the high current injector consists of two 4–rod–RFQ resonators [3] operating at an eigenfrequency of 108.48 MHz. With a rf–power of 80 kW (25% duty cycle) an electrode voltage of 71 kV should be reached in order to accelerate ions with a charge to mass ratio q/a ≥ 1/9 as required for Be²⁺. The electrodes with 3 m length are milled out of a hollow profile from a copper–tin alloy to provide sufficient cooling (35% of the rf power is dissipated at the electrodes) as well as mechanical stability. However, the maximum diameter of the rods is limited by the capacity between the electrodes to preserve a high shunt impedance [3]. To provide optimal electrical conductivity the electrodes were copper plated at the GSI. The first RFQ–resonator was constructed and tested in full length this year. The mechanical alignment of the electrodes was performed successfully and the achieved tolerance (±0.02 mm) measured after installation is satisfying. Massive copper plates were installed between the stems to adjust the eigenfrequency to 108.48 MHz. The resonator has a Q–factor of 3800. Power tests up to 20 kW in cw–mode were carried out without any problems. Weak ponderomotoric oscillations – which could be observed in pulsed high power operation – could easily be eliminated by

Figure 2: Calculated (line) and measured (dots) energy distribution at an electrode voltage of 15.8 kV

Figure 3: Comparison between the calculated (solid line) and measured (dots) energy spread ΔE/E to determine the shunt impedance. U₀=15.8 kV is the design voltage for an H²⁺–beam.

means of mechanical decoupling between the cryo–pumps and the resonator–tank. Moreover, a mechanical stabilization was used at the long ends of the electrodes to suppress mechanical oscillations.

In order to determine the shunt impedance Rₜ of the structure the energy gain of an accelerated H²⁺–beam behind the first RFQ–resonator was measured. The set up consists of a penning ion source with electrostatic lenses and an analyzing 90°–double focusing bending magnet with two diagnostic boxes. First acceleration tests have been carried out and compared with PARMTEQ–calculations [6] at different rf–power levels. The measured and simulated energy spread of the beam at 7.4 kW is shown in fig. 2. The comparison between calculated and measured energy spread, fig. 3, leads to a shunt impedance Rₜ = 101 kΩm. With

Figure 4: Diagram of the optimizing algorithm.
this shunt impedance it is not possible to reach an electrode voltage of 71 kV (design value) with a rf power of 80 kW. Therefore the electrodes are redesigned with a lower voltage of 60 kV by means of an optimizing algorithm. This new method is based on random variations of the design parameters synchronous phase \( \phi_s \), modulation \( m \) and focusing parameter \( B \) and governed by the value of a scalar function \( b(T, L) \) which takes only two criteria into account: the length \( L \) of the resonator for a fixed final energy and the calculated particle transmission \( T \) [see Fig. 4]. Fig. 5 shows the parameter behavior of the old 71 kV-design and the re-designed 60 kV electrodes. By reducing the electrode effect caused by \( \pm 0.2 \text{mm} \) misalignment of the rods and is therefore tolerable.

5 The 7-gap resonators

With increasing ion velocity, RFQ acceleration becomes less efficient and other accelerating structures such as seven-gap resonators are more economical. Therefore the third part of the high current injector consists of 8 seven-gap resonators with an eigenfrequency of 108.48 MHz operating at 80 kW rf power with 25% duty cycle. To simplify the construction, the resonators are designed as four pairs of identical resonators for synchronous velocities of \( \beta_s = 3.7, 4.5, 5.1 \) and 5.7% [5]. All 7-gap resonators have been calibrated with a particle beam with synchronous velocity. From the energy distribution of the beam behind the resonator, the accelerating voltages could be derived [table 2], and were found in good agreement with the beam perturbation measurements. The resonators are finished and have successfully undergone high power–rf tests up to 100 kW at a duty cycle of 25%. Neither mechanical vibrations due to ponderomotive forces nor multipactoring problems have been observed.

<table>
<thead>
<tr>
<th>( \beta_s ) [%]</th>
<th>( U_0 ) [MV] ((N=80kW))</th>
<th>( \beta_s ) [%]</th>
<th>( U_0 ) [MV] ((N=80kW))</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7 I</td>
<td>1.73</td>
<td>5.1 I</td>
<td>1.69</td>
</tr>
<tr>
<td>3.7 II</td>
<td>1.67</td>
<td>5.1 II</td>
<td>1.74</td>
</tr>
<tr>
<td>4.5 I</td>
<td>1.79</td>
<td>5.7 I</td>
<td>1.70</td>
</tr>
<tr>
<td>4.5 II</td>
<td>1.73</td>
<td>5.7 II</td>
<td>1.71</td>
</tr>
</tbody>
</table>

Table 2: Measured resonator voltages with beam tests.

6 Acknowledgement

It is a pleasure for us to thank the technicians of the Max-Planck-Institute for their excellent work.

7 References

MODELING OF THE ALS LINAC

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Abstract

The ALS injector linac is used for the Beam Test Facility (BTF) and the Damping Experiments when it is available in between the ALS fillings. These experiments usually require higher quality beams and a better characterization than is normally required for ALS operations. This paper focuses on the beam emittance, energy tilt, and especially the longitudinal variation of the beam parameters. For instance, we want to avoid longitudinal variations at the low beta section of the BTF. On the other hand, a large energy tilt is required for post-acceleration compression of the bunch using an alpha magnet. The PARMELA code was modified to calculate and display longitudinal variations of the emittance ellipse. Using the Microsoft Development Studio under Windows NT environment the code can handle a much larger number of particles than was previously possible.

Introduction

The ALS linac was designed in 1986 to serve as a preinjector for the ALS. High charge per bunch was required for fast filling of the storage ring in the few bunch mode. Subharmonic bunchers and an S-band buncher were deployed to achieve this goal. [1] Recently many interesting experiments were proposed in the Beam Test Facility [2] which uses the ALS Linac when it is not used for ALS injection. These experiments may have special requirements for beam parameters and/or require a better characterization of the beam. Good simulation and modeling will help meet these requirements.

A version of the well-known linac code PARMELA adopted for the Windows NT environment was used to model the linac. With the recent hardware and software advances, personal computers now have the attractive speed and memory capacity for doing interesting particle simulations.

The code calculates the motions of macro particles (test particles which are also used for estimating the space charge forces) in 3D under the influence of rf fields and space charge forces. The space charge forces are assumed to be axially symmetric. An older PC version was used by R. Miller, C. Kim, and F. Selp [1] for designing the bunching system for the ALS linac.

The present version is written in FORTRAN 90 and compiled with a 32 bit compiler, Microsoft® FORTRAN Power Station. The compiler comes with an excellent debugger. It takes a PC, with a Pentium 133 MHz processor running in double precision, about 1 hour to finish a complete run for modeling the ALS linac with 1,000 test particles, and 10 hours with 10,000 test particles. Test runs with less than 100 particles are useful for adjusting the phases and amplitudes of the various rf systems. These runs take less than ten minutes.

The code runs with a double precision and has the provision of restarting from the particle locations saved from a previous run.

The code saves particle coordinates as they pass through element boundaries and writes to a binary file which can be analyzed with a post-processor PARGRAPHER. PARGRAPH calculates emittances and other ellipse parameters and plots some selected two dimensional projections of the electron distribution at a given location.

Run-time graphics similar to the post-processor have been implemented in PARMELA to plot some selected two dimensional projections of the electron distribution at every time step or at a user specified time interval.

Run time graphics are like windows to the code through which one might peek and see what is going on. It is useful for debugging the code, and for optimization of designs and operations.

\[
\text{betem: ave = 11.383, rms = .755}
\]

\[
Z: \text{ ave = 335.5, rms = .266 cm}
\]

Figure 1. An example of the \(\beta_f\)-z phase space distribution plotted by the run-time graphics. This particular distribution was captured at a time when a low current bunch had traveled through the first third of linac section 1. Typically, six such projections out of 15 possible projections can be displayed in a video screen with a resolution of 1024x780.

The Linac

Two subharmonic bunchers, operating at frequencies of 125 MHz and 500 MHz, are used to compress the electron bunch from the gun to the entrance of the S-band buncher. Both the 125 MHz buncher and the 500 MHz buncher consist of re-entrant cavities, and can generate maximum of 45 KV peak including the transit time factor. The S-band buncher is a 10-cm-long 4-cavity traveling-wave waveguide with \(\beta=0.75\) in
The Linac has two sections of 2-m traveling-wave structures with \( \beta = 1 \) in 2\( \pi / 3 \) mode and can produce a maximum accelerating gradient of about 13 MV/m. 

The drift distance from the 500 MHz buncher to the beginning of the S-band buncher A simulation with one half the drift distance showed an excellent result.

Results for the 1 Ampere simulation are consistent with our nominal operation in which we start with 2 nC and accelerate 1 nC of them to 50 MeV.

Table 1. Summary of three simulations. Electron bunch length (pico seconds rms) and the fraction of the remaining electrons at the beginning of each element.

<table>
<thead>
<tr>
<th>Element</th>
<th>locat-bunch length (psec) / fraction of remaining electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Gun</td>
<td>0 / 498 / 1.0 / 498 / 1.0 / 498 / 1.0</td>
</tr>
<tr>
<td>125 MHz Buncher</td>
<td>100 / 499 / 1.0 / 505 / 1.0 / 511 / 1.0</td>
</tr>
<tr>
<td>500 MHz Buncher</td>
<td>246 / 82 / 1.0 / 124 / 1.0 / 157 / 1.0</td>
</tr>
<tr>
<td>S Band Buncher</td>
<td>278 / 50 / 1.0 / 51 / 1.0 / 58 / 1.0</td>
</tr>
<tr>
<td>Linac Section 1</td>
<td>290 / 24 / 1.0 / 25 / 0.84 / 30 / 0.57</td>
</tr>
<tr>
<td>End of Section 1</td>
<td>490 / 8 / 1.0 / 9 / 0.84 / 11 / 0.57</td>
</tr>
<tr>
<td>Quad Triplets</td>
<td>533-578 / 8 / 1.0 / 10 / 0.84 / 12 / 0.57</td>
</tr>
<tr>
<td>End of Section 2</td>
<td>805 / 8 / 1.0 / 10 / 0.83 / 12 / 0.56</td>
</tr>
</tbody>
</table>

### Emittance Growth

Most of the emittance growth occurred in the bunching region \( z = 100 - 288 \) cm as shown in Figure 3. Large chromatic effects caused longitudinal variation of emittances and eventual emittance growth in this region.

![Figure 3. Growth of normalized emittance in the ALS Linac for three currents.](image)

Space charge effects caused a rapid emittance growth near the S-band buncher \( z = 278-288 \) cm, but the resulting beam loss caused the emittances to decrease because outlying electrons are preferentially lost. A simulation showed that this type of emittance growth and particle loss can be reduced.
significantly by decreasing the drift distance from the 500 MHz to the beginning of the S-band buncher by a factor of 2.

Figure 4 shows the phase space distribution of electrons at the final energy of 50 MeV. Out of the initial 2.0 nC, 1.1 nC are accelerated to this energy. The electron distributions in the X - X' and E - E' phase space are shown in figure 4. The sine-wave footprint in the longitudinal distribution is obviously made by the accelerating rf field. The linac parameters corresponding to this run have not been optimized but just represent a set of self-consistent beam parameters which we are going to use for further analysis. For instance the rf phase of the linac section 2 was lagging by about 10 degrees behind which produced an energy tilt as shown in figure 4.

![Figure 4. Phase space distribution of electrons at 50 MeV point. One degree of RF is 0.927 pico seconds](image)

Average beam parameters at the final energy are summarized in table 2. These parameters were calculated by the post processor.

Table 2. Beam parameters at the final energy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge per Bunch</td>
<td>1.1 nC</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>51 MeV</td>
</tr>
<tr>
<td>emitt x rms unnorm</td>
<td>0.95 mm mrad</td>
</tr>
<tr>
<td>emitt y rms unnorm</td>
<td>1.0 mm mrad</td>
</tr>
<tr>
<td>emitt z rms unnorm</td>
<td>24 MeV deg</td>
</tr>
<tr>
<td>Xrms</td>
<td>3.99 mm</td>
</tr>
<tr>
<td>Yrms</td>
<td>3.90 mm</td>
</tr>
<tr>
<td>X',Y'rms</td>
<td>0.45 mrad</td>
</tr>
<tr>
<td>pulse length</td>
<td>11.5 deg</td>
</tr>
<tr>
<td>alpha x</td>
<td>-1.6</td>
</tr>
<tr>
<td>alpha y</td>
<td>-1.4</td>
</tr>
<tr>
<td>beta x</td>
<td>16.8 m</td>
</tr>
<tr>
<td>beta y</td>
<td>15.2 m</td>
</tr>
</tbody>
</table>

**Longitudinal Variations**

The post processor was modified to calculate the longitudinal variation of the beam parameters. The beam is cut into 10 longitudinal sections where 1 section is 1 sigma long. Number of electrons in each section is counted and the same set of beam parameters as shown in table 2 are calculated for each section. Some of these parameters are plotted in figure 5.

The longitudinal variation of the ellipse parameters are quite flat over the central 4 sigma region and generally weaker than that of the bunching region (not shown in this paper).

![Figure 5. Variation of longitudinal beam parameters as functions of the distance along the bunch](image)

**Acknowledgments**

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**References**

HIGH-POWER LINAC FOR A US SPALLATION-NEUTRON SOURCE

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Abstract

We present the status of the high-power linac-design studies for a proposed National Spallation Neutron Source (NSNS), based on a linac/accumulator-ring accelerator system. The overall project is a collaboration involving five national laboratories. The Oak Ridge National Laboratory will be responsible for the target, facilities, and the conceptual design; Brookhaven National Laboratory will be responsible for the ring; Lawrence Berkeley National Laboratory will be responsible for the injector, including the RFQ and a low-energy chopper located in front of the RFQ; Los Alamos National Laboratory will be responsible for the main linac, and the Argonne National Laboratory will be responsible for the instrumentation. The facility will be built at Oak Ridge. In the first phase, the dual-frequency linac with frequencies 402.5 and 805 MHz must deliver to the accumulator ring an H⁺ beam with nominal energy near 1 GeV, with a pulse length of about 1 ms at a repetition rate of 60 Hz, and with a nominal average beam power of at least 1 MW. The linac can be upgraded by a factor of four in beam power by increasing the dc-injector current, and by funneling the beams from two 402.5-MHz low-energy linacs into the 805-MHz high-energy linac. Requirements for low beam loss in both the linac and the ring have important implications for the linac design, including the requirement to provide efficient beam chopping, which is necessary to provide low-loss extraction for the ring. The linac-design options and initial parameters will be presented, together with initial beam-dynamics simulation results.

Introduction

In 1995 the US Congress commissioned Oak Ridge National Laboratory to conduct a two-year conceptual design study for a new pulsed spallation neutron source. Oak Ridge has formed a collaborative partnership with four other US national laboratories, LBNL, BNL, LANL, and ANL for the design and construction of the new facility. The design work builds on a strong base of recent studies for high-power spallation sources performed at ANL1, LANL2, BNL3, and the European Spallation Source (ESS)4 study. The conceptual design effort has been underway for about 8 months, and significant progress has been made in defining the reference design parameters.5 The facility must initially deliver a beam in the 1-MW power range with high confidence, and must be upgradable to the 5-MW power range.

Two architectures for the accelerator were considered for the Reference Design, a full-energy linac plus an accumulator ring, and a lower-energy linac and a synchrotron ring. Based on consideration of the technical risks and the upgrade paths, the accumulator ring approach was chosen for the reference design. For the initial stage of the reference design the nominal parameters include a beam to target power of 1-MW, a beam energy of 1 GeV, and a repetition rate of 60 Hz.

Linac Reference Design

The main design requirements for the NSNS linac for the first phase of a 1-MW facility are 1) 1.1-MW average beam power at 1 GeV for the linac output beam (the extra 0.1 MW accounts for the minimum 90% injection efficiency into the ring), 2) 60-Hz pulse repetition rate, 3) linac beam losses below about 10⁻⁷/m to avoid high accelerator radioactivation, so that remote maintenance is not necessary, and 4) chopped beam to allow low-loss extraction from the ring. Table 1 shows the main reference-design parameters, and Fig. 1 shows a block diagram of the NSNS-linac reference design.

Table 1: Linac Reference Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion</td>
<td>H⁺</td>
</tr>
<tr>
<td>RF frequency</td>
<td>402.5/805 MHz</td>
</tr>
<tr>
<td>Final energy</td>
<td>1000 MeV</td>
</tr>
<tr>
<td>Average beam power</td>
<td>1.1 MW</td>
</tr>
<tr>
<td>Average beam current</td>
<td>1.1 mA</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Pulse period</td>
<td>1.03 ms</td>
</tr>
<tr>
<td>Beam duty factor</td>
<td>6.11%</td>
</tr>
<tr>
<td>Chopper transmission</td>
<td>0.65</td>
</tr>
<tr>
<td>Average pulse current</td>
<td>18.0 mA</td>
</tr>
<tr>
<td>Peak pulse current</td>
<td>27.7 mA</td>
</tr>
<tr>
<td>DC injector output current</td>
<td>34.6 mA</td>
</tr>
<tr>
<td>DC injector rms normalized emittance</td>
<td>0.14 mm-mrad</td>
</tr>
<tr>
<td>Peak beam power</td>
<td>18 MW</td>
</tr>
<tr>
<td>Peak structure-power losses</td>
<td>96 MW</td>
</tr>
<tr>
<td>Peak rf power</td>
<td>114 MW</td>
</tr>
<tr>
<td>Average rf power</td>
<td>8.0 MW</td>
</tr>
<tr>
<td>No. 1.2-MW, 402.5-MHz klystrons</td>
<td>3</td>
</tr>
<tr>
<td>No. 5.0-MW, 805-MHz klystrons</td>
<td>30</td>
</tr>
<tr>
<td>Total length</td>
<td>566 m</td>
</tr>
</tbody>
</table>

Fig. 1 Block diagram of the NSNS 1.1-MW linac

As the proton energy increases, different accelerating structures provide maximum power efficiency, while satisfying the beam focusing requirements. The H⁺ multi-cusp volume source delivers a nominal 65-keV 35-mA beam into a compact electrostatic Einzel-lens low-energy beam transport (LEBT), which transports the beam and matches it into the first linac structure, the radiofrequency quadrupole (RFQ). The RFQ is a
4-vane structure operating at 402.5 MHz with a vane length of 3.7 m, which bunches the dc beam with high transmission and accelerates it to 2.5 MeV, while focusing the beam using rf electric quadrupole fields. After the RFQ, the medium-energy beam transport (MEBT) matches the beam into the next structure, a drift-tube linac (DTL), and provides beam shaping, which will be described later. The ion source, LEBT, RFQ, and MEBT will be designed and manufactured by LBNL. The rest of the linac, as well as the 2.5-nscc chopper system in the MEBT will be designed and manufactured by LANL. The RFQ is designed to accommodate the full 55 mA required for the future upgrade, but will operate at 27.7 mA for the initial 1-MW operation. The all-electrostatic LEBT with chopping will be similar to one reported on at this conference. The RFQ beam dynamics are conservative, and like the rest of the linac, an important engineering issue will be the thermal management at the high 6% duty factor operation. This requirement, and that of stabilizing an RFQ structure that is five wavelengths long, are the main design issues, which are currently being studied using extensive 3-D simulations.

A two-tank 402.5-MHz DTL, with SmCo permanent-magnet quadrupole lenses in the drift tubes, accelerates the beam to 20 MeV. This is followed by an 805-MHz linac, which is comprised of two sections. First is the coupled-cavity drift-tube linac (CCDTL), which accelerates the beam to 100 MeV. The CCDTL consists of a chain of coupled accelerating cavities, each accelerating cavity containing a single drift tube. The accelerating cavities, which are 3λ/2 in length, are electromagnetically coupled through side cavities in the same manner as the familiar side-coupled linac (SCL), and therefore is really a side-coupled drift-tube linac. The CCDTL structure operates in a mode that is completely equivalent to the stable π/2 operating mode of the SCL. Transverse focusing is provided by electromagnetic quadrupoles that are periodically installed in spaces that would have been occupied by an accelerating cavity and that are easily accessible for alignment. The next and final accelerating structure is the SCL, which accelerates the beam to 1 GeV with focusing provided by electromagnetic quadrupoles installed between the tanks. The parameters of the initial SCL design are given in Table 2.

Table 2: Side Coupled Linac Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>805 MHz</td>
</tr>
<tr>
<td>Cells per tank</td>
<td>14 to 11</td>
</tr>
<tr>
<td>Bore radius</td>
<td>2.2 cm</td>
</tr>
<tr>
<td>Axial accelerating field EqT</td>
<td>2.8 MV/m</td>
</tr>
<tr>
<td>Effective synchronous phase</td>
<td>-390</td>
</tr>
<tr>
<td>Peak cavity-power loss</td>
<td>84 MW</td>
</tr>
<tr>
<td>Peak beam power</td>
<td>16 MW</td>
</tr>
<tr>
<td>Peak rf power</td>
<td>100 MW</td>
</tr>
<tr>
<td>Number of 5 MW klystrons</td>
<td>27</td>
</tr>
<tr>
<td>Total length</td>
<td>496 m</td>
</tr>
</tbody>
</table>

The linac must contain two frequencies which differ by a factor of two to allow an upgrade with beam funnelling. Optimum choices range between about f/fo = 200/400 MHz to 500/1000 MHz. We have chosen f/fo = 402.5/805 MHz because of 1) compatibility with the 805-MHz system of rf and beam diagnostic hardware of the LANSCE linac, 2) immediate availability of existing 402.5-MHz klystrons and rf equipment from a previous project, and 3) immediate applicability of the results from the previous LANSCE upgrade study, which used exactly these frequencies.

The beam-chopping requirement is such that the linac must inject a beam with 278-ns current-free (to better than 10^{-4}) gaps every 795 ns to limit the beam spill in the ring, when the kicker magnets are energized for beam extraction. The chopping is most easily implemented at the low-energy end of the linac to facilitate the thermal management of the chopped beam. The reference design calls for three stages of chopping, so that most of the beam to be chopped is removed at the lowest energy, and the most effective chopping structure can be used at a high enough energy that space-charge effects do not degrade the beam quality. The three stages are 1) chopping in the ion source, 2) chopping in the 65-keV electrostatic LEBT, where each Einzel lens is split into four quadrants to add a pulsed transverse deflecting field to the constant focusing field, and 3) a chopping system based on a traveling-wave deflecting structure in the MEBT. The chopping in the ion source and the LEBT chopping will remove most of the beam to be chopped. In the 2.5-MeV MEBT the beam is focused in all three planes so that the beam is not allowed to debunch, and the chopping system in the MEBT provides the final clean chopping. The present MEBT design uses triplet quadrupole lenses to create three long drift spaces for the basic elements of the chopping system, 1) a traveling-wave deflecting structure for the chopping, 2) a collimator to remove the deflected beam, and 3) a traveling-wave deflecting structure to restore to the beam axis the beam that is not removed by the collimator, because it enters the chopping structure when the field is rising or falling.

The 805-MHz rf-system design is based on nominal 5-MW klystrons. For high reliability only 4-MW is supplied from each klystron to the accelerator. Because of power limitations of the rf windows, the total rf power per klystron is split into two parts of 2-MW each, which are then delivered through an iris coupler into the accelerating structures. The field distribution of the accelerating cavities is not sensitive to the exact placement of the drive points, because of the strong coupling (near 5%) of the cells and the stability of the π/2 operating mode.

The DTL focusing is provided by a FFDD lattice. For the CCDTL and the CCL, both sinlget and doublet focusing lattices are being studied. Beam dynamics simulation studies including the effects of the space-charge forces will be an important tool for predicting the output beam emittances and the beam losses. Initial simulation studies have been carried out for the SCL structure assuming a doublet focusing lattice and using constant-length and constant-strength focusing quadrupoles. We have inserted an input beam with uniformly charged ellipsoidal bunches and with an initial mismatch such that the initial beam projections are smaller than the matched values by 20% for the two transverse axes and by 50% for the longitudinal axis. For initial rms normalized emittances of 0.025 cm-mrad for x and y and twice as large for z, we find an emittance growth of less than 10% in x and y, and less than 5% in z. After the initial transient caused by the mismatch, the ratio of aperture radius to transverse rms beam size ranges from
about 8 near 100 MeV to about 13 at 1000 MeV, values which should produce acceptably small beam losses, provided that errors such as misalignment of the quadrupoles are sufficiently small. Eventually, an end-to-end beam simulation from the ion source to the end of the linac will be needed to provide the expected values of the important emittances and aperture to rms beam size parameters that characterize the beam dynamics.

An upgrade for the linac to 4.4 MW can be achieved through the following steps: 1) doubling the ion-source output current to 70 mA, 2) installing a second 20-MeV linac, and a beam funnel at 20 MeV, which will fill all buckets of the 805-MHz linac, and 3) installing the additional rf power needed for the increased beam current.

Two important technical questions for the NSNS linac are: 1) how clean and effective the beam chopping can be made without degrading the linac-output-beam quality, and 2) how well the beam losses can be controlled for the \( H^+ \) beam. The losses are expected to be lower than for the LANSCE linac for three reasons: 1) for LANSCE the beam tune is optimized primarily for the higher intensity \( H^+ \) beam, which results in missteering for the \( H^+ \) beam, 2) the \( H^+ \) emittance from the ion source is 50% larger than that expected for the NSNS source, and 3) the use of an RFQ promotes good low-energy bunching, which eliminates unwanted tails in longitudinal phase space.

**Summary**

We have presented a linac reference design for the NSNS linac. The initial beam dynamics simulations suggest that excellent beam-dynamics performance should be achievable. The next steps will be to study the chopping systems, and to produce end-to-end beam simulations from the ion source to the accumulator ring to study both chopping and beam loss.

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+ Lawrence Berkeley Laboratory, Berkeley, CA 94720

**References**

THERMAL/STRUCTURAL DESIGN AND FABRICATION DEVELOPMENT OF HIGH POWER CCDTL AND CCL STRUCTURES

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Abstract

Thermal management, resonance control, and reliability requirements become predominant when designing “conventional” copper coupled-cavity linac (CCL) structures for very high duty factors and accelerating fields. Whereas the outer body of the coupled-cavity drift-tube linac (CCDTL) is in most ways comparable to the CCL, the cooling and support of the added drift tubes present totally new and interesting challenges. Making provisions to limit thermal distortion calls for many cooling passages, high quality materials, and new fabrication schemes and techniques.

Thermal designs for a 700MHz linac are presented, along with results of prototype tests and fabrication developments which offer solutions to all of these problems.

Introduction

Active mechanical elements, such as movable slug tuners, are used to regulate the resonant frequencies of many existing room-temperature copper accelerating structures. Many others are regulated by modulating the structure temperature. (Increasing the average temperature of a room-temperature copper structure by 1°C causes it to expand approximately 1.8e-5 % in all directions unless it is constrained somehow. Uniform thermal expansion lowers the resonant frequency of the rf structure proportionately.) Resonant frequency control via temperature modulation is the better choice for high-power rf structures since they require active, closed-loop temperature control anyway, and since mechanical tuning elements add significant cooling problems of their own.

However, because cooling cannot be perfectly distributed, temperatures are, in general, not perfectly uniform, given rise to local thermal distortions. These distortions can greatly effect the resonant frequency and field distribution in the accelerating structure, even when the “average” structure temperature is “right”. This paper explores the sensitivity of various types of rf cavities to distortions, and discusses means for controlling these distortions appropriately.

Room Temperature Linac Cooling Design

A common “room-temperature” accelerating structure is the coupled-cavity linac (CCL, also sometimes called a side-coupled linac, or SCL). Typically, the CCL structure consists of several of these cavities in series, as shown in Figure 1. For low-power applications (low accelerating fields, or low duty factor), coolant passages incorporated into the outer cylindrical walls are often sufficient. For high-power application, the end and internal walls and drift tube noses must be actively cooled to prevent marked steady-state frequency errors, and, in some cases, permanent plastic deformation during rf transients.

Figure 1. Typical CCL segment construction, showing integral cooling passages inside brazes joints.

The fabrication scheme shown in Figure 1 provides an easy means for incorporating many integral coolant passages. Interconnected rectangular grooves are cut into the flat interfacing surfaces of the various pieces that make up the stacked assembly. Typically, these interfaces are hydrogen-furnace brazed using copper/gold or copper/silver alloys to form a quasi-monolithic structure. In a high-power application, it is virtually impossible to avoid having some water-to-vacuum braise joints. Although several laboratories remain adamantly opposed to such joints, at LANL, we have had no significant problem with water-to-vacuum leaks in copper-to-copper braise joints.

Current LANL linac design standards limit the coolant water velocity inside these enclosed passages to about five meters per second. This is much higher than recommended in commercial copper piping. Nonetheless, many OFE copper linacs have been built and operated for many years with velocities in this range. (Two recent failures have occurred in the Alvarez Drift Tube Linac portion of the 25+ year-old LANSCE accelerator, where local water velocities over 6.5m/s caused erosion through thin-walled copper parts, but near-by braise joints were not effected [1].) Avoiding sharp bends and sudden cross-section changes in the vicinity of thin walls is recommended.

CCL Cooling Design

The 700MHz CCL segment shown in Figure 2 is for particle $\beta = 0.86$, where $\beta$ is the ratio of particle velocity to the speed of light. Its thermal distortion is shown, exaggerated by 2000X, corresponding to the cooling design planned for the APT room temperature linac. For the following discussion, consider the structure broken into three zones, the outer cylindrical body, the end walls and noses, and the internal walls and noses.

*Work supported by the US Department of Energy.
Obviously, when the outer cylindrical body gets hot, it expands outward, increasing the electrical inductance of the cavities, and thereby lowering the resonant frequency. Less obvious is its structural interaction with the end walls, described later.

Typically, there are several cavities in series, so most of the walls are internal, with equal rf heating on both sides. As the noses get hot, they grow too long, closing the accelerating gaps somewhat, and they expand radially. Both of these components act to increase the electrical capacitance of the cavities, lowering the resonant frequency. The wall itself is loaded symmetrically, so its principal movement is radially outward, pushing part of the cylindrical outer body ahead of it. This increases the electrical inductance somewhat, which also lowers the cavity frequency.

The end walls are generally thicker than the internal walls because they must react vacuum loads. Their thermal distortion is less well behaved because the thermal loading is one-sided. A simple disk, heated on one side and cooled on the other would deform into a dish shape, convex on the heated side. However, the end wall is rigidly attached at its perimeter to the outer cylindrical body. If the end wall is hotter than the outer cylindrical body, the mismatch causes the end wall to bow outward rather than inward. This greatly increases the cavity's electrical inductance. It also increases the length of the accelerating gap of this end cavity. This latter effect is offset somewhat by the lengthening of the nose and its radial expansion. The net effect is still to lower the frequency of the end cavity. If the end wall is cooler than the body, it is bowed inward, with equally mixed effects. Thicker end walls bow less, and behave more like internal walls.

In this high-beta example, the end wall and internal wall temperatures have about equal influence on the resonant frequency of individual cavities. At lower β, the end wall can have a much greater effect than an internal wall. This is mostly because the nose-to-nose gaps are shorter, so small end wall displacements are large in proportion. Also the noses themselves are shorter, and less of a factor in the structural interplay. Nevertheless, because there are so many internal walls and only two end walls in a typical CCL accelerating segment, the "average" resonant frequency of the segment is not strongly affected by the end wall and nose temperatures.

**CCDTL Geometry**

The CCDTL accelerating structure has been proposed for use on high-current, intermediate velocity beam [2]. In the 700MHz APT linac, it appears in three forms [3,4]. For $\beta=12$–13, two-gap cavities, one cavity per segment are used, (ref. [2]). For $\beta=13$–20, individual three-gap cavities are used (left side of Fig. 3). For $\beta=20$–43, two-gap cavities, two cavities per segment are used (right side of Fig. 3).

Figure 3. Transition from 3-gap cavities to 2X2-gap cavities at ~20MeV in 700MHz APT linac design.

**CCDTL Body and Wall Cooling**

The outer bodies, end walls and internal walls of CCDTL structures are made and behave exactly like those of the CCL structure described earlier. However, because there are only one or two cavities per accelerating segment, the end wall behavior can have a surprising and significant frequency effect.

Figure 4. β=0.2 CCDTL segment with overheated end wall.

Figure 4 shows an exaggerated shape for a β=0.2 segment whose end walls have been artificially heated 2.8°C (5°F) above their normal operating conditions. As expected, it has bowed outward. However, because the initial gaps are small, the gap increase is relatively quite large. Although the inductance increase is significant, it is not enough to compensate for this big capacitance drop. The net effect is a substantial increase in the cavity frequency.

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The β=0.43 segment, shown in Figure 5, has larger initial gaps. The capacitance and inductance factors almost exactly cancel, making resonant frequency independent of end wall temperature!

**Figure 5.** β=0.43 CCDTL segment with overheated end wall.

### Drift tube cooling

In CCDTL cavities, a large fraction of the rf loss occurs on the drift tubes, and their thermal distortion has a very marked effect on the resonant frequency of all of these cavities. In the 700MHz β=0.43 cavity, heating the drift tube 5°C causes the resonant frequency to decrease 29kHz, while uniform heating of the outer body and wall causes a 34kHz decrease. Most of the drift tube’s frequency/temperature dependence resides at its noses, nearest the accelerating gaps. Analysis shows that artificially heating only the drift tube noses by 5°C lowers the cavity frequency 25.7kHz. As the noses get longer and larger in diameter, the gaps get shorter and the surface area increases, increasing electrical capacitance, and thereby lowering the cavity frequency. In contrast, heating the middle portion of the drift tube has very little effect on the cavity resonant frequency. Although the middle portion growth shortens the accelerating gaps, increasing electrical capacitance, it also moves outward into the high magnetic field region, decreasing electrical inductance. In the β=0.43 case, the frequency effects almost exactly cancel.

Thus, cooling the drift tube noses becomes very critical. Getting coolant to the noses is not easy. Several schemes were analyzed and rejected before the construction shown in Figure 6 was developed. Three copper cylinders are made with approximately 75microns radial clearance when assembled. Coolant passage grooves were lathe-cut into the outer surface of the two inner copper cylinders, and then interconnected with milled slots on alternating sides. 50micron Cu/Au alloy foil is inserted between the cylinders, and the entire assembly is surrounded with a molybdenum TZM ring and an appropriate amount of 304 stainless steel shim. When the assembly reaches braze temperature, the copper has expanded much more than the molybdenum sleeve which forces the soft copper to compress onto the inner cylinder. Two stems are added, through which the coolant enters and exhausts. The cool inlet water is routed to the nose passages first.

### References


ION LINACS DESIGN WITH SUPERCONDUCTIVITY USE

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Abstract

Two principal schemes of CW high current linac design based on superconductivity use are proposed. Superconducting accelerating structures are suggested to use along the whole linac for acceleration of beams with the currents up to 30 mA. Focusing by longitudinal magnetic field generated by superconducting solenoids are suggested to use for the beams with the currents up to 500 mA. It is shown that in both cases accelerator efficiency is higher than 50% and beam losses is lower than 10⁻⁵. Problems of accelerator main system design and its resolution are discussed.

Introduction

Research works on the concepts in designing of high current proton (ion) linear accelerators with the output energy of about 1 GeV for electronuclear purposes are carried out in MRTI for years [1-8]. The works are carried in two aspects: development of CW linac with current of 10-30 mA (first type) for solution of the problems of conversion of weapon-grade plutonium and nuclear-power problems ("power amplifiers") [9]; development of CW linac with current of 100-300 mA for accelerator transmutation (second type). These concepts and technological systems are developed according to the following demands: provision of efficiency more than 50% and high reliability, as well as radiation purity (beam losses - 10⁻⁵).

In the first case the problem of high efficiency is brought to the fore. Estimations carried out in MRTI bring out that CW linac version with superconducting accelerating cavities is preferable.

In the second case problems of reliability and efficiency are dictated by solving the problems of superpower HF supply system design and essentially by lossless beam transport along linac. The solving of these problems provide radiation purity as well. As discussed in MRTI papers [1, 6, 8] the problems can be solved by use superpower Regotron-type amplifiers in HF supply system [4] and application the focusing system based on superconducting solenoids.

CW Superconducting Proton Linear Accelerator with the Energy of 1 GeV and current of 10-30 mA

Solution of the problems of conversion of weapon-grade plutonium and of nuclear-power tasks ("power amplifiers" [9]) requires proton beams with the energy of 1 GeV and average current of 10-30 mA. The most expeditious way to obtain such proton beams is CW linear accelerators with superconducting accelerating structures.

CW superconducting linear accelerator of protons [8] possesses a number of decisive advantages in comparison with "room" temperature accelerators in the region of average of beam currents of tens mA: consumed HF power is significantly decreasing and as a consequence the cost of construction and of routine operation are going down, reliability rises and not less than twice the length of the accelerator decreases. Total efficiency of such accelerator under acceleration of beam 10 mA and more will be not lower than 60%. High margin of acceptance in the considered version of linear accelerator allows to expect that losses of the beam in the process of acceleration will not exceed 10⁻³. Modern level of tectonics and of technology allows to realize the proposed project of linear accelerator.

Proposed scheme of the CW proton linear accelerator is as follows.

The injector produces a beam of protons with energy of 60 keV. Further the protons are accelerated in the initial part of the linear accelerator (IPA) - RFQ-type accelerator. A four-chamber H-resonator excited by the TE₂₁₁ wave of 425 MHz accelerates protons to energy of 3 MeV.

The first part of the linear accelerator consists of short four-gap cavities with drift tubes excited at the frequency of 425 MHz. Energy of protons in this part of the accelerator rises up to 50 MeV. Separation of the accelerating structure to short resonators is dictated by necessity to place between them quadrupole permanent magnets focusing lenses. The structure of the focusing period is FODO.

The second (main) part of the linear accelerator provides acceleration of protons up to the energy of 1 GeV. Accelerating structure consists of 304 nine-cell axially symmetric cavities with elliptical shaped cells excited at the frequency of 1275 MHz. Odd frequencies ratio of the first and the second parts of the linear accelerator is equal 3 and this allows, if necessary, simultaneous acceleration of protons and negative ions of hydrogen. Acceleration rate at the length of the cavities is 5 MeV/m. Averaged acceleration rate along the whole length of the acceleration is 2.5 MeV/m.

The main parameters of the linear accelerator are presented in the Table 1. The parameters of the acceleration will not change for the case of acceleration of hydrogen negative ions beam.

In order to rise reliability and to decrease the costs it is desirable to decrease number of HF channels due to excitation of a group of cavities by one HF generator. In these proposal groups of four cavities are excited by one of generators. Klystrons with output power 500 kW for acceleration of 30 mA beam and about 150 kW for beam current of 10 mA will be needed for excitation of a group of four cavities. In main part of the system of HF power distribution to the cavities of group is constructed with the aid of bridge-type devices proposed for decoupling of two loads and division of
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial Part</th>
<th>First Part</th>
<th>Second Part</th>
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<td>Type of accelerator, resonator</td>
<td>RFQ</td>
<td>4-gaps drift tubes</td>
<td>9-cell resonators</td>
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<tr>
<td>Injection energy, MeV</td>
<td>0.06</td>
<td>3</td>
<td>50</td>
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<tr>
<td>Output energy, MeV</td>
<td>3</td>
<td>50</td>
<td>1000</td>
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<tr>
<td>Frequency of accelerating field, MHz</td>
<td>425</td>
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<td>1275</td>
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<td>304</td>
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<td>Period of focusing, m</td>
<td>0.007-0.056</td>
<td>0.6-2.0</td>
<td>2.0-4.0</td>
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<td>Acceptance, specified, π cm-mrad</td>
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<td>(-45-30)</td>
<td>-30</td>
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<td>45+40</td>
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<td>0.08</td>
<td>0.025</td>
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<td>0.25-0.85</td>
<td>0.35-0.93</td>
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<tr>
<td>Diameter of resonator, cm</td>
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<td>49-45</td>
<td>24-21.6</td>
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<tr>
<td>Aperture diameter, mm</td>
<td>3-6</td>
<td>15-20</td>
<td>30-40</td>
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<tr>
<td>Accelerator length, m</td>
<td>3.5</td>
<td>25</td>
<td>380</td>
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<tr>
<td>Power for beam, kW</td>
<td>I₀ = 10 mA</td>
<td>30</td>
<td>470</td>
</tr>
<tr>
<td></td>
<td>I₀ = 30 mA</td>
<td>90</td>
<td>1410</td>
</tr>
<tr>
<td>Losses removed by helium, W</td>
<td>50</td>
<td>580</td>
<td>3400</td>
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</table>

HF power to equal parts. Split-type of double T-shape bridges may be used as prototypes of such devices. In part 1 four cavities of each group are coupled with the aid of three resonant bridges. Such group is excited by klystron through mean bridge.

In order to provide superconductivity the resonators, its operating surfaces are covered by niobium layer and cooled by liquid helium. Adopted temperature of 2K corresponds to minimum of capital investments and the cost of routine operation. The version of the cryogenic system consists of typical cryo-modules is chosen in these technical proposals. A cryo-modules consists of a cryostat with several resonators together with adjacent devices inside it.

The following ideology linked with quantitative characteristics of heat removal by helium is adopted. Total power of losses for helium in the cavities of the linear accelerator is approximately 4000 W (see Table 1). Acceptable losses by helium due to losses of the beam in the linear accelerator with hand controlling are 380 W or approximately 10% of the losses in the cavities. The same value is taken for acceptable heat flux from the external space through the cryostat. It defines the requirements to thermal insulation of the cryostat. So the total thermal power (Pₘₜₜ) removed by helium is 4700-5000 W.

This approach demand to place in cryo-modules cavities as many as possible. Different versions of cryo-modules are considered. Fragment of cryo-module is shown in Fig. 1. Cryo-system design of accelerator under consideration is the development of RHIC and CEBAF base ideas. One of the main characteristics of particle accelerators for considered nuclear-power utilization is the value of total efficiency of the conversion of electric power into beam power [10].

Full efficiency of a superconducting linear accelerator may be presented by the expression

\[ \eta = \frac{P_b}{P_r + P_{ec}} \]

where \( P_b \) is HF power for acceleration of the proton beam, \( P_r \) and \( P_{ec} \) - powers of electric feeding of the HF system and of cryogenic system of the accelerator. Let us introduce notations for efficiency of HF and cryogenic system \( \eta_{HF} = P_{HF}/P_r \) and \( \eta_c = P_{HF}/P_{ec} \). Then

\[ \eta = \frac{P_b}{(P_b + P_{HF}) \cdot \eta_{HF}^{-1} + P_{HF} \cdot \eta_c^{-1}} \]

Where \( P_{HF} \) is power of HF losses in the walls of the cavities. As \( P_b >> P_{HF} \) then \( \eta = \frac{P_b}{P_r \cdot \eta_{HF}^{-1} + P_{HF} \cdot \eta_c^{-1}} \).

Accepting for estimation \( \eta_{HF} = 0.7 \), \( \eta_c = 2 \cdot 10^{-3} \) and \( P_{HF} = 5 \text{ kW} \) we shall obtain expression for calculation of efficiency of superconducting accelerator as a function of \( P_b \):

\[ \eta = \frac{P_b}{(1.41 \cdot P_b + 2.5 \cdot 10^5)} \]

With beam current 10 mA \( P_b = 10^7 \) efficiency of the accelerator is equal 60%. For beam current 30 mA we have \( \eta = 65\% \). Tectonics of fabrication of the main devices of the accelerator is well experienced in the world though quite similar accelerators were not yet constructed. The accelerator of INR of RAS (protons energy is 600 MeV, average current - 1 mA) developed by MRTI of RAS jointly with invited institutions and superconducting electron accelerator CEBAF may be looked as prototypes. Time necessary for realization of the project is estimated as 7–10 years.

**Linear Accelerator With Superconducting Solenoids. With the Energy of 1 GeV and Current of 100–300 mA**

The considered concept of the linac with 100–300 mA current is the further outgrowth of the MRTI quests [1–8] for linac for transmutation of long-living radioactive wastes of
nuclear reactors. Novelty of this concept is associated with the use of superconducting solenoid focusing (SSF) in all accelerating parts [8].

Beam transport along the length of accelerator with minimal losses should be closely studied. The most limiting regions are: initial part of acceleration - IPA (up to 3 MeV); matching between focusing channels with different types and structures; high energy part of accelerator (HBL) with high number of focusing elements and accelerating structure.

Single-channel scheme (HILBILAC-DTL-HBL) is used in the linac as before. High acceptance of HILBILAC (IAP) and high current limit (700 mA at a frequency of 350 MHz) make possible to form beam at the IPA output with good transverse characteristics.

Use of focusing by superconducting solenoids at DTL and HBL alleviates the other problems: a) single-type focusing makes possible good matching between different linac part: (HILBILAC-DTL section and DTL-HBL section); b) changing quadruple lenses to solenoids decreases channel sensitivity to random perturbations approximately by a factor of 10; c) use SSF at HBL section makes possible use of "long" cavities (10–13 m in length) based on D&W structure without subdivision on sections. Abandonment of sectionalized HBL cavities structure and coupling bridges between sections make possible essential decrease accelerating field sensitivity to geometrical errors of cavity. Requirements for evenness of "long" cavity excitation thought 7 power input from regotron are reduced as well [4, 6].

Development of such type linac indicates that DTL section realization is not improbable but there are a diversities of difficulties. The main problems are associated with high inductive coupling between solenoids, with strong ponderomotive forces and with scattering fields.

With the beam current higher than 100 mA total efficiency of accelerator will exceed 50%

References

[4] B.P. Murin et al., Superhigh-Power RF Regotron-Type Generator For Linear Accelerator with High Mean Current, Ibid.
REGOTRON AS CW HIGH-POWER RF SOURCE FOR ION LINAC

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Abstract

The problems and requirements to the RF power supply system are considered. Characteristic features of regotron-type generator are described. Physical processes that determine advantages of regotron in comparison with other RF generator with analogous beam parameters are considered. The problems of regotron operation into the accelerating structure are discussed.

The Problems And Requirements To The RF Power Supply Systems

The system of RF power supply of a high current linac is its most complex and expensive system which determines to a considerable degree the construction cost of the whole accelerating complex and its reliability. The required parameters of this system may be formulated only after studying of the linac design as a whole since some of them determine the linac structure. These are the output power of a generator, its efficiency, the term of faultless operation, the range of automatically controlled RF field amplitude and phase variation in accelerating cavities and so on. For the time being a multichannel RF power supply system with a power ramification at a low level is widespread. It is used, for example, in ITEP [1], MMF [2, 3] and LAMPF [4]. The two contradictory requirements gave rise to such a system: on the one hand, maintenance of accelerating fields in cavities requires a high level of RF power a certain portion of which is transferred to the beam; on the other hand, it is necessary to regulate RF voltage phase at the low power level (approximately 1 W). The last requirement is connected with the absence of powerful fast phase-shifter. Such a scheme allows to fulfill the longitudinal particles dynamics requirements: to provide amplitude stabilization accuracy to ±0.1% and phase stabilization accurate to ±0.5°.

The traditional scheme has RF supply channels quantity usually equal to the number of the accelerating cavities. Together with this the value of RF power, consumed by the accelerating cavity and the beam, is determined by the generator output power.

It is easy to notice that with the essential increase of the consumed by the accelerator RF power, the requirements must grow also, firstly, to the powerful output tubes of the generator. Naturally, the construction and reliability of the high-current linac will be possible when solving the problem of provision it with extra-reliable RF amplifiers of the increased power. Linac reliability increases with the increase of output power of RF channels (because of channels number decrease). So it is appropriate to use generator with output power of about 5 MW and efficiency up to 70%.

Regotron

As it was mentioned, it is necessary to have channel RF power amplifiers of $P \approx 5$ MW and efficiency of > 70% to provide RF supply system of continuous mode linac reliable operation with a total power of 500 MW. Nowadays this device is under development in MRTI by the name "regotron".

Firstly, the idea of such amplifier was suggested in the paper [5]. In the papers [6, 7] one can find the development of the idea before its realization by the scheme "regotron" [8]. By now regotron theory is worked out, mathematical simulation of the main processes programs are created and the first nature experiments are begun.

The principle regotron scheme is shown in Fig. 1. Low perveance electron gun (1), klystron type buncher (2) and distributed RF power takeoff system (4) were used in it. The distributed power takeoff system consists of a number of $(N + M)$ disconnected active (N) (see n.5) and passive (M) cavities (see n.6).

![Regotron Scheme](image)

**Fig. 1.** Regotron scheme. 1 - high voltage electron gun; 2 - buncher; 3 - buncher passive cavities; 4 - distributed RF power takeoff system; 5 - active cavity; 6 - passive cavity; 7 - RF feeder; 8 - collector; 9 - focusing solenoid

When specifying maximum (limited) klystron power as $P$, maximum regotron power may be determined as following:

$$P_r = \eta P_r$$

Where $P_r = U I$ - electron beam power at the output of the electron gun, $\eta$ - regotron efficiency. (Power limited value, usually determined by the electric rigidity of the dielectric window).

If beam losses are neglected in the device tract the efficiency may be determined by the equation

$$\eta = 1 - \frac{P_{col}}{P_r}$$

where $P_{col}$ - beam power in the collector. In order to decrease $P_{col}$ in the distributed takeoff system it is necessary to implement a well-known in the field of proton (ion) linac technology autophasing method, which allows to bring clustered electron bunches in the process of takeoff RF power by active cavities up to small energy values.

The autophasing effect is produced by couples of cavities [6] of which the active one with the resonant frequency equal
to the signal frequency takes off RF power from the beam and the passive one detuned to an angle nearing π/2 bunches the beam without change of its average energy. The proper choice of parameters of both cavities determines the synchronous phase.

Theoretical calculations show that efficiency of 0.9 is achievable with voltage about 1 MV. But magnetic bunching must be applied to the beam of such a high energy, the realization of which gives rise to certain problems. The additional investigation shows that regotron is highly efficient with lower beam energy about 500 keV. In this case routine klystron bunching serves well and therefore the generator RF system consists of single toroidal cavities with drift tubes between them [15]. For focusing solenoid lenses on permanent magnets are preferable.

The beam dynamics investigation showed that phase oscillations amplitude is determined by the combination of parameters \( \delta p / R_i \), where \( i \) is the distance between neighboring active cavities; \( \delta p \) - the mean value of the beam reduced momentum in the \( n \)-th cavity, \( R_i \) - the \( n \)-th couple passive cavity shunt impedance. The proper choice of \( l, R_i \) depending on the deceleration rate, compensates considerably the parametric growth of phase oscillations amplitude. The 5 MW regotron efficiency is more than 70% at the frequency of 991 MHz.

The regotron main parameters are shown in Table 1.

It is necessary to mention that in spite of very high total power all the regotron elements may be made with necessary supply in the electric ruggedness and heating. This allows to maintain high reliability of regotron.

**Table 1**
The 991 MHz Regotron Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Voltage</td>
<td>500 kV</td>
</tr>
<tr>
<td>Current</td>
<td>15 A</td>
</tr>
<tr>
<td>Excitation power</td>
<td>0.2...0.5 kW</td>
</tr>
<tr>
<td>Overall output power</td>
<td>5 MW</td>
</tr>
<tr>
<td>Power per an output</td>
<td>0.75 MW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt; 70%</td>
</tr>
<tr>
<td>Buncher cavities number</td>
<td>3</td>
</tr>
<tr>
<td>Power takeoff system cavities number</td>
<td>15 (7 active)</td>
</tr>
<tr>
<td>Buncher length</td>
<td>5 m</td>
</tr>
<tr>
<td>Power takeoff system length</td>
<td>2.8 m</td>
</tr>
<tr>
<td>Overall length</td>
<td>7.8 m</td>
</tr>
</tbody>
</table>

**Regotron Operation Into Accelerating Structure**

It is appropriate to use bi-periodic accelerating structure with disks and washers (D&W) for protons acceleration from 100 MeV to units GeV. This structure has been used at the main part of linear proton accelerator MMF. With the choice of this structure has been done on the base of close examination of radiotechnical, tuning, structural and technological parameters of side-coupled structure and D&W one. Because of very high coupling factor between cells (from 20% to 30%) D&W structure has a number of advantages in comparison with other bi-periodic ones:

- vacuum conductivity is tens times larger;
- rather simple construction and manufacture technology;
- thither stability of accelerating field relative to manufacture errors, tuning errors and beam loading (accelerating field sensitivity to disturbances is inversely proportional to coupling factor squared).

The last advantage allows to simplify structure tuning and, consequently, to decrease cost of accelerating structure. Structure has high shunt impedance.

The number of cavity entry equals to the number of regotron outputs. It is appropriate to vary total regotron power during the tests and operation by regulating the current of electron gun. (In this case distribution of power along regotron outputs is more uniform). For fine-tuning of operating mode frequency and coupling oscillation it is necessary to vary geometry of module for power entry. Characteristics of the D&W structure (high coupling factor) allows to achieve demanded distribution of accelerating field.

**Conclusion**

The previous analysis has shown that regotron is the only RF amplifier which can meet the requirements for the main (high energy) linac part. In this case RF power supply system will consist of 50-70 channels of amplification and coefficient of linac downtime because of supply system failure will approximately the same value as for LAMPF. In the case of 1 MW klystron use, RF channel number have to be increase in 5-7 times. Downtime coefficient increase respectively and it may amount to 15-30%. At the first linac part RF system has to provide power of the order of 20-30 MW. Taking into account moderate power in this accelerator part, both klystrons and regotrons can be used. However in this case regotron use is preferable, because of the high reliability of the system operation. Regotron help to solve problems of design of CW linacs with current of 100-300 mA for accelerator transmutation [9-11].

**References**


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Abstract

CANDELA photo-injector is made of a 2-cell S-band RF gun, using a dispenser cathode illuminated by a Ti:sapphire laser. This electron source provides a single bunch (at 12.5 Hz), with a charge of 1 nC and an energy of 2 MeV. This paper presents the measurement of the bunch length which is done 1.8 m downstream of the gun exit. The measurement system includes a 0.3 mm thick sapphire plate used to produce Cerenkov radiation, a 27 m long optical beamline and a streak camera. Bunch lengths of less than 10 ps were measured. These measurements are the first experimental proof of the fast response of dispenser photocathodes.

Introduction

Many applications (including high energy linear colliders, free electron lasers, and X-ray radiation sources) need electron sources that can produce intense, bright and short electron pulses. The photo-injector being very attractive with these respects, it is studied in many laboratories around the world [1]. The CANDELA photo-injector is part of this worldwide effort, and has its own specific features. It is made of two decoupled 3 GHz cells [2, 3, 4] and uses a dispenser photocathode [5]. The Ti:sapphire laser system [6] used to illuminate this photocathode is able to produce subpicosecond pulses. To date, CANDELA that was first operated at the end of 1993 [7], is the only S-band photo-injector to use such a short laser. Basic experimental results, such as quantum efficiency were already reported in [8]. This paper is therefore concentrating on new experimental results concerning bunch length measurement. After presenting the experimental set-up, results are given for several conditions (laser spot size and charge).

Experimental setup

The gun RF cavity characteristics are given in reference [9], the cathode performance in reference [8] and the laser system in reference [6]. In order to analyze the beam properties, several diagnostics systems are located along the beamline as shown in figure 1.

Bunch charge is measured with Faraday cups and wall current monitors. The latter have the advantages to be non-destructive and to respond only to the photo-emitted current. The Faraday cup followed by an integrator gives an indication of the total current (photo-current plus dark current). Two ceramic fluorescent screens and CCD cameras allow to visualize the beam. A commercial software designed for laser profile analysis [10] provides the information on beam profile.

Figure 1: CANDELA beamline showing diagnostics devices

The bunch length measurement system includes a 300 μm thick sapphire plate, an optical beam transport system and a streak camera. The sapphire plate is mounted on an actuator that allows both to withdraw it from the beam path and to rotate it to match the Cerenkov angle. Due to experimental room constraints, the Cerenkov light has then to be transported back the laser room, through a chicanes. The optical transport system, very similar to the one described in reference [11] includes 5 lenses, and several mirrors with a diameter of 70 mm or less. The total length of
the transport system is about 27 m. Due to the size of the different elements, including the vacuum chamber window, this transport system has a very small acceptance. It doesn't allow to "see" images larger than 1 mm in diameter. This situation is very constraining, since in order to maximize the photon flux, one should keep the electron bunch spot size on Cerenkov plate of the order of 1 mm square. The tuning of the quadrupole triplet to achieve this condition is done while observing the beam spot size on the screen located at the same position as the Cerenkov plate.

The alignment procedure is done in the following way. The optical transport system is first aligned with the help of a He-Ne alignment laser. The impact of this laser on the ceramic screen is then recorded. The electron beam is then steered to impinge the screen at this recorded location. Once this is done, the Cerenkov plate is introduced into the beam, the final alignment tuning being done while observing the Cerenkov light spot on the streak camera.

The streak camera used is from ARP [12] and has a temporal resolution of 1.5 ps (at 800 nm), 2.5 ps (at 400 nm) and 3.5 ps (at 266 nm). For this measurement, the mirrors used in the transport line are designed for visible light.

The triggering of the streak camera is made via a photodiode illuminated by a properly delayed unused laser pulse.

Bunch length measurements

Since the laser impinges the cathode at an angle of 54.5 degrees with respect to the normal axis (see fig. 1), the laser spot size on the cathode can induce some bunch lengthening due to path length difference for the photons illuminating the two sides of the cathode. This effect introduces a correlation between the transverse and longitudinal planes. Bunch length measurement were done in the case of a small spot size were this effect is very small, and in the case of a larger spot size for which the correlation effect was clearly observed.

Small laser spot size

Figure 2 shows a streak image corresponding to an electron beam of 0.85 nC, and a rms laser spot size of 0.7 mm (horizontal) and 0.45 mm (vertical). Figure 3 shows the corresponding temporal profile, from which we can estimate an rms bunch length of 4 ps. For 0.22 nC and 0.4 nC pulses, we obtained 3.1 ps and 3.7 ps respectively. For these measurement the camera resolution was 2.3 ps.

Large laser spot size

Figure 4 shows a streak image corresponding to an electron beam of 0.22 nC, and an rms laser spot size of 1.1 mm (horizontal) and 0.7 mm (vertical). From this figure, it is clear that there exists a correlation between one of the transverse direction and the longitudinal one.
By slicing a laser image in the transverse direction, it is possible to obtain the bunch length corresponding to the beam dynamics effects.

Figure 4: Large laser spot size: streak camera image

In order to compensate for this effect, it is necessary to rotate the laser wavefront. This can be done with a staircase mirror. Figure 5 shows the streak image of the laser after reflection on a staircase mirror made of a commercial grating with 30 µm steps. Unfortunately, this grating was not made for UV light and therefore its reflection coefficient was poor (12 %), so that it was not possible to use it on CANDELA.

Conclusion

This paper described the first bunch length measurements done on CANDELA rf gun, used with a dispenser cathode. Since bunch lengths as short as 4 ps were measured, this is the first clear indication that dispenser cathodes are fast response photocathodes. The measurements done for different laser spot sizes, have also shown that if the spot is small enough, a large incident angle is not too troublesome.

Acknowledgements

We are pleased to thank J.N. Cayla for his enthusiastic participation during these experiments and for the efforts he made to keep the hardware alive. Many thanks also to all the colleagues that participated to the design and construction of CANDELA, and especially to our colleagues from the "Institut d'Optique Théorique et Appliquée" at Orsay, who designed and built the laser system.

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[12] ARP, Centre de Transfert de technologies, Route de Hausbergen, F67088 Strasbourg, France.
STATUS OF THE TTF LINAC INJECTOR


CEA, DSM/DAPNIA, Saclay, France.

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Abstract

The TESLA Test Facility linac injector is currently under installation at DESY. The front end of the injector, consisting of an RF modulated thermionic electron gun, an electrostatic accelerating column, and solenoidal focusing transport line (along with its associated diagnostics) has already been tested in France. Other key components of the injector such as the pre-bunching cavity, superconducting "capture" cavity and cryostat have been tested individually. The results of these tests will be presented and the status of the installation at DESY will be described.

Introduction

The TESLA Test Facility injector essentially consists of: (i) a 250 keV electron source, (ii) a beamline containing a 216.7 MHz sub-harmonic bunching (SHB) cavity, solenoidal focusing elements, and beam diagnostics, (iii) a cryostat housing a 9 cell, 1.3 GHz superconducting cavity, (iv) a triplet magnet associated with an OTR diagnostic which will allow the accelerated beam emittance and bunch length to be determined, (v) a 1 T dipole magnet which can be used to bring the beam onto an analysis line for measurement of the beam energy spread (so verifying the correct adjustment of the RF cavity phases). When the beam is not deviated it passes through a second triplet which, along with the one mentioned above, can be used to match the injector beam to the linac, (vi) a 3 m transport line containing various diagnostics, in particular three different beam position monitor (BPM) designs (two of which will be provided by DESY-Zeuthen). For convenience we refer to parts (i) through (vi) as sectors 100 through sector 600.

The Electron Source and 250 keV Beamline

Figure 1 shows a schematic of sectors 100 and 200 (the pre-injector). The source consists of a 30 kV thermionic gun followed by an electrostatic column to increase the beam energy to 250 keV. Tests of the electron source and the beamline have been performed in France before shipping the pre-injector to DESY. These measurements concerned essentially the transverse beam dynamics and so the SHB cavity was not mounted during these tests. A report on this work can be found in [1]. Briefly, the gun was operated at its nominal settings as given in Table 1.

Table 1
Pre-Injector Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Beam voltage</td>
<td>250 kV</td>
</tr>
<tr>
<td>Average current</td>
<td>8 mA</td>
</tr>
<tr>
<td>micropulse repetition rate</td>
<td>216.7 MHz</td>
</tr>
<tr>
<td>macropulse repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>micropulse width (at base)</td>
<td>640 ps</td>
</tr>
<tr>
<td>macropulse width</td>
<td>800 μs</td>
</tr>
<tr>
<td>normalised RMS emittance</td>
<td>3 mm-mrad</td>
</tr>
</tbody>
</table>

The various diagnostics on sector 200 were successfully tested along with the regulation of the beam optics. Having measured the beam emittance it was possible, by using various

Fig. 1 Schematic of electron gun and 250 keV beam line.

* Visitor from BINP Protvino, Russia.
measured beam profiles, to calculate the envelope of the beam along the beam line. Such calculations indicated that the beam leaves the electrostatic column with a radius (2 rms) of 12 mm and divergence of 7 mrad. Recent calculations of the transport inside the electrostatic column are in excellent agreement with these values (Figure 2).

![Graph](image)

Fig. 2 Beam envelope calculated through electrostatic column and past the first lens.

In December of last year (1995) the pre-injector was dismantled to be shipped off for installation in DESY the following January. By the end of February the pre-injector had been completely re-mounted along with the SHB cavity and was ready for tests with beam.

The SHB is a single re-entrant cell with a transit-time corrected R/Q =130 Ω. The unloaded Q of the cavity with all its coupling loops and tuning plungers in place is measured to be 20,600. A nominal 50 kV is required across the buncher gap to provide the desired pre-bunching before the beam enters the superconducting "capture" cavity. For this we require 400 W in the cavity which is supplied from an amplifier capable of furnishing 2 kW. The cavity had already been conditioned to full power but it has been tested with beam for the first time at DESY.

Beam loading signals in the cavity (with no external RF power), measured via a small coupling loop (-40 dB), correspond well to the low power measurements of shunt impedance. A view screen mounted on sector 200 shows that the transverse beam size changes as a function of the phase of the cavity, indicating that the SHB has a net focus effect on the non-relativistic beam (νc = 0.74). Tests of the cavity feedback systems and tuning plungers show that they work as foreseen.

**The Control System.** The injector control system is built from EPICS (Experimental Physics and Industrial Control System) software tools. EPICS was developed at the Los Alamos and Argonne National laboratories and is well suited for accelerator applications. The principal components of EPICS are: A Unix based station or Operator Interface; VME crates or Input-Output Controller; Local Area Network (Ethernet using the TCP/IP communication protocol). The application software for the gun, sub-harmonic buncher, beamline magnets, diagnostics, timing system as well as special tools (e.g. for saving/restoring machine settings) etc. are all running satisfactorily.

**The capture cavity**

Sector 300 contains the capture cavity which is the first cryogenic device on the TTF linac. Following the pre-bunching on the 250 keV beam line, it accelerates and further bunches the beam before it enters the first cryomodule. The cavity is a standard TTF niobium cavity, fabricated by CERCA S.A. (France), which has undergone the normal treatment and preliminary tests at DESY before being mounted in the cryostat.

During the first series of tests in a vertical cryostat, using High Peak Power (HPP) processing, high field values (Eacc = 21 MV/m) and good quality factors (Q0 = 2 x 1010) were obtained. Following these tests the cavity was completely equipped with its helium tank, cold tuner and couplers. This assembly phase takes place in the clean room with intermediate chemical polishing and high purity pressurised water rinsing. A test with the helium tank and HOM couplers was performed in a horizontal test cryostat (CHECHIA) at DESY giving Eacc = 18 MV/m and Q0 = 2 x 1010 at maximum field, without electron emission. The nominal beam energy required from the capture cavity is 10 MeV.

The final tests with the main coupler (which was built by FNAL) have shown that the assembly phase was completed with good clean conditions maintaining the performance of the cavity at its high level [2]. After some conditioning period of the main coupler a maximum power of 400 kW, during pulses of 1.3 ms, was applied to the coupler with the cavity detuned. With an external Q of 3 x 106 and a tuned cavity an incident power of 200 kW was reached. The onset of electron emission in the cavity was measured at Eacc = 22 MV/m. A precise RF measurement was performed for Eacc = 16.9 MV/m, showing an amplitude stability of < 0.3% during the pulse and a phase stability < 0.5°. In parallel the capture cavity cryostat (CRYOCAP) was tested using a "dummy" cavity with a special cryogenic interface box [3]. Commissioning of the cryostat at 1.8 K and first measurements of the static losses were obtained during a series of tests performed at the IPN, Orsay. After some improvements of the thermal contacts which allow a faster cool down procedure, the nominal temperature was reached and the level in the helium vessel was precisely regulated. The total static losses (helium vessel, cryogenic interface box and transfer line) were 2.9 W. The helium vessel contributes 1.6 W but this does not include the losses of the RF cables, the main coupler and the beam tubes which are mechanically connected to the 300 K vacuum vessel (through the 70 K shield). These elements must add some additional loss.

At the beginning of July 1996, the cavity was mounted into the cryostat. All the equipment is now assembled including a special beam position monitor located at the cavity output which must operate at low temperature. After the final cryogenic test of the completely equipped cavity an RF test with the dedicated klystron, driven by the amplitude and phase control systems will be performed at the CEA laboratory in Saclay.
The provisional beamline. In order to benefit from a delay in the installation of the capture cavity cryostat we have mounted a provisional beam tube in the space separating sectors 200 and 400. The beam tube has two small lenses mounted on it which allows the beam to be transported to a viewscreen on sector 400. The interest in this provisional line is two fold;

(i) the beam passes through two toroidal current monitors, one on each sector. As differential current measurements between such monitors will be used to detect beam losses in the injector and linac [4], the provisional beamline allows us to test the electronics of this differential protection (DP) system prior to the installation of the superconducting cavity. Beam losses between the two toroids are provoked by scraping the beam on a collimator ($\phi = 15$ mm) mounted downstream of the beamtube;

(ii) by placing a button electrode BPM on the beam tube it is possible to monitor the micropulse width of the bunch as it passes the BPM by observing the signal induced on one of the electrodes using a fast oscilloscope. Thus we can roughly adjust the phase of the SHB by looking for a reduction in the bunch length as a function of the cavity phase.

The DP system exists in both fast (FDP) and slow (SDP) versions. In the fast version the toroid signals are sampled at a rate of 100 kHz and if a difference exceeding 500 $\mu$A on three successive samples is detected then the gun is tripped off. To prevent a continuous undetected loss of 0.5 mA, the SDP compares the integrated signals during the beam pulse. If a net charge loss corresponding to 100 $\mu$A $\times$ 800 $\mu$s is exceeded then, again, the gun is tripped off. To adjust the optic of the machine for the tests of the DP it was necessary to de-tune the SHB so that beam loading effects, coupled with an off-centred beam, would not diminish the signal seen on the second toroid (once the optic is correctly regulated it is possible to tune the cavity and then "fine-tune" the magnetic lenses to achieve 100% transmission between the two sectors. Subsequent tests of the SDP and FDP showed that it functions correctly.

The tests of the pre-bunching were made using a BPM mounted at the location which would normally correspond to the first iris of the capture cavity. PARMELA simulations indicate that, for the nominal buncher voltage and optimum phase, it is possible to produce a bunch of width 53 ps (25$\mu$s at 1.3 GHz) at this point. This calculation assumes that one produces a bunch of 640 ps from the gun. In practice we measured a beam of 700 ps at the output of the column. The smallest pulse width measured at the bpm is 220 ps after correction for the response of the monitor (the smallest pulse we can resolve is approximately 130 ps). Although a careful variation of cavity phase was made it is not sure that the RF amplitude setting corresponded exactly to the one used in the PARMELA calculation. Further measurements of this type will performed later this year.

**Sector 400**

Sector 400 was installed in the DESY tunnel last February and all the components for this sector have been delivered. These include, (a) average current and BPM monitors, to check that the beam is transported cleanly through the capture cavity, (b) the first triplet for matching the beam to the main linac, as well as providing a variable focusing element for measurements of the transverse profile at 10 MeV. An alignment mirror is mounted on this section to be used in conjunction with a small He-Ne laser. An optical transition radiator will be used to make emittance measurements. As the total width of the 10 MeV micropulse is calculated to be of the order of 7 ps it is foreseen to perform bunch length measurements using a streak camera. An optical bench will be placed adjacent to this sector for these measurements.

**The Beam Analysis Line**

A 60° bend angle dipole will be used to bring the beam onto this analysis line to regulate the RF phase by minimising the beam energy spread. The horizontally dispersed beam will be measured using an SEM-grid mounted in the horizontal focal plane of the dipole. A large retractable OTR radiator in the vertical plane will allow one to verify that the beam is well centred in the beam tube. DP monitoring will also be performed on this line although the larger beam size necessitates the use of a larger toroid (CF100 rather than CF35). The undeviated part of this sector contains the second triplet for matching. All the components for this sector are at DESY although the OTR, SEM-grid and a beam dump remain to be mounted.

**Sector 600**

Sector 600 is the last beam transport section before the first cryomodule. Consequently it contains a number of beam diagnostics and steering devices to verify that the beam is well centred before injection into the linac. The sector contains a retractable Faraday cup which can be inserted while the injector optics are regulated. This sector will be used to test the performance of a various BPM's with a view to their application in future linacs. The components for this sector are currently being mounted on their support girder in a clean room at LAL. The sector will be ready for delivery to DESY at the beginning of September.

**Acknowledgements**

We are indebted to the technical staff of LAL and CEA-Saclay for their efficient installation of the injector components on the DESY site. The injector uses a timing system built and provided by M. Shea and M. Kucera of FNAL.

**References**


PRECISE FABRICATION OF 1.3M-LONG X-BAND ACCELERATING STRUCTURE

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Abstract

Precisely controlled frequency distributions of the higher modes in each cell and the good frequency of the cells along the structure are the key issues on the detuned structure for the main linac of the Japan Linear Collider. The fabrication studies of a few full-size accelerating structures have been performed based on the technique of the ultra-precise machining of the cells and the diffusion bonding to join them. As of today, the frequency controllability of each cell was found to be better than 1MHz in the standard deviation of the accelerating mode and the alignment of the cells along the structure was found to be better than 10 μm.

Introduction

The preservation of the multi-bunch emittance is one of the key issues to reach a required high luminosity for the most of the present-day linear colliders[1]. One of the source of the emittance growth is the dipole wake field due to the accelerating structure. Three methods have been proposed so far, heavily damping, detuning with a medium damping and purely detuning. In the present paper was studied the last approach, “purely detuned structure”.

In order to realize this approach, the control of the frequency distribution of the dipole modes and the transverse positions of those modes with respect to the beam is essential to realize the designed cancellation of the wake field. In the Japan Linear Collider, JLC[1], each structure consists of 150 cells and four structures are interleaved in dipole mode frequency. In this case, the frequency spacing between nearest neighbor is about 1MHz. Because the stored energy of most of the modes are spreading in more than 20 cells, it is enough to control the random error in each cell frequency better than 1MHz. The tolerance of the alignment of those modes along the structure is assumed as 5 μm from the simulation results for NLC[2], where most of the parameters are similar to those of the JLC.

To meet the tight tolerance of the frequency control, the cells which consist of the structure are firstly machined with an ultra-precise lathe and a milling machine. Secondly they are bonded through a diffusion process between the flat surfaces of the cells. No tuning is performed after bonding.

From the previous fabrication studies of 30cm-long constant-impedance structures, the bonding at a temperature above 800°C was found reliable to obtain the vacuum tight junction for the present quality of the machined cells[3]. The change of the accelerating mode frequency is less than 1MHz out of 11.4GHz. It is necessary to study the applicability of the present fabrication technique to the 1.3m detuned structure.

Electrical design parameters

In order to make the detuning of the dipole modes, the beam hole radius and the disk thickness are varied so that the unperturbed dipole modes are distributed in a truncated Gaussian. The actual parameters are shown in Fig. 1. The cell inner radius “b” was determined to make the 2n/3 mode to be the operating frequency. Practically, the frequencies at three points along the structure were studied experimentally by measuring the frequencies of the resonant 2n/3 modes in varied number of regular cells with half end cells at both ends to estimate the frequencies in the periodic structure. Using these three points as a correction to the precise numerical estimation of the frequencies at the other points in the structure, all the dimensions “b” were determined[4].

![Design Parameters](image)

Fig. 1 Cell parameters (a,t) along the detuned structure.

Structure description

Three 1.3m structures were fabricated. The first one, called “M1”, came out with severe vacuum leakage after the first diffusion bonding at 800°C. We speculate that this failure is largely due to the complex shape of the cells where four slots are sitting on the bonding surface so that there might be many burrs which make the reliable bonding difficult. In the following two structures, “M2” and “IH1”, the slots on the bonding surface were removed. The rather large diameter of 80mm is for stabilizing the stacking and bonding processes in addition to integrate the water cooling channels to make the fabrication as simple as possible for mass production purpose. The coupler cells are firstly milled to make the two symmetrical wave guide ports with a precision of 1 μm and then the cell inner surface and bonding surface are cut by the ultra-precise lathe. In Table 1 are listed various fabrication informations of the two structures.

All the cells are machined using an ultra-precise lathe to make the bonding surface to be as flat as possible, typically 0.3 μm or better, with a surface roughness of 50nm. These cells were chemically rinsed in a series of weak acid, pure water and acetone bath. The cells are stacked along a Vee block and compressed in the axial direction. Keeping the
compression force and hanging vertically in a vacuum furnace, the stack is diffusion bonded to join all the important part of the structure. The symmetrical wave guide ports, which are coated with 10 μm thickness of silver were brazed in the next furnace operation with a wire brazing alloy as a backup.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Fabrication process informations.</th>
</tr>
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<td>Structure</td>
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</tr>
<tr>
<td>temperature</td>
<td>°C</td>
</tr>
<tr>
<td>period</td>
<td>hours</td>
</tr>
<tr>
<td>pressure at top</td>
<td>kg</td>
</tr>
<tr>
<td>stacking</td>
<td>hor. V</td>
</tr>
<tr>
<td>furnace</td>
<td>vacuum</td>
</tr>
</tbody>
</table>

**Frequency control**

The first step to realize the good frequency control is of course to cut the cells in a good precision. In the case of M2, the standard deviation σ of 2b is 0.41μm while maximum deviation is +2σ, which is precise enough to satisfy the tolerance of 1Mhz.

Fig. 2. Dwelling points in nodal shift measurement of M2.

To check the frequency change due to the bonding process, the reflection phase seeing from the input wave guide were measured by shifting the plunger of 5mm in diameter inserting from the output coupler side. This nodal shift measurement were performed just after stacking and just after bonding. An example is shown in Fig. 2. The plunger was moved in 0.2mm step and the dwelling points were deduced by finding the point of a minimum movement in the reflection phase. Due to the large difference of diameter between the plunger and the beam hole, especially near the input side, the dwelling points were shifted by more than 0.5mm from a nominal position along the structure. This behavior appeared in the reflection phase shifting from a simple line of 240°cell near the input coupler.

From the nodal shift measurement, the phase difference due to the movement of the plunger through three cells were used to estimate the frequency shift of the cells. This analysis removes such effects as the mismatch at the input and becomes more precise than the direct comparison of those between the adjacent cells. In Fig. 3 are plotted the frequency changes due to the whole bonding processes of M2. The standard deviation σ of the frequency change was found 0.66Mhz while almost all the cells are within +1.5σ. It is to be noted that the standard deviation of the frequency change in the first diffusion bonding of IH1 case was as large as 1.1Mhz while that through the additional diffusion bonding and the final brazing only 0.4Mhz. The larger value in the first bonding than that of M2 case might be due to the poor surface flatness or a higher temperature of bonding comparing to the M2 case. The frequency shift in M2 is tolerable but the characteristics of the frequency change on the bonding parameters should be studied further.

![M2 frequency change due to diffusion bonding and brazing](image)

**Alignment**

The cell alignment was measured just after stacking the cells but before removing from the vee block. The measurement was performed by capacitive sensor, microsensc. In Fig. 4 are shown the case of IH1. The cells were found to follow the vee block within 8μm by a simple stacking in a horizontal vee. Because of the miscut of some of the cells in their outer diameter, OD, the alignment data were corrected by using measured OD's. Some data points which deviate much from the smooth line are speculated to be due to the misalignment of the OD of the particular cell. The alignment change due to the bonding was found less than 10μm. A similar characteristics but a little worse alignment of the order of 20 μm was found in the case of M2 than that of IH1. It should be noted that the cell to cell movement was very small in M2 case, where almost 1 μm. There are a few different points between the fabrication process of IH1 and M2, such as vertical stacking or horizontal, and there is a room to further study and refine the alignment of the cells to meet the required tolerance of several μm reliably.

**Shrinkage**

In order to proceed the plastic deformation to fill the gap between the cells during the diffusion bonding process, the pressure was applied ranging from 3 to 20g/mm². Rather long period of diffusion bonding process under this pressure at
high temperature makes the cells shrink. In Fig. 5 is shown the case of IH1. The measurement was performed by measuring the distance from the end of the structure to the cell position. The shrinkages of both first and second diffusion bonding at 890°C were about 1 μm per cell. That of the final brazing at 800°C was found only 0.3 μm. The shrinkage was found 0.87 μm in the M2 through a diffusion process and a final brazing in total.

Summary and discussion

Three structures were fabricated to study the precise fabrication method of a 1.3m accelerating structure. The last two structures came out to be vacuum tight and various characteristics were discussed.

The accelerating-mode frequency of each cell can be controlled with the standard deviation of 0.41MHz in cell machining while that due to bonding 0.66MHz. The relative frequency error of the TM110 mode is estimated to be almost the same as that of the accelerating mode. Therefore, the standard deviation of the random frequency error of the TM110 mode in each cell is about 1MHz.

The alignment of the cells along the structure were better than 10 μm. The present simple stacking method should be refined to make the alignment better by a factor of 2. Each cells were found to be shrunk by about 1 μm.

Acknowledgment

The authors would like to thank Dr. S. Koizumi for encouraging us continuously on the ultra-fine machining activities at KEK machining center. Many experimental studies, especially the furnace-related operations were performed in the collaborative activities with Ishikawajima-Harima Heavy Industry and Mitsubishi Heavy Industry. They are greatly acknowledged.

REFERENCES

A NEW OPTICAL DESIGN FOR THE BNL ISOTOPE PRODUCTION TRANSPORT LINE

A. Kponou, J.G. Alessi, D. Raparia, N. Tsoupas, and M. Mapes
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Abstract

The 200 MeV linac at BNL has recently been upgraded. As a result, 2.5 times more average beam current can be delivered to the Brookhaven Isotope Resource Center (BIRC), formerly called BLIP, a facility which produces radionuclides and radiopharmaceuticals for the medical community, and also supports a research program seeking more effective diagnostic and therapeutic agents. The optics of the beam transport line to BIRC was redesigned to (a) reduce transverse fluctuations of the beam at the target due to any linac energy fluctuations, (b) produce a flat beam distribution at the target, in order to avoid melting certain target materials, and (c) handle the higher beam intensity while keeping radiation levels low. A profile monitor was also modified to monitor the flatness of the beam using the algebraic reconstruction technique (ART). The above improvements will be described, and results of the commissioning of the line during the 1996 running period will be discussed.

Introduction

The recent upgrade of the 200 MeV linac, reported in these proceedings[1], has resulted in a 150% increase in the average beam current that can be delivered to the BIRC facility, which is the largest consumer of the linac’s pulses. The optics of the transfer line was redesigned in order to keep radiation levels within acceptable limits and to produce a flat, rectangular beam at the target location, in order to avoid melting certain target materials. The redesign also included making the two bends in the transfer line achronic, as well as the addition of a third wire to an existing secondary emission monitor (SEM) to make possible a 3-D reconstruction of the beam profile using ART, also reported in these proceedings[2].

The constraints of the exercise were that the existing physical layout of the line would be retained, and existing equipment in the line and/or available equipment at the AGS, would be used whenever possible.

Most of the design effort went into producing a beam with a flat intensity distribution and rectangular cross-section at the BIRC target, and the rest of this paper will deal exclusively with this aspect of the project. Achronicity of the two bends was provided for by mounting a second quadrupole between the bending magnets, while keeping the beam size small wherever possible minimized radiation levels.

Beam Flattening

Beam flattening exploits the aberrations introduced by non-linear lenses. In principle, any non-linear focusing elements, i.e., those for which the restoring force on the beam particles \( \propto r^n \), where \( n = 3, 5, 7, \ldots \), will do. In practice, octupoles, \( n=3 \), are generally used. The principle of the method is to manipulate the beam envelopes in such a way that, at two suitable locations, the beam envelope is small (large) in one plane, and large (small) in the other. The octupole magnets are placed at these locations, and their strengths adjusted to give the required beam properties at the target. (This arrangement of having the beam small in one plane and large in the other at the octupoles, minimizes the horizontal/vertical coupling and makes tuning the octupoles easier; it also results in a rectangular cross section at the target.) The appropriate beam correlation coefficient, C12 or C34, at each octupole in the plane where the beam is large should also be very close to unity, in order that the intensity distribution at the target falls off sharply.

Experimental confirmation of this approach was obtained at BNL’s Radiation Effects Facility[3]. A schematic layout of the new BIRC line is shown in Fig. 1. Total length of the line is 33.5 m.

![Fig. 1. Schematic layout of the BIRC beam line. showing quadrupoles (Q), octupoles (O), dipole magnets (D) and profile monitors. Total length is 33.5 m, and is to be scale horizontally.](image)

Software Tools

The following programs were used for the study: TRANSPORT[4], TURTLE[5], TRACE3D[6], and NSC[7]. TRANSPORT was used to find the first-order beam parameters required for flattening while determining possible locations of the octupoles. NSC, similar to TURTLE, was used to find the octupole strengths which gave the desired beam properties on the target. TURTLE repeated the third order calculations, but provided information to reconstruct the third-order beam envelopes in a straightforward manner. TURTLE, and TRACE3D were used to examine the sensitivity of the final design to misalignments and magnet imperfections, in particular, the (sub)harmonics of the octupole magnets.

Fig. 2 shows the design beam envelopes for flattening. The corresponding phase space plots and profiles are in Fig. 3.

Commissioning

Commissioning was parasitic to other BIRC activities, hence it proceeded very slowly. The activation method of measuring beam profiles at the target location has a turnaround time of several hours at best, and several days at worst, thus making it impossible to tune the beam on target while monitoring it on a pulse-to-pulse basis. As a result, most of our studies concentrated exclusively on the multiwire profiles. (A 3 m drift separates the last profile monitor and the target.)

* Work performed under the auspices of the U.S. Dept. of Energy.
Fig. 2. The design beam envelopes for the new beam line.

Fig. 3. [a] Phase space of the design beam at the target. Vertical plot is displaced 8 cm to the right. [b] The corresponding beam profiles displaced to line up with phase space plots.

**Diagnostic Equipment**

Equipment used included: multiwire harps at locations REFMW and BIRCMW in Fig. 1, to provide horizontal and vertical beam profiles; a 3-wire SEMM at SEM3 which provides data for 3-D reconstruction of the beam intensity profile using ART; a system for exposing aluminum targets to the beam and measuring their activity profiles as a means of obtaining the 3-D beam profiles at the target. SEMs immediately after the Linac were used for emittance measurements, while radiation monitors along the beamline showed when and where beam was hitting the beam pipe.

The data collected consisted of the quadrupole and octupole currents, and the multiwire and irradiated target profiles. Beam emittance was measured infrequently.

**Data Analysis**

The magnet currents were converted to fields using measured, and for the last three quads, calculated characteristic curves. The fields were then used in the computer model of the line to obtain beam envelopes, and 2-D and 3-D profiles, which were compared to those measured.

**Results**

We mentioned earlier that most of our effort to understand the optics of the line was concentrated on beam profiles at REFMW and BIRCMW. The latter is of more interest because it is after the octupoles. Figs. 4 and 5 show observed and calculated beam profiles for a tune which produced a flat vertical profile and another tune with the octupoles off. The agreement between observation and theory (TURTLE) is excellent. The widths and relative heights of the measured and calculated profiles agree very well.

**Discussion**

The objective of a flat rectangular beam on the BIRC target needs more work to be fully realized. Progress has been slow due mainly to the slow feedback from profile measurements at the target and the absence of measured characteristics of the last three 6 in. aperture quads. Three-dimensional modelling of the quads has recently been used, tested on the original 4 in. aperture magnets, and then on the modified 6 in. aperture quads. It gave reasonably accurate characteristics which were used in the TURTLE model. (Radiation levels permitting, one of the quads may be removed for bench measurements during the present shutdown.) Work continues on finding a better and faster way to measure the profiles at the target.

We now know that the difficulty in flattening the beam horizontally was due to the smaller horizontal beam envelope and lower correlation, C12, at the first octupole. In the initial stages of commissioning, the line was retuned for a smaller envelope upstream of the second bending magnet because of high radiation losses. A first-order tune will be found to address this problem.

**Acknowledgements**

We acknowledge the very valuable and continuing contributions of Leonard Mausner and his team at BIRC, Brian Briscoe at the Linac, Dave Schlyer of the Chemistry Department for the activation measurements, and the staff of SIGMAPHI (France) for meeting our very tight schedule for manufacture and delivery of the octupole magnets.

**References**

7. N. Tsoupas, private communication. (The significance of the letters NSC has long since been lost.)
Fig. 4. [a] Observed horizontal profiles at the BIRCMW location in Fig. 1 with octupoles ON (left) and OFF (right). [b] The corresponding profiles predicted by TURTLE.

Fig. 5. [a] Observed vertical profiles at the BIRCMW location in Fig. 1, with octupoles ON (left) and OFF (right). The tilt of the vertical 'flat-top' was due to vertical mis-steering and could be removed or reversed with the vertical steerers. The downstream quads were set differently than in Fig. 3. [b] The corresponding profiles from TURTLE.

* Supplied by SIGMAPHI (France). They have a 15.24 cm $\varnothing$ aperture, $L_{\text{eff}}$ is 33.7 cm, and maximum pole-tip field is 6.3 kG.
* A typical SEM has two thin wires, mounted horizontally and vertically, which are stepped through the beam at an angle of 45° to the vertical, in a transverse plane to the beam, to give beam profiles. For ART, a third wire is mounted at 45°, co-planar with the other two.
UPGRADE OF THE BROOKHAVEN 200 MEV LINAC*

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Abstract

The Brookhaven 200 MeV linac serves as the injector for the AGS Booster, as well as delivering beam to the Biomedical Isotope Resource Center. During the past year, many linac systems have been upgraded to allow operation at 2.5 times higher average current (150 μA). This was achieved by an increase in rep-rate from 5 to 7.5 Hz, an increase in beam current from 25 mA to 37 mA, and a slight increase in pulse width to ~530 μs. Additional upgrades were made to improve reliability and modernize old systems. This paper describes improvements made in the 35 keV and 750 keV beam transport, 200 MeV beam transport, rf transmission line, rf power supplies, control systems, and instrumentation.

Introduction

The AGS 200 MeV linac accelerates H⁺ ions for injection into the AGS Booster. The linac operates at a 7.5 Hz rep-rate, and since the Booster takes only 4 pulses every ~3 seconds, all remaining pulses are sent to the Biomedical Medical Resource Center (BIRC). This facility produces radioisotopes for the pharmaceutical and medical community, as well as supporting a medical research program. In order to meet increased demand for isotopes, we have nearly completed all phases of a program to upgrade the average current out of the linac. The AGS has also benefited from the improvements, since higher peak current out of the linac improves Booster injection, and the reliability of the linac was improved through modernization of systems. Most of the improvements were funded as part of the BIRC project, through DOE OHER, but parts have also been supported through AGS Department Accelerator Improvement Projects. As a result of these improvements, the average current out of the linac has increased by a factor of 2.5, to 146 μA. Table 1 shows the linac performance before and after the upgrade. The improvements made to the various subsystems are described in the following sections.

Table 1

<table>
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<tr>
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<th>After Upgrade</th>
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<tr>
<td>H⁺ Beam Current</td>
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<tr>
<td>Repetition Rate</td>
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<td>Beam Width</td>
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<td>530 μs</td>
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<tr>
<td>Average Current</td>
<td>62 μA</td>
<td>146 μA</td>
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</table>

35 keV Beam Transport Line

The beam from the magnetron surface-plasma H⁺ source is matched in to the RFQ by two pulsed magnetic solenoid lenses. Until this year, the distance between source and RFQ was 2.1 m. This line also included an emittance measuring device and a fast beam chopper. Because fast beam chopping is now done much more effectively in the transport line after the RFQ, this 35 keV chopper box was removed to improve the matching in to the RFQ. In addition, calculations showed that matching could be further improved if the first solenoid were moved closer to the source, and the second solenoid closer to the RFQ. With the new distance of 1.4 m, the first solenoid moved 4 cm upstream and the second solenoid moved 4 cm downstream, the transmission through the RFQ improved by ~10%, from the 70-80% range to 80-90%, depending on source operating conditions. The emittance of the beam in front of the RFQ was reduced by about ~20%. Typical current out of the RFQ is now 65 mA, and the maximum current through the RFQ was 80 mA, 82% transmission. (In our case, the "transmission" is the ratio of output current, measured 61 cm after the RFQ, to input current measured 55 cm before the RFQ).

750 keV Beam Transport Line

There is a 6 m transport line from the RFQ to linac, to accommodate a pulsed dipole where polarized H⁺ comes from a second beamline, and a fast beam chopper. There are three bunchers and 13 quadrupoles in this line. Transmission in this line was only ~75%, with losses early in the line caused by the fact that the first quadrupole after the RFQ was not close enough to catch the beam before it got too large. In order to reduce the beam divergence quickly coming out of the RFQ, a 1.1 cm aperture, 3.5 cm long permanent magnet quadrupole was placed in the endflange of the RFQ, only 2.1 cm from the RFQ vane tip. In addition, this quadrupole can be moved transversely while running beam, via micrometer adjustment outside vacuum, in order to steer the beam. A picture of the RFQ endflange with PMQ is shown in figure 1. Additional changes in the line were to move the first quadrupole triplet 9 cm closer to the RFQ, and to convert a final quadruplet (which had been running as a triplet), into a real...

*Work performed under the auspices of the U.S. Dept. of Energy.
triplet. We also removed all magnets from the line and had the fields precisely measured by the RHIC magnet group. All magnets were carefully surveyed when reinstalled, particularly trying to eliminate quadrupole rotations, which leads to emittance growth of the beam. With these improvements, the transmission from the RFQ to linac was improved to ~85%. We believe that the remaining loss comes from the 12 "grids" (made of thin tungsten strips) in the line, in the three buncher cavities.

With this 50% higher current at the linac entrance, the linac transmission remained the same, with ~70% being captured in the first tank. This agrees with calculations of the line, and comes from the fact that the line is too long to match longitudinally with only three bunchers. The calculations show that with a fourth buncher the capture into the linac could be >95%.

200 MeV Beam Transport Line

There were both vacuum-related and beam optics improvements in the transport line between the end of the linac and the BIRC target. Most of the vacuum components in the line were replaced. O-rings were eliminated, and the line now uses all contact flanges. Aluminum pipe was used in much of the line to minimize activation. Pumping of the line was increased, with new turbo pumps and ion pumps. Apertures in the line were increased wherever possible, and most of the line has either 6" or 8" diameter beampipe.

Details of the optics of the line are given in another paper at this Conference.[1] Briefly, there are two bends between the linac and BIRC target, and a quadrupole was added to make these bends achromatic. Further downstream, two octupoles and two quadrupoles were added in order to produce a uniform current density on the BIRC targets, to prevent melting of some target materials at this increased beam power. While we have been able to produce flattened beam profiles on an upstream profile monitor, progress on producing a flat distribution on target has been slow, due to the long turnaround time (1 day) on profile measurements at the target location (via activation of foils and counting).

High Power Transmission Line

In order to improve reliability at the increased linac duty factor, all the 12" coaxial transmission line was replaced. Up to 6 MW peak power is fed from each of the nine rf systems, through a 3 db power split, and into two ports on each of the nine accelerating cavities, a total of over 200 m of transmission line for the full linac. Our 25 year old system had disadvantages of having aluminum inner conductor, spring ring rf contacts, and was unpressurized. The new transmission line system was built and installed by Dielectric Corporation. It has a copper inner conductor and an aluminum alloy outer conductor, is pressurized to 15 psi with dry air, and the connectors for the center conductor are EIA-type finger contacts. We replaced the full system, including the 3 db power splitters, waster loads, breakup and telescoping sections, and reflectometers. A hybrid phase shifter (mechanically variable) was replaced with a transmission line section of optimum length in each system.

The removal of the old transmission line took one week, and the actual installation time for the new system was approximately three weeks, although total time to fully complete, test and debug was three months. The new system has operated very reliably, with low insertion loss, very low probability of voltage breakdown, and improved S-parameters.

Linac RF Power Supplies

7385 Anode Power Supply

The 6 MW power amplifiers for the linac use Burle 7385 triodes. At the increased current and duty factor of the linac, some of the 60 kV, 2 A, 7383 anode power supplies would be running at their 2 A limit, a concern for reliability. In addition, these power supplies, constructed in 1968, are oil filled units that are outside the linac building, connected to capacitor banks by a long high voltage transmission system. Servicing the power supplies can be a problem because of weather and the need for a crane. Also, the placement of the power supplies would not meet current code requirements for fire protection or oil containment. It was felt that with the present technology, a dry type power supply could be built, and in order to meet any future requirements, we settled on a 50 kV, 5 A supply.

While several vendors offered high frequency switching supplies, the final selection was a conventional 6 pulse primary phase controlled dry type transformer rectifier (TR) set, built by Universal Voltronics (UVC). To save money, the power supplies were housed in existing linac cabinets that formerly housed the charge control amplifiers. These cabinets are 4x8x8 feet and are fully compatible with the existing lifting fixtures, building crane, and floor space requirements.

The high voltage secondary coil of the transformer presented the greatest technical challenge. In the final design, each of 6 secondary coil assemblies was divided into two individual coils, lowering the layer to layer voltage by a factor of two. The coils were then wound with vertical spacers to allow the epoxy to flow between each of the layers. The final, completed 250 watt transformer assembly is compact, measuring 1.5'x4'x4'. None of the temperatures on the transformer secondary exceeded 60 C after 24 hours running.

The power section is a straightforward six pulse primary phase control. The voltage and current regulating loops are compensated for the capacitive load. The power supply charges the capacitor bank at a constant current (current mode) until the preset voltage is reached (voltage mode).

Seven power supplies have been delivered to BNL and tested, with the remainder due shortly. They will go online in January '97.

4616 Anode Power Supply

The Burle 4616 tetrode is used in the driver stage of the linac rf system. The anode power supply is being upgraded to improve the feedback control, employing both current and voltage feedback, and replace unavailable SCR controllers.

PLC Controls for RF Systems

The linac is made up of 9 identical rf stations. Each station has several subsystems, including the driver, 7835 filament supply and cavity, 50 kV supply, capacitor bank, modulator, and local control station (LCS). Each of the subsystems has individual control buckets for AC and high voltage logic. These buckets were designed and built in 1968 around 7400 TTL series components. Replacing these control buckets with more modern components is a necessity because many of the components are no longer available.

We are beginning to implement a new control system, utilizing programmable logical controllers (PLC's). It is designed for fully independent operation of each rf system, flexibility and reliability. An Allen Bradley 5/40 processor was chosen for each LCS. A 5/50 ethernet processor was selected for the control room. Each of the 5/40's can scan the subsystems of
a system (scanner mode), or be scanned by the host in the control room (adapter mode).

There are 3 networks that make the backbone of the system. The first network is responsible for the data collection and control of each station. The S/40 in the LCS scans the subsystems of a station. To minimize the wiring, each of the subsystems has a miniature processor (Allen Bradley flex I/O) that multiplexes the data at 230 kbaud for the S/40. A single twisted pair links all of the subsystems of a mod together. The subsystems are connected together via the Allen Bradley Remote I/O network. The second and third networks are links between each of the systems. The DH+ network runs at 57 kbaud and is responsible for the remote monitoring and control of all 9 systems. The Allen Bradley graphical interface program, Control View, is used to control the supplies. An additional remote I/O network allows the S/40 E in the control room to monitor each mod at 230 kbaud for fast global control. For example the S/40 E can turn off all the 50 kV supplies at the same time if needed.

**Linac Controls**

This past year the original 25-year-old Linac control system was replaced with a modern modular system fully integrated into the existing AGS distributed control system. Unix workstations provide the operator interface, and are networked using ethernet to front-end computers which are implemented using VMEbus components. A front-end computer located in the Linac Control Room sources four high speed serial communication links using the Datacom field bus, a long-standing BNL standard. Although an old system, Datacom is extremely robust and noise immune, can operate over 2000 ft. of coaxial cable, and is relatively inexpensive. Each Datacom link can address up to 256 devices, delivering a 24-bit command and accepting a 32-bit reply. All devices are accessed for each Linac pulse (7.5 Hz), and in particular, device setspoints are rewritten for each pulse; thus any sequence of different Linac clients (Booster, BIRC) requiring possibly different settings can be accommodated - a feature termed pulse-to-pulse modulation (PPM). The individual devices are interfaced to the Datacom link via dual-channel cards housed in crates at 11 locations along the Linac. We are controlling and/or monitoring over 400 devices.

At the heart of the Datacom field bus system is the VME Datacom engine. This device was developed at BNL using modern field programmable gate array (FPGA) and RISC processor technology. The Datacom engine supports multiple Datacom channels with each Datacom channel capable of addressing the full Datacom address space. The Datacom engine has an on-board timeline decoder and local memory so that all Datacom transactions can be preloaded into tables, sent on previously programmed timing events, and data returned and stored without intervention by the VME processor. This has resulted in a many fold increase in data throughput compared to older Datacom implementations.

**Linac Timing System**

There are two aspects of the linac timing system which will be upgraded in FY'97. The "local" timing system provides specialized "fixed" delays, generates sequences of triggers required for rf systems, etc., and checks to make sure that external triggers coming in to the linac are in the proper sequence. It will allow us to time shift the triggering of rf power to individual accelerating cavities, and with downstream cavities time shifted out of beam time we can run at different energies on a pulse-to-pulse basis. This local Linac timing hardware will consist of Altera PLD chips for designing the logic controls. An 8051 microcontroller chip will provide the processing of data to and from the PLD chips. A RAM chip will store the data for each user. The microcontroller will control the data flow. A PC with control software will provide the interface.

A second part of the timing system provides external trigger signals (from downstream accelerators) to the linac local timing, as well as triggers to some specific linac hardware. This new Linac timing system will be an encoded timeline using RHIC generation VME timing system modules. With these modules a Linac timeline can be built without hard wiring or hard coding. The timeline can be changed by command from computers on the accelerator control network and/or by cable changes between modules at the generator. The timeline generator will be located in the Linac control room and the encoded timeline will be distributed along the linac via fiber optic cables. Decoder/delay modules, fully programmable through the VME processor, connect directly to the timeline and provide decoded pulses from events, or can provide delayed outputs from an event.

**Instrumentation**

A stripline position monitor was added between the bends to the BIRC target, at a high dispersion point, to allow monitoring of the linac energy. As suggested by P. Ostromou (INR), a diagnostic was added at the end of linac cavities #1 and #4, to aid in the setup of the phase and amplitudes. This is a series of Al plates of appropriate thickness, each electrically isolated and on which the current can be read. Successive plates will stop partially accelerated particles from successive cavities, allowing one to do phase and amplitude scans for coarse setup of the tank. Finally, a third wire at 45° was added to two SEM units, giving beam profiles in 3 projections by stepping through the beam. With this, we are able to get 3-dimensional tomographic reconstructions of the beam distribution, as described in [2].

**Conclusions**

With improvements in beam transport through the 35 keV and 750 keV lines, we can now operate at currents 50% higher than previously. The average current out of the linac has reached our goal of 146 μA, and still higher currents should be possible. Most of this past running period was at reduced beam pulse width, due to BIRC target limitations. (They expect to be able to run at full average current next year). Therefore, we can not yet say if reliability will suffer over long periods at 150 μA, but so far indications are that there is an overall improvement in linac reliability.

**Acknowledgments**

We acknowledge the excellent work on this project of the entire Linac staff, the AGS controls group, and the AGS vacuum group. We also thank the RHIC magnet group for their assistance.

**References**


THE SOURCE DEVELOPMENT LAB LINAC AT BNL

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Abstract

A 210 MeV SLAC-type electron linac is currently under construction at BNL as part of the Source Development Laboratory. A 1.6 cell RF photoinjector is employed as the high brightness electron source which is excited by a frequency tripled Titanium:Sapphire laser. This linac will be used for several source development projects including a short bunch storage ring, and a series of FEL experiments based on the 10 m long NISUS undulator. The FEL will be operated as either a SASE or seeded beam device using the Ti:Sapp laser. For the seeded beam experiments, direct amplification, harmonic generation, and chirped pulse amplification modes will be studied, spanning an output wavelength range from 900 nm down to 100 nm. This paper presents the project’s design parameters and results of recent modeling using the PARMELA and MAD simulation codes.

Introduction

The National Synchrotron Light Source has been engaged in the development of an FEL facility operating in the ultra-violet for more than five years. The Source Development Lab (SDL) has been established to pursue critical experiments on the path to short wavelength FELs, including development of high brightness beams, bunch compression and transport to high energy, and a broad range of SASE and seeded single pass FEL experiments. These FEL experiments will include study of startup, optical guiding, saturation, linewidth and fluctuations. The SDL is comprised of three major programs:

- Electron beam development and experiments.
- Coherent synchrotron radiation experiment.
- UV project FEL.

The electron beam development will be devoted to producing high brightness beams with peak current of 1 kA, normalized RMS emittance of 1π mm-mrad, and subpicosecond bunch lengths. The effects of coherent synchrotron radiation[1] and space charge forces[2] are expected to be significant with these parameters. Beam experiments will be devoted to studying their effect on emittance.

Our FEL program starts with SASE operation of the FEL at 900 nm. Harmonic generation[3] and chirped pulse amplification[4] experiments will follow with the addition of an energy modulation wiggler and dispersive section.

Laser Driven RF Photocathode

The electron source[5] is a radio-frequency photocathode developed by a collaboration from BNL, SLAC, and UCLA. It consists of a 1.6 cell RF structure driven at 2856 MHz. The maximum gradient has been measured at 140 MV/m, yielding an exit energy of approximately 8 MeV. Improvements over the original BNL design[6] include elimination of the side coupling into the half-cell to reduce emittance growth due to the TM_{11} mode, installation of a removable cathode allowing different cathode materials (e.g. magnesium) to be used, and increasing the half-cell length to increase RF focusing and decrease the peak field on the cell-to-cell iris. The emittance correction solenoid has also been improved with the addition of a re-entrant iron flux return to produce a more uniform magnetic field with little fringing. PARMELA runs[5,7] indicate that this RF gun is capable of producing electron bunches with 7 ps flat top, 1 nC charge, and normalized RMS emittance of 1.3π mm-mrad. The laser system used to excite the RF photocathode is based on a wide-band Ti:Sapp oscillator[8] mode-locked to the 35th subharmonic of the RF frequency. Phase jitter is less than 1 ps. The light output from the oscillator enters a multipass amplifier that stretches the pulse, amplifies it, and recompresses to produce 10 mJ in a final pulse length of 150 fs. Up to 0.4 mJ of the 266 nm third harmonic of the amplified pulse is then stretched to a final pulse length adjustable from 300 fs to 20 ps. An aberrated telescope is used to produce an elliptical beam for a square transverse intensity profile and 65 degree wavefront tilt to match the incidence angle on the RF photocathode. The square intensity profile is optimal for emittance correction. The wide bandwidth of the Ti:Sapp laser allows for longitudinal pulse shaping so that nonlinear emittance correction may be investigated.

Linac and Magnetic Bunch Compressor

The linac (Figure 1) currently consists of four SLAC-type constant-gradient linac tanks operating at 2856 MHz, with provision for installation of a fifth section.

The first two linac tanks are used to accelerate the beam to approximately 84 MeV. They also produce an energy chirp on the electron beam in preparation for bunch compression in a magnetic chicane. The compressor may be operated at any value from zero field to full strength. A phosphor flag and collimator are installed at the point of maximum dispersion.
for use as energy-spread diagnostics, and for slice emittance studies. Tracking studies with MAD indicate the bunch should compress by a factor of 12, from an RMS length of 600 μm to 50 μm. Following the chicane the beam is accelerated through two more linac tanks to a maximum energy of 230 MeV.

![Diagram of SDL linac and experiments](image)

Fig. 1. Layout of SDL linac and experiments.

**Wiggler**

Following the linac is the 10 m long NISUS wiggler originally built by STL, Inc. for Boeing Aerospace (see Table 1). This wiggler is constructed of vanadium-permendur poles and samarium-cobalt magnets, with iron shims added for error reduction. The gap is remotely adjustable, has a maximum field strength of 0.56 T, and can produce a compound taper to improve efficiency for high gain FELs. There are 256 periods, each of length 3.89 cm.

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<td>Peak Current</td>
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<table>
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<td>Num. Poles</td>
<td>256</td>
</tr>
<tr>
<td>aw</td>
<td>1.44 max</td>
</tr>
<tr>
<td>Min. Gap</td>
<td>1.44 cm</td>
</tr>
<tr>
<td>Energy Taper</td>
<td>&lt; 20%</td>
</tr>
<tr>
<td>Wavelength</td>
<td></td>
</tr>
<tr>
<td>FEL</td>
<td>80 nm &lt; λ &lt; 1000 nm</td>
</tr>
<tr>
<td>Peak Power</td>
<td>70 MW</td>
</tr>
</tbody>
</table>

The vacuum pipe through the wiggler is constructed of 8 independent sections. Each section has two ports for pop-in phosphor screens, two ports for pick-up electrodes, and two sets of steer/focus wires that can produce external dipole and quadrupole fields. The wiggler poles are canted to produce focusing in both planes.

**Electron Beam Experiments**

Several of the important beam parameters for the FEL experiments have an unusually large range of adjustment. The pulse length and energy spread can be varied and optimized with both the drive laser and the magnetic chicane. The initial pulse length may be varied by nearly two orders of magnitude via the Ti:Sapp laser alone. Recent magnetic compression studies have shown that increasing the initial pulse length can lead to shorter final pulses. This is because the more intense wakefields and higher space charge of an initially short bunch increase the nonlinear distortion in the energy-phase correlation used for compression. Finally, one can optimize the bend angle in the compressor so that the nonlinear effects of the longitudinal wakefield and
RF are partially canceled by the effect of the nonlinear dependence of path length on the energy deviation.

Very short, high current bunches propagating through bends can experience significant transverse emittance growth through two distinct effects, the longitudinal coherent space charge force (CSCF), and coherent synchrotron radiation (CSR). Emittance growth due to CSCF scales as \( Q(a/\delta)^2 \) where \( Q \) is the bunch charge, \( a \) is the bunch radius, and \( \delta \) is the bunch length. Similarly, CSR scales as \( Qa/\delta^3 \). Simulations with a version of MAD modified by one of us (TR) to include CSR indicate that the emittance grows from 1.2\( \pi \) mm-mrad to 2.0\( \pi \) mm-mrad in the final bend of the compressor when compressed to a final bunch length of 0.6 ps. Greater compression is possible, but results in larger emittance. The bunch length, transverse size, and charge will be varied in order to study the magnitude and scaling of these effects. The compressor vacuum pipe has a radiation port to capture synchrotron radiation which will be used as a diagnostic for bunch length and beam size. The emittance may be measured immediately before and after the compressor to isolate the effects of CSR and CSCF.

At high energy, the bunch length will be verified through two methods. By passing the beam through a foil, coherent optical transition radiation (OTR) will be generated at wavelengths comparable to the bunch length. An experiment is planned following the linac which measures the coherent OTR spectrum. Additionally, the final linac section and bend may be used to produce an energy chirp which can then be "streaked" on a phosphor screen to measure bunch length. This profile measurement combined with charge measurements in the Faraday cup or BPMs will give the bunch charge profile. The drive laser pulse is approximately 1 mm long by 1 mm in radius. The very short longitudinal profile significantly affects the minimum emittance achievable via solenoidal emittance correction[13]. By varying this profile, we will study the relative strength of the nonlinear terms in the emittance correction. Measurements of the slice emittance as developed at BNL's Accelerator Test Facility will be used in these studies.

**FEL Experiments**

The FEL development program for the SDL can be broken into stages based on machine requirements and modifications. In the first stage, a normalized emittance of 6.5\( \pi \) mm-mrad at a beam energy of 130 MeV is required. SASE experiments will be conducted at roughly 1\( \mu \)m wavelength with an anticipated peak power of 70 MW. Tapering and harmonic content will be investigated. The first seeded beam operation will be at the Ti:Sapp fundamental (900 nm). Chirped pulse amplification experiments at this wavelength will yield photon pulses as short as 10 fs. After adding an energy modulation wiggle and dispersive section at a later date, the FEL output wavelength will be pushed to 200 nm using harmonic generation. A 400 kW beam from the Ti:Sapp at 400 nm will bunch the electron beam, which will then lase on the 2\textsuperscript{nd} harmonic, producing 70 MW at 200 nm. With the addition of a 5\textsuperscript{th} linac section increasing the beam energy to 310 MeV, and emittance of 1\( \pi \) mm-mrad, FEL operation below 100 nm should be possible, including the demonstration of CPA at 80 nm with a 5 fs pulse duration.

**Acknowledgments**

Thanks to J. Gallardo of BNL and D. Palmer of Stanford for PARMELA input for the linac, to L. DiMauro of BNL for discussions on the Ti:Sapp laser, to L.-H. Yu of BNL for the FEL parameters, and to B. Carlsten of LANL for PARMELA simulations of the RF gun.

**References**


Comparisons Between Modeling and Measured Performance of the BNL Linac

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Abstract
Quite good agreement has been achieved between computer modeling and actual performance of the Brookhaven 200 MeV Linac. We will present comparisons between calculated and measured performance for beam transport through the RFQ, the 6 m transport from RFQ to the linac, and matching and transport through the linac.

1 INTRODUCTION
The Brookhaven 200 MeV linac serves as the injector for the AGS Booster and as well delivers beam to the Brookhaven Isotope Resource Center. It consists of a 35 keV magnetron surface plasma source, a low energy beam transport (LEBT) [1], 201 MHz radio frequency quadrupole (RFQ) [2], medium energy beam transport (MEBT) and 200 MeV Linac [3]. In this last year we have gone through a linac upgrade to get 2.5 more average current (146 μA) [4]. This was achieved by increasing repetition rate 5 to 7.5 Hz and increasing peak current from 25 to 39 mA. In this paper we compare computer modeling with actual performance.

2 LEBT AND RFQ
LEBT had two pulsed solenoids, two sets of x and y steerer, beam chopper, emittance probe, and two current toroids. The chopper was removed from the line, making the line shorter by 70 cm. Computer modeling of this line showed that we should move the 1st solenoid as close to the ion source as possible to reduce the beam size in the 1st solenoid and the second solenoid as close to the RFQ as possible to increase the convergence angle required by the RFQ acceptance. Figure 1 shows the ion trajectories through this line and phase space at the exit of the ion source, middle of the line and entrance of RFQ. The RFQ acceptance is shown as a solid line ellipse. This calculation assumed that the beam space charge is neutralized.

Shortening of the line resulted in lower measured emittance. Due to lower emittance and better matching transmission through the RFQ was improved by about 10 percent. Figure 2 shows the transmission as a function of input beam current.

*Work performed under the auspices of the U. S. Department of Energy.
3 MEBT AND LINAC

This is where we have recovered most of the beam losses. This line is 6 meter long and is shown in Figure 3. It consists of four triplets, three bunchers, one slow chopper, one fast chopper, two emittance measurement units, three current transformers, two sets of x, y steerers, and a dipole to accommodate polarization beam coming at 60 deg angle. The ideal match between RFQ and DTL could have been obtained with a 5 βλ long FODO lattice with quadrupole spacing about βλ and at least two bunchers. But the requirement of beam chopping and polarized beam dictated a triplet solution [5].

The first quadrupole after the RFQ was too far; by the time the beam reached the quadrupole it had gone through a waist in the x plane, hence was diverging in both planes. No matter which polarity quad one puts, beam size in the other direction is very big. Also the longitudinal beam size is too big before it reaches the first buncher. To improve the capture and transmission of the beam in MEBT, the RFQ end flange at the high energy end was modified to accommodate a permanent magnet quadrupole (PMQ). The PMQ was similar to one as used in the SSC DTL [6]. We have also rearranged the gate valve and current transformers at the beginning of the line, and also measured and aligned all the quadrupoles very carefully. Measurement as well as simulation showed that as little as a 1.5 degree quadrupole rotation can increase the emittance by 50%. The last quadruplet was changed to a triplet to reduce coupling. Figure 4, shows the measured and calculated phase spaces after the second buncher. Table 1 shows calculated (TRACE3D) and measured Twiss parameters for Figure 4.

Table 2, compares measurements and PARMILA results at various locations. We believe that lower values for currents after the second buncher and at the entrance of the Linac are caused by the grids in the buncher drift tubes (four in each buncher). These grids are placed in the bunchers to reduce RF defocusing effects. Emittance measurements at 200 MeV are done using profiles at five places. Agreement between calculations and measured Twiss parameters at 200 MeV is poor because there are 296 quadrupoles, and calibration and misalignment errors are not known to a good accuracy.

Table 1: Calculated and measured Twiss parameters after the second buncher. β is in mm/mrad and ε (unmTR,M) in π mm mrad.

<table>
<thead>
<tr>
<th>Planes</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α_x</td>
<td>β_x</td>
</tr>
<tr>
<td>Meas.</td>
<td>-0.60</td>
<td>0.79</td>
</tr>
<tr>
<td>Cal.</td>
<td>-0.31</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Table 2: Comparison between simulations and measured beam parameters.

<table>
<thead>
<tr>
<th>Location</th>
<th>94-95</th>
<th>95-96</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current mA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RFQ</td>
<td>50.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Buncher</td>
<td>50.0</td>
<td>41.0</td>
</tr>
<tr>
<td>MEBT</td>
<td>42.4</td>
<td>37.3</td>
</tr>
<tr>
<td>Tank 1</td>
<td>27.4</td>
<td>28.4</td>
</tr>
<tr>
<td>Tank 9</td>
<td>26.2</td>
<td>26.7</td>
</tr>
<tr>
<td>Emittance, (nor, RMS) π mm mrad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RFQ</td>
<td>0.400</td>
<td>0.400</td>
</tr>
<tr>
<td>Buncher</td>
<td>0.44</td>
<td>0.56</td>
</tr>
<tr>
<td>200 MeV</td>
<td>1.32</td>
<td>2.8</td>
</tr>
</tbody>
</table>
4 ALGEBRAIC RECONSTRUCTION TECHNIQUE (ART)

A radiograph of the beam at the BLIP target taken last year showed a tilted ellipse in the x-y plane. Sources of this coupling can be quad rotation or vertical offset in the dipole. This triggered the need for an x-y density profile. We found that algebraic reconstruction technique (ART) could help us. ART was introduced by Gordan, Bender and Herman [7] for solving the problem of three dimensional reconstruction from projections. The ART algorithms have a simple intuitive basis. Each projected density is thrown back across the reconstruction space in which the densities are iteratively modified to bring each reconstructed projection into agreement with the measured projection. The reconstruction space is an n x n array of small pixels, \( \rho \) is grayness or density number which is uniform within the pixel but different from other pixels. Assume \( \mathbf{P} \) is a matrix of \( m \times m \) and the \( i \) component column vector \( \mathbf{R} \). Let \( p_{i,j} \) denote the \( (i,j) \)th element of \( \mathbf{P} \), and \( R_i \) denote the \( i \)th element of reconstructed projection vector \( \mathbf{R} \). For \( 1 \leq i \leq m \), \( N_i \) is number of pixels under projection \( R_i \), defined as \( N_i = \sum_j p_{i,j}^q \). The density number \( p_{i,j}^q \) denotes the value of \( p_{i,j} \) after \( q \) iterations.

After \( q \) iterations the intensity of the \( i \)th reconstructed projection ray is

\[
R_i^q = \sum_j p_{i,j}^q \rho_j^q
\]

and the density in each pixel is

\[
\rho_j^{q+1} = \rho_j^q + \rho_j^q \frac{R_i - R_i^q}{N_i} \quad \text{with starting value } \rho_j^0 = 0
\]

where \( R_i \) is the measured projection and,

\[
i = \begin{cases} m, & \text{if } (q+1) \text{ is divisible by } m, \\ \text{the remainder of dividing } (q+1) \text{ by } m, & \text{otherwise}
\end{cases}
\]

and,

\[
\rho_j^q = \begin{cases} 0, & \text{if } \rho_j^{q-1} \leq 0 \\ \rho_j^{q-1}, & \text{if } 0 \leq \rho_j^{q-1} \leq 1 \\ 1, & \text{if } \rho_j^{q-1} \geq 1
\end{cases}
\]

It is necessary to determine when an iterative algorithm has converged to a solution which is optimal according to some criterion. We are using as the criteria of convergence the discrepancy between the measured and calculated projection elements

\[
D^q = \left( \frac{1}{m} \sum_{i=1}^{m} \left( R_i - R_i^q \right)^2 / N_i \right)^{\frac{1}{2}}
\]

We have added a third wire at 45 degree in wire scanners in two places. Figure 5 compares the measured and reconstructed profiles in the BLIP transfer line [8] after the 1st octupole and figure 6 shows the reconstructed 3D density distribution.

5 REFERENCES

Improved Beam Stability with New Parameter Set for the S-band Linear Collider

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Abstract

With sufficient damping of long-range Higher Order Modes, the emittance dilution in the S-band Linear Collider is dominated by single bunch effects. We present an improved parameter set with reduced bunch charge which allows to relax the positioning tolerances in the main linac. The consequences for the other subsystems of the collider are also briefly discussed.

Introduction

The S-band approach towards a next generation Linear Collider of 500 GeV center-of-mass energy represents the most conservative one of several concepts presently under investigation [1]. The technology is well known for many years and the experience from the only existing Linear Collider, the SLC, can be used most directly. The relatively low frequency (3 GHz) is beneficial for keeping emittance dilution from wakefields small. In this context, a low bunch charge \( N_b \) is favorable since it reduces the short-range wakefields. This led us to a modification of the beam parameters, as will be described in the following.

New Parameter Set

The dilution of the beam emittance in the linac due to transverse short-range wakefields scales approximately as

\[
\Delta \varepsilon \propto N_b^2 \sigma_b^2 < \beta > \delta y_c^2
\]

(1)

Here, \( \sigma_b \) denotes the bunchlength and \( \delta y_c \) the rms error of transverse structure alignment w.r.t. the beam orbit. The average focussing strength in the linac is expressed by \( < \beta > \), we assume a scaling \( \beta = \beta_0 (E/E_0)^{1/2} \) with \( \beta_0 = 13 \text{m} \) at \( E_0 = 3 \text{GeV} \). Stronger focussing seems advantageous with regard to transverse wakefield effects, but would lead to increased emittance dilution from chromatic aberrations.

The parameter optimization consists in a reduction of bunch charge by a factor of 0.4 and of bunch length by a factor of 0.6. The pulse current (and thus the average beam power) is kept unchanged by an appropriate reduction of bunch spacing and the interaction parameters are adjusted in order to keep the beamstrahlung constant. A complete overview of the S-Band Linear Collider (SBLC for short) parameters is given in table 1. According to eq. (1), we gain an order of magnitude reduction in transverse short-range wakefield effects. Part of this improvement is used to lower the vertical beam emittance (yielding a higher luminosity), the other part to relax the structure alignment tolerances. With the modified beam parameters, a complete simulation of beam dynamics also including other important effects such as long-range wakefields and chromatic aberrations has been performed.

<table>
<thead>
<tr>
<th>parameter</th>
<th>NEW</th>
<th>OLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>total length</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>( t_{pulse} )</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>( N_b/pulse )</td>
<td>333</td>
<td>125</td>
</tr>
<tr>
<td>( \Delta t_b )</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>( f_{acc} )</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>( N_b/bunch )</td>
<td>1.1</td>
<td>2.8</td>
</tr>
<tr>
<td>( e_x/e_y )</td>
<td>5/0.25</td>
<td>10/5</td>
</tr>
<tr>
<td>( \beta_x/\beta_y )</td>
<td>11/0.45</td>
<td>22/0.8</td>
</tr>
<tr>
<td>( \sigma_{e_x}/\sigma_{e_y} )</td>
<td>335/15</td>
<td>670/29</td>
</tr>
<tr>
<td>( \sigma_y )</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>cross. angle ( \theta_x )</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>( &lt;\Delta E/E&gt;_{rad} )</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>( P_b ) (2 beams)</td>
<td>14.5</td>
<td>14.5</td>
</tr>
<tr>
<td>( P_{AC} ) (2 linacs)</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>( \eta_{AC} ) (beam)</td>
<td>10.3</td>
<td>10.3</td>
</tr>
<tr>
<td>luminosity L</td>
<td>5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Table 1: New parameters of the S-Band Linear Collider in comparison with the original parameter set

Computer Simulation of Beam Dynamics

The beam dynamics in the S-band linac have been investigated by using the L3 particle tracking code [2]. The following assumptions are made for this study:

- initial alignment tolerances of 0.1 mm (rms) for the accelerating structures, the quadrupoles and the position monitors (BPM's)
- one-to-one orbit correction followed by the “wake-free” correction algorithm [3] to reduce dispersive effects (assumed BPM resolution 5µm)
- beam-based alignment (by measuring the signal from two HOM-couplers per 6m long structure) of accelerating structures w.r.t. the beam orbit with an accuracy of 50µm (rms)
- damping of HOM’s by using the “lossy iris” concept [4]

For the reduced bunch charge, the longitudinal wakefield [5] is sufficient to provide BNS damping so that an rf-phase of zero deg., i.e. on-crest acceleration, is chosen. The correlated energy spread in the bunch is 0.35% in this case, about a factor of two smaller than in the previous design. Thus the parameter change is also beneficial for reducing chromatic emittance dilution from spurious dispersion. At the injection energy of 3GeV, an additional uncorrelated energy spread of 1% is taken into account. The bunch-to-bunch energy spread can be kept smaller than the single bunch energy spread by suitable beam-loading compensation [6] and is neglected here.

The simulation is performed for different values of the HOM quality factors in the range Q=2,000...10,000 using 10 different random seeds for each value of Q. The results for the vertical emittance growth are shown in fig. 1. The “lossy iris” HOM damping concept yields Q-values of 2,000...3,000 and we obtain a relative increase of the emittance of \( \Delta \sigma_y = (20 \pm 10)\% \).

\[ \Delta \sigma_y^2 = A \cdot T \cdot L \]  

(2)

where L is the distance between two points along the linac and T the time. From measurements of orbit motion in HERA [7] we obtain A=10^{-17} m/s as a conservative upper limit. Starting with an ideal machine without alignment errors, the evolution of emittance dilution with time is determined. We find an emittance growth of 6% after 25 min. This means that after finding a “golden orbit” with the WF-method, an orbit correction which steers the beam back to this “golden orbit” has to be applied every 25min. in order to limit the additional emittance dilution to an average of 3%.

The effect of diffusive ground motion on the WF-correction method has also been studied. Since this method is based on measuring difference orbits after changing quadrupole strengths, which will require a certain amount of time, ground motion has the potential to spoil the measurement. We find that the time required for taking the difference orbits should not exceed 100s to avoid significant emittance dilution with the WF-method (see fig. 2).

![Fig. 2: Emittance growth caused by diffusive ground motion with A=10^{-17} m/s during the process of WF-correction as a function of time between orbit measurements.](image)

The results of the beam dynamics study show that the reduced vertical emittance of the new parameter set can be obtained with reasonable alignment tolerances, which, in case of structure alignment, are more than a factor of two relaxed compared to the older version of the S-band parameters. In the studies presented here, empirical minimization of emittance dilution by using orbit bumps (common praxis at the SLC) is not yet included. This provides an additional safety margin in the S-band design.
Consequences for other Linear Collider Subsystems

The change of the beam parameters has a significant impact on the SBLC subsystems such as the damping ring and the final focus system.

The damping ring has to provide an emittance which is reduced by a factor of two in both planes. Fortunately, the original damping ring design [8] is capable of providing the required beam quality. With regard to single bunch instabilities the reduced bunch charge is an advantage. In case a multi-bunch feedback system is needed (this question is under study), the reduced bunch spacing can cause larger bandwidth requirements.

With the reduced bunchlength, stronger requirements for the bunch compressor result, but a single stage compressor device as described in [9] still seems feasible.

The final focus system must provide beta functions at the interaction point which are reduced by about a factor of two. This turns out to be straightforward without any problems concerning the momentum bandwidth. The vibration tolerances are somewhat tighter than for the older design, though. It is planned to use a fast orbit steering device at the interaction point to minimize luminosity loss from transverse beam separation [10].

The concept of dispersive crab-crossing [11] using the correlated energy spread in the bunch becomes more efficient, mainly due to the smaller bunchlength. For a given energy spread and dispersion, the maximum crossing angle which can be compensated scales like $\sigma_z^{-1}$. We make use of this advantage by increasing the crossing angle from 3 mrad to 6 mrad, thus creating more aperture for the outgoing beam, beamstrahlung and synchrotron radiation leaving the interaction region. The residual luminosity reduction due to the crossing angle amounts to about 5% in this case.

Conclusions

It has been shown that with the new parameter set for SBLC, a higher luminosity and at the same time relaxed tolerances can be obtained. The impact of the parameter modification on the overall design has been studied and found acceptable.

References


A 375MW Modulator for a 150MW Klystron at the S-Band Linear Collider Testfacility at DESY

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* on leave from IHEP
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Abstract

The S-Band linear collider testfacility at DESY serves as a testbed for components which will be necessary to build an S-Band linear collider. The testfacility requires two S-Band klystrons operating at 2.998GHz, each producing an output power of 150MW at a pulse duration of 3μs and a repetition rate of 50Hz. The high voltage pulses for the klystrons will be supplied by two line type modulators, which produce pulses of up to 535kV at currents of 700A with a flat top duration of 3μs and a repetition rate of 50Hz. The first klystron-modulator system has been installed and was commissioned at the S-Band testfacility at DESY.

This paper describes the layout and the hardware of the klystron-modulator system. The results of the commissioning of the first system will be presented.

Introduction

Two of the main issues for future linear colliders are klystrons and modulators. They represent one of the major contributions to the total cost of a linear collider and determine to a major part besides other things its reliability and stability. Therefore klystrons and modulators are among the research objects at all linear collider testfacilities around the world.

The S-Band linear collider testfacility under construction at DESY is a 400MeV electron linac with four 6m long accelerating structures [1]. In order to achieve the loaded accelerating gradient of 17MV/m it requires two klystrons operating at 2.998 GHz at an output power of 150MW. In 1993 a collaboration between SLAC, DESY and Philips started to develop and build two 150MW klystrons which could be used at the S-Band testfacility. Two klystrons have been built at SLAC and shipped to DESY until 1995 [2]. A line type modulator has been constructed to test the 150MW klystrons at SLAC [3]. In parallel DESY started to build two line type modulators for the operation of the klystrons at the S-Band testfacility. Therefore both modulators, the SLAC and the DESY modulator, have a very similar PFN unit and pulse transformer tank.

Although it is necessary to investigate alternative techniques for high voltage modulators for future linear colliders, the well established technique of the line type modulator has been chosen for the modulators at the S-Band testfacility. The first reason was, that line type modulators represent the most advanced method to produce high voltage pulses at this power level. The second reason for choosing line type modulators was, that they are of course one possible choice for the generation of pulsed high voltage for the klystrons of a linear collider. Therefore they are still one object of investigation and research. Alternative techniques are also under investigation at DESY in addition [4].

This paper describes the first 375MW line type modulator at the S-Band testfacility at DESY, the requirements, the circuit and the hardware. Results of the commissioning are reported.

The Klystron

Two 150MW klystrons have been developed and built at SLAC. Table 1 shows the design goals and the achieved parameters of the two klystrons.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Tube#1</th>
<th>Tube#2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Out</td>
<td>150 MW</td>
<td>153 MW</td>
<td>150 MW</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>3 μs</td>
<td>3 μs</td>
<td>3 μs</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>60 Hz</td>
<td>60Hz</td>
<td>60Hz</td>
</tr>
<tr>
<td>Beam Voltage</td>
<td>535 kV</td>
<td>527 kV</td>
<td>508 kV</td>
</tr>
<tr>
<td>Beam Current</td>
<td>700 A</td>
<td>680 A</td>
<td>652 A</td>
</tr>
<tr>
<td>Microperveance</td>
<td>1.79</td>
<td>1.78</td>
<td>1.80</td>
</tr>
<tr>
<td>Efficiency</td>
<td>40 %</td>
<td>43 %</td>
<td>45 %</td>
</tr>
<tr>
<td>Gain</td>
<td>&gt; 50 dB</td>
<td>56 dB</td>
<td>57 dB</td>
</tr>
</tbody>
</table>

Table 1
Klystron Parameters

The klystrons require a solenoid, which is made of three independent coils. Two of them are supplied by one common power supply, whereas the third coil around the output cavity is controlled independently by another supply. Typical currents are 42A at 285V and 35A at 45V. In order to achieve zero magnetic field on the klystron cathode a bucking coil is needed. It typically runs at 3A and 4V. The parameters in Table 1, especially the beam voltage and current and the RF pulse duration, determine the modulator requirements. The required repetition rate at DESY is only 50Hz.

The Modulator

The modulator consists of four separate big components, the PFN unit with the pulse transformer tank, the charging unit (CHU), the HV power supply and a control unit. The
basic parameters of the modulator are shown in Table 2. The electrical circuit can be seen in Fig. 1.

<table>
<thead>
<tr>
<th>Parameter</th>
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<tr>
<td>Pulse Current</td>
<td>700 A</td>
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<td>Equivalent Square Wave Duration</td>
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<td>Rise Time 10-90%</td>
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<td>PFN</td>
<td>four lines parallel, each line ten sections</td>
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<tr>
<td>PFN impedance</td>
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<td>Total Capacitance</td>
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<td>Peak Current (primary side)</td>
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<tr>
<td>Pulse Transformer Ratio</td>
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</table>

Table 2
Modulator Parameters

![Fig. 1. Schematic Drawing of the Electrical Circuit](image)

**PFN Unit and Pulse Transformer Tank**

The cabinet of thePFN unit is 1.4 * 1.5m wide and 2.6m high. All components in the cabinet are under air. Each of the four PFN lines consists of 10 capacitors and 10 coils (see Fig. 1). The capacitors (CSI, San Diego, USA) have a capacitance of C=45nF and a voltage rating of 50kV. They are mounted horizontally and connected with one side to an aluminum rack. One copper coil is fastened on top of each capacitor. The inductance is adjustable by changing the tap on the coil and by changing the position of a slug inside the coil. The nominal inductance of one coil is L = 1.3μH. The equivalent square wave pulse duration of the PFN calculated by T=2N(L/C)=4.8μs (N is the number of sections per PFN). The nominal impedance of the PFN is 1.34Ω. The total capacitance is 1.8μF, which gives a stored energy of 2.25kJ at 50kV. In order to protect the klystron in case of arcing an End of Line Clipper (EOLC) is installed in the PFN. It consists of six 20Ω resistors in parallel, a varistor and a diode stack with 28 high voltage diodes in series and varistors in parallel. The mounting rack is connected by a copper line and a feed through to a 1:23 pulse transformer (Stengenes, Palo Alto, USA) in the transformer tank. Two thyratrons (ITT F-303) are installed in the cabinet. The anode side of the thyratrons is connected to a thyratron mounting rack, which is attached to the other copper stripe of the feed through. This copper stripe serves as current return pass from the pulse transformer. A fast voltage divider (30ms risetime) is connected to the capacitor mounting rack. This allows to measure the primary pulse voltage.

Directly connected to the PFN unit is the oil filled pulse transformer tank. It has a diameter of 1.3m and a height of 1.6m. The klystron with its solenoid sits on top of the tank with the klystron gun ceramics in the oil. The design klystron resistance at full power is 764Ω, which together with the step up ratio of the transformer of 1:23 represents a load impedance of 1.44Ω to the PFN. A 1:10000 capacitive voltage divider is connected to the secondary side. A Pearson current monitor allows to measure the gun current. The filament transformer and the blocking coil for the core bias power supply are also installed inside the tank. The interior of the PFN unit is shown in Fig. 2.

![Fig. 2. Interior of the PFN Unit](image)

**Charging Unit**

The PFN unit is connected to the charging unit (CHU) by a HV cable. The CHU cabinet is 1.35 * 1.45m wide and 2.45m high. Inside the cabinet one can find the charging choke (Kirchner, Hamburg, Germany) with an inductance of 16H. This inductance together with the total PFN capacitance of 1.8μF gives a charging time of 17ms. The maximum charging current is 9A. 36 high voltage diodes, two times 18 parallel diodes in series, serve as charging diode. A despiking network made of chokes and resistors is connected to the cable to the PFN. The charging choke has a secondary
winding. This allows to install a deQing circuit in the charging unit, if better pulse to pulse regulation of the charging voltage might be necessary.

**HV Power Supply**

The HV power supply is a commercial power supply (Heinzinger, Rosenheim, Germany) with the dimensions 1.4 * 1.85m wide, 2.25m high. It has an output voltage of 26.5kV max. at a maximum average current of 5A. The supply has an SCR controller, which leads to a stability of the voltage better than 1%. The power supply can be controlled locally or remotely via a GPIB interface.

**Control Unit**

All the controls are installed in four 19” racks of 2m height. The modulator can be operated locally from this unit. Inside the racks one can find the heater supplies for the thytratrons and the klystron, the vacion and bucking coil power supplies, the control unit for the core bias power supply, scopes, trigger generators, monitors and printers. One 19” rack is reserved for a programmable logic controller (Siemens S5-135U). All technical components of the klystron and the modulator are interlocked by the PLC. In addition temperatures, flows and pressures are recorded by the PLC. The PLC is connected to a SUN workstation via profibus, which will make it possible to operate the modulator remotely from the SUN workstation. The cycle time of the PLC program is less than 20ms. In case one component fails the modulator could be shut off pulse to pulse. The additional personal interlock is made by a relay unit.

**Commissioning and Operation**

The first tests of the klystron and modulator were done without applying drive power to the klystron. Operation started at a low repetition rate of 10Hz and short pulse width. For this purpose five capacitors per PFN line were removed. This resulted in half of the full pulse width. The klystron was brought up to more than 500kV without problems. After it drive power was applied to the klystron. Two waterloads, each capable of 75MW, had been installed on the two output waveguides of the klystron. It took in the order of two hundred hours to improve the vacuum conditions in the waveguide of the waterloads before 150MW at 1.2μs and 50Hz repetition rate were achieved. The maximum beam voltage was 550kV at 700A. After it all capacitors were installed. Conditioning started again with low repetition rate, but full pulse width. As oscillations had been observed in klystron #1 at certain voltage levels and magnetic field settings during testing at SLAC, commissioning at full pulse duration needed to be done very carefully. It is necessary to adjust the magnetic field very carefully each time one increases the beam voltage. In addition the vacuum conditions in waterloads limited the speed of conditioning.

Almost 150MW at 3μs have been reached. Fig. 3 shows typical waveforms at this level. The 10 to 90% rise time is 700ns and the flat top duration 3μs as required. Up to now no efforts have been made to improve the flatness of the pulse top. This will be done in the next step by adjusting the inductance of the PFN coils.

**Outlook**

It is planed for the next steps to bring the klystron up to full power at 50Hz repetition rate and to smooth the pulse top. The remote control of the system will be tested in addition. After it the waterloads will be removed and an accelerating structure will be installed and conditioned.

A second modulator is under construction. It is planed to start with the operation of the second system at the beginning of next year.

**Acknowledgments**

The authors would like to acknowledge the support of S. Gold and D. Sprehn of SLAC. Thanks for many helpful discussions.

**References**

PERFORMANCE OF THE FIRST PART OF THE INJECTOR FOR THE S-BAND TEST FACILITY AT DESY

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I. Abstract

The injector for the S-Band Test Facility at DESY is based on a conventional design. Equipped with a gridded cathode a 90kV thermionic gun produces 2µs long multibunch trains with a repetition of up to 50Hz. The micropulses have a FWHM-length of less than 2.5ns containing a maximum charge of about 10nC (6.25×10^9 e^-). For the purpose of wakefield related studies the interbunch spacing can be varied between 8ns, 16ns and 24ns, while keeping the average beam current within the bunchtrain constant at 300mA.

The bunching will be done by means of two single cell stainless steel buncher cavities running at 125MHz (1/24 subharmonic) and 500MHz (1/6 subharmonic) followed by two S-band travelling wave structures with different phase velocities.

Since summer 1995 the injector beamline is assembled up to the 500MHz buncher as shown in figure 1. Four wall current monitors, three button-type position monitors, a fluorescent screen, a multihole aperture for the purpose of emittance measurement and a faraday-cup at the end serve as diagnostic tools. Emphasizing on the bunching behavior, results from the operation of this first part of the injector will be presented and compared with predicted results from simulation codes.

II. Introduction

The S-Band Test Facility currently under construction at DESY investigates the feasibility of a large S-Band Linear Collider (SBLC) project. Delivered by an injector the beam will be accelerated by 4 (β=1, 2π/3-mode, 17MV/m) traveling wave sections of 6m length each, intersected by 3 quadrupole triplets and fed by two 150MW/2µs S-band klystrons. Before being dumped at the end of the 40m long test facility the quality of the 400MeV/c beam will be measured using a spectrometer beamline including an OTR screen.

The SBLC-design is based on the same bunchtrain structure and current as used in the test facility except for the interbunch spacing. This value has been recently changed in the SBLC-parameterizer from 16ns to 6ns giving a reduced bunchcharge with looser tolerances in the main linac. From this point of view the test facility runs under more severe operation conditions. Before entering the first section of the testlinac the bunches have to be shorter than FWHM=16°/10m=14.8ps and sufficiently relativistic with E_{beam}≥3MeVβ≥0.99. This guarantees a corresponding energy spread of less than ±0.5% and no further longitudinal dynamics in the accelerating sections.

Based on these requirements the injector was designed on a conventional scheme by means of EGUN and PARMELA calculations [1]. Nevertheless it is a step into a challenging operation domain due to the combination of high bunchcharge and short interbunch spacing. The pulses are generated at a thermionic gun and compressed by means of two standing wave subharmonic bunchers SHB1 (125MHz/34kV) and SHB2 (500MHz/36kV) as well as two travelling wave structures (β=0.6, 4cell, 2π/3, 7MV/m and β=0.95, 16cell, 8π/9, 12MV/m). The latter one serves also for acceleration. Two 7MW klystrons will be used to supply both travelling wave bunchers individually. A low group velocity is necessary to build up the high gradient in the 16cell structure with only 7MW. Therefore the 8π/9-mode was chosen. Starting with a 90kV gunpulse carrying 12nC (7.5×10^9 e^-) in a FWHM-bunchlength of 2.5ns, PARMELA simulation predicts a compression by a factor of more than 250 to a pulse length shorter than 10ps with a transmission of better than 95%.

The injector hardware will be built up following the direction of the beam. In this process intermediate setups are used in order to commission major parts of the components. In the first half of 1995 a short beamline was installed for gun commissioning [2]. A short review of the results is given in section III. In the next stage the injector was expanded by including SHB1 and SHB2 as can be seen in figure 1. Starting at the gun anode at z=0cm the beamline ends 219.3cm further downstream with a faraday-cup. The gap centers of both SHB’s are sitting at z=75cm and z=191cm.

Since tuning concentrates on transmission and bunchlength most important diagnostic tools are 3 wall-current monitors 31.6cm behind the gun (CM1), 45cm behind SHB1 gapcenter (CM2) and 13.8cm behind of SHB2 (CM3). 4.8cm downstream of every CM button-type position monitors (BPM1,2,3) are installed. Transverse beamprofile can be

Figure 1: Setup of first part of the injector
measured at $z=146.3$ cm with a fluorescent screen. Together with a multihole aperture (pepperpot), 86.7 cm upstream of the screen, emittance measurement is possible and will be discussed in section IV. Instead of the screen a mirror can be put in at the same place offering the possibility of inspecting irregularities at the heated cathode while not pulsing the gun.

Getting shorter, the beam pulses are transversely focused by means of a longitudinal magnetic field created by solenoids AF4-AF12. With a level of 100 Gauss around SHB1 the field strength increases up to about 1000 Gauss at the end of the beamline. Matching the beam coming from the gun is done by AF2 and AF3. The first solenoid AF1 centered at $z=0$ is powered reversely and used to compensate the magnetic field at the cathode as good as possible.

In addition 3 corrector dipoles in both planes, each 25 cm long with a maximum field of 20 Gauss, located behind the gun, behind SHB1 and in front of SHB2 are used to compensate orbit distortions and alignment errors. One has to keep in mind, that the resultant displacement of the beam depends on the strength of the longitudinal field $B_z$, since both the corrector field and $B_z$ add like perpendicular vectors.

Pumping is done at the gun and both SHB's by means of large 400-l/s getter pumps. A vacuum valve (V1) at $z=43.9$ cm can separate the gun vacuum from the upstream system. The aperture of the whole system has a diameter of 35 mm, except at the gun, where the hole in the anode measures only 20 mm in diameter. This setup was operated from autumn 1995 until end of June 1996. Bunch compression results are presented in section V.

### III. Bunchtrains from the Gun

Production of 2 ns long bunchtrains with 300 mA average current as required. The single bunch FWHM-length has to be less than 2.5 ns in order to be cleanly accepted by SHB1. Depending on the chosen interbunch spacing the single bunchcharge has to be at least:

1) $2.4 \times 10^{-11}$ C at 8 ns spacing and 250 bunches/train
2) $4.8 \times 10^{-11}$ C at 16 ns spacing and 125 bunches/train
3) $7.2 \times 10^{-11}$ C at 24 ns spacing and 83 bunches/train

These bunches are produced at a 90 kV thermionic gun operated at air and equipped with a gridded cathode of the EIMAC Y796 type. The gun geometry was modelled with the EGUN code. At a 34 mm cathode anode distance it results in a calculated pereance of $0.22 \mu A/V^2$. At 90 kV this is equivalent to 6A spacecharge limited current, which was experimentally proven when driving the gun with a testpulsed that creates $\mu$s-long single pulses.

Extraction of bunchtrains consisting of short pulses is achieved by means of a special pulsar that is housed inside the 240 cm long gunceramic closely to the guncathode. The input pulse is amplified with a three stage triode circuit interconnected by ferrite loaded coaxial transformers in which the third triode with its anode directly connected to the guncathode operates in a current source mode. Supplying the pulsar input with 2 ns wide pulses of 60 V peak and the desired time structure the gun produces the required bunchtrains. Measured at CM1 (see fig. 2a) the beam pulses have a FWHM-length of typically 2.2 ns, a subnanosecond risetime and a peakcurrent of up to 4.5 A, which is less than the gun capability, since it is limited by the current output of the last triode stage. Nevertheless the bunches carry a charge of about 10 nC ($6.25 \times 10^{-10}$ C) giving a 40% safety margin with respect to 7伦C as desired in 24 ns mode.

The amplitudes of all bunches as measured at CM1 are stable within less than 4% over the whole bunchtrain in 24 ns mode. The same stability is achieved at 16 ns or 8 ns operation except at the beginning of the train. In the 16 ns mode the first pulse has a 15% increased amplitude and in the 8 ns mode there is a drop down to 70% over the first 3 pulses after reaching equilibrium level. This effect can be explained by saturation of the interstage transformer cores, which can not relax totally when pulse spacing is getting shorter. Since the required bunchcharge is inversely proportional to the interbunch spacing the safety margin is even higher at 16 ns or 8 ns operation.

For the S-Band Test Facility this scheme of bunchtrain production has been successfully commissioned and fulfills all the requirements in terms of time structure, bunchcharge as well as stability of intensity and timing. Not being tested yet it may even work in 6 ns operation mode as proposed for SBLC. If not applicable a resonant driving circuit for the gun can be used for this purpose.

### IV. Emittance Measurement

At $z=59.6$ cm a pepperpot can be driven into the beamline. It is made from a 5 mm thick copper plate drilled with 0.4 mm holes on the vertical, horizontal and both diagonal axis in a radial distance of every 2 mm starting from the center hole. These holes define the position of the beamlets. Their angular width can be calculated from the corresponding spot size at the screen, which is located $l=86.7$ cm further downstream. From both informations the emittance at the position of the pepperpot can be derived. For simplicity in most applications a drift space is chosen between pepperpot and screen [3].

Unfortunately the large getters create a transverse magnetic strayfield of the order of 2 Gauss at the beam axis, which totally prevents transmission between pepperpot and screen without any solenoidal field. Thus the emittance measurement was made within a longitudinal magnetic field $B_z$ [4]. If $B_z=constant$ the transfer matrix of a solenoid with length $l$ can be applied. Unity matrix is achieved when $k=1/2=n\pi$, with $k=e-B_z/p$, $n=1,2,...$, electron charge $e$ and beam momentum $p$. In case the screen shows a 1:1 picture of the pepperpot but the information on the beamlet angles is not accessible. If $k=1/2=(n+1/2)\pi$ all the elements of the transfer matrix are zero, except the ones on the secondary diagonal. In this case the screen looks at the focal plane, i.e. angles at the pepperpot are translated into displacements at the screen. With $n=1$ corresponding to $B_z=114.5$ Gauss emittance measurement was made in the test facility. From the horizontal (vertical) width of the spot size at the screen the vertical (horizontal) angular width of the corresponding beamlet at the pepperpot was derived. Particular attention has to be paid on the right correspondence, since the transverse plane is rotated by 90° around the z-axis in this situation. When moving the pepperpot horizontally the picture on the screen moves vertically. Measuring the area $F=\rho \gamma \delta_{mm}$ of the reconstructed x-y phase space gave a normalized rms emittance $\delta_{mm}$ of about 3-5 mm-mrad at the position of the pepperpot. Since this value was not corrected for additional effects contributing to the spotsize like spacecharge and finite pepperpot hole diameter, it can be regarded as an upper limit of the emittance.

The typical bunchcharge during this measurement was 7 nC, resulting from a 2 ns gunpulse of 3.5 A peak. Starting with 1.8 nC-mm-mrad at the gun exit the PARMELA predicted normalized rms emittance at the pepperpot is 6.6 nC-mm-mrad.
for a bunchcharge of 7nC. The input parameters for the PARMELA simulation were derived from EGUN calculations with a spacecharge limited current of 6A and absence of magnetic field over the whole gun area. The simulations do not represent the experiment very well which might be one reason for the discrepancy of more than a factor of 2.

V. Bunching Performance

According to PARMELA calculations SHB1 and SHB2 have to run at a gapvoltage of 34kV and 36kV respectively. In that case the program predicts a bunch of 200ps FWHM-length at the position of CM3. This bunch can be cleanly observed through the electron scaling wave S-band buncher with its first cell centered at z=215cm. The time of arrival of the bunch at CM3 changes when the rf-phase is varied in SHB1 or SHB2. From these measurements the gapvoltage U, an information on the absolute phase setting with respect to the beam and together with the measured power P flowing into the cavity the absolute shunt impedance \( R_s = U^2/(2P) \) was experimentally determined. The quality factor \( Q_0 \) was measured with a spectrum analyzer. The results as shown in Table 1 agree within 10% with MAFIA calculations.

Combining phases and amplitudes of both SHB’s a bunch of 300ps FWHM-length with 26A peakcurrent giving 7.8nC was achieved at CM3 (see fig. 2b) for a typical gunpulse (2.2ns/4.5A) of about 10nC. Four 50Ω resistors are soldered across the ceramic gap of CM3. Together with the gapcapacitance an upper frequency limit around 1-1.5GHz was estimated by the design engineer of this monitor. Combined by a 4 to 1 circuit of 2 GHz bandwidth (bw) the monitor signal is guided by a 12m long 7/8'' air dielectric flexwell coax-cable with a 3db bw of 5GHz on to a 6GHz oscilloscope (Tektronix TDS 684B). Taking into account the measured cable attenuation of 0.8db at 1GHz, which is around the fundamental for a 300ps pulse, the charge transfer of CM3 is better than 85%. As a result of the bandwidth limits, mainly at the monitor itself, a pulse shorter than 300ps is not measurable. The answer whether the real bunchlength agrees with the expected 200ps will be given in the next stage of the injector extended by the S-band buncherstructures. As expected the phases of both SHB’s have been set within 5° around zero crossing. Running at 30kV the SHB1 amplitude agreed fairly well with the predictions, but SHB2 operated at 52kV instead of the expected 36kV.

Without further measures the transmission and bunching is only valid for the first pulses in the bunchtrain, since the following ones are affected by amplitude and phase changes in the cavities due to beamloading (see fig. 3a). Neglecting its decay the beam induced voltage (\( U=\alpha R/Q \)) after half of the 2μs bunchtrain with 300mA average current has passed the cavities has risen up to 19kV in SHB1 and 95kV in SHB2. Starting with the design amplitudes a phase change of 30° respectively 70° appears in SHB1 and SHB2. The amplitudes will change from 34kV to 39kV respectively from 36kV to 102kV. These variations can be compensated when feeding an external signal of optimized shape, amplitude and timing into the phase and amplitude control circuits of both rf-transmitters. After having carefully adjusted this feedforward system all 83 bunches in 24ns mode are comparable to the first one within 5% peakcurrent and 10% bunchlength variation seen at CM3 (see fig. 3b). Nevertheless more detailed studies are necessary to improve the influence of the feedforward especially at the 500MHz system where it has to fight against large amplitude and phase changes.

VI. Summary

The first part of the Injector for the S-Band Test Facility including the gun and two subharmonic buncher cavities (SHB) was successfully commissioned. The gun produces 2μs long bunchtrains with different interbunch spacing. Each single pulse with a 2.2ns FWHM-length carries up to 10nC of charge. Measured with the peperpot technique inside a constant solenoidal field the normalized rms-emittance was 3-π-mm-mrad being a factor 2.2 smaller than expected. Optimized for bunching the gapvoltages differ from PARMELA predictions by -12% in SHB1 and +44% in SHB2. They were measured by a time of flight method taking advantage of the 90kV nonrelativistic beam. 200ps long pulses are expected after compression by both SHB’s. Bandwidth limited by the wall current monitor 300ps long signals and a transmission better than 85% were observed. Otherwise heavily affected by beamloading a feedforward-system keeps the cavity parameters almost constant over the whole train of pulses.

VII. References


Temperature stabilisation of the accelerating structure

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Abstract

An important issue for the operation of a Linear Collider with heavy beam loading is the temperature stability of the accelerating structure. The phase and energy error is a function of the temperature distribution on the surface of the accelerating structure. Calculations prove, that keeping the temperature constant at a specific point on constant gradient accelerating structure minimises the energy error. This will be used for a feedback system. The temperature at this point is a function of the inlet water temperature, the average RF-power and the beam loading.

Temperature Distribution

An important issue for the operation of a Linear Collider with heavy beam loading is the temperature stability on the accelerating structure. The heat source is the difference of the total input power and the power extracted by beam loading. This difference can be calculated as the vector sum of the accelerating voltage and the beam loading. The shunt impedance, the attenuation, the repetition rate and the pulse length are additional parameters. The phase error itself is a function of the temperature distribution calculated by this difference voltage. It is a function of the wavelength, the group velocity, the thermal expansion coefficient and the temperature difference between the steady-state situation and the instantaneous average temperature at every point on the surface [1].

The taper of the group velocity is linear and its value at the inlet side is \( \approx 4\% \) and at the outlet side \( \approx 1.3\% \) of the velocity of light. The temperature rises almost linear, but the temperature distribution on the surface is not.

In order to calculate this temperature distribution the following assumptions were made:

- the heat flow over the circumference is at every point the same
- because of the symmetry only 1/8 of the geometry is calculated
- the temperature gradient over the thickness has been neglected
- the water inlet and outlet are on the same side as the beam input (counter flow)

The following picture shows the average temperature between the cooling tubes.

Fig. 1: Distribution of the surface temperature

- curve 1: no beam
- curve 2: beam current 100 mA
- curve 3: beam current 200 mA
- curve 4: beam current 300 mA

The temperature at the surface rises along the length of the structure in absence of beam current. With increasing beam current the power which is dissipated along the structure decreases. Therefore the heat flow into the water is lower at the end of the structure than at the beginning. This effect is more pronounced with increasing beam current. Because the heat flow from the surface to the water is a function of the temperature difference between them, the surface temperature increases at first and then decreases along the length with increasing currents.

The strong gradients on both ends are produced by the heat flow into the tubes and in addition the return of the water at the end.

The temperature distribution in a 3D-plot is shown in the next picture. The beam current is 300 mA.
the temperature remains constant with varying beam or RF power, and varying inlet water temperature for compensation.[2]

![Graph showing temperature distribution over length](image1)

Fig. 2: Distribution of the surface temperature
beam current 300 mA

The next picture shows the phase error caused by the temperature distribution from figure 1. The temperature for the steady-state system was arranged to be 40 °C with a constant temperature at the inlet.

![Graph showing phase error over length](image2)

Fig. 3: Integrated Phase error along the section
curve 1: no beam
curve 2: beam current 100 mA
curve 3: beam current 200 mA
curve 4: beam current 300 mA

The integrated phase error turns into a beam energy error along the structure length. This energy error on the other hand can be minimised by changing the inlet water temperature unless the integrated phase error is zero, which is always possible because positive and negative phase deviations appear along zero. Calculation shows that at a specific point

![Graph showing surface temperature with optimised inlet water temperature](image3)

Fig. 4: Surface temperature with optimised inlet water temperature in order to cancel the sum of the single cell phase error towards the end of the structure
curve 1: no beam
curve 2: beam current 100 mA
curve 3: beam current 200 mA
curve 4: beam current 300 mA

Cooling circuit

There are two layouts for the cooling circuit of the linac:
The first one is for the test-facility. The main demand for this cooling circuit was the high temperature stability over a large range of power deviations.[3]
The second is for the overall layout. The main demand here was to have a simple cooling system with only a few elements but flexible power handling capabilities

For the control of both systems the same elements will be used:
the temperature is measured by a sensor at the specific point, the temperature of the inlet water and the RF-power difference between the input and output. The last one will be used for a fast feedback system: with beam loading a definite input temperature is required and therefore it is possible to change the inlet water temperature before the surface temperature changes. The time available to do this depends on the water flow and the heat capacity of the structure and is about two seconds. Therefore in both systems a hot and a cold line is required and the required temperature is mixed by fast pneumatic mixing valves.
At the test-facility the solenoid of the klystron is used as the main heat source for the hot line and for the power reduction (cool line) a heat exchanger. The rectangular waveguides have a similar control system. The scheme is presented in the next picture.

Fig. 5: Outline of the cooling system for the test-facility

For this circuit a simulation [4] was made (without the feedback-system): the power in the section and in the waveguide was reduced by a factor of five (this means e.g. changing the repetition frequency from 50 Hz to 10 Hz). The next picture shows the result:

Fig. 6: Temperature of the surface by changing the repetition frequency from 50 Hz to 10 Hz
curve 1: accelerating structure temperature
curve 2: waveguide temperature

For the Linac Collider the klystron collector is used as a main heater source. It isn’t possible to connect the heater with the supply water tube because the water flow wouldn’t be enough for cooling the section. Therefore it is connected with the return water tube and so a booster-pump is needed. The next picture shows such a possibility using only a few elements but on the other hand not applicable for a large range of power changes.

Fig. 7: Outline of the cooling system, overall layout

For this circuit a simulation was also made without the advantages of the feedback-system for the control. The next picture shows the inlet water temperature into the structure and the structure temperature when the power into the structure and klystron is reduced to a third of the previous value.

Fig. 8: Temperatures by changing the power into the structure and klystron

References

Positron Production for the S-Band and TESLA Linear Colliders

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Abstract

Future linear colliders require positron sources with intensities up to two orders of magnitude higher than the existing ones. This would be very difficult to realize with conventional sources. A more reasonable way is to use photons generated in a wiggler or a superconducting helical undulator which are converted into positrons in a thin target. In order to ensure the passage of the beam through the wiggler or undulator without mechanical damage and to provide a small radiation spot size of the photons on the target, the horizontal and vertical emittances are limited. For economical reasons it is advantageous to use the disrupted high energy electron beam after the collision to generate the photons. The demands on the emittance and the specific beam properties after the interaction region (IR) require a careful handling in the following capture optics for both the TESLA and the S-Band linear collider.

It has been found that it is rather simple to fulfill the requirements on the unpolarized positron source for both linear collider schemes. The realization of a polarized source for TESLA is more difficult but possible whereas the polarized source for the S-Band linac is still under study.

Introduction

Based on the idea of V.E. Balakin and A.A. Mikhailichenko [1] the concept to realize a high intensity positron source using the disrupted electron beam has been worked out by K. Flöttnan [2]. It has been shown that a 35m long planar wiggler is sufficient to produce the photons for the unpolarized source, while the polarized positron source needs a 120m long superconducting helical undulator. From aperture limitations in these devices the captured spent beam has to fulfill certain emittance requirements.

An additional constraint exists for the polarized positron source. Analytical calculations (see [2]) of higher harmonics of undulator radiation show that the emitted photons have different polarization properties related to the angle of emission with respect to the electron path through the undulator.

For using the circular polarized radiation on the target it is not only important to focus the electron beam such that the emitted photons hit the target in a certain area. It also has to be ensured that no mixture of photons with different spin orientations dilutes the polarization of the positrons.

The requirements on the emittances from ref.[2] are shown in tab.1

<table>
<thead>
<tr>
<th></th>
<th>hel. undulator</th>
<th>wiggler</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e_x/\text{rad} \cdot \text{m} )</td>
<td>(5 \cdot 10^{-10})</td>
<td>(1 \cdot 10^{-8})</td>
</tr>
<tr>
<td>(e_y/\text{rad} \cdot \text{m} )</td>
<td>(5 \cdot 10^{-10})</td>
<td>(6 \cdot 10^{-9})</td>
</tr>
</tbody>
</table>

Table 1: Maximum tolerable beam emittances for the planar wiggler and the helical undulator.

---

Figure 1: Distribution of energy deviation of the disrupted beam for the TESLA linear collider.

---

The beam after the IR

Due to the very strong beam-beam force the particles perform oscillations around the beam axis during the bunch crossing. The particles are receiving kicks depending on the relative displacement of the orbits. This effect, called disruption, causes a broadening in the angular distribution after the IP. The beam size remains nearly constant or even decreases due to the focussing pinch effect.

The oscillating particles emit high energy synchrotron radiation (so-called beamstrahlung). This statistical process causes a broad energy spread of the disrupted beam.

---

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Table 2: 

<table>
<thead>
<tr>
<th></th>
<th>S-Band</th>
<th>TESLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_x/\beta_y$</td>
<td>3.10/0.34</td>
<td>6.06/0.66</td>
</tr>
<tr>
<td>$\sigma_x/\sigma_y$</td>
<td>1.88/0.49</td>
<td>1.94/0.93</td>
</tr>
<tr>
<td>$\varepsilon_{x/\varepsilon_{xy}} \text{m-rad} \cdot 10^{-15}$</td>
<td>34.5/0.88</td>
<td>113.0/1.2</td>
</tr>
<tr>
<td>$\sigma_{x/\sigma_{xy}} \text{mm}$</td>
<td>326/17.2</td>
<td>626/28.6</td>
</tr>
<tr>
<td>$\Delta E_{\text{mean}} \text{ }%$</td>
<td>2.76</td>
<td>3.15</td>
</tr>
</tbody>
</table>

Beam properties behind the IR for the S-Band and TESLA linear collider

and a mean energy loss of the order of 3.0% of the initial energy. A non negligible part of the beam has lost more than 10% energy.

Fig.1 shows the energy distribution after the interaction for TESLA. The energy distribution for the S-Band linac looks similar.

For all investigations a data set of roughly 12000 particles was created with a beam-beam simulation program by R. Brinkmann [3] using the parameters at the interaction point for the TESLA [4] and S-Band linear collider [5]. Tab.2 shows the beam properties behind the interaction.

The spent beam separation

The disrupted electron beam leaving the IR must be separated from the oncoming positron beam to avoid parasitic interactions.

The bunch spacing of 212.4 m for the TESLA linear collider allows to separate the beams over a long distance. Therefore a crossing angle is not needed. The spent beam is focussed by the FFQ doublet for the oncoming beam.

An electrostatic separator is proposed to extract the spent beam from the oncoming beam line. The separator consists of electrostatic and magnetic deflectors combined in the same unit to provide deflection of the outgoing beam and not to effect the incoming beam [6].

Since the vertical emittance after the interaction is about two orders of magnitude smaller than required, it is sufficient to compensate only the horizontal chromaticity.

Boundary conditions for the design

For a most cost efficient way of integrating the positron source into the collider layout, the collimation system and the radiation production device with the target and the following positron capture optics has to fit into the tunnel of the oncoming positron beam.

The chromatic effects which would increase the emittance by three orders of magnitude have to be compensated by a chromatic correction system (CCS).

Even with an optimized achromatic system it is not possible to transport the whole beam from the IR on through the capture optics and afterwards through the wiggler or undulator. Thus the low energy tail of the beam has to be collimated.

To fulfill the demands on the emittance the spent beam has to be separated from the oncoming beam as smoothly as possible to avoid emittance growth due to quantum fluctuations.

Methods

To investigate the feasibility of the positron source for the TESLA and S-Band linear collider a tracking code which simulates the beam transport including the quantum emission was set up.

The tracking step width was chosen such that the average number of the emitted photons per step was much smaller than one. Then the process of photon emission follows the Poisson distribution and the probability of radiating more than one photon per step was low.

To consider the geometrical boundary conditions a program was developed which allows to study both the beam optics and the geometry of the capture system with regard to the oncoming positron beam line.

The chromatic fit was done taking into account the asymmetric energy distribution and the phase space distribution after the IR. During the interaction the particles on axis are not deflected by the oncoming beam. The deflection increases with the distance to the bunch center due to the net coulomb force. After a maximum has been reached, the kick strength decreases with increasing distance. Thus the horizontal phase space exhibits an S-shape.

The goal energy bandwidth of the CCS was divided into 10 intervals. For each energy a set of 9 test trajectories was created representing the initial phase space distributions.

Each trajectory was supplied with a weight factor to represent the energy spectrum and two weight factors representing the phase space densities of the complete ensemble.

The chromatic aberrations by optimizing the sextuple strengths in the beam line such that the effective emittance at the end of the CCS was minimized.

Results for the TESLA linear collider

An optical system has been developed which fits the boundary conditions of the tunnel geometry (see fig 2).

After tracking all particles through the capture system the emittance as a function of the energy deviation was estimated. So it was possible to find out the particles which had to be collimated along the beam line to fulfill the emittance requirements.

The remaining beam after the collimation has been focussed providing a small radiation spot size on the target and avoiding that particles hit the wiggler or undulator, respectively.

It has been found that 83.2% of the particles can be captured to produce radiation for the unpolarized source in a 35 m long wiggler.

A polarized source using radiation produced in 120 m long superconducting undulator with an aperture of 2.5 mm can be realized using up to 61.7% of the initial spent beam.
As worked out in [2] a capture efficiency of 70% of the spent beam would fulfill the demands on the positron production rate with a safety factor of 2. Hence both positron sources are feasible for the TESLA linear collider.

![Graph](image)

Figure 2: Beam line for the disrupted beam with the 120 long undulator (lower branch) and the oncoming positron beam (upper branch) for the TESLA linear collider [7]. At the end of the capture optics the separation is 1.3 m.

**Peculiarities for the S-Band linear collider**

For the S-Band collider the bunch spacing of 6ns would cause a parasitic interaction with the oncoming beam after 0.9 m. To protect the oncoming from the disrupted beam and from the high power beamstrahlung a crossing angle of 6 mrad is foreseen.

Thus the disrupted beam after the IR enters the final focus quadrupoles (FFQ's) for the oncoming positron beam about 12 mm displaced from the axis in the pole tip region. The magnetic field in this region has higher order multipole terms which cause an additional increase of the horizontal emittance due to geometric aberrations.

The field was analysed and the particles were tracked through it.

It has been found that 83.4% of the spent beam at the end of the horizontal and vertical achromatic section fulfill the emittance requirements for the unpolarized source.

The polarized positron source for the S-Band linear collider is still under study.

**Conclusion**

It has been shown that both positron sources can be realized for the TESLA machine. The capture efficiency for the polarized source could even be increased by changing the horizontal β-function at the IP by a factor of 2. This would cause a luminosity loss only by a factor 1/√2 but the efficiency would rise up to 85 - 90%.

For the S-Band linear collider it is possible to drive the unpolarized source taking the beam after the FFQ's only with a chromatic correction of the downstream optical elements.

To realize the polarized source a multipole analysis of the FFQ fields along the path of the disrupted beam through it and a following correction of their influence looks very promising.

**References**


OTR MONITOR FOR ATF LINAC

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Abstract

A bunch by bunch profile monitor system using optical transition radiation (OTR) is developed for an Accelerator Test Facility (ATF) linac. The ATF consists of a 1.5 GeV linac and a damping ring is now under constructing in KEK. The linac accelerates a multi-bunch beam (20 bunches/pulse, $2 \times 10^{10}$ electrons/bunch, 2.8 ns spacing between bunches). The energy spread of the multi-bunch caused by the transient beam loading is a significant problem for the injection of the damping ring. The linac has energy compensation system to compensate the energy spread of the multi-bunch. In order to measure the energy and energy spread of each bunch, we developed the monitor system. The system and the measurement result are reported.

Introduction

The Accelerator Test Facility (ATF) consists of a 1.5 GeV linac and a damping ring (DR) is now under constructing in KEK. The DR is designed to realize a small vertical emittance, $\varepsilon_{y} = \sim 30$ nm, for future Linear Collider. The commissioning of the ATF linac had been started from November 1995 and the commissioning of the DR will be started at the end of this year. The linac accelerates multi-bunch beam. The beam has 20 bunches of $2 \times 10^{10}$ electrons with 2.8 ns spacing. In order to reduce the energy spread of the multi-bunch beam, due to the transient beam loading, Energy Compensation System (ECS) were installed and the preliminary experiment was carried out [1].

The measurement system of the energy and the energy spread of each bunch is needed for tuning the ECS. The optical transition radiation (OTR) monitor was already developed for the 80 MeV injector section [2]. The OTR is emitted when the charged particles go through the interface which have different dielectric constants. The polished stain less steel was employed as the emitter for the OTR monitor. A fast gate camera (Hamamatsu C2925) is used for observed the bunch by bunch profile in the multi-bunch beam when apply the gate signal to each beam timing. This monitor could measure the beam emittance, energy and energy spread of each bunch at the 80 MeV injector section. The OTR monitor at 1.5 GeV section is designed and tested for the above purpose. The spot size limit of the OTR monitor according to $\sim \gamma \lambda/2 \pi$ [3]. At 1.5 GeV section, the spot size limit is 0.24 mm for 500 nm wavelength. This value is assumed that is not so affected the beam size measurement. Recently, the spot size limit was discussed and tested [4, 5].

OTR monitor system

The monitor setup is shown in Fig. 1. The OTR monitor is located at the downstream of the first bending magnet and the first quadrupole magnet of the beam transport line. The position deviation at the place is calculated by

$$\Delta x = \pi \frac{\Delta E}{E}$$

where $\pi$ is the dispersion function.

![Diagram of OTR monitor system]

From the actuator, fluorescent screen, OTR screen, Mirror, Half Mirror, Coated camera, the current transformer, wall current monitor, the OTR monitor is observed by the gate camera. Both profile by these monitors can compare each other.

Trigger control and video analyze system

The control system of the gate camera is shown in Fig. 2. The gate camera can observed the bunch by bunch beam profile when apply the appropriate gate width and timing. The timing signal is created from the beam trigger. The signal is delayed in 2.8 ns step and met to each beam timing by the delay module. The delay module makes delay by count the reference clock from start signal. The reference clock is synchronized to the accelerating frequency. The trigger jitter of the delay module is less than 10 ps. The fine delay C1097 (Hamamatsu) adjusts the gate timing to the center of the beam timing. The
pulse generator 8112A (H.P.) makes the gate width included offset of -16.5 ns. The gate pulse of 3 ns is applied when the pulse with 19.5 ns pulse width is generated by the pulser. The 8112A and the C1097 are controlled by sub-control computer (PC) thorough GPIB.

![Control computer diagram]

Fig. 2. Trigger system of the gate camera.

The video signal of the gate camera is fed to the operator room through CATV and analyzed by the video analyzer using a work station. The analyzer calculates x- and y-direction of the projection and the fwhm, the peak position, the peak value, etc., in real time. The automatic data acquisition system from Accelerator control computer (VAX VMS) is under development.

**Gate characteristics**

The characteristics of the gate camera is measured by using the beam signal. The gate timing is scanned with 250 ps step. The intensity of the profile is intensified and eliminated by the gate timing. The characteristics is plotted in Fig. 3. There is a dip between the previous bunch timing and the next one. This means that the gate camera is distinguishable the profile between the previous bunch and the next bunch. The appropriate gate timing is decided from this data.

**ECS experiment**

**ECS system [6]**

The ATF linac uses 18 accelerator structures of S-band frequency. 16 regular sections which uses 2856 MHz and two compensation sections which uses 2856±3.3 MHz. At the regular sections, the first bunch feel the maximum field of the cavity and the following bunches feel the reduced field caused the transient beam loading effect. At the compensation sections, each bunch feel the field of the different phase of the cavity. The phases of compensation sections are synchronized the beam from decelerate phase (first bunch) toward to accelerate phase (20 the bunch). The compensation effect is adjusted by changing the power of compensation section and the relative phase of regular sections and compensation sections.

![Characteristics of first gated camera(C2925)]

Fig. 3. Gate characteristics of the gate camera.

**Relative phase and energy gain measurement**

The relative phase and the power of the compensation sections were measured by scan the phase of the compensation sections. The profile center of one of the bunches measured by the OTR monitor were plotted in Fig. 4. The deviation from fitted value is come from the non-linearity of the phase shifter.

![Phase scan of the ECS]

Fig. 4. Phase scan of the compensation section.

**Multi/single bunch energy spread measurement**

The experiment was carried out following conditions, Energy = 1.16 GeV, bunch number = 20, total charge/pulse = 3.2 × 10^9, 5.3 × 10^9 electrons. It was measured at the case of a) ECS off, b) ECS+ Δf on, c) ECS±Δf on. The bunch shape is
shown in Fig. 5. The multi-bunch energy spread was calculated from the current of the bending magnet and the deviation from the center position of the profile which was measured by the OTR monitor. The single-bunch energy spread was measured from the FWHM of the x-direction distribution of the profile. The multi-bunch energy spread and the single-bunch energy spread was plotted in Fig. 6a), 6b) and Fig. 7a), 7b), respectively.

**Summary**

We could measure the multi-bunch energy spread and the single-bunch energy spread of the ATF linac using the OTR monitor. The ECS effect was confirmed that the multi-bunch energy spread was reduce from 3% to 0.5% at the case of total charge/pulse = 3.2 \times 10^{10}, 5% to 1% at the case of total charge/pulse = 5.3 \times 10^{10}, respectively. These results were larger than the calculated value from the transient beam loading. It's assumed that the RF timing of each section were not optimized for minimize the multi-bunch energy spread. The single-bunch energy spread was less than 0.5% except for first bunch at the case of total charge/pulse = 5.3 \times 10^{10}. Some deterioration for single bunch energy spread by the ECS effect wasn't observed in these intensities.

**Acknowledgment**

We would like to express our thanks to Professors Y. Kimura and K. Takada for their encouragement. We also thank other members of ATF group and Mr. S. Morita of E-cube Corporation for their support.

**References**

TOOL FOR DEVICE HISTORIES AT THE KEK LINAC

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Abstract
Almost all of the signals of the linac control devices, roughly 6000 bytes in total, are scanned with a one-second interval. The changes are recorded into log files during the linac operation as long as three months. A tool, called 'dev_hist', has been developed in order to display the histories of specified devices from these log files. This tool provides mouse-oriented controls to select a device and a time-window of interest.

Introduction
The KEK injector-linac has provided 2.5-GeV electron and positron beams to the downstream rings, Photon Factory and TRISTAN. The control system for the linac was replaced by a new one in 1993 [1, 2]. The system comprises: a) 7–8 VME stations running under the OS-9 operating system, b) a few Unix-based servers, and c) a communication network by which computers are connected. So far it has operated successfully [3].

The present control system includes surveillance processes which survey almost all of the signals of the linac control devices at a one-second interval. The total amount of signals is roughly 6000 bytes. The change reports from these processes are recorded into log files.

Since the log files consist of a large bulk of ASCII strings, it is not easy to extract useful information from them. Thus, a tool, called 'dev_hist', has been developed in order to provide an easy-to-use environment to display the histories of specified devices from these log files.

This article describes how log files are created in the section "Processes and log files". In the section "Tool for device histories", the components of the tool are presented with some examples for a performance demonstration.

Processes and log files

Processes
Each VME station has a few (typically 4) field network lines. These field networks have been used to link the distributed device controllers [4]. As shown in Fig. 1, polling processes are running at each VME station. They scan all of the signals of the device controllers, and write them in the shared memory area. The scan rates are set at 1–2 Hz. As a matter of fact, the shared memory area keeps up-to-date values of all the controller signals.

A surveillance process, called "change monitor", surveys the values on the shared memory area with a one-second interval. It creates reports only when changes are detected. The reports from all of the VME stations are collected at a workstation, and are redirected to some alarm applications as well as to log files.

The number of signals with one change monitor in a VME is: a) 440 bytes for eight klystrons and one booster, b) 160–600 bytes for 3–8 power-supply controllers for magnets, c) 60–180 bytes for 1–3 vacuum system controllers, and d) 10–120 bytes of other signals. As a result, the whole system takes care of 6000 bytes of the signals.

The average number of reports during normal operations is 10 per one second. It is also worth noting that the CPU consumption rate by a change monitor is roughly 10% with a 68040 CPU running at 25 MHz.

Log files

The reports from the change monitors consist of ASCII strings. They are identified and redirected into appropriate log files, which exist for each device controller.

Fig. 2 shows a part of the log file for the klystron 'K42'. The first line shows that the 28-th\(^1\) signal of the klystron changed from 036b to 04d7 at the time 10:21:08. The next change of the same data is found in the third line, which shows that the signal changed to 0634 at 10:21:13.

During the three-month operation from October to December in 1995, the total amount of log files was 1.7 GB. The number

\(^1\) '1c' is the hexadecimal expression of the decimal '28'.
of files is about 200, and the largest one has a size of 130 MB.

27/Nov/1995 10:21:08> K42-ADC 1c,04d7,036b
27/Nov/1995 10:21:13> K42-ADC 1a,0c14,0aa7
27/Nov/1995 10:21:13> K42-ADC 1c,0634,04d7
27/Nov/1995 10:21:19> K42-ADC 1a,0a67,0c14
27/Nov/1995 10:21:19> K42-ADC 1c,0497,0634

Figure 2: Example of a history log.

Tool for device histories

Overview

In order to display the histories of linac devices, a graphic tool, called dev.hist, has been developed. This tool is based on a commercial graphic package\(^2\) which provides command-driven interactive functions. We have developed three essential procedures.

hist_read - read a history log   The hist_read reads a specified log file and loads the values into internal arrays. Since the sizes of the log files are typically a few MB, and it takes a few minutes to read a file, a special read-in routine was developed with C language instead of using a default read-in procedure. The present read-in times are less than 10 seconds for most cases. It may take a minute when the size is as large as 100 MB.

hist_draw - draw a history graph   The hist_draw displays a history graph according to the contents of internal arrays. The time-window can be issued in a command-line with keywords. A typical example of a history graph is shown in Fig. 3.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{hist_graph.png}
\caption{One-week history for the RF phase of the klystron 'K58'.}
\end{figure}

dev.hist - control with menus and buttons   The dev.hist procedure creates a window with many buttons and menu-bars. A user can select a device and a time-window by clicking buttons/menus with a mouse. The dev.hist invokes the previous two procedures in order to draw a history graph in the drawing area. An overlook of dev.hist is shown in Fig. 4.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{dev_hist.png}
\caption{View of the tool 'dev.hist'.}
\end{figure}

Demonstration

Some examples to demonstrate the performance of the tool are presented.

A typical example: A typical example is already shown in Fig. 3, which shows a one-week history for the RF phase of klystron 'K58'. The phase alternates between 170 degrees and 90 degrees several times. These two values correspond to those for electron and positron injection, respectively. In addition, zero values for very short duration (actually a few seconds) are observed, which implies the occurrences of a self-reset procedure of the klystron controller due to large electro-magnetic noise from the klystron itself.

A graph with log scaling: Fig. 5 is an example with log scaling on the Y-axis. Note that the values of the Y-axis are calculated with pre-defined calibration coefficients. In Fig. 5 the vacuum level of the ion-pump 'IPK3-1' is shown for two weeks. Some obvious peaks, which result from sudden changes in the vacuum to worse, are observed on Tuesdays and in the afternoons of Thursdays. Those originated from the occasional output stops of all the klystrons due to the weekly maintenance every Thursday afternoon and accelerator studies every Tuesday. Each time that we restart the high-power klystrons, it causes immediate changes of the vacuum to a worse condition, followed by gradual changes which make it better.

A bit-style display: Another functionality is a display in bit-style, which is suitable for indicating logic signals. Two-week histories of 16 logic signals of the klystron 'K54' are shown in Fig. 6. Since the 6th bit indicates the high-power output, it is usually 1 (output on). Thus, the observed changes of this bit to 0 correspond to the output downs of the klystron. The same as in the above example, all of the output downs are on Tuesdays and Thursdays.

\(\text{\footnotesize\textsuperscript{2}}\)We use PVWAVE provided by Visual Numerics Co.Ltd.
Discussion

Before the *dev.hist* became available, only a few members who were very familiar with text-processing tools (i.e. sed, grep, cut, etc.) could extract device histories from the log files. On the contrary, the *dev.hist* provides everybody possibilities of getting device histories by themselves. The tool is especially useful in cases of troubles, since it has abilities to prove the behaviors of any device at the time of the problem.

References

A Low Loss Drive Line Concept for Linear Colliders

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Abstract

In a linear collider, the drive line is the power feed line which is used to excite the high power klystrons, along the linac tunnel. The drive line typically has to fulfill a number of requirements, e.g. phase stability, amplitude and phase control as well as power distribution. A concept, especially fitting the needs of a linear collider, is presented.

Introduction

Following the multibunch energy compensation concept presented in another paper [1], amplitude and phase control are required at every klystron along the linac. In the proposed 500 GeV center of mass S-Band linear collider [2] for example, 2500 klystrons will require approximately 400 W drive power each. These klystrons are distributed along the 30 km long accelerator. Therefore approximately every 12 m the drive line has to deliver this amount of power with the appropriate phase and amplitude control within one pulse and with the required pulse to pulse stability. So far different ideas have been discussed to solve this problem. For example, a low power glass fiber could be used to drive a solid state preamplifier in front of every klystron, or a special drive klystron could power groups of klystrons. While the first version turns out to be a rather cost intensive one, it has certainly the greatest flexibility, because the low power rf can be manipulated in front of every klystron. The second version is certainly cheaper but also requires a widely distributed rf control network. Both systems involve a dedicated distribution system for the low power rf and consist of a large number of components which tend to fail or have to be replaced according to their lifetime. In this paper a technical solution will be discussed which is based on the idea of using a single high power drive line for many klystrons. This drive line would be powered by the same type of klystron used to feed the accelerating structures (150 MW peak power) and is a passive system which should not require any maintenance. Such a drive line system has a number of implications but also many advantages.

General Description

The main problem of a very long drive line is dispersion and energy propagation velocity. The rf pulse which fills the accelerating structure and accelerates the beam is only 2.8 μs (∼ 900 m) long. To excite every klystron in time, the drive pulse has to travel with the speed of the beam pulse, here the velocity of light, along the linac. At the same time the pulse shape (amplitude and phase) is not allowed to change (mainly due to dispersion and mode conversion), especially if phase or amplitude modulation is used within each single rf pulse.

There are basically two concepts for realizing such a drive line. Either a transmission line which supports a TEM mode or a shielded waveguide without inner conductor may be used. Both approaches will be discussed.

Transmission line

The main advantage of a coaxial transmission line compared with any other waveguide is that it supports an almost dispersion-free TEM mode. The remaining dispersion is due to the finite conductivity which increases the series inductance of the line. Nevertheless, the increase in the inductance due to wall losses does not lead to a significant dispersion for practical lines.

Therefore the maximum length of such a drive line is limited by damping. Fig. 1 shows the attenuation constant α of a coaxial transmission line for various geometries. Let us assume a radius of the outer conductor of 10 cm and a ratio a/b = 0.3. With these parameters a damping of only 6 · 10^-3 dB/m is achievable if the drive line is made of copper with a conductivity of 5.8 · 10^7 S/m. If we assume 150 MW rf power the maximum electric field strength is about 3 MV/m which is sufficiently small to avoid breakdown.

Figure 1: Attenuation constant corresponding to the fundamental mode of a coaxial waveguide versus the ratio of the radii of the inner and outer conductor a and b, respectively. The radius of the shield serves as parameter.
Up to this point of the discussion we have considered the drive line as a pure transmission line. Nevertheless a coaxial line is also a waveguide which supports TE and TM modes. Assuming a geometry as given above and a frequency of 2.998 GHz, ten propagating higher order modes exist. Some of the power of the fundamental TEM mode is converted into higher order modes at the output couplers and at the struts, see Fig. 2, which are necessary to support the inner conductor. Two serious effects arise from this mode conversion. Obviously some of the power in the fundamental mode is lost if it is converted into other modes with higher damping. The second more serious effect gives rise to signal distortion if the fundamental mode is converted into higher order modes and some of the power of these modes is converted back into the fundamental mode at a position further along the waveguide. In order to avoid signal distortion by conversion and reconversion the undesired modes have to be suppressed (attenuated) to avoid reconversion. Due to the large variety of traveling higher order modes it seems to be impossible to construct mode filters in order to suppress all of these modes. Therefore the cross sectional dimensions of the coaxial line have to be reduced down to the single mode operation regime in order to obtain mode stability. This requirement limits the radii of the inner and the outer conductor to 0.75 cm and 2 cm, respectively. On the other hand, the damping of such a drive line amounts to $24 \cdot 10^{-8}$ dB/m which is not acceptable because less than 2 km could be fed only.

From the above discussion it can be concluded that a coaxial waveguide is not suitable for a long drive line because a low loss coaxial line with a large cross section tends to mode instability while a structure with reduced cross section has too excessive losses.

**Waveguides**

In a waveguide which does not support a TEM mode, signal distortion occurs due to the non-linear frequency dependence of the propagation constant $\beta$. Different parts of the signal travel with different velocities leading to a dispersed output signal, because no unique signal velocity exists. Nevertheless, for narrow band signals the transmitted signal is identical to the input signal, apart from the amplitude and a time delay. Let us assume an operating frequency of 3 GHz, a bandwidth of 1 MHz and a group velocity of 98% of $c_0$. In order to achieve such a high group velocity the corresponding mode has to be far above cutoff. With these parameters and $L = 2$ km, one obtains $\Delta v_g/v_g = 1.4 \cdot 10^{-5}$ corresponding to a transmission time error of $\Delta T = 90$ ps which is small compared to the rf pulse length.

Nevertheless one has to keep in mind that delay lines with well-defined length have to be inserted between the drive line and each individual klystron feed, if the group velocity is smaller than the velocity of light, in order to keep the drive pulse synchronous with the particles (see Fig. 3). The length of the first delay line is chosen to be 40 m according to $(1 - v_g/c_0) L$ m whereas the last accelerator feed is directly connected to the drive line. In between, the length of the delay lines has to be linearly decreased. For practical reasons one would realize the delay lines as coaxial cables which unfortunately suffer from a high damping, typically 0.4 dB/m. Hence the first delay line leads to an additional damping of 10 dB which is not serious because the full klystron power of 150 MW is available at the beginning of the drive line. However no significantly smaller group velocity is allowable due to the high damping of the delay lines.

**Circular waveguide**

If we consider the use of a circular waveguide as a drive line, it would be desirable to use a $TE_{0m}$ mode due to the unique damping property of these modes, namely, the attenuation decreases as $f^{-\frac{3}{4}}$ for high frequencies. This feature of the $TE_{0m}$ modes makes it possible to construct a very low-loss drive line in the case of $f > f_{g,0m}$. On the other hand, the circular waveguide must have a radius of more than 30 cm in order to achieve a group velocity too close to the light velocity.
of 98% - c0. This however seems not practicable. Besides the fact that such an overmoded waveguide in general generate mode instabilities, mode conversion turns out to be especially crucial using TE0m modes because of the degeneracy of the TE0m and the TM1m modes. In order to avoid this problem a mode filter which suppresses modes with current flow directed along the waveguide axis (TM1m modes) is necessary. Nevertheless such a filter leads to a rather complicated structure of the drive line.

In conclusion it has to be stated that a circular waveguide exhibits excellent damping properties. Nevertheless this design is not suitable for a drive line because a small signal delay due to the frequency dependence of the propagation constant requires a large cross sectional dimension of the waveguide which directly implies mode instabilities.

Ridge waveguide

In order to keep the group velocity close to the velocity of light it cannot be avoided to use a highly overmoded waveguide. Such a waveguide may be used if one can control the higher order modes.

In a ridge waveguide, see Fig. 4, the electromagnetic field is concentrated in the vicinity of the ridges whereas higher order modes extend throughout the cross section of the waveguide. These modes can be suppressed by suitable absorbers located at the side walls. Furthermore the fundamental mode of the ridge waveguide has a relatively low cutoff frequency due to the high capacitive loading associated with the ridges. This leads to a high group velocity compared with conventional waveguides.

A ridge waveguide with outside dimensions of \((a = 200 \, \text{mm}) \times (b = 100 \, \text{mm})\) and a ridge radius of \(r = 33 \, \text{mm}\) is assumed. Due to the high field strength in a drive line it is not recommended to use rectangular ridges which may lead to discharge close to the edges. Instead, circular ridges seem to be more suitable. Fig. 5 shows the transverse electric field of the fundamental mode \((\varepsilon = 98.4\% \cdot c_0)\). Again, for a 2 km long drive line a coaxial delay line of 32 m has to be used at the first klystron feed (see Fig. 3).

The attenuation of the dominant mode (7.11 dB/km) is comparable to the above discussed coaxial drive line. Since the field distributions of all higher order modes are spread throughout the cross section of the waveguide these modes are strongly attenuated by losses at the side walls, whereas the damping of the fundamental mode is not significantly increased. If we insert two absorbers of 4 mm thickness and a loss tangent of 0.2 at the side walls of the waveguide the attenuation of the fundamental mode is increased by only 3.29 dB/km whereas the increase in damping for the higher order modes is much higher. The absorbers give rise to an attenuation of at least 35.1 dB/km for the third higher order mode which seems to be strong enough in order to guarantee mode stability.

Conclusions

A drive line concept for a linear accelerator has been presented which allows the simultaneous and synchronous excitation of a large number of high power klystrons. Various types of waveguides, namely, coaxial transmission lines, circular waveguides and ridge waveguides have been investigated. From the different types proposed here only the ridge waveguide fulfills all the necessary requirements which are low losses, low signal distortion due to dispersion and good suppression of higher order modes. From the calculation provided in this paper, it seems feasible to supply a 2–3 km long subsection of the linear collider with a single drive line if one of the 150 MW high power klystrons is used to generate the drive signal.

References


A BEAM BASED INTERACTION REGION FEEDBACK FOR AN S-BAND LINEAR COLLIDER

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Abstract

Fast ground motion will cause independent orbit movements in the two linacs of a linear collider such, that the beams may miss each other at the interaction point (IP). But even at rather large vertical beam-beam separations at the IP, beams will deflect each other through their electromagnetic fields. By measuring the position of a beam, which has just passed the IP and compare in it the position of a first pilot bunch -which does not have a partner in the opposing beam- with that of the following bunches in the same bunch train, the opposing beam can be steered with ultra fast kicker magnets for optimum collision at the IP. A feed-back system based on this principle will make the necessary steering corrections within a time short compared to the duration of the bunch train.

Introduction

Fast beam steering at the interaction point, which relies on the beam-beam effect of colliding bunches, is a powerful tool to relax nanometer tolerances for final focus quadrupoles in linear colliders. Even betatron amplitude growth excited by vibrating quadrupoles further upstream in the linac, which is not filamented by the time the beam reaches the IP, can be corrected with fast beam steering. From Tracking calculations we expect only 30% filamentation over the entire length of the linac [1].

One stringent requirement for a feedback, which corrects the bunch train offset in the IP is, that the beam pulse is long compared to the overall processing time of the detected signal from the beam position measurement (BPM) to the kicker magnet. Parameters that influence this delay are the distance of the beam position monitor to the IP, the processing time of the feedback loop and the required magnetic field strength compared to the available peak power of the amplifier (compare Figure 1). The amplitude of pulse to pulse ground motion which can be expected from measurements done in the HERA tunnel, which is a tunnel under the city of Hamburg with an colliding beam facility, [2, 3] is approximately 70 nm rms for Frequencies below 1 Hz which is roughly six times the design vertical beam size. In order to limit the Luminosity reduction to 5%, the jitter at the IP should be smaller than 30% of the beam size, which is 5 nm in our case. A list of the interaction region parameters is extracted [4] from the complete list and given in Table 1.

One possibility to achieve this tolerance is to design a passive support system that keeps the final doublets at a given position over a time scale much larger than the repetition rate of the accelerator. This is certainly a challenging task for the technical design of the quadrupole supports which are part of the experiment of a linear collider. Vibrations from the linac quadrupoles are not correctable by this method with respectful effort.

Figure 1 Sketch of the interaction region layout and the location of the beam position monitor and the kicker magnet. The pilot bunch is the first bunch in the left train with no interacting counter part.

| Table 1: Interaction region parameters for the 500 GeV S-band Linear Collider Study |
|---------------------------------|-----------------|-------------|
| N, per bunch | $1.1 \times 10^{10}$ |
| vert. beam size (no pinch) | nm | 15 |
| horiz. beam size (no pinch) | nm | 335 |
| Disruption (vertical) | | 7.1 |
| Disruption (horizontal) | | 0.32 |
| $\beta$, at IP | mm | 0.45 |
| $\beta$, at IP | mm | 11.0 |
| bunch length | mm | 0.3 |
| crossing angle | mrad | 6 |
| bunch train length | $\mu$sec | 2 |
| bunch to bunch distance | nsec | 6 |
| distance: BPM to IP | m | > 2 |
For the S-Band Linear Collider study two feedback loops are foreseen to relax this tolerance well beyond the measured value of 100 nm which was mentioned before. One loop relies on a direct measurement of the quadrupole vibration in combination with a mechanical (or correction magnet) feedback. Such a loop has been tested already and a suppression of a factor of 4 in amplitude for the rms value at 2 Hz has been proven [5]. This feedback loop has mainly been developed to correct the linac quadrupole vibration. The second loop will be described in more detail in the following text.

The Principle of the Measurement and the Resolution

For a round beam the beam-beam force of two colliding bunches is proportional to the separation of the two bunches over approximately one $\sigma$. Operating with an aspect ratio ($\sigma_y/\sigma_z$) of 20 (or more), as it is foreseen in Linear Colliders to reduce the beamstrahlung, produces an almost linear beam-beam force over approximately 10 $\sigma$. According to the beam-beam simulations using the parameters from Table 1, the kick angle $\alpha$ per $\sigma$, separation of the two colliding beams is given to within a good approximation by:

$$\alpha[\text{mrad}] = \frac{\Delta y}{\sigma_y} \times 0.057 \text{ mrad}$$

(1)

Let us assume that the BPM next to the IP is located at the position of the first quadrupole of the final doublet, which is 2 meters away. At this position the beam offset in the monitor according to formula (1) would be 120 $\mu$m per $\sigma$, separation at the IP, which is easy to measure as compared to the 4 micrometer resolution being required for the rest of the linac BPM's.

A method based on beam-beam deflections to measure precisely the offset of the two colliding beams has been used for single bunch operation in the SLC from pulse to pulse already [6]. On the other hand, a bunch to bunch measurement of the beam position, as being proposed for the TESLA Linear Collider study for both outgoing beams within one pulse can not be used, because of the delay time for signal processing as compared to the overall pulse length and bunch to bunch distance (compare Table 1). Therefore, in case of the S-Band Linear Collider study, a combination of both methods is proposed which uses a pilot bunch in one of the two colliding beam pulses and only a single BPM in combination with a single kicker magnet. Using such a scheme has the significant advantage, that almost no mechanical disturbance with an amplitude larger than a nanometer (vibration, girder resonance etc) can separate the colliding beams on the time scale of one bunch train length (2 $\mu$sec -> 500 kHz), once they are colliding.

The Interaction Region Layout

The location of the beam position monitor and the kicker has to be as close as possible to the IP in order to reduce the processing time of the feedback loop. Because the quadrupole next to the IP will have an integrated BPM the shortest distance is 2.2 meters from the IP. If the delays on cables, the response time of the feedback amplifier and the finite rise time of the kicker are added up, an overall delay of 50 nsec is expected. If we assume in addition that one bunch train will have a pilot bunch, the delay will increase to about 60 nsec. Therefore 3% of the 2 $\mu$sec long beam pulse will not be corrected and, if far enough separated between pulses, will not contribute to Luminosity. In case of SLED operation with a 500 nsec long beam pulse, as foreseen for the energy upgrade to 800 GeV, the potential loss will increase to 12%. A continuous measurement of the beam-beam separation during the pulse will be done to correct even displacements which change along the bunch train.

The Kicker Magnet and Amplifier

The beam-beam force with flat beam operation is approximately linear over 10 $\sigma$.

In order to allow orbit corrections at the IP for a value of 150 nm, the required kick is only 0.07 $\mu$rad, if a distance from the kicker to the IP as close as the BPM position is assumed. For the 250 GeV beam a magnetic field of 6 x 10^{-4} T is sufficient. The kicker will be a stripline type kicker fed by two broad band amplifiers which can excite a maximum magnetic field of 1.1 x 10^{-4}. The parameters are given in Table 2.

Table 2: Design values for the feedback kicker and the broad band amplifier.

<table>
<thead>
<tr>
<th>Stripline Kicker</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>aperture radius</td>
<td>mm</td>
</tr>
<tr>
<td>effective length</td>
<td>mm</td>
</tr>
<tr>
<td>magnetic field (max. possib.)</td>
<td>Tm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>power amplifier</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>pulse duration</td>
<td>$\mu$sec</td>
</tr>
<tr>
<td>bandwidth of amplifier</td>
<td>MHz</td>
</tr>
<tr>
<td>peak power /amplifier</td>
<td>kW</td>
</tr>
<tr>
<td>pulse current</td>
<td>A</td>
</tr>
<tr>
<td>rise time</td>
<td>nsec</td>
</tr>
<tr>
<td>repetition rate</td>
<td>Hz</td>
</tr>
</tbody>
</table>

The power amplifiers deliver a peak power of 2.5 kW each and have a bandwidth of more than 50 MHz to power each strip. A sketch of the kicker is shown in Figure 2.

The Beam Position Monitor

In order to measure the beam position of the pilot bunch with respect to the colliding bunches an analogue delay will be used to subtract the two signals from the pilot bunch and the first colliding bunch directly. In addition the bunch intensity must be determined as well because the beam-beam kick is proportional to the bunch charge in the opposite beam. The resolution of the beam position measurement is 5 $\mu$m [7] which is 4% of effect of a one $\sigma$, separation and the bunch
intensity measurement should be of the same order of magnitude. A sketch of the BPM set-up and the readout electronics design is shown in Figure 3.

![Kicker strips](image)

**Figure 2:** Sketch of the Kicker magnet and the pulse forming network. (gibt noch ein besseres).

**Figure 3:** Schematics for the beam position monitor and the readout electronics.

### Acknowledgment

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### References


MULTIPLE BEAM COUPLED CAVITY MICROWAVE PERIODIC STRUCTURE

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Abstract

Concept of parallel electrical circuit was applied to microwave structures and resulted in multibeam or quasi-hollow beam structure (MBS) concept [1]. The proposed concept allows to modify magnetically or electrically coupled periodic microwave structure into the proposed multibeam or hollow beam structure and can be used for any charged particles. Concept analysis and some results were presented at EPAC96 conference. A prototype with four beams - four beam structure (FBS) based on a side coupled structure has been studied both theoretically and experimentally [2]. A number of applications is expected for this concept. It permits to transmit higher beam current in multiple beams compared to a single beam current which is restricted due to space charge limitations, especially at higher frequency. First prototype of the designed FBS is built in X-band. 10 cm long electron beam head is designed for 1.2 MeV electron energy, 1 A total electron beam current and 1 kW average beam power. Various applications in microwave tube technique are studied.

Introduction

An idea of building microwave linear accelerators in a frequency range close to and beyond 10 GHz has lately become very popular both for high energy and portable accelerators. However, difficulties of this "state-of-the-art" technique such as manufacturing and tuning of microwave cavities become much more complicated at 10 GHz and higher compared to S and L band.

Operating at higher frequency permits a reduction in outline dimensions and weight of the final package. However, in higher frequency ranges one faces a problem of beam current restriction among a number of other complications. Beam current is restricted by physical aperture size due to space charge limitation and, in commonly used structures, it is difficult to exceed this limitation of approximately $10^9$ 1/cm$^3$ without affecting structure efficiency and energy gain.

Multiple Beam Concept and Structure

Multiple or hollow beam concept for microwave structure design is proposed [1] to expand range of beam current which could propagate through the structure. Example of MBS design is shown in Fig. 1. MBS permits exceeding the space charge limitations due to reduction of aperture size at high frequency observed, for example, in X-band.

Fig. 1. Magnetically Coupled MBS.

Beam cross section at radius R is shown as quasi-continuous, though it could be built of multiple small apertures.

Fig. 2. Electrically Coupled MBS.

The proposed structure could also be used to increase energy gain for the same linac length in a mode of multiple pass operation.

Energy gain will be increased in proportion to $N^{1/2}$, where N is number of beam passes, assuming that we use the same power source and structure volume grows proportionally to N. Therefore, with four passes, energy gain would be two times higher, with 16 - four times higher, etc. Bending magnets could be used to bend the beam 180 degrees.

Potential application of the proposed concept and the corresponding variations of structure design could be found in many areas where accelerators are used. We can foresee various commercial applications, such as non-destructive testing, sterilization, etc. Concept could be applied to design of microwave amplifier tubes. Hollow beam instabilities have been studied and observed by Kyhl and Webster at low

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1 - work was supported by Department of Energy, SBIR grant FG03-95ER82065
energies (<100 keV) for TWT[3] applied to traditional structures with beam concentrated in the center. One of the ideas, expressed in the accelerator physics community is to develop a "table-top" FEL for commercial applications with an acceptable price range. X-band accelerator for 9 - 13 MeV is a potential source for that application. The proposed system seems also to be attractive for devices using beam-beam interaction.

The coupled circuits model and microwave theory was used to analyze one of the simple realizations of the proposed concept. An FBS cavity was designed which is capable of accelerating four parallel beams, the tuning procedure was refined and microwave properties of the structure were studied. The study could be considered successful as our analysis confirmed predictions made at the very early stage of development.

**Study of Four Beam Structure (FBS)

Theoretical Analysis and Coupled Circuit Model**

To study MBS properties, we decided to start with a simplified version of FBS resonator [2]. The resonator is shown in Fig.3. Two "rings" of four cavities, coupled through a central coupling cavity have formed the complete resonator.

![Fig.3. One-period FBS Resonator Analyzed By Means of Coupled Circuit Model.](image)

Schematic for two rings of coupled half cells, coupled together through a single coupling resonator is illustrated in Fig.4. This element represents a period of the four-beam accelerator structure. The modes of resonantly coupled, multibeam structure were analyzed by establishing the notation and normalization for the simple structure so that the impedance matrix of the more complicated multibeam structure can be written by inspection.

![Fig.4. Schematic representation of two "rings" of FBS cavities coupled through a single coupling cavity.](image)

The analysis shows that the structure behaves like a normal biperiodic coupled-cavity linac structure with coupling factor $k_1$, with the addition of the non-propagating modes due to the internal resonances of the multiple gap accelerating cells.

**Experimental Verification**

Test resonator was made by combining the cells, shown on Fig.5.

![Fig.5. Manufactured X-band Cavity](image)

Coupling between the cavities in the rings was introduced and changed during the measurements to study theoretical predictions, which were in a good agreement with experimental results. We found that the structure behaves like a conventional biperiodic structure with multiple resonant frequencies which correspond to the case of unexcited coupling cavity. Each of this frequencies represent various modes for single "ring" of four resonators. Detailed analysis of the experimental results was provided earlier [2].

**Four Beam 1.2 MeV Linac Head**

Presently, we plan is to build a working prototype which will deliver 1.2 MeV electron beam at 1 A current in four beams in 12 cm long X-band structure, using the studied FBS (Fig. 5). The goal is to achieve 1 kW average power stored in four beams at 0.001 duty factor and 70 percent beam efficiency. Comparative view of 6 MeV single beam side coupled...
Comparative view of 6 MeV single beam side coupled structure designed for MINAC accelerator and the proposed 1.2 MeV four beam linac and is shown in Fig.6. Dimensions are shown in millimeters.

Fig. 6. Comparative view of two structures

Length of FBS linac, which is approximately equal to \( L_{\text{minac}} /4 \), where \( L_{\text{minac}} \) is obviously length of MINAC-6. The latter is designed for energy of 6 MeV. The improved version utilizes a shorter section and delivers 5 MeV electron beam with beam current of approximately 100 mA. As RF length \( L_{\text{minac}} \) equals 40 cm, corresponding RF length of a projected FBS approximately 10 cm.

Calculated and experimental load lines for MINAC-5 were in a very good agreement. The maximum current transported through the section is 110 mA. This is a maximum value which we were able to achieve in X-band linac using magnetron as a power source.

If the proposed FBS linac would have similar characteristics and four accelerated beams, simple considerations tell us that using four times higher power magnetron (6 MW), beam current would be 440 mA at the same energy of 6 MeV.

In FBS, we expect to increase beam efficiency to about 60 to 70% and have 1 A at 1.2 MeV with the same magnetron power (1.5 MW CTL1100).

Load line and efficiency for the proposed FBS is shown on Fig. 7. Maximum energy is about 1.8 MeV, and efficiency reaches its maximum at approximately 1.5 A beam current.

Beam dynamic analysis for the FBS short segment has been made using PARMELA computer code. It shows that no focusing is required for the electron beam in order to propagate down the structure.

**Fig. 7. Load Line for 10 cm long at 1.8 MW RF power.**

**Conclusion**

FBS was studied as an example of MBS concept, described in [1,2]. The proposed technical study appears to be successful and might help to solve the problem of beam current limitation or increase energy gain by using multipass operating mode. The proposed concept seems to be a new technical approach in accelerator structure construction and has a number of various practical realizations. The concept could be used for e-beam processing, high energy radiography, computer tomography, and other applications. It does not seem possible to have every proposed design studied in details in a reasonable period of time. However, we are hoping to continue our study of various types of the proposed structure design. Potential application of the proposed structure could be found in many areas where accelerators are used.

This article concludes an analysis made during the first stage of a study conducted in order to introduce the multibeams structure design. We have proposed a “turn-key” prototype linac using a miniature 12 cm long FBS and a 1.5 MW X-band magnetron as a power source. Performance goal for the electron beam head is to operate at beam energy of 1.2 MeV and beam peak current of 1 A with no external focusing, providing, therefore, around 1 kW average power stored in four beams at 0.001 duty factor.

**References**

1. A.V. Mishin, Multiple Beam Coupled Cavity Concept and Structure, Proceedings of EPAC96.
DESIGN AND APPLICATION OF MICROWAVE STRUCTURE
FOR LOW VELOCITY PARTICLES

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Abstract

A microwave structure design concept invented in 1988 has been studied and tested for a number of years. The structure employs Alvarez type resonators coupled to each other through coupling cavities to maintain satisfactory neighboring resonance separation and beam stability. This design is applicable for charged particles with velocities in a region of 0.1 c to 0.5 c. As an example, the structure was applied for various electron linacs both with on-axis electrical and off-axis magnetic coupling in a lower velocity region. Achieved accelerator performance makes the concept highly recommended for practical applications.

Introduction

As was described in earlier publications [1, 2, 3], the proposed concept combines the principle of standing wave coupled cavity structures with Alvarez structure, providing, therefore, a way to cover a range of charged particle relative velocity from 0.1 to 0.5, where standard coupled cavity structure is ineffective. In a period of approximately eight years from 1988 to 1996 the concept and properties of the proposed design were studied and two working electron linacs [3, 4] were developed. This concept is used to increase efficiency of particle capture and acceleration in the corresponding velocity range. In 1994, the concept and a similar structure called CCDTL was studied [5] as applied for proton and/or ion accelerator design by a group at Los Alamos National Laboratory. The concept has proved itself as vital for both electron and proton linacs and appears to be a powerful tool for microwave accelerator design.

Description of Concept

The original patent [1] describes an improvement of an on-axis coupled regular or biperiodic resonant structure formed by the sequence of disk irises in a waveguide. This configuration is well known as disk loaded waveguide (DLWG). During operation in \( \pi/2 \) mode, every other cavity has an accelerating field component. Cavities between them play role of phase shifting, or coupling cavities.

In the case of the well-known side coupled structure, the coupling cavities are removed from the beam axis in order to increase the value of shunt impedance of the structure, as shown on Fig.1a and Fig.1b. Modification of the side coupled structure is made in a similar way [1].

a. On-axis coupled structure

b. Side-coupled structure.

Fig. 1 Conventional biperiodic structures.

a. On-axis coupled structure

b. Side-coupled structure.

Fig. 2. Modified structures with a drift tube in the center of accelerating cavity.

An additional drift tube is introduced close to the center of an accelerating cavity, maintaining phase locked fields on both sides of the drift tube. Thus, fields on each side of the drift tube oscillate with phase shift \( \Theta \), equal to \( 2\pi n \), where \( n \)
is integer. Coupling between the two newly formed cavities which form a single Alvarez resonator is very high to have a good mode separation. Phase shift between the neighboring Alvarez resonators remains equal to $\pi$, so that the structure conserves properties of a regular biperiodic coupled cavity structure.

This introduction, in fact, creates a sequence of Alvarez resonators, coupled to each other through the same coupling cavities, as shown on Fig. 2a and Fig. 2b.

For the conventional structure, one can find the minimum theoretical particle relative velocity $\beta_{\text{min}}$ when the corresponding accelerating gap, or a distance between two neighboring irises becomes equal to zero.

$$\beta_{\text{min}} = \frac{2\pi}{(\lambda\Theta)}$$

where $\lambda$ - wavelength in free space;
$t$ - iris thickness;
$\Theta$ - mode, or phase shift per cell, $\pi/2$ in this case.

It is assumed that when the accelerating gap is negligibly small, the period of the structure $D$ remains constant along the central Z axis. Moreover, at particle velocities $\beta$ close to $\beta_{\text{min}}$ the accelerating cavities in the structures shown on Fig. 1a and Fig. 1b look nearly the same. The drift tube length (Fig 1b) becomes equal to the iris thickness, as for DLWG design (Fig 1a). The problem of noticeable reduction of the structure efficiency in the range from 0.1c to 0.5c becomes more noticeable at a higher operating frequency, for example in X-band. Increasing the shunt impedance of the standing wave structures in the 10 GHz frequency range was one of the goals that stimulated this research.

**Theoretical and experimental study of the concept**

First description of the concept and study of the properties was made for the electrically on-axis coupled DLWG, shown on Fig. 1a and Fig. 2a in 1988. A certificate of invention [1] described the problem using a formula (1) and a concept of including a drift tube into the center of accelerating cavity creating a set of Alvarez resonators coupled to each other through coupling cavities which provide $\pi$ phase shift between the neighboring accelerating resonators. Introduction of the tube permitted using the structure at the lower velocities. At the same time, quality of performance of the coupled cavity structure at $\pi/2$ mode was conserved. Therefore, it was concluded that this design provides a new, practical approach for accelerating charged particles at lower velocities from 0.1c to 0.5c. For an electron linac, it allows us to extend the practical range of injection voltages down to 2 keV and increase bunching and accelerating efficiency up to 80 keV. For a proton linac, it establishes the range of particle energy approximately from 5 to 150 MeV.

Reference to the side coupled structure shown on Fig. 1b and Fig. 2b, rebuilt in a similar way, was first made in 1992 [2].

As it was already mentioned above, the invention is particularly important for higher frequencies, where along with higher shunt impedance one faces the problems of higher attenuation and the difficulty of building cavities for accelerating low velocity particles.

**Section with electrical on-axis coupling**

The first working linac for accelerating electrons using the concept was built and tested in 1992 [2, 3]. It was designed for a 9.37 GHz magnetron. Detailed description of the studied structure and the linac was made in [2, 3], so we provide only a list of parameters.

**Magnetron**
Peak Power...........................................0.5 MW
Frequency (tunable)............................9368 MHz
Anode Voltage....................................25 kV

**Section**
Injection Energy.............................25 keV
RF Length........................................11.6 cm
Q..................................................4000
Number Acc. of Cavities......................8

**E-beam**
Energy............................................0.7 MeV
Peak current......................................30 mA

A single cavity with a drift tube located in the center of the cavity formed an Alvarez resonator. A prototype of this cavity was modeled and studied before incorporating into an accelerator structure based on biperiodic DLWG design.

Because the study was made for the on-axis coupled structure shown on Fig. 1a, shunt impedance was not outstandingly high, although much higher than for the conventional coupled cavity structures at the required injection energy of 25 keV, which corresponded to the magnetron anode voltage. For the chosen cavity configuration it was approximately 20 MOhm/m.

In order to provide strong coupling between the cavities on both sides of the incorporated drift tube, three kidney-shaped coupling slots were milled in the iris which supports the drift tube, leaving, therefore, three narrow stems holding the drift tube. This mechanical interpretation was simple enough to use it in X-band and provide strong coupling and good heat

1 - The first Alvarez-type two cell resonator is counted as a single cavity.
conduction from the central tube to the outer walls of the structure.

**Section with magnetic off-axis coupling**

A section using the side-coupled structure shown on Fig. 2b at 0.1c to 0.5c was built and tested for intraoperative e-beam therapy [4].

The structure has π phase shift between the accelerating cavities, provided by a side coupling cavity. The first accelerating cavity is a 3β/2, two-cell Alvarez resonator designed for 0 or 2πn (were n - integer) phase shift on two sides of a drift tube located in the center of the resonator. This drift tube separates the resonator into two accelerating cells which are very strongly coupled to each other. The drift tube is supported by three stems, formed by the borders between three kidney-shaped slots, as it was done in the structure shown on Fig.2a and tested before [3].

Even though the Alvarez resonator was not optimized, it has the shunt impedance of approximately 70 MOhm/m.

The injector voltage in this section can be regulated from 6 to 20 kV. The two-section linac (Fig. 3) is designed for energy 13 MeV and smoothly regulated from 4 to 13 MeV.

Fig. 3. Two-section linac built for intraoperative therapy. Modified side-coupled structure with Alvarez resonator is incorporated into standard side-coupled structure.

Results of the low-velocity structure performance were successful. We have measured the capability of regulation of the injection energy from 6 to 13 keV with no substantial change in output beam current.

Recently, a detailed study of a similar structure using the proposed concept was made by a group at LANL. It was called CCDTL and described in application to ion linacs [5]. It was found that shunt impedance maximizes at 70 MOhm/m with average value of 50 MOhm/m in a range from 0.2c to 0.5c, measured at a frequency of 700 MHz. Converting this value of shunt impedance to X-band one can obtain approximately 150 MOhm/m.

Two stems were used to support the drift tube in the center of an accelerating cavity. This is a good decision for a lower frequency band, in particular at 700 MHz

The authors have confirmed the conclusion regarding the high potential of the concept, made in [1, 2, 3, 4]. They have made a series of calculations and measurements which are an important contribution to the concept. For example, a nice addition to the design was the introduction of a two drift tube, three-cell resonator.

**Conclusion**

The proposed concept [1, 2] describes a set of Alvarez resonators coupled with π phase shift through phase-shifting cavities. The concept establishes a structure which is highly efficient in the range of charged particle relative velocity from 0.1 to 0.5, where a standard coupled cavity structure is ineffective. In the period of eight years from 1988 to 1996 the concept and properties of the proposed design were studied and two working electron linacs [3, 4] were developed using this concept.

The concept raised interest in application to both electron and proton linac design. Recently, a similar structure called CCDTL was studied [5] and applied to ion accelerator design.

The author is planning to apply the structure to various linac designs [to be published].

**References**


PRE-INJECTOR OF THE KEK 2.5-GEV LINAC AND HIGH-CURRENT SINGLE-BUNCH ACCELERATION

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Abstract

The timing stability required for the electron source of the pre-injector is determined by the energy acceptance of the KEKB rings. The jitter requirements for the gun pulse itself are somewhat mitigated by the subsequent bunching process. A system by which a beam trigger stability of $3\sigma = 20$ ps is achieved is described, and the method to estimate the phase jitter of the accelerated beam from the energy jitter is discussed.

Introduction

The KEK 2.5-GeV Linac which is presently being upgraded will provide beams of 8 GeV electrons and 3.5 GeV positrons for direct injection into the KEKB rings [1]. The energy acceptance of the rings is 0.5%, which places constraints on both the drift and the jitter in the energy of the injected beams. This paper discusses the manner in which the energy of the injected beams will be controlled to meet the requirements of the KEKB rings, with emphasis on the energy jitter.

The PF Linac pre-injector has been described elsewhere [2]. The half of the pre-injector is shown schematically in Fig. 1. A 119-MHz subharmonic buncher (SHB1) has been installed last January between the electron gun and a 476-MHz subharmonic buncher (SHB2) to produce S-band single-bunch beams with better bunch purity. A fast grid pulser located near the cathode of the triode gun produces an electron pulse of up to 15 A in a 2 ns pulse. The electron bunch length is first reduced by two pulsed RF cavities operating at respectively the 24th and the 6th subharmonics of the primary 2856 MHz of accelerating RF, then further compressed by two S-band prebunchers and a buncher. The fully bunched beam emerges at the end of the pre-injector with an energy of about 40 MeV, where the beam is momentum analyzed with a 90°-bending system.

The energy of a particle varies as $\cos\theta$, where $\theta$ is the angle between the particle and the negative crest of the RF. The buncher of the PF Linac consists of two parts: a bunching section of 6 cells with gradually different phase velocities and a accelerating section of 29 cells with a phase velocity of the speed of light, where bunched electrons are accelerated at a large phase, typically $\theta = 40^\circ$. Furthermore a short bunch of high intensity must be positioned several degrees ahead of the crest of the accelerating RF in order to minimize the resultant energy spread.

If a particle is accelerated at an angle $\theta_0$ in the accelerating section of the buncher and then at an angle $\theta_1$ in the following accelerating sections, the resultant energy of the particle becomes $E_f = E_0 \cos(\theta_0 + \delta\theta) + E_1 \cos(\theta_1 + \delta\theta)$ at any position along the beam line of the linac. Then the energy jitter, $\delta E_j = \delta E_j / E_{center}$ is given by

$$\delta E_j = -\frac{E_0 \sin \theta_0 + E_1 \sin \theta_1}{E_0 \cos \theta_0 + E_1 \cos \theta_1} \delta \theta_j \quad (1)$$

where $\delta \theta_j$ is the jitter in the RF phase relative to the beam position. Consequently the deleterious effects of $\delta \theta_j$ grow as $\theta_0$ and $\theta_1$ increase. At the end of the linac where $E_0 \ll E_1$, the energy jitter is given approximately

$$\delta E_j \approx \frac{\delta \theta_j}{\tan \theta_0}. \quad (2)$$

Typically $\theta_0$ is set to about $10^\circ$ for the 10-nC beam. If the phase jitter $\delta \theta_j$ is $1$ ps, the energy jitter becomes as large as 0.3% at the end of the linac. Inevitably the phase jitter should be no more than 1 ps to meet the energy acceptance of 0.5% of the KEKB rings even if the energy compressing system is introduced.

Then it becomes important how to measure accurately the phase jitter as small as 1 ps. Because of large $\theta_0$ and $\theta_1$, in the pre-injector the phase jitter $\delta \theta_j$ can easily be estimated by measuring the energy jitter $\delta E_j$ at the exit of the pre-injector.

Source Timing Stability

Any timing change of the beam relative to the accelerating S-band phase results in a beam energy change. Thus, beam timing stability is required to avoid excessive energy jitter or drifts.

Within the first few centimeters of the buncher section the electrons become fully relativistic and subsequently do not

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Fig. 1 New layout of the PF linac pre-injector. Abbreviations used are GUN for electron source, SHB1/SHB2 for 119-MHz/476-MHz SHB, PB1, PB2 for S-band prebunchers, and ACC for 2m-accelerating section. Others are beam monitors (screen monitor: PRM, and current monitor: WCM) and components of the beam transport system (magnetic lens: ML, focusing coil: FC, and quadrupole magnet: QM).
change their timing relative to a speed-of-light signal. However, before becoming relativistic the beam is susceptible to timing changes of several origins.

From the bunching process, three potential sources of jitter in the timing of the accelerated electron pulse can be identified: trigger timing jitter; grid pulser instability; and RF phase jitter in the source bunchers. The first two items give the same effect to the source pulse. As far as in the pre-buncher the effect of the last item is thought to be small, since the accelerated beam position is determined by the bunchers relative to the RF, which is supplied from a klystron except for SHBs. Therefore changes in phase relative to the beam can be the result of a shift in the timing of the electron bunch itself.

The basic timing trigger for the grid pulser is a trigger derived from the PF Linac timing system. The problem from the outset has been to place this timing signal on the gun high voltage deck without loss of stability. The fiber optical link which has been used was introducing a jitter of several tens of picoseconds (3σ = 60 ps). While it is expected to be possible to transmit the trigger with this improved link which have the required stability, this time as a trial, we placed a CW RF signal (476 MHz) on the high voltage deck where the trigger was resynchronized.

The fiber optical link is shown schematically in Fig. 2. The link utilizes about 50 m of a 100-m graded-index fiber optical cable. A high speed ECL circuit (TD2) was used to resynchronize [3]. With this new link, no timing jitter can be detected in the output of the TD2 above 20 ps threshold of the measuring instrumentation. But of cause at $\theta_i = 10^6$, an energy change of 0.3% is produced at the end of the linac when the timing jitter of the accelerated gun pulse shifts by only 1 ps. Fortunately the timing jitter at the gun output is mediated by the bunching process itself.

![Fig. 2. Schematic diagram of the resynchronization system.](image)

**Beam Energy Stability**

The overall bunch compression ratio is typically between 50 and 100 as is shown in Fig. 3, which varies depending on both the timing conditions of the bunching system and the beam charge. The fully bunched beam of 10 nC emerges at the end of the pre-injector with an energy of about 40 MeV, compressed into a bunch length of about 13 ps. Since the bunch compression ratio decreases as the beam charge increases, it becomes difficult to stabilize the energy of the high current beams.

Energy shift of a beam of 10.5 nC was measured at the end of the pre-injector as a function of timing changes introduced in the electron gun trigger circuit. Substituting the measured energy shift into Eq. (1), we obtain the phase shift of the beam in Fig. 4.

![Fig. 3. Bunch compression ratios obtained experimentally and from PARMELA simulations.](image)

![Fig. 4. Phase shift of the beam (10.5 nC) as a function of timing changes introduced in the electron gun trigger circuit. The slope of the linear fit is 0.02 (deg./ps).](image)

The beam energy has been measured by a 90°-bending magnet system at the end of the pre-injector. A vidicon camera is used to view the beam hitting a fluorescent screen in vacuum at the exit of the analyzer where the dispersion is well known. The video is digitized in 2-dimensional to determine both the centered position and the width of the energy spectrum. When a beam charge was as low as 1 nC, the beam was stable and the energy jitter was not seen on the screen monitor. When the beam charge, however, was increased to 5 nC, the energy jitter of ± 200 keV (± 0.5%) was observed before resynchronizing the beam trigger. By resynchronization the timing jitter decreased to less than 20 ps, the energy jitter has been improved to ± 0.12% as listed in Table 1.

| Table 1. Phase jitter $\delta\theta_j$, $\delta\theta_j$ calculated from measured energy and timing jitter $\delta\theta_j$, $\delta\theta_j$ respectively. |
|------------------|------------------|------------------|------------------|------------------|
| Beam trigger | $\delta\theta_j$ (3σ/%) | $\delta\theta_j$ (3σ(deg)) | $\delta\theta_j$ (3σ(ps)) | $\delta\theta_j$ (3σ(deg)) |
| not resynchronized | 1.0 | 1.6° | 60 ps | 1.2° |
| resynchronized | 0.25 | 0.41° | 20 ps | 0.4° |
Phase jitter $\delta \theta_j$ relative to the beam can be calculated from the measured energy jitter $\delta E_j$ using Eq. (1). On the other hand, from the timing jitter $\delta t_j$, the phase jitter $\delta \theta_j$ is estimated from the relationship of Fig. 5. The obtained values are well agree in each case, which indicates that energy jitter of the beam is due to the timing jitter of the electron bunch itself as far as pre-injector is concerned.

![Graph showing the comparison of beam energy stability before and after resynchronization in the 5nC condition.](image1)

Fig. 5 Beam energy stability measured at the exit of the pre-injector. The beam became stable after the beam trigger was resynchronized.

The fact the the phase jitter was reduced to the required level has been confirmed by accelerating a beam to the end of the linac. Energy changes of a 0.5 nC beam were measured with two conditions. It was actually observed that before being resynchronized the beam energy was changing from every pulse to pulse. After being resynchronized, although residual drift exists in the beam energy, the fast energy jitter disappeared as being seen in Figs. 6a and 6b, which is consistent with the phase jitter ($3\sigma = 0.12^\circ$) calculated from measured energy and timing jitter.

![Graph showing beam energy stability before and after resynchronization in the Emax condition.](image2)

Fig. 6a. Beam energy jitter measured at the end of the PF 2.5-GeV linac. Fast jitter in pulse to pulse was observed before the beam trigger was resynchronized.

![Graph showing beam energy stability before and after resynchronization in the Emin condition.](image3)

Fig. 6b. Beam energy jitter measured at the end of the PF 2.5-GeV linac. Fast jitter in pulse to pulse disappeared after the beam trigger was resynchronized.

Conclusion

By resynchronizing the beam trigger, it was confirmed that the fast jitter of the beam energy from pulse to pulse is due to the timing jitter of the source, and reduced to the required level for the KEKB Linac.

References

KEK-PF SLOW-POSITRON FACILITY

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Abstract

A slow-positron facility, aiming at the use of slow-positron beams (ranging from eV to keV) in various fields of solid-state physics, was constructed utilizing the 2.5-GeV electron linac at the Photon Factory, KEK (KEK-PF) as its primary beam source. The KEK-PF slow-positron source comprises a beam line for the primary electron beam, a target-moderator assembly for positron production, a slow-positron beam-transport line and relevant assemblies. We expect a slow-positron intensity of more than 2x10^9 e+/s with a maximum primary beam power of 30 kW. Since we achieved an intensity of 10^8 e+/s with a nominal primary beam power of 2 kW, we opened this facility to slow-positron users.

Introduction

A positron beam is a useful probe for investigating the electronic states in solids, especially concerning the surface states. The advantage of utilizing positrons beams is in their simpler interactions with matter, owing to the absence of any exchange forces, in contrast to the case of low-energy electrons.

However, such studies as low-energy positron diffraction, positron microscopy and positronium spectroscopy, which require high-intensity slow-positron beams, are very limited due to the poor intensity obtained from a conventional radioactive-isotope-based positron source. In conventional laboratories, the slow-positron intensity is restricted to 10^6 e+/s due to the strength of the available radioactive source.

An accelerator-based slow-positron source is a good candidate for increasing the slow-positron intensity [1-6]. We, therefore, started construction of the KEK-PF slow-positron facility [7,8] from FY1991, aiming to produce more than 2x10^9 e+/s slow-positrons, utilizing our 2.5-GeV electron linac [9,10] as its primary beam source.

We describe here the KEK-PF slow-positron facility and its performance as well as its recent progress.

Layout of the KEK-PF Slow-Positron Facility

Figure 1 shows the KEK-PF slow-positron facility, which is located at the end of the KEK 2.5-GeV linac. It comprises a beam line for the primary electron beam, a target-moderator assembly, a slow-positron beam-transport line and relevant assemblies.

The primary electron beam is injected into the target through an achromatic beam-transport line comprising two 18° deflecting magnets and a quadruple magnet. The nominal beam power of the KEK 2.5-GeV linac is 6.25 kW (an energy of 2.5 GeV, a peak current of 50 mA, a pulse length of 1 μs and a pulse repetition rate of 50 pulse/s), and an average beam power of 30 kW can be expected from this linac as its maximum beam power [9,10].

The target-moderator assembly comprises a water-cooled tantalum rod of 5 radiation lengths and a moderator with multiple tungsten vanes (thirteen 25-μm thick sheets). The most efficient target thickness for an incident electron energy of 2.5 GeV was decided using the EGS4 Code [11,12]. A maximum slow-positron beam intensity of 2x10^9 e+/s can be expected with a full beam power of 30 kW, according to the calculated energy spectra of positrons emitted from tantalum targets [13]. Electrostatic focusing grids are located just above the moderator.

The extracted slow-positron beam is directed by a 30-m long beam-transport line with an axial magnetic field of 100 G to an experimental area at the ground level through a 2.5-m thick radiation shield floor. Twenty sets of steering coils were installed along the slow-positron beam-transport line in order to adjust the slow-positron beam trajectory. A high-voltage station capable of applying 60 kV was installed in the initial part of the beam-transport line in order to vary the energy of the positron beam, which is useful for depth-profile measurements. A device controller, combining a personal computer and a programmable sequence controller through
optical fiber, has been adopted to control the monitors and power supplies at a high-voltage potential. Penning-trap electrodes are also installed at this station in order to make a dc beam from a pulsed beam.

At an experimental area, a slow-positron beam switch system, which comprises a pair of beam deflecting coils and two pairs of Helmholtz coils with magnetic-field directions crossing each other (see Fig. 2), was installed. This system enables us to direct slow-positron beams to several experimental stations one by one without breaking the vacuum.

As for the beam monitors, channel-electron multipliers (CEM) for the beam intensity and micro-channel plates (MCP) for the beam profile are intensively used.

![Figure 2: Schematic view of the slow-positron beam switch system. Two pairs of crossed Helmholtz coils and a pair of deflecting coils direct the slow-positron beam. The deflecting coils are inevitable if one wants to get rid of any unwanted beam offset immediately after a deflection of the slow-positron beam.]

An excellent improvement in the positron yield was achieved by annealing of the moderator assembly (tungsten foils) at 2270 K for 10 minutes under ultra-high-vacuum conditions. A slow-positron flux of $1 \times 10^8$ e$^+$/s was successfully achieved with a 2.0-GeV, 2-kW primary electron beam power. The achieved conversion efficiency has almost reached our designed goal; we can therefore expect a slow-positron intensity on the order of $10^8$ e$^+$/s with a maximum beam power of 30 kW in the near future.

The energy of the positron beam was successfully varied from 400 eV to 40 keV by applying a voltage to the high-voltage station at the initial part of the slow-positron beam transport line (see Fig. 1). Although radiation from the target chamber, at a kW primary beam operation, caused severe damage to the programmable sequence controller at the high-voltage station (RAM bit error), reinforcement of the radiation shield for the target chamber cured this trouble. A slow-positron beam with a beam energy of 800 eV was successfully switched from one direction to another utilizing the slow-positron beam-switch system. We can therefore supply slow-positron beams to several experimental stations without any waste of time.

Since we have already achieved a slow-positron intensity of $10^8$ e$^+$/s in our facility, we have opened this facility to slow-positron users.

**Positronium Time-of-Flight (TOF) Experiment**

As an example experiment at the KEK-PF slow-positron facility, we briefly describe here energy-distribution measurements of the positronium (Ps) emitted from a single-crystal quartz. Ps is known to form in the interior of many insulators with a wide band-gap energy. The energy loss and slowing-down process of positrons in matter is becoming well understood. For positrons with energies of less than the band gap, the production of Ps and phonon excitation become the dominant energy-loss mechanism. To date, very little has been studied about the kinetics of the formation and diffusion of Ps, which is in the state immediately after the production and before its delocalization.

We obtained the energy distribution of Ps by adopting the time-of-flight (TOF) method to emitted Ps [14]. The TOF was determined by measuring the time interval between the arrival time of a pulsed-positron beam and the detection of radiated $\gamma$-ray from annihilated Ps. Since the lifetime of Ps is well known, we can easily deduce the energy distribution of Ps from the TOF spectra, which were measured by changing the distance between the sample surface and the annihilation $\gamma$-ray detector, only if the pulse width of the injected positron beam (20 ns in the present case) is shorter than the lifetime of the Ps.

Figure 3 shows the preliminary result of a positronium TOF spectrum measured with a distance between the sample surface and the $\gamma$-ray detector of 135 mm. Two energy peaks are clearly resolved, which correspond to Ps energies of 3.3 and 0.8 eV, respectively. Although the 3.3 eV peak had already been reported by Sliferlazzo et al. [15], the 0.8 eV peak was identified for the first time by the present measurements [14]. This 0.8 eV peak might be due to a thermalization process of the Ps.

Present Status

At the very initial stage of its performance tests, the observed positron yield was 1/20 of the estimated value [8]. During these tests, the positron intensity at the end of the transport line was estimated by detecting annihilation $\gamma$-rays utilizing a BGO scintillator with a photomultiplier tube (HAMAMATSU H2611). This discrepancy was thought to be due to the condition of the moderator, since we put the moderator into the target-moderator chamber without performing any thermal treatment.
Fig. 3. Positronium (Ps) time-of-flight (TOF) spectrum measured at a distance between the sample surface and the annihilation γ-ray detector of 135 mm.

**Future Plan**

The KEK 2.5-GeV linac is now undergoing a reformation process relevant to the KEKB project [16]. There are two major goals of the upgrade [17]: 1) to increase the energy of electrons and positrons to 8 and 3.5 GeV, respectively, and 2) to increase the bunch intensities of positrons by roughly one order. In accordance with this upgrade plan, we must relocate our KEK-PF slow-positron facility to the 1.5-GeV point of the upgraded linac. Although this relocation will take more than one year, there is a possibility to install a dedicated linac for slow-positron use only if we use the remnants of the present 2.5-GeV linac smartly.

**Summary**

The KEK-PF slow-positron facility has successfully produced $10^8 \text{ e}^+/\text{s}$ slow positrons with a 2.0-GeV, 2-kW primary electron beam power. The energy of the slow-positron beam was easily varied from 400 eV to 40 keV. This enables us to measure the depth-profile, which is very useful for locating any defects in materials. Slow-positron beams have been smoothly supplied to several experimental stations without breaking the vacuum by the aid of the slow-positron beam switch system. We have opened our slow-positron facility to slow-positron users and several experiments are in progress.

**Acknowledgments**

The authors are greatly indebted to Director General, Prof. H. Sugawara as well as to the staff of the KEK administration department for their encouragement and continuous support of this slow-positron project. The staff of the KEK 2.5-GeV linac is also gratefully acknowledged for machine operation.

References

Abstract

The work on the construction of the $e^+e^-$ factory complex is in progress at Budker INP. For an effective operation of these machines the injector complex is designed. It consists of a preinjector for the production of $e^-$ and $e^+$ bunches and their acceleration up to an energy of 510 MeV, and a damping ring. This paper presents the general scheme and the current status of the preinjector.

Introduction

The main preinjector parameters are given in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Output energy</td>
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</tr>
<tr>
<td>Number of electrons per bunch</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>Number of positrons per bunch</td>
<td>$10^9$</td>
</tr>
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<td>Repetition rate</td>
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<td>Energy spread: electron bunch</td>
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<tr>
<td>Energy spread: positron bunch</td>
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</tr>
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<td>Klystron pulse power</td>
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</tr>
<tr>
<td>Number of klystrons</td>
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</tr>
</tbody>
</table>

The preinjector output energy of 510 MeV is an operation energy of the $\phi -$ factory of the VEPP-5 complex [1]. A number of $(5 \pm 10) \times 10^{10}$ electrons and positrons per second is required to provide for a simultaneous operation of the $\phi -$ factory and the whole VEPP-5 complex at designed luminosities.

General scheme

The preinjector main components are shown in Fig. 1. The preinjector comprises a thermionic electron gun, a subharmonic buncher, a 300 MeV electron linac, a 180° isochronous turn, a conversion system, an RF photogun, and a main 510 MeV linac [2, 3].

The thermionic 200 kV triode gun delivers 2 ns pulse current of 10 A. The emittance of the beam is less than $10^{-2}$ $\pi \cdot cm \cdot rad$.

This bunch comes to the subharmonic buncher operated at the 16th subharmonic of the basic frequency of 2856 MHz. The buncher contains two quarter-wavelength

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Fig. 1: General scheme of the preinjector.
cavities with drift gaps. The transverse focusing of the beam is realized with the help of the longitudinal magnetic field produced by current coils, placed around the cavities. Such a bunching system provides a short intensive beam, 18 ps long, at a low initial gun current. The short bunch length is needed to provide a small energy spread (±1%) during a further acceleration.

The first linac consists of 5 accelerating sections and produces an intensive 300 MeV electron bunch for the positron production. The second linac includes 9 accelerating sections and accelerates both positrons after the conversion system and the electron bunch created by RF photogun up to an energy of 510 MeV. The accelerating sections are 3 m long and have a constant impedance structure operating at a travelling wave (2π/3). The transverse focusing of the bunch along the linacs is realized by the solenoid field at the first sections of each linac and two quadrupoles in each of the other sections. The accelerating gradient in the first sections of each linac is 25 MeV/m, and in the other sections it is up to 18 MeV/m.

The 300 MeV electron bunch passes through a 180° isochronous bending system in a horizontal plane. The bending system consists of three 60° bending magnets and 4 quadrupole lenses. This system provides the transportation of the bunch with an energy spread of ±3% with an insignificant increase in the bunch transverse size. After that, the triplet focuses the bunch at a converse target (the conversion constant is higher than 3%).

Typically, (approximately 98% of the total time) the preinjector produces positrons to store a required number of particles in the damping–ring. For the electron beam production, one-time injection is enough. The RF photogun placed between the focusing triplet and the converse system is used for this purpose. In this case, it is needed just to remove the target without readjustment of the focusing system. In future, it is planned to obtain polarized electron bunches from the photogun.

The 14 accelerating sections are powered by 4 RF modules based on S-band klystrons 5045 (SLAC, USA). A SLED system permits to obtain the necessary gradients of accelerating fields. The output power of SLED is fed to three or four accelerating sections. In order to maintain the reliable capturing, the first 300 MeV and the first 510 MeV linac sections have a high accelerating rate. It is attained by applying half of the RF power from the corresponding klystron to these sections, then the second half of this power is divided equally between two regular sections. The power of the other two klystrons is divided half-and-half between four regular sections. After SLED the power is divided by 3 dB hybrids.

At present the tests of the first RF module are done, and the experiments on the linac prototype at a frequency of 2787 MHz have been started.

**RF module**

The RF module consists of a 5045 klystron and a high voltage pulse modulator. The high voltage pulse for the klystron is produced by the modulator made at the Budker INP. The modulator is a conventional line type modulator with an oscillatory charge of a pulse forming network (PFN). It consists of a high voltage power supply, a charging choke, PFN and a thyratron switch [4]. During a joint klystron–modulator test the control and the klystron protection systems were also tested. The RF module operation was stable for different values of the input RF power and amplitudes of the high voltage pulses at a repetition rate from 1 to 50 Hz.

Now the assembly of the second modulator for the next RF module is under commissioning, the tests of its separate elements are in progress.

**Preinjector prototype**

The preinjector prototype is built to perform simultaneous tests of the main preinjector elements at a high output power level (see Fig. 2). The electron beam formed in the thermionic electron gun enters the short disk–loaded bunching section and then the accelerating structure. The bunch transverse focusing is the same as in the first linac of the preinjector: the set of focusing coils and one solenoid.
The accelerated beam then enters either a 180° spectrometer or a Faraday cup.

The RF power for the prototype is produced by a KIU-12 klystron (2797 MHz operating frequency, 2.5 μs pulse duration, output pulse power up to 20 MW) and a power compression system. The required phase shift between the accelerating structure and the buncher is carried out by the phase shifter at a high power level. The phase shifter is made of a cut waveguide which could be compressed mechanically. The power is delivered to the buncher through a matched coupler and a retuning attenuator.

Before the assembly of the prototype all its elements were preliminarily tested.

The prototype of the thermionic 100 kV triode gun is able to produce 2 ns pulses with a pulse current of up to 2 A. The emittance of the beam is less than 10⁻²π·cm·rad and the transverse size at the crossover after adjusting the lenses is 0.5 cm.

The beam position and the beam profile monitors are tested and calibrated using a 100 kV electron beam from the electron gun.

The buncher section of the prototype consists of 4 coupled cylindrical cavities and operates on the backward travelling wave (2π/3) of the main prototype frequency [5]. The buncher is matched to the feeding waveguide with VSWR better than 1.1.

The accelerating section of the prototype is a 3 m long disk-loaded structure of a constant impedance operating on the travelling wave (2π/3). The obtained VSWR value at 2797 MHz is not worse than 1.02, and less than 1.2 in the frequency range ~ 13 MHz.

The Faraday cup is designed for measuring the total charge of short bunches after the first section of 300 MeV accelerator.

The high power tests of the power compression system are done at the prototype operating frequency. The compressor is SLED-like (3 dB hybrid and two resonators which operate at a TE₀₁₅ mode). The resonator diameter and length are 196 mm and 359.6 mm respectively. The resonator has a precise tuning device. The side wall of the resonator is a thing disk which can be bent by means of a regulating screw, the quality factor of resonators Q₀ = 10⁵, the coupling coefficient β = 5.5. The pulse durations of the master oscillator and the output SLED were 2.5 μs and 0.5 μs, respectively. The power step-up ratio (~ 4.5) of the input pulse power of 10 MW is obtained.

Status of other work

At the present time the prototype of the RF photogun with a GaAs photocathode is complete [6]. The operating frequency of the prototype is 2797 MHz. The vacuum of 10⁻¹¹ torr is reached. The input RF power during the first tests is about 1 MW, which corresponds to 500 kV/cm of the field amplitude in the RF cavity.

The assembly of the master oscillator system is in progress. The system consists of a generator-synthesizer operating at the 32th subharmonic (89.25 MHz) of the main linac frequency (2856 MHz), RF pulse forming amplifiers feeding 2 quarter-wavelength cavities of the subharmonic buncher (178.5 MHz, 16th subharmonic of main linac frequency) each at a peak power of 20 kW, and amplifiers for 4 RF modules provide a power of up to 1 kW each with a 180° fast phase switch at a frequency of 2856 MHz.

The manufacture of the waveguide elements, including 4 systems of power compression at a frequency of 2856 MHz, quadrupole lenses, correctors and 60° bending magnets of the preinjector is in progress.

A dedicated high-vacuum technology area for the series production of preinjector accelerating sections is presently under commissioning.

References


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HOM DAMPING IN SBL C ACCELERATING SECTION USING INPUT COUPLER

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Abstract

An application of the symmetrical SBL C section coupler for the Higher Order Mode (HOM) damping was investigated. The demands to the own frequency and Q-factor of the coupler at HOM have been obtained on the basis of an equivalent scheme of the Disk Loaded Waveguide (DLW) with this coupler. HOM field amplitude distribution along the structure and an influence of the coupler cavity own frequency on the HOM field distribution were investigated. The influence of some elements inserted in the coupler cavity to obtain the necessary frequency shift between fundamental and hybrid modes was studied.

Introduction

Excitation of the trapped high order modes in travelling wave accelerating structures is a big problem to save the required beam parameters. There are various concepts of diminishing the trapped modes influence on the beam dynamics in the DLW accelerating structures.

![Fig. 1. Plan of the investigated input coupler: 1- tuning pins; 2 - absorbing loads; 3 - short-circuiting plungers.](image)

One more technique of the trapped modes damping may be the use of the symmetrical coupler for a 6 meter SBL C accelerating structure [1]. It has been designed on the basis of the input coupler with additional coupling holes for withdrawing the Y-polarised mode (see Fig.1). It is necessary in addition to the HOM damping to secure the coupler matching at the operating frequency. Works in that direction were carried out on the SBL C accelerating section [2]. We try to study some questions connected with the conception of the trapped modes damping SBL C by the input coupler in an initial 1 meter part of the SBL C accelerating section.

Equivalent scheme at hybrid mode

The analysis of the hybrid waves excitation in the SBL C section was carried out on the basis of an equivalent scheme of DLW at \( \text{HEM}_{11} \)-modes, which is shown in Fig. 2.

![Fig. 2. Equivalent scheme of a DLW at hybrid modes.](image)

The series branch \((L_{in}, C_{in}, r_{in})\) represents the existence of the \( \text{E}_{11} \)-mode electromagnetic field. On one hand the coupling between cells is realised by magnetic field that is represented by mutual inductance \( M_n \). On the other hand there is resonance type coupling by means of the \( \text{H}_{11} \)-mode electromagnetic field that is represented by parallel branches \((L_{2n}, C_{2n}, r_{2n})\). The cell excitation is modelled by introducing of complex e.m.f. \( E_n \) into the series branch.

It is more convenient to operate with the following parameters expressed in terms of \( L, C, r \):

\[
\begin{align*}
 f_{1n} &= \frac{1}{2\pi \sqrt{L_{1n}C_{1n}}} ; & f_{2n} &= \frac{1}{2\pi \sqrt{L_{2n}C_{2n}}} ; \\
 K_{n} &= \frac{M_n}{2 \sqrt{L_{1n}L_{2n}}} ; & K_{2n} &= \frac{C_{1n}C_{2n}}{2 \sqrt{L_{1n}L_{2n}}} ; \\
 Q_{1n} &= \frac{L_{1n}1}{C_{1n}r_{1n}} ; & Q_{2n} &= \frac{C_{2n}r_{2n}}{L_{2n}} ; \\
 X_{n} &= \sqrt{L_{1n}r_{1n}} ; \\
\end{align*}
\]

(1)

By using these parameters one can obtain the equations set with respect to complex values \( X_n \).

Note that in the equivalent scheme the number of parallel branches is equal to \( N+1 \), whereas that of series branches equal \( N \), where \( N \) is the number of cells in the section. Both first and last parallel branches (indexes 0 and \( N+1 \)) are introduced for modelling a beam pipe in the input and output couplers.

Voltages across the capacitive element \( C_{1n}(U_{2n}) \) and \( C_{2n} \) (\( U_{2n} \)) are related to \( X_n \) by the expressions which are found by using the equivalent scheme.

Modelling of the input coupler was realized by means of addition of the coupler cell coupled with first cell of DLW. Frequency \( f_{1c} \) and Q-factor \( Q_{1c} \) of this additional cell are
chosen in such a way that we should have: the travelling wave regime in the DLW consisting of cells similar to the first one; the operational frequency of the travelling wave regime being \( f_{op} \); the phase shift per cell at this frequency being \( \phi_{op} \).

Higher order mode field amplitude distribution

The trapped modes were studied in initial 1 meter part of the real section with the symmetric coupler matched to the structure at the fundamental mode. Measurements were carried out by the small perturbation method with moving a thin cylindrical body (0.1 mm diameter and 8 mm length) along the accelerating structure at the distance 3 mm from the symmetry axis. The obtained field distributions are shown in Fig.4. It is seen how the HOM fields are being trapped in the constant gradient structure if nothing is done on their damping. The first trapped mode (\( F=4130 \) MHz) occupies five initial cells and has a \( \pi \)-like mode distribution. With this there is no a longitudinal field component in the coupler cavity. The last mode fully trapped in the structure has the frequency \( F=4161 \) MHz. In this case the \( \pi \)-like mode occupies from 24 to 30 cells and is being transformed along the structure toward the input coupler where at this frequency the field is just beginning to show up.

At higher frequencies (\( F=4164+4194 \) MHz) the field penetrates into the coupler cavity and has the amplitude which is comparable with that in the neighbouring cells, but at that \( \pi \)-like mode should be in cells with number more than 30 (see Fig.4). At frequencies higher than 4194 MHz the field amplitudes are reduced in the first cells.

One may see in Fig.3 that the matching of the coupler at the hybrid mode reduces the amplitude of electric field more than five times in broad frequency band. The analogous results for DLW with constant gradient but without a coupler was presented in a paper [2].

![Fig.3. Cell voltages \( U_n \) versus cell number \( n \) cells](image1)

![Fig.4. The longitudinal electric field amplitude distribution (in units) in the 30 cells' SDL structure](image2)
It means that at those frequencies the section initial part itself begins to trap the dipole modes.

Hence, it is clear that the own frequencies of TM_{11}-type dipole modes of the coupler cavity differ from those of SBLC structure first cells and supposedly lie in the frequency band 4164-4194 MHz and higher. So for providing the coupling of the first dipole modes with the input waveguides through the coupler cavity it is necessary to correlate the coupler cavity dipole modes frequencies with those of the section first cells.

Influence of the coupler cavity own frequency on the dipole modes field distribution along the structure.

The influence of the coupler frequency on the HOM field distribution was studied with the structure having the coupler, which allowed to vary the own frequency. Fig. 5 presents the roll of the unchanged coupler (a) and in the coupler with reduced own frequency on 30 MHz (b). One can see that the coupler cavity has its influence on the field distribution at this frequency. By means of changing the distance from the X-axis to the Y-junction (i.e. the short-circuiting plane position for the dipole modes) and using the tuning pins (see Fig.1) the Q-factor value was reduced from 8000 to 2000-4000 over the frequency band about 20 MHz. The obtained Q-factor dependencies on the frequency band for minimal Q-values at certain frequencies 4152 MHz (a) and 4146 MHz (b) of the X-polarisation are shown in Fig.6.

In case of hybrid coupler with forth coupling slots for the dipole modes of both polarizations the coupler cavity own frequency is decreased by the value which is more than required one. Here the different width of the coupling slots would result in the discrepancy of the coupler own frequencies for one dipole mode with different polarizations by about 50-70 MHz. It is demonstrated in Fig.7, where one can see that it is possible to reduce the external Q-factor value of the trapped modes with Y-polarization (a-at frequency 4145MHz and b-at 4152MHz) whereas the Q-factor of the modes with X-polarization is not changed(c).

Fig.7. External Q-factor depends on frequency.

The major problem consists in large difference between the coupler cavity own frequencies for the same mode with X and Y-polarizations. Such a problem can be solved if the dipole modes symmetry in the coupler cavity is rejected while the field symmetry for the fundamental mode is kept unchanged. It is realized by means of a replacement the matched load only in one port for the X-polarization. In this case we provide the required drop in the trapped modes Q-factors for both polarizations in three time over the frequency range from 4130 MHz to 4160 MHz by changing the coupler parameters.

Conclusion.

Another approach to match the coupler at the fundamental and hybrid modes simultaneously consists in to study the influence of some elements inserted inside the coupler cavity. This problem is to be solved by combining calculations of structures and experiments of prototypes and it is now under solution.

References


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CALCULATION AND EXPERIMENTAL INVESTIGATION OF ELECTRODYNAMICS CHARACTERISTICS OF SBLC DLW

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Abstract

In this paper the electrodynamic characteristics of the 6 meter SBLC accelerating section with constant gradient are considered. The values of resonant frequencies, longitudinal and transverse shunt impedances, Q-factor for the fundamental and first dipole modes were calculated using MAFIA code and also were measured by small perturbation method with disk and cylindrical probes. The results measurements and calculations for the first and last SBLC DLW cells are presented.

Electrodynamics characteristics at the fundamental mode.

Two sets of cells for the input (cell N1) and output (cell N178) ends of 6-m long section Disc Loaded Waveguide of S-Band Linear Collider (SBLC DLW) [1] were fabricated. All measurements of ElectroDynamics Characteristics (EDC) were carried out by means of those cell sets since the resonance measuring units were assembled on the basis of cells with the same dimensions. Before measurements some calculations were conducted with the using of programs URMEL-T and MAFIA [2]. To simplify the calculation procedure and obtain more complete information in particular at $\pi$ phase shift on some cells there were no rounding. The absence of rounding decreased the effective shunt impedance from 45.13 to 43.27 M$\Omega$/m for cell N1 and from 61.52 to 58.85 M$\Omega$/m for cell N178. Other EDC were changed insignificantly. But in the case without rounding we can assemble resonant sections consisting of several full cells and half-cells at the ends. For such sections with electrical walls at the ends one can calculate the EDC at the frequencies corresponding to $\pi$-mode of the fundamental and hybrid modes.

Experimental studies were carried out with resonant sections consisting of 6 similar cells with dimensions corresponding to the first and the last cells of 6m long SBLC DLW (its first version where $2a$ for the first cell equals 31.02 mm and for the last one 21.77 mm). Measurement of resonance frequencies, Q-factors and longitudinal and transverse shunt impedance were conducted according to the technique [3]. For the measurement of shunt impedance at dipole mode frequencies a device was developed and fabricated which could provide the relative frequency stability $10^{-7}$ in the range from 4 up to 6 GHz. The results of EDC measurement for two mentioned resonant sections operating in the fundamental mode are presented in detail for the DLW cell with $2a=21.77$ mm. According to the handbook on DLW [3] one for the structure under consideration the following parameters can be predicted: $\beta_{g23}=0.0128$,

$$\frac{E_0A_{23}}{\sqrt{P}} = \xi_{e1} = (485 \pm 20) \Omega^{1/2},$$

$$\frac{r_{sh1}}{Q} = \frac{\beta_{g23}}{2m\lambda_{23}} \xi_{e1} = 4.77 \frac{k\Omega}{m},$$

where $\beta_{g23}$ is group velocity at $2\pi/3$ mode, $\lambda_{23}$ is wave length in free space corresponding to $2\pi/3$ mode, $E_0$ is first harmonic amplitude of accelerating field, $P$ is input power, $r_{sh1}$ is longitudinal shunt impedance.

The value of Q was equally 14700. At $Q=13200$ the value of $r_{sh1}$ is equal to $(63\pm 2) M\Omega/m$

The measured values of frequencies and Q-factors at those modes are given in Table 1. All the cells were tuned to the 0-mode frequency with the error $\pm 0.1$ MHz before measurement of the longitudinal shunt impedance.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>$\pi/6$</th>
<th>$\pi/3$</th>
<th>$\pi/2$</th>
<th>$2\pi/3$</th>
<th>$5\pi/6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$, MHz</td>
<td>2966</td>
<td>2968.9</td>
<td>2977.9</td>
<td>2987.6</td>
<td>2997.8</td>
<td>3007</td>
</tr>
<tr>
<td>$Q\times 10^6$</td>
<td>9400</td>
<td>9400</td>
<td>9400</td>
<td>10000</td>
<td>10700</td>
<td>9700</td>
</tr>
</tbody>
</table>

Fourier analysis of the field distributions was carried out for the middle part of the section over three cell length. For $\theta=2\pi/3$ the relative amplitude of the main harmonic has been determined to be

$$A_1 = \sqrt{A_0^2} = 4652 Hz^{1/2}.$$  

The form-factor of the bead used for the measurements appeared to be

$$K_s = (0.84 \pm 0.01) \times 10^{-19} \frac{m^2 s}{\Omega}.$$  

The electrical field strength parameter for the resonant section of DLW has been defined as

$$\eta_{e1} = \frac{A_1}{\sqrt{2m\Gamma_{g23}} f_{23}^2} = (214 \pm 10) \frac{\Omega^{1/2}}{m}.$$  

For the traveling wave case the electric field strength parameter is introduced as ($L = 2\lambda_{23}$) [4]:

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\[ \xi_{z} = \eta_{z z} \sqrt{\frac{\pi L_{z}^{2}}{\beta_{z z}}} = (471 \pm 18) \frac{\Omega^{1/2}}{m}. \]

As for the parameter \( \frac{r_{sh}}{Q} \) it can be written as

\[ \frac{r_{sh}}{Q} = \frac{1}{2} \eta_{z z}^{2} = (458 \pm 0.3) \frac{k \Omega}{m} \]

and for \( Q = 13200 \) one can obtain \( r_{sh} = (60.5 \pm 3) \frac{k \Omega}{m} \). Note, that at \( \alpha/\lambda_{2/3} = 0.109 \) the cells should be finely tuned to their own frequency to obtain good field symmetrization.

The longitudinal shunt impedance at the fundamental mode of DLW first cell was measured with the use of metallic and dielectric cylinders. The measurements were carried out for 2\( \pi/3 \) and \( \pi \) modes. The calculation of \( r_{sh} \) was based on the determination of the ratio \( r_{sh} / Q \). If Q-factor was equal 14500, the longitudinal shunt impedance at 2\( \pi/3 \) mode was 48.1M\( \Omega \)/m (measured by metallic bead) and 44.49M\( \Omega \)/m (measured by dielectric bead). At the \( \pi \) mode these values were 43.5M\( \Omega \)/m and 38.8M\( \Omega \)/m correspondingly.

**Electrodynamics characteristics at hybrid mode.**

In the beginning of study of the first dipole mode EDC for the structure which consists of cells similar to the last one of SBLC DLW (2a=21.77mm) preliminary individual tuning of each cell to the frequency of the hybrid wave 0-mode was have again carried out. It should be noted that even slight defect of a cell caused arising of not strongly expressed resonance of the second dipole mode. The resonant frequency of the hybrid wave was measured in the assembled prototype consisting of 6 tuning cells. The measured values of frequencies and Q-factors are presented in Table 2.

<table>
<thead>
<tr>
<th>Qo</th>
<th>9500</th>
<th>9200</th>
<th>9000</th>
<th>9000</th>
<th>9000</th>
<th>9200</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>50.6</td>
<td>4464</td>
<td>4482</td>
<td>4509</td>
<td>4546</td>
<td>4583</td>
</tr>
<tr>
<td>MHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Experimental data of the dispersion curve for the first dipole mode SBLC DLW with 2a=31.02mm are shown in Table 3.

<table>
<thead>
<tr>
<th>Qo</th>
<th>9200</th>
<th>9000</th>
<th>9000</th>
<th>9000</th>
<th>9000</th>
<th>9200</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>4184.0</td>
<td>4151.1</td>
<td>4127.4</td>
<td>4119.5</td>
<td>4117</td>
<td></td>
</tr>
<tr>
<td>MHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These data were obtained experimentally on the resonant prototype consisting of 3 full specially shaped cells (the cell surface is rounded) and two half-cells without rounding. We have used such a structure because it is not possible to excite the first dipole mode with \( \pi \) phase shift in the structure consisting of full cells. The half-cells diameter was determined on the prototype exited at the fundamental mode with 2\( \pi/3 \) phase shift. The dispersion relation indicates that \( \pi \)-mode and neighboring 3\( \pi/4 \)-mode have frequencies which differ only by 2.4MHz. It results in complications in the study on the basis of small perturbations method. For obtaining the correct electric field pattern in the prototype, consisting of 3 full cells and 2 half-cells, we have to retune individually the prototype elements with high precision (about 0.02 MHz). Moreover, the choice of perturbing bodies is also limited because maximal perturbation should not exceed 0.5MHz. That limits the directness coefficient of the perturbing body.

The transverse shunt impedance \( r_{sh} \) was determined in terms of the longitudinal shunt impedance \( r_{sh} \) according the formulae:

\[ r_{sh} = \frac{r_{sh}}{(kr)^{2}}, \]

where \( k \) is the wave number in the free space.

Using MAFIA program the values of \( r_{sh} \) and \( r_{sh} \) were obtained for \( \pi \)-mode and other mode of the first dipole wave of the first and last DLW cells. The knowledge of \( r_{sh} \) and \( r_{sh} \) values at modes different from the \( \pi \)-mode is helpful for the precise determination of \( r_{sh} \) at frequencies corresponding to the hybrid wave phase velocity equal to the light velocity. The results of \( r_{sh} \) calculation by MAFIA code are in satisfactory agreement.

The ratio of the longitudinal shunt impedance to the Q-factor as a function of the distance from the structure axis, obtained with by MAFIA program is shown in Fig.1. The calculations were carried out for the structure, consisting of 3 full cells and 2 half-cells with dimensions 2a=31.02mm, 2b=81.38mm, D=33.33mm, t=5mm. There were no rounding of the disk apertures and cell inner surfaces. It is clear that such a structure differs from one experimentally studied. But this calculation is more simple due to the absence of rounding.

The following results were obtained:

\[ \frac{r_{sh}}{Q} = 1300 \frac{\Omega}{m} \]

at \( \pi \)-mode and \( \frac{r_{sh}}{Q} = 500 \frac{\Omega}{m} \) at 3\( \pi/4 \)-mode.

Similar computations were conducted by means of URMEL-T program for the structure, consisting of 3 full cells with rounding and 2 half-cells without rounding. The value of \( \frac{r_{sh}}{Q} \) at \( \pi \)-mode had appeared to be 700\( \Omega \)/m.
Fig. 1. Relation of longitudinal shunt impedance to Q-factor vs distance from the axis for DLW with 2a=31.02 mm.

Measurements of the transverse shunt impedance in the structure, consisting of three full cells and two half-cells, were carried out by means of disk and cylinder shaped perturbing bodies. The form-factor of disk shaped perturbing body with diameter 3.5 mm and thickness 0.5 mm was

\[ k_r = (0.483 \pm 0.015) \times 10^{-10} \text{ m}^2 \text{s}/\Omega. \]

Calculations of experimental data with using of the fundamental harmonic have given the following result:

\[ r_{shl}/Q = (639 \pm 60) \Omega/\text{m}. \]

At \( Q = 13000 \) the value of transverse shunt impedance \( r_{shl} = (8.3 \pm 0.8) \Omega/\text{m} \). Similar measurements were carried out with cylindrical perturbing bodies which had length 6 mm, diameter 0.7 mm, form-factor \( k_r = 0.944 \times 10^{-10} \text{ m}^2 \text{s}/\Omega \), and directivity coefficient \( k_d = 7 \pm 1 \). In this case we have the result:

\[ r_{shl}/Q = (805 \pm 110) \Omega/\text{m}. \]

At \( Q = 13000 \) \( r_{shl} = (10.4 \pm 1.5) \Omega/\text{m} \).

Comparison of experimental and calculated values of the transverse shunt impedance at \( \pi \) mode (Table 3) shows the experimental ones are somewhat lower than for the case of SBLC DLW with 2a=21.77 mm.

The transverse shunt impedance values calculated by MAFIA code (last version) in DESY was 9.9 \( \Omega/\text{m} \) for cell with 2a=31.02 mm and 14.9 \( \Omega/\text{m} \) for cell with 2a=21.77 mm. The experimental result for cell with 2a=21.77 mm was equal 11.5 \( \Omega/\text{m} \).

Table 4.

<table>
<thead>
<tr>
<th>Experimental data</th>
<th>Calculated data</th>
</tr>
</thead>
<tbody>
<tr>
<td>disk bead</td>
<td>cylinder bead</td>
</tr>
<tr>
<td>7.8±8.3</td>
<td>10.4</td>
</tr>
<tr>
<td>MAFIA</td>
<td>16.9</td>
</tr>
<tr>
<td>URFEL</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Fig. 2. \( E_z \) field distribution versus position of the disk bead on the axis of structure SBLC DLW with 2a=31.02 mm (\( \Theta = \pi \)).

Conclusion.

We investigated the electrodynamics characteristics of the SBLC accelerating structure. The resonance frequencies, Q-factor, longitudinal shunt impedance were measured at the fundamental and first dipole modes for the first and last cells of DLW. The values of transverse shunt impedance were measured by small perturbation method with disk and cylindrical probes and also were calculated by MAFIA code.

References.


STATUS OF THE HIMAC INJECTOR

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Abstract

Clinical studies of cancer treatment began in June, 1994, using heavy-ion beams from a medical accelerator, HIMAC. About 150 patients had already been treated by the end of July, 1996. HIMAC is operated 24 hours per day from Monday through Saturday. Experiments on basic research, including physics, chemistry, engineering, and biology are carried out during the night and on weekends, while the day time is devoted to clinical trials. A combination of two synchrotron rings and two pulsed-operated switching magnets (SWM) allows three user groups to share the beam time (two beams from the synchrotron and one from the injector), if all groups utilize the same ions. To remove this restriction, a system involving a time-sharing mode, which allows the delivery of different ion species to three user groups, was designed and is being installed. Three ion sources have been prepared, and all magnets between the ion sources and the SWM of the synchrotron rings will be replaced by pulsed-operated magnets. Excitation of the magnets and the RF power of the linear accelerators will be controlled pulse to pulse so that three kinds of beams with different \( q/A \) values can be accelerated under optimum conditions.

Introduction

Heavy-ion beams have excellent properties for applications to cancer treatment: a large biological effectiveness and good dose localization. A clinical study was, however, carried out at Bevalac, LBL, on a limited scale. To investigate the effectiveness and extent of heavy-ion therapy, a medical accelerator, HIMAC (Heavy Ion Medical Accelerator in Chiba), was constructed at NIRS, Japan. A clinical study using heavy-ion beams from HIMAC began in June, 1994. Since then, about 150 patients had been treated by the end of July, 1996.

HIMAC is a facility having a synchrotron with two identical rings, an injector, three treatment rooms, and four experiment rooms. The synchrotron accelerates ions from He to Ar up to a maximum energy of 800 MeV/u for \( q/A = 1/2 \) ions; the energy corresponds to a range of 30 cm in tissue for Si beams. The treatment rooms have vertical (rooms A and B) and/or horizontal courses (rooms B and C). Beams from the two rings are transported to these courses according to a treatment schedule.

Accelerators which can deliver heavy-ion beams with energies ranging from 100 MeV/u to 800 MeV/u are very scarce in the world. Therefore, applying HIMAC beams to basic research was strongly desired, without interfering with clinical studies. High-quality treatment also requires detailed knowledge of beam-material interaction processes. Thus, basic-research programs started in the fall of 1994.

New Devices and Course

The HIMAC injector, shown in Fig. 1, comprises an RFQ and Alvarez linacs (DTL) operated at a frequency of 100 MHz. Two types of ion sources, 10 GHz ECR and PIG, are in operation. The linacs can accelerate ions with \( q/A \leq 1/7 \), and a charge stripper is installed downstream of the DTL. Details concerning these accelerators and ion sources were described at a previous conference [1, 2]. A new device was recently installed and a new course was
Pulse-Width Controller

A pulse-width controller, which varies the beam-pulse width from 1 μs to 0.7 ms, was installed upstream of the RFQ linac (see Fig. 1). An electric field of 2 kV, applied between two electrodes, deflects the beam direction, and unnecessary beams are stopped by beam slits. The purpose of the system is twofold: (1) While the pulse width required for synchrotron injection is on the order of 0.1 ms or less, the ion sources require a longer operation time for a stable beam supply. Unnecessary beams may be harmful to the linacs due to beam loading and possible contamination of linac electrodes. (2) A variety of experiments in the MEXP course (see a next section) require beam pulses having a much different width.

Medium-Energy Experiment Course

A new beam course, the medium-energy experiment course (MEXP), was constructed downstream of the DTL, as shown in Fig. 2. The new course enables users to utilize the beams from the DTL (6 MeV/u), which attract a lot of concern. The MEXP course can be branched off from the transport line by using a pulse-operated magnet (SWM2), so that it can be run in parallel with the synchrotron operation. Although MEXP users must use the same ion species as synchrotron users, they can obtain different lengths of beams from those injected to the synchrotron using the pulse-width control system described above.

Operational Schedule of the Injector

Daily Operation

The HIMAC is operated 24 hours per day from Monday through Saturday. The daytime (from 9:00 to around 20:00) from Tuesday through Friday is devoted to clinical trials or related data compilation. Monday is dedicated to a weekly inspection, the conditioning of new beams, and the technical training of operators. Experiments on basic research are being carried out during the night and on weekends.

Clinical Study

The clinical studies presently employ C beams with energies of 290, 350, and 400 MeV/u. Beams of C4+ supplied by the ECR ion source are accelerated by the injector up to 6 MeV/u, and pass through the C stripper foil to be fully stripped. About 250 μA of C5+ beams are provided to the synchrotron.

Precise positioning of the patients takes from 20 to 30 minutes, while beam irradiation continues for 2 minutes or less in typical cases. Irradiation corrected for respiration motion began in May, 1996. The treatment sites include the brain, head and neck, lung, liver, prostate, and uterus.

Basic Research

There are four experiment rooms: medium energy, physics and general, biology, and RI beam irradiation rooms. (The last one is not completed.) Experiments involving basic research include wide areas: physics, chemistry, engineering, and biology. In 1996, nearly 100 proposals were accepted, half of which were related to physics. The C beam is most commonly used in basic research, because the biology researchers are now concentrating their attention mostly on C beams. Experiments other than biology employ other kinds of beams, such as He, Ne, Si, and Ar. Seven proposals have been made which would use injector beams of He, C, Ne, and Ar. About 300 researchers inside and outside the institute participate in those researches. The beam time assigned for basic research in FY 1995 was 2200 hours in total.

Time-Sharing-Acceleration Mode

The two rings of the synchrotron can be operated independently, and injection beams into the rings are deflected by a pulse-operated switching magnet (SWM1). Using the associate of MEXP, it is possible even now that three user groups share the beam time (two beams from the synchrotron and one from the injector), if all groups utilize the same ion species. Since the condition is, however, not always satisfied, a system for a time-sharing-acceleration mode (TSA) was designed. Using TSA, it is possible to deliver different ion species to three user groups.

Our design policy is that all ions should be accelerated under the optimum condition, even in the case that beams with very different q/A values are accelerated simultaneously. Therefore, the excitation of the RF level and Q-magnets is changed on a pulse-to-pulse basis, as shown in Fig. 3.
The installation comprises several steps: (1) installing the third ion source. The new ion source was chosen to be an 18-GHz ECR ion source, so that heavier ions, such as Fe, which are strongly desired by many users, would be available [3]. The new ion source and their power supplies have already been installed. The new ion source was placed on an elevated deck 2.5 m high, as shown in Fig. 4, and the beam is extracted downward. Conditioning of the ion source started in June, 1996, and will continue until March, 1997.

(2) All of the DC-operated magnets were replaced by pulse-operated magnets. They include a switching magnet downstream of the ion sources, which distributes the beams from the three ion sources to the RFQ linac. The bending magnets and quadrupole magnets in the transport line were also replaced by pulse-operated ones. The replacement of those magnets and the installation of power sources are near completion.

The following steps are scheduled for 1996 or 1997. (3) Non-destructive-type current monitors will be installed in the transport line, since the measurement of a beam should not affect any other beams. The presently used profile monitors will be used in the TSA mode, although they are multi-wire and destructive types, since no alternatives are available at present. The controllers of the profile monitors will be replaced by new ones, and profiles of three beams can be observed, independently.

(4) The control of the entire system, especially the man-machine interface, was the most controversial issue. The present control system in HIMAC employs four touch panel CRTs as input and display devices. In principle, the TSA system employs the same hardware. The CRTs are assigned to the selected ions, exclusively, and it seems for operators that there exist three independent accelerators.

The scheduling of hardware/software replacements and conditioning of the new system is the biggest difficulty. A long halt of the beam supply must be avoided in order to insure a treatment time as long as possible. Six weeks around the summer and spring are the only periods reserved for accelerator-related work. The steps described above are divided into a few sub-steps and processed during these periods. The devices and programs are tested at the factories as much as possible before installation.

The first phase of the TSA, which supplies the different beams to the MEXP and synchrotron users, is scheduled to begin in March, 1997. The second phase, which will deliver different ion species to three groups, will begin in March, 1998.

Acknowledgments

We are very thankful to the operation crew of AEC. The members of the synchrotron division of the accelerator group have provided many helpful suggestions. Sumitomo Heavy Industries is appreciated for its skillful design of the devices in the injector.

References

DEVELOPMENT OF 700 PPS HIGH-DUTY-CYCLE LINE-TYPE PULSE MODULATOR

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Abstract

High-duty-cycle line-type pulse modulator has been developed to drive 5.5 MW S-band klystron at 700 pps maximum repetition-rate and 14 μsec flat-top pulse-width. To keep enough recovery time to thyratron-tube, the command charging scheme was adopted. To do this, a charging SCR-bank has been developed, which is capable of handling peak charging current of 50 A. The system achieved world wide highest average output-power of 205 kW.

Two modulators have been installed in a new high-duty-cycle electron linear accelerator, which has been started its business operation in March 1996 as an electron-beam sterilization facility.

Introduction

The electron beam sterilization facility needs very high-duty-cycle beam of energy around 10 MeV. For this purpose, a high-duty-cycle electron linear accelerator was designed, which requested to develop a new modulator to drive S-band klystron at 5.5 MW peak rf-output power, 14 μsec flat-top pulse-length and 700 pps repetition rate. The overall specifications related to the modulator are listed in Table 1.

To develop high-duty-cycle modulator, how to design the switching circuits is critical. In this paper, choice of switching device, understanding its proper usage and design of damage protection circuit will be described.

System Description

Figure 1 shows the system diagram of the modulator and Fig. 2 shows outlook of installed modulator in the electron beam sterilization facility. The system is basically a conventional line-type modulator, except its unique design on charging block using SCRs. Design details are described below.

Table 1 Overall specifications of the modulator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klystron beam voltage [kV]</td>
<td>140</td>
</tr>
<tr>
<td>Klystron beam current [A]</td>
<td>108</td>
</tr>
<tr>
<td>Electron Injector Gun voltage [kV]</td>
<td>150</td>
</tr>
<tr>
<td>current [A]</td>
<td>0.7</td>
</tr>
<tr>
<td>Modulator peak output power [MW]</td>
<td>15.1</td>
</tr>
<tr>
<td>Pulse width [μs] for flat top</td>
<td>14</td>
</tr>
<tr>
<td>-3 dB</td>
<td>19.2</td>
</tr>
<tr>
<td>Pulse stability and flatness [%]</td>
<td>±0.7</td>
</tr>
<tr>
<td>Pulse rise time [μs]</td>
<td>2.5</td>
</tr>
<tr>
<td>Pulse repetition rate [pps]</td>
<td>60–700</td>
</tr>
<tr>
<td>Maximum average output power [kW]</td>
<td>205</td>
</tr>
</tbody>
</table>

Fig. 1. Block diagram of the modulator.

Fig. 2. The modulator installed in the electron beam sterilization facility.
Command Charging System

When we use a thyatron-tube at very high repetition-rate, it is very important to keep enough recovery time before starting the successive charging process after the PFN discharge, otherwise the thyatron will start to continuously discharge. The conventional 'swing-charge method' can not be applied, since the time-constant of the swing becomes shorter in high-repetition modulator, thus the thyatron voltage can reach to a few hundred volt within the recovery time of 25 μsec, resulting in continuous discharge.

To solve this problem, we adopted a command charging system, which operates in a time-sequence as shown in Fig. 3. Switching the thyatron and discharging PFN capacitors, the next charging process is started by triggering the charging SCR by command after waiting-time, during this period the thyatron can be recovered perfectly. At the maximum repetition rate, the waiting time becomes minimum of 510 μsec, which is much longer than the required recovery-time to the thyatron. By varying the length of the waiting-time, repetition rate can be changed for wide range of 60 to 700 pps.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Thyatron switching parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
<td>Rated max.</td>
</tr>
<tr>
<td>Peak anode forward voltage</td>
<td>33</td>
</tr>
<tr>
<td>[kV]</td>
<td>1080</td>
</tr>
<tr>
<td>Peak anode current [A]</td>
<td>14.4</td>
</tr>
<tr>
<td>Average anode current [A]</td>
<td>-</td>
</tr>
<tr>
<td>Recovery time [μsec]</td>
<td></td>
</tr>
</tbody>
</table>

Choice of SCR

We chose Toshiba SH400EX29C for switching SCR, since it has one of the highest rated voltage among high speed switching SCRs except expensive optical-switching SCRs. To ensure reliable operation, we designed the operating voltage much lower than the maximum rated voltage. We use total number of 30 SCRs in series, thus the sum of the maximum rated voltage becomes 75 kV, which is 2.5 times higher than the operating voltage.

Trigger Circuit

Figure 4 shows the trigger circuit of one SCR-module, each module consists of six SCRs in a series. We use five SCR-modules in a series connection. Triggering signal is distributed via isolation pulse transformer into the six SCRs.

![Trigger circuit for SCR module.](image)

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Parameter of charging system</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFN charging voltage [kV]</td>
<td>33</td>
</tr>
<tr>
<td>Charging peak current [A]</td>
<td>50</td>
</tr>
<tr>
<td>rms current [A]</td>
<td>30</td>
</tr>
<tr>
<td>average current [A]</td>
<td>16</td>
</tr>
</tbody>
</table>

Protection Circuit for SCR

In order to protect the SCRs from excessive over-voltage due to different turn-on time between SCRs, series RC snubber circuits were connected in parallel to the SCRs as seen in Fig. 4, which compensates the voltage differences between SCRs. The RC parameters were optimized by computer simulations as not to generate over reaction voltage associated with PFN discharge [1].

Low Noise Design

In order to eliminate unwanted EM-noise radiation, it is very important to make low-impedance return-circuit to transfer the very high rush-current of wide frequency components associated with PFN discharge. In our design, a sheet copper of 365 mm width and 0.1 mm thickness was used to form a ground circuit, which runs through the charging circuit, the PFN, the thyatron, end-terminal of the tri-coaxial cable, the pulse-transformer tank and the klystron. In high
power operation, we do not see a noise ripple nor a jitter at any monitor signal on an oscilloscope.

**High Power Test**

We tested high power performances of the completed modulator connecting to an S-band klystron. Figure 5 shows the voltage waveforms at the klystron cathode at the design voltage of 142 kV, and the generated rf output power from the klystron at the designed output power of 5.5 MW and repetition of 700 pps. Ripple in the flat top was 1.6 kVpp ($\pm 0.6\%$) which is within the requested value. Figure 6 shows current trances in de-Q'ing circuit, they show designed waveform without any excessive rush currents. Figure 7 shows the charging patterns in PFN circuit and de-Q'ing trigger. Every waveforms showed expected design performances.

![Fig. 5 Channel 1 (top): RF output power, 5.5 MW peak. Channel 2 (bottom): Klystron beam voltage, 140 kV peak. Ch. 1 = 50 mV/div, Ch. 2 = 20 kV/div, Time Base = 5 ms/div.](image1)

![Fig. 6 Waveforms in de-Q'ing circuit. Channel 1 (top): de-Q'ing current on resistor, 300 A peak. Channel 2 (middle): total de-Q'ing current, 800 A peak. Channel 3 (bottom): de-Q'ing current on capacitor, 800 A peak. Ch. 1, Ch. 2, Ch. 3 = 200 A/div, Time Base = 200 µs/div.](image2)

![Fig. 7 Charging cycle on PFN capacitor. Channel 1 (up): PFN charging voltage, 33 kV peak. Channel 2 (down): de-Q'ing trigger. Ch. 1 = 5 kV/div, Ch. 2 = 5 kV/div, Time Base = 500 µs/div.](image3)

**Conclusions**

We have succeeded in developing a high-duty-cycle line-type modulator, which can handle the world-wide highest average output power of 205 kW at 700 pps repetition rate. Two modulators have been installed in the S-band electron linacs, which has been constructed for a dedicated use of 'electron beam sterilization' and started its business operation at March 1996.

**Acknowledgment**

The authors would like to thank to Dr. Hiroshi Matsumoto and Dr. Satoshi Osawa for their useful discussions on HV components.

**References**

[1] Details of the optimization work will be published in separated paper soon.
10 MeV 25KW INDUSTRIAL ELECTRON LINAC

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Abstract

A 10 MeV 25 KW class electron LINAC was developed for sterilization of medical devices. The LINAC composed of a standing wave type single cavity prebuncher and a 2 m electro-plated traveling wave guide uses a 5 MW 2856 MHz pulse klystron as an RF source and provides 25 KW beam power at the Ti alloy beam window stably after the energy analyzing magnet with plus-minus 1 MeV energy slit. The practical maximum beam power reached 29 KW and this demonstrated the LINAC as one of the most powerful S-band electron LINACs in the world. The control of the LINAC is fully automated and the "One-Button Operation" is realized, which is valuable for easy operation as a plant system. 2 systems have been delivered and are being operated stably.

Introduction

A 20 KW (beam power) class LINAC has the greatest market in the electron beam sterilization market. Several types of 20 KW class S-Band (2856 MHz or 2998 MHz) LINACs have been developed and marketed but most of them are unstable at the 20 KW operation and the practical beam power is limited to under 20 KW range. Under this situation, a small, stable and efficient S-Band sterilization LINAC with the capacity of 25 KW plus class (marginal beam power) is looked forward to for an expanding sterilization needs. We have developed a 25 KW plus class sterilization LINAC system successfully and two systems are operated at the customer's plant stably. In this paper, the detail of this new age 25 KW plus class S-Band electron LINAC is presented.

Design Concept

The main cause of the instability of most of the S-Band LINACs is the thermal instability of the accelerator guide under an intense heat load. In some cases, 20 to 30 KW RF power is dissipated in a 1 to 2 m accelerator guide with less than 10 cm diameter cavities. Beam loss in the accelerator guide gives an additional lumped heat load to some part of the accelerator guide where the beam is lost. The intense and uneven heat load distorts the cavities of the accelerator guide to destruct a correct acceleration phase relationship and cause the beam instability.

Our design concept is to reduce the RF loss and beam loss to the theoretical limit.

System Outline

The system construction is shown in Fig. 1. The system block diagram is shown in Fig. 2. The operational parameter and the performance is as follows.

Beam Energy : 10 MeV variable from 9 to 11 MeV
Energy Spread : 1 MeV (90% beam current)
Beam Power at beam window : 25 KW (guaranty) PPS = 550 Hz
PPS : 29 KW (actual) PPS = 630 Hz
Beam pulse width : 13.5 micro sec (nominal)
Beam current : 340 mA peak (nominal)
Frequency : 2856 MHz
Klystron power : 5 MW peak
Irradiation Surface : 60 cm from the beam window
Beam spot size : 16 cm diameter on the irradiation surface
Beam Scan Width : 30 cm to 80 cm variable
Scan Uniformity : within plus minus 5% (guaranty)

Fig. 1: System construction (accelerator side view).

Accelerator Guide

A traveling wave CG type guide is selected because a circulator and dummy load system for the input wave guide which constitutes a major loss can be deleted with the traveling wave guide and the klystron output port can be connected directly to the input port of the accelerator guide. The guide parameter is selected as 2 m long (60 cavities) and 0.38 Neper (attenuation factor) CG type to get the 10 MeV beam energy at the nearly heaviest loading condition with available klystron power of 4.8 MW at the guide input by the load line analysis. The beam current is 360 mA. The initial 8 cavities of the accelerator guide is the tapered buncher section and the disk spacing is determined by the electron phase analysis to get the best bunch suppression ratio for a tight energy spectrum and the phase limit of - 90deg (just on the crest of the accelerating field) for the best energy conversion efficiency. The energy conversion efficiency of the accelerator guide with the injection in the next paragraph is as high as about 70% (measured value) and nearly the theoretical limit. This good energy conversion efficiency reduces the heat load of the accelerator guide to as low as 10 KW (average) under the 25 KW beam power operation.
The new cooling scheme of the accelerator guide - ADAPTIVE COOLING (PAT. Pending) is introduced to control the phase relationship under the intense and uneven heat load.

Injector

The electron gun is a triode gun. A rather high gun voltage (140 KV) is selected for a better capture of injected electron beam at the buncher section. The gun voltage is supplied from the klystron modulator as a pulse voltage from the pulse transformer for the klystron. The electrode geometry of the electron gun is designed with simulation code E-GUN to get the best optics at the designed beam current of 400 mA. The gun cathode assembly is CPI EIMAC Y-845. The electron gun has a grazer type magnetic lens to compensate the variation of the optics due to the mounting tolerance of the cathode. The beam current is controlled by the grid voltage and stabilized with a feedback control. The current stability is less than plus minus 1% for a long period of operation.

The prebuncher cavity is a nose reentrant type cavity to suppress a multipactor discharge. The cavity is made of OFHC and the RF power is supplied with a over-coupled condition (coupling coefficient beta = 30). The effective Q factor is 300. This coupling scheme realizes a broad frequency characteristics to allow the frequency control of the accelerator guide (for reactive beam distortion compensation and adaptive cooling) and to reduce the phase and amplitude perturbation due to the beam loading.

Beam Dynamics

The beam dynamics is evaluated with PARMELA. The calculated and measured transmission efficiency are 90.2% and 90% respectively. Both values coincides fairly well. The calculated and measured beam profiles coincide well both in the spatial distribution and in energy distribution. The system is designed as a practical production machine and cannot accommodate a faraday cup and a slit for quantitative energy analysis. The energy spectrum is measured with a fluorescent plate (Desmarquest AP995R) at the slit position. The beam profile (Fig. 3) shows that the almost all current is included in the range of 1 MeV. The FWHM is about 0.4 MeV. There is no low energy tail which is usually observed for the industrial and medical LINAC systems which becomes a large amount of current integrated over a wide energy range and constitutes a large amount of beam loss at the energy slit. There was some high energy component observed but the component disappeared after the gun triggering timing alignment to the RF pulse to compensate an initial beam loading effect. The beam loss in the accelerator guide is 10% and the beam loss of the energy slit is 5%. The total beam loss between the electron gun and the beam window is only 15%.

The heavy beam loading causes a reactive phase distortion. This is compensated by adjusting the RF frequency upward by about 200 KHz to get the heaviest beam loading [1, 2].

Beam Break Up Consideration

The beam break up (BBU) is evaluated thoroughly, because a longer pulse width (13.5 micro sec) compared with other existing LINAC and a rather large beam current (400 mA) will lead to the BBU which results in a fatal failure in satisfying the performance specification.
A Regenerative BBU (R-BBU) is the BBU expected for this LINAC. The starting current of R-BBU is inversely proportional to the electron beam energy and occurs at the initial part of the accelerator guide where the electron beam energy is low. In CG type accelerator guide, HEM11 modes excited in the upper stream region can not go through the down stream region, because the HEM11 modes excited in the upper stream region fall in the stop band in the down stream region and are trapped and become standing waves. The 15 cavities (tapered buncher section-8 cavities and initial part of CG section-7 cavities, 15 cavities in total) are modeled and all dipole modes are sorted out with MAFIA. There are 10 dipole modes. In these dipole modes, pi-like modes are selected and three modes with the highest shunt impedance are evaluated as follows. The starting current estimation is based on Wilson's method [3, 4] including the effect of the magnetic focusing and the pulsed nature. The following value is a rough estimation, but a great margin is secured for 400 mA operation. There is no indication of BBU observed in the real operation and the beam pulse shape is quite stable.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Dipole Mode Freq. (MHz)</th>
<th>Starting Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 3</td>
<td>4213.2</td>
<td>3.25</td>
</tr>
<tr>
<td>No. 4</td>
<td>4226.8</td>
<td>2.10</td>
</tr>
<tr>
<td>No. 5</td>
<td>4234.8</td>
<td>3.09</td>
</tr>
</tbody>
</table>

Klystron Modulator

The klystron modulator is a line type pulser with a high average current thyatron (EEV CX-1720MN) as a main switching device. The command charging is introduced to secure the recovery time of the thyatron and a long life of PFN capacitors by minimizing the HV time of the capacitors. The klystron is Thomson TH-2154.

System Control

The whole accelerator system is controlled by a Programmable Logic Controller. A whole monitor and control function is integrated on a LCD touch sensing panel to realize 'ONE BUTTON CONTROL'. The communication with other computer system is provided to realize a fully remote control and one-man operation of a whole sterilization plant. The accelerator system reaches the predetermined operational condition from the stand-by mode in 1 minutes after the start up command full automatically.

Conclusion

A 10 MeV 25 KW plus class electron LINAC for sterilization of medical devices is successfully developed with the state of the art LINAC technology. Two systems are being operated stably at the customer's sterilization plant.

Acknowledgement

The author is grateful to Dr. P.B. Wilson of SLAC for his assistance in study of beam break up theory and Dr. J.W. Wang, also of SLAC for his theoretical assistance and prebuncher development. The author is grateful to engineers at Nihon Koushuha Co. Ltd. for their contribution in developing a Klystron modulator and RF components (RF window, etc).

The author is grateful to HOGY Medical Co. Ltd. for giving him the chance to develop the significant system and various valuable suggestions as a pioneer in the field of commercial high energy electron beam sterilization in Japan.

References

Dielectric Response of Particle Beams to Periodic Focusing

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Abstract

The dielectric response of a charged particle beam to a periodic focusing field enhances the effective focusing strength, reducing the matched beam radius and affecting the motion of halo particles. The change in the effective focusing strength is found for a uniform-density beam with a diffuse halo in a quadrupole channel, giving increases of 2% to 8% for some typical examples. These changes are important for both the production and behavior of halos in intense, high energy beams, in which fractional current losses as small as $10^{-8}$/m can result in radioactivation.

The effective focusing strength of a periodic channel is an important factor for accelerator applications requiring high beam intensities, such as heavy ion inertial fusion, radioactive waste transmutation, spallation neutron sources, tritium production and muon production. Limiting currents have been found in the past using the smooth approximation [1] to find the effective focusing strength of a periodic channel which, along with the aperture, determines the current that can be transported through a given channel [2]. Accurate knowledge of the effective focusing strength is also important for matching. Transverse mismatch has been shown to be an important cause of halo production and the resulting particle losses [3-5]. Fractional current losses as small as $10^{-8}$/m can result in radioactivation, inhibiting routine maintenance [6]; this can also be the limiting factor in the transport of intense, high-energy beams [7].

The dielectric response of a plasma to the periodic field of a Paul trap was recently shown to enhance the effective focusing strength of the trap [8]. The dielectric response results from the correlation between the oscillations in the space charge field and the periodic focusing field [9]. The dielectric response is shown here to increase the effective focusing strength of the channel, by an amount that depends on the shape of the beam, the type of focusing, and the ratio of the plasma frequency of the beam, $\omega_p$, to the frequency of the focusing, $\omega$. The dielectric response and the fractional change in the effective focusing strength are found for a uniform-density continuous beam with a diffuse halo and for a uniform-density ellipsoidal (bunched) beam, both in a quadrupole channel. The increase in the effective focusing strength results in a higher transverse phase advance per period, a higher average beam density and a lower average beam radius. Since accurate matching is important for beam applications requiring low losses, the effect of the dielectric response on the matched beam parameters can be important for the applications listed above.

A beam in a periodic focusing channel experiences a fluctuating electric field $E_f(r, s_0)$, which consists of the fluctuating component of the focusing field, $E_{rf}(r, s_0)$, and small fluctuations in the space charge field, $E_s(r, s_0)$. The position relative to the center of the beam is $r$, and the focusing is periodic in $s$, the longitudinal distance along the channel. Although particles with different longitudinal positions within the beam are at different phases in the periodic field, it is assumed that the effects of this are negligible so that the fluctuating fields can be written as periodic functions of the longitudinal position of the beam center along the channel, $s_0$. The focusing field and the space charge field are each divided into two parts so that the fluctuating components have an average value of zero and the steady-state components vary slowly or not at all with $s_0$.

The frequency of the focusing is $\omega = 2\pi v_B/S$, where $S$ is the period of the focusing along the longitudinal direction and $v_B$ is the beam velocity. In general there are three periods ($S_x$, $S_y$ and $S_z$) and three frequencies ($\omega_x$, $\omega_y$ and $\omega_z$), one for each of three directions in Cartesian coordinates ($x$ and $y$ are transverse and $z$ is parallel to the beam axis; for most practical applications $S_y = S_z$). The focusing field can be the result of electrostatic or magnetic quadrupole lenses, induction-aceleration gaps, and magnetic solenoids (if the beam is considered in the Larmor frame). It can also be the result of focusing by electromagnetic fields which are periodic in time and space, as in the case of radio-frequency quadrupole (RFQ) focusing. The focusing field is written as an electric field with the approximation that particle motion in the beam frame is nonrelativistic, so that magnetic focusing can be represented by equivalent electrostatic fields. The force resulting from the magnetic field of the beam is included in the self electric field (the space charge field) with the same approximation. Unless otherwise stated, all quantities are considered in the lab frame. With RFQ focusing and induction-acceleration gaps, it is assumed that acceleration along the longitudinal direction is slow enough that it can be treated as adiabatic, and that the beam is in phase with the time-varying field so that the focusing field can be treated as periodic only in longitudinal distance along the channel.

The effective focusing field can be found from the average field of a particle due to its motion in the periodic field [10]. The motion of a particle in the periodic field is first found with the fluctuating field as a function of position fixed at $E_f(r, s_0) = E_f(r_0, s_0)$, where $r_0$ is the position of the particle averaged over a period. The resulting particle position is $r_0 + \delta r$, the first-order variation in the position of the particle resulting from the fluctuating field is $\delta r$. The effective field that results from the fluctuating field is then found to first order from

$$E_{eff} = \langle E_f(r, s_0) \rangle = \langle (\delta r \cdot \text{DEL}_\theta) E_f(r_0, s_0) \rangle,$$

where $\text{DEL}_\theta$ is the gradient with respect to $r_0$ and the
brackets represent averages over a focusing period. The effective field of Equation (1) has previously been derived for a Paul trap without space charge [10] and for a periodic focusing channel without space charge fluctuations [11]. Solving for $\delta r$ from the fluctuating field and substituting into Equation (1) gives an effective field of

$$E_{\text{eff}} = \frac{q}{\gamma m v_B^2} \left( \int_{0}^{e} \int_{0}^{s_1} E_f (r_0, s_0^1) ds_0^1 ds_0^1 \cdot \text{DEL} \right)$$

where $q$ and $m$ are respectively the particle charge and mass, and $\gamma = (1 - v_B^2/c^2)^{-1/2}$ is the relativistic factor. In a quadrupole channel the steady-state component of the transverse focusing field is zero, so the field of Equation (2) is the total effective focusing field. For focusing by solenoids or longitudinal focusing by induction-acceleration gaps, the steady-state component of the focusing field is typically much larger than the effective field of Equation (2), so that the dielectric response, which affects only the fluctuating component of the field, has much less effect than in a quadrupole channel with the same frequency and focusing strength.

The dielectric response occurs through the effect of space charge fluctuations on $E_f (r_0, s_0)$. This will be found first for the core and halo of a uniform-density continuous beam with a diffuse halo in a quadrupole channel with average axial symmetry. The dielectric response will then be considered for the core of a uniform-density ellipsoidal (bunched) beam in a quadrupole channel with average axial symmetry.

The electric field in a transverse direction $\xi$ of a continuous, uniform elliptic beam with current $i$ and velocity $v_B$ is $E_{\xi \xi} = L x(x \epsilon) x^2 v_B x_m (x_m + y_m)$, where $x_m$ and $y_m$ are respectively the beam envelopes in the $x$ and $y$ directions, and $v_0$ is the permeability of free space [12]. In a quadrupole channel which has average axial symmetry, the fluctuations in the two transverse directions have the same magnitude and functional form, and are out of phase by $\pi$. The beam envelopes can then be written as $x_m = x_m + \delta x_m$ and $y_m = y_m + \delta y_m$, where $x_m$ is nearly independent of $x_m$ and $\delta x_m$ has an average value of zero. The electric field can then be split into a steady-state component and a fluctuating component with a linear expansion in $\delta x_m$. The resulting fluctuating field component is

$$E_{\delta x} = - \frac{i \delta x_m}{2 \pi v_0 x_m}.$$  

Using Equation (3), setting $E_{\delta x} = E_{\delta x} + E_{\delta x}$, where $E_{\delta x}$ and $E_{\delta x}$ are respectively the $x$ components of the fluctuating parts of the effective focusing field, the space charge field and the focusing field, and solving for $\delta x_m$, gives

$$E_{\delta x} = E_{\delta x} / \varepsilon,$$

in which $\varepsilon$ by definition is the dielectric constant. The dielectric constant for this case is

$$\varepsilon = 1 - \frac{\rho^2}{\omega^2},$$

in which $\Gamma = 1/\omega$, $\rho_0 = (q^2 n_0 / e \gamma m)^{1/2}$ is the plasma frequency, and $n_0$ is the particle number density. Equation (4) will be used for other types of beams and for halos with different values for $\Gamma$, depending on the geometry.

In deriving Equations (4) and (5) it was assumed that $\rho_0^2 / \omega^2 << 1$, and that fluctuations in the focusing fields and space charge fields occur sinusoidally with the same frequency. For most focusing channels the fluctuating component of the focusing field is not a sinusoidal function of longitudinal distance along the channel. In order to define the dielectric constant, the fluctuations are approximated as sinusoidal functions of $s_0$. Small deviations in the functional form are assumed not to have a significant effect on the dielectric response of the beam.

Since $\rho_0^2 / \omega^2 << 1$, Equation (4) represents an enhancement of the periodic focusing field. This effect results from the fact that the beam has maxima in its extent along any axis, and minima in the magnitude of its space charge field, at longitudinal positions along the channel where the focusing field along that axis is at a maximum. Likewise, the beam has maxima in the magnitude of its space charge field where the focusing field is at a minimum. Fluctuations in the space charge field are therefore correlated with the focusing so that they enhance the effective focusing field.

Substituting Equation (4) into Equation (2) leads to the conclusion that the effect of the dielectric response of the beam is to increase the effective transverse focusing field of a quadrupole channel by the factor $1/\varepsilon^2$. For example, a continuous beam in a quadrupole channel with $\rho_0 / \omega = 0.2$ has a dielectric constant of 0.98. The dielectric response increases the effective focusing field of this channel by about 4%.

The same technique can be used to find the effect of the dielectric response on halo particles surrounding the uniform-density core of a continuous beam. The model of a uniform-density continuous beam core that is mismatched in a continuous (nonperiodic) focusing channel has been used to study the evolution of halo particles [5], in which variations in the space charge field resulting from the oscillating core were found to drive some particles to larger radii. Here, the effect on the effective focusing strength is found from oscillations of the space charge fields for a matched beam in a periodic channel. The same result applies to a mismatched beam in a periodic channel if the frequency of the mismatched oscillations is much less than $\omega$.

The beam has average axial symmetry, and variations in $x_m$ and $y_m$ are out of phase by $\pi$. The dielectric response of halo particles arises from the periodic motion of the particles relative to the beam axis, and also from the periodic variations in the shape of the core. The position of a halo particle is written as $(x, y) = (x_m + \delta x_m, y_m + \delta y_m)$, and the envelopes are again $x_m = x_m + \delta x_m$ and $y_m = y_m + \delta y_m$. Using the electric field along a transverse direction outside of a continuous, uniform-density elliptic beam core [12], the self electric field can be written in terms of a steady-state component and a fluctuating component with linear expansions in the fluctuating quantities. Solving for the resulting particle motion by the same method as in the previous case, the
fluctuating field is again described by Equations (4) and (5). In this case
\[ \Gamma = \frac{x^2_{\text{m}} (x_0^2 - y_0^2)}{(x_0^2 - y_0^2)^2} + \frac{x^2_{\text{m}} (3y_0^2 - x_0^2)}{(x_0^2 - y_0^2)^2}. \]  
(6)

For example, with \( x_0 = 1.5x_{\text{m}} \) and \( y_0 = 0, \omega_{p}/\omega = 0.2 \) gives a dielectric constant of approximately 0.99. The dielectric response increases the effective focusing field at this location by about 2%.

The same method will now be used for the core of a bunched beam with average axial symmetry, which is taken as a uniform-density ellipsoid. The envelope fluctuation in the longitudinal direction is typically either out of phase with the transverse fluctuations by \( \pi/2 \) or it has a different (and nonresonant) frequency from the transverse fluctuations; either way it can be ignored in finding the effective transverse focusing. The electric field in a transverse direction inside a uniform ellipsoid without images [12] can be split into a steady-state component and a fluctuating component with a linear expansion in \( \Delta z_{\text{m}} \). The remaining integral is solvable analytically, resulting in a fluctuating field component of
\[ E_{\text{fkt}} = -\frac{3\Omega x_{\text{m}}}{4\pi c} \cdot \frac{z_{\text{m}}}{z_{\text{m0}}} \cdot \frac{1 - 3(1 - \xi^2)^2 \ln(1 + \xi)}{2 \xi^2} + \frac{3(1 - \xi^2)^2}{8 \xi^4} \]  
(7)

where \( \xi = (1 - x_{\text{m}}^2/2z_{\text{m0}}^2)^{1/2} \) is the eccentricity of the bunch in the beam frame, \( z_{\text{m}} \) is the beam envelope in the z direction and \( Q0 \) is the total charge of each bunch. For a bunch that is spherical in the beam frame \( (\gamma z_{\text{m}} = z_{\text{m0}}) \), Equation (7) becomes \( E_{\text{fkt}} = -\frac{3\Omega x_{\text{m}}}{4\pi c} \cdot (10\pi x_{\text{m}}^2)^{-2} \). The same method as in the previous cases results again in Equations (4) and (5), in which \( \Gamma \) equals the quantity in square brackets in Equation (7). For the special case in which the bunch is spherical in the beam frame, \( \Gamma = 0.4 \). For example, a bunch with an aspect ratio of \( \gamma z_{\text{m}}/z_{\text{m0}} = 2 \) (for which \( \Gamma \) is approximately 0.4) in a quadrupole channel with \( \omega_{p}/\omega = 0.3 \), has a dielectric constant of approximately 0.964. The dielectric response increases the effective focusing field of this channel by about 8%.

The envelope equations [13] can be used to relate \( \omega_{p}/\omega \) to the transverse space charge tune depression \( (k_v/k_{\text{v0}}) \) and the phase advance per beam \( (\sigma_{v0}) \), giving
\[ \frac{\omega_{p}}{\omega} = \sqrt{1 - \frac{k_v^2}{k_{\text{v0}}^2}} \cdot \frac{\sigma_{v0}}{\pi \sqrt{2g}}, \]  
(8)

in which \( g = 1 - g_{\text{r}}^2/2g_{\text{m}} \). \( g_{\text{r}} \) is the radial geometry factor, which is a function only of the aspect ratio of the bunch, \( \gamma z_{\text{m}}/\gamma z_{\text{m}} \), when image fields are negligible; it is a function also of the pipe radius when image fields are significant [14]. Without image fields, \( g \) can be approximated as \( 2\gamma z_{\text{m}}^3 x_{\text{m}} \) when \( 1 \ll \gamma z_{\text{m}}/x_{\text{m}} \ll 4 \) with about 10% accuracy. Equation (8) applies for a continuous beam with \( g = 1 \). The first example of a continuous beam with \( \omega_{p}/\omega = 0.2 \) could therefore correspond to \( k_v/k_{\text{v0}} = 0.5 \) and \( \sigma_{v0} = 59^0 \).

The example of a bunched beam with \( \gamma z_{\text{m}}/x_{\text{m}} = 2 \) and \( \omega_{p}/\omega = 0.3 \) could correspond to \( k_v/k_{\text{v0}} = 0.5 \) and \( \sigma_{v0} = 80^0 \).

Two uniform-density beams with the same energy, current, space charge tune depression, and aspect ratio will have different matched beam properties if one is in a periodic quadrupole channel and one is in a channel with continuous focusing, if both channels have the same effective focusing strength in the absence of space charge. With space charge, the effective focusing strength of the periodic channel is increased over that of the continuous channel, resulting in a smaller phase advance per period, a higher average beam density and a smaller average beam radius.

Reducing the frequency of the focusing increases the dielectric response and increases the effective focusing strength for a uniform-density beam, but also results in greater oscillations of the matched beam envelope. For applications in which current loss into the conducting channel is an important factor, the increase in the magnitude of the envelope oscillations as the focusing frequency is decreased could lead to greater particle losses even as the effective focusing field on the beam core is enhanced.

Acknowledgment

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References

[13] Reference 11, Section 5.4.11.
A GRAPHIC USER INTERFACE FOR THE PARTICLE OPTICS CODE TRANSPORT

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Abstract

A graphic user interface (GUI), providing for easy problem set up and data input, has been integrated with the TRANSPORT program. TRANSPORT is a third-order optics code that is one of the standard programs used in the design of charged particle beam lines. We have developed a GUI for TRANSPORT using the Shell for Particle Accelerator Related Codes (S.P.A.R.C.), a software environment developed specifically to support accelerator simulation programs. Problem set up is accomplished graphically. The configuration of a TRANSPORT beam line is defined by selecting icons representing transport elements from a palette and dragging them to a window. A dynamic data structure is used, which expands as the beam line model is built. Default data is provided for all elements so each beam line is fully defined as it is constructed. Specific problems are formulated by editing the data presented in specialized windows: different options for describing each element are available, word descriptions for every parameter are given, several choices of units including “smart units” are offered, and user guidance limits are displayed for all parameters. TRANSPORT is executed using a MAD-type data file written by the GUI. This new approach to using TRANSPORT is described and examples from the interface are illustrated.

Introduction

TRANSPORT [1] is one of the standard programs used to model and design charged particle transport lines. Although TRANSPORT offers powerful fitting and other analysis capabilities, new users often find the initial set up of a design problem challenging and time consuming. We have developed a new approach to using TRANSPORT by integrating it with a GUI designed specifically to support particle beam simulation and analysis programs. Known as the Shell for Particle Accelerator Related Codes (S.P.A.R.C.), this GUI provides a unique software environment customized to the needs of the accelerator community [2]. The approach adopted for TRANSPORT is similar to that used for integrating other programs into the S.P.A.R.C. environment [3,4,5]. Figure 1 shows a computer interface screen for the TRANSPORT GUI. Several advanced capabilities have been added to S.P.A.R.C. that are aimed at improving the productivity of new users. These new features were evaluated using a prototype of the TRANSPORT GUI as the primary computer tool in a recent course at the U. S. Particle Accelerator School (USPAS). This paper emphasizes several of the new features as well as other improvements implemented following the USPAS.

![Figure 1. Example of the TRANSPORT graphic user interface.](image-url)
Overview of the GUI for TRANSPORT

Three primary elements of the interface are similar to those of other S.P.A.R.C.-based applications and are shown in Figure 1: a Menu Bar, Palette Bar, and Document Window. The Menu Bar contains standard (File, Edit) menu items, specific menus (View, Commands, Preferences) used to support TRANSPORT, and a special menu (Trajectories) that supports new ray tracing modules built in to the GUI that do not use TRANSPORT. The ray tracing modules were developed for a cross-platform educational version of the software that is described elsewhere [6]. The Document Window and Palette Bar are the primary interface components for setting up a beamline. An example of a TRANSPORT beamline appears on the lower part (Model Space Pane) of the Document Window in Figure 1. To build a beamline, transport elements are selected from the Palette Bar and dragged to the Model Space Pane of the Document Window. The Palette Bar contains icons representing all of the transport components and other elements available in TRANSPORT.

Data Input

Parameters are input using Data Tables. The Global Parameter Pane shown in Figure 1 illustrates the basic Data Table which contains five fields for each parameter: the parameter name, a value input box, the units of the parameter, and two user guidance limits for the parameter value. The guidance limits can incorporate expert system type rules-of-thumb [2,3] to assist the user in setting up problems. All guidance limits are soft, so that any value can be entered and it will be passed to TRANSPORT. The limits serve only to provide users with a visual alert if an entered value may have impractical consequences.

Users may select different options for the units of a parameter via pop-up menus in the units field. The guidance limits, as well as the current value, are immediately displayed in the selected units. The Global Parameters include all of the top level beam parameters, the particle charge and mass, the initial beam energy, etc. Only some of the Global Parameters are used for TRANSPORT calculations while others, such as the beam current, are used by the ray tracing modules [6].

Data input for individual components ("Pieces") of the beamline is accomplished using Data Tables in Piece Windows. A Piece Window is accessed by "double clicking" the mouse button while the cursor is on the desired beamline component. The Piece Windows developed for the TRANSPORT GUI have several enhancements that distinguish them from those used in previous S.P.A.R.C.-based applications. Figure 2 illustrates an example of a new Piece Window.

One of the new features of the enhanced Piece Windows is the ability to use different sets of parameters to describe a beamline element. For the bend element illustrated in Figure 2, there are five different ways of defining the dipole strength of the bending magnet. The selection of input options shown in Figure 2 is based upon the different ways that a magnetic bend can be specified in a TRANSPORT input file, although other options could also be included in the Piece Window. When the user selects one of the dipole strength options, the value input boxes for the parameters associated with that selection become active (can be edited), while other (dependent) parameter values are presented in a display-only mode (cannot be edited). The S.P.A.R.C. expert rule system immediately updates all display-only parameters whenever an editable value is changed, providing users feedback on other bend parameters.

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Figure 2. Example of new Piece Window, for parameter input to the magnetic bend element of TRANSPORT.

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Output Displays

Graphic displays of TRANSPORT output data have traditionally been available only by using postprocessor programs with data archive files. Our GUI provides built-in plotting and graphical tools that display plots immediately after a TRANSPORT calculation. Three options are available for setting up plots using the current version of the GUI. Plots can be specified for (a) up to four matrix elements as a function of the beamline accumulated length, (b) up to four beam half-widths or centroids as a function of the beamline accumulated length, or (c) plots of the transverse (horizontal and vertical) phase space ellipses at the location of the Final Piece in the beamline. Figure 3 shows an example of the phase space ellipse plots.

![Final Ellipse Plots](image)

Figure 3. Example of Final Ellipse Plots.

Once a graph such as that shown in Figure 3 has been generated, several support functions are available to the user for further analysis of the data. Specific plotted points used to generate the graphs are displayed by selecting Show Points. The coordinates of any plotted point are displayed by clicking on the symbol for that point. Any region of the graph may be selected and the Zoom In button used to expand the display for that region. An unlimited number of zooms are available for any region of the graph. An increasingly detailed display of the graph data can be generated by using multiple applications of the Zoom In feature.

Other Features

The GUI for TRANSPORT includes several other advanced features to aid researchers in solving beamline design problems, and to assist students in learning about particle optics. A full compliment of GUI tools has been developed to support TRANSPORT's fitting and parameter variation capabilities [1], including the ability to define algebraic functions of input and output parameters for use as fitting constraints. The Trajectories menu contains options [6] for tracing (and displaying) the transverse beam envelopes through the beamline, including space charge, and for tracing a single ray through the beamline, incorporating the effects of the envelope space charge forces. The TURTLE [7] program can also be run directly from the interface to trace up to 10,000 rays through the beamline.

Summary

A new graphical user interface has been developed for the TRANSPORT code. The integrated TRANSPORT-GUI program provides an interactive and intuitive package for designing beamlines. Both accomplished and novice users of TRANSPORT have realized increased productivity using the GUI. The new package compliments other codes operating in the same software environment [3-5] and provides accelerator scientists with a useful new tool.

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WAKEFIELDS IN THE TRACE 3-D CODE

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Abstract

TRACE 3-D is an interactive code that calculates and displays the envelopes of a bunched beam through a user-defined transport system. Accelerating elements and linear space-charge forces are included. The beam is described by a 6-D sigma matrix of second moments. We have extended the capabilities of this code to include effects, such as wakefields, related to the variation of the beam bunch in the longitudinal direction. This nonlinear capability was implemented by adding centroid tracking and describing the beam by a collection of slices, each described by a 6-D centroid and sigma matrix. External forces, space-charge forces, and wakefields act on the collection of beam slices. Results are presented in terms of an overall sigma matrix, computed by combining the slice distributions. The new TRACE 3-D has been integrated with an improved graphic user interface (GUI) based on the Shell for Particle Accelerator Related Codes (S.P.A.R.C.). This new approach to modeling wakefields demonstrates the flexibility of extending the capabilities of moment codes to handle important physical effects, and the rapid incorporation of the new capabilities into the graphic interface illustrates the ease of customizing the new GUI. The wakefield model and features of the new interface are presented.

Introduction

The TRACE 3-D program [1] is one of the standard codes used in the design of linear accelerators and transport lines. A new version of TRACE 3-D has been developed that computes the short-time (single bunch) wakefield effects that can alter the bunch distribution. In order to model the effects of wakefields, we imagine the beam bunch to be divided into a number of slices longitudinally. Each slice of the bunch is then described by its own 6-D centroid and 6x6 sigma matrix. The effects of wakefields are modeled using a multipole expansion of the forces which act on the beam as a function of the longitudinal position within the bunch. Monopole, dipole and quadrupole terms (wake functions) are included. These terms can be expressed as transfer (R) matrices which act on the centroids and sigma matrices of each slice. The approach has been outlined by Chan [2], and follows the development of Chao and Cooper [3] for the code LTRACK, but we do not assume that the beam is traveling at the speed of light.

To implement this model in TRACE 3-D, new wakefield "optical" elements have been developed that are used to describe the monopole, dipole and quadrupole wakefield functions [2]. These are currently modeled as a second-degree polynomial in the longitudinal position, although other parameterizations could be readily implemented. One of the key differences is the use of a GUI designed specifically to support particle beam simulation and analysis programs. Known as the Shell for Particle Accelerator Related Codes (S.P.A.R.C.), this GUI provides a unique software environment customized to the needs of the accelerator community [4]. Earlier versions of TRACE 3-D have been integrated with the S.P.A.R.C. GUI for several years [5]. New capabilities have been added to S.P.A.R.C. that are aimed at improving the customization of the GUI to meet the differing needs of users. These new features were utilized to create a prototype GUI for use with the new TRACE 3-D.

Overview of the Beam Model

The initial beam bunch is assumed to be uniformly filled, upright ellipsoid in \((x, y, z)\) with

\[-z_{\text{max}} \leq z \leq z_{\text{max}}\]  

(1)

The bunch is divided into \(2N+1\) equal-length slices, labeled from \(-N\) (head) to \(+N\) (tail). Slice number 0 is centered at \(z=0\). Let \(z_i\) be the \(z\) value at the upstream face of slice \(i\) and define \(z_{i+1}\) to be \(z_{\text{max}}\). Since the number of particles, \(n_i\), in a slice of length \(\Delta z\) is proportional to the square of the distance from the bunch center. Introducing the variable \(z_{\text{max}} = \frac{z}{z_{\text{max}}}\) one has

\[
\Delta n_i \sim (1 - C^2) \Delta z
\]

(2)

With this distribution, the \(z\)-centroid of slice \(i\) is given by

\[
\langle z_i \rangle = \frac{[6z_{2i} - 3z_{4i} - 6z_{6i}^2 + 3z_{8i}^3 + 1]}{[12z_{2i} - 4z_{4i} - 12z_{6i}^2 + 4z_{8i}^3]^2} z_{\text{max}}
\]

(3)

The fraction of particles in slice \(i\) is given by

\[
n_i = \frac{[3z_{2i} - 3z_{4i} + z_{6i}^2]^2}{4}
\]

(4)

To estimate the \(z\)-centroid of each slice, it is assumed that the ratio of the centroid values \(\langle z_i \rangle / \langle z \rangle\) is the same as \(z_{\text{opt}} / z_{\text{max}}\), where \(z_{\text{opt}}\) is the maximum value of \(z\) for the \(z\) ellipse and \(z_{\text{max}}\) is the value of \(z\) at \(\zeta = z_{\text{max}}\). From the definition of the Twiss (Courant-Snyder) parameters for the \(z\) ellipse, then

\[
\langle z \rangle = \frac{\alpha_z}{\beta_z} \langle z \rangle
\]

(5)
The transverse emittances, \(e_x\) and \(e_y\), are adjusted at each slice according to

\[
e_x = \frac{1}{f} - \frac{\langle\varepsilon_x^2\rangle}{2\sigma_{x\text{max}}^2} \exp \frac{\langle\varepsilon_x^2\rangle}{f}
\]

where the factor \(f\) is the ratio of the average to maximum emittance value

\[
f = \sum_i \left[ 1 - \frac{\langle\varepsilon_x^2\rangle}{\sigma_{x\text{max}}^2} \right] n_i.
\]

The values of \(\sigma_{55}\) and \(\sigma_{66}\) for the \(i\)-th slice are estimated from

\[
\sigma_{55i} = \left(\frac{\Delta z}{2}\right)^2,
\]

\[
\sigma_{66i} = \left[ \frac{\langle\varepsilon_x^2\rangle}{\beta_x} - \frac{\langle\varepsilon_y^2\rangle}{\beta_y} \right] e,
\]

where \(\Delta z = 2\sigma_{\text{max}} / (2N+1)\), and \(e\) is ratio of the average to maximum \(\sigma_{66}\) value

\[
e = \left[ \frac{\beta_x}{\beta_y} \right] \sum_i \left[ \frac{\langle\varepsilon_x\rangle}{\beta_x} - \frac{\langle\varepsilon_y\rangle}{\beta_y} \right].
\]

The centroids and sigma matrices for each slice are transformed through the beamline using the usual transfer matrix formalism. Each TRACE 3-D optical element [1] is described by a 6x6 R-matrix, \(\mathbf{R}\), that transforms the beam over a distance \(\Delta s\) in the element according to

\[
\mathbf{X}(s + \Delta s) = \mathbf{R}(\Delta s) \mathbf{X}(s),
\]

\[
\sigma(s + \Delta s) = \mathbf{R}(\Delta s) \sigma(s), \mathbf{R}(\Delta s)^T.
\]

where \(<\mathbf{X}(s)>\), \(\sigma(s)\), and \(\sigma(s)\) are the 6-D centroid and \(6\times6\) sigma matrix for the beam slice at position \(s\). Existing TRACE 3-D subroutines are used to compute the \(R\)-matrix elements for the standard optical elements, but new subroutines have been written to carry out the transformations described by (11) and (12). As described in the next section, new subroutines for modeling the wakefield optics have also been written.

The longitudinal slices for the beam bunch are recomputed to compute effective bunch centroids and sigma matrix elements. The overall bunch centroid is given by

\[
<X> = \sum_i n_i <X>_i.
\]

The individual elements of the overall bunch sigma matrix are given by

\[
\sigma_{ij} = \sum_k n_k \left[ \sigma_{ijk} <u_x^k> <u_y^k> - 5 \sum_k n_k \Sigma_i <u_x^k> \Sigma_i <u_y^k> \right],
\]

where \(u_i\) represents \((x,x',y,y',z,z')\) for \(i=1,6\) and

\[
\sigma_{ijk} = \frac{1}{5} \langle u_x^k u_x^l u_y^k u_y^l \rangle,
\]

is the sigma matrix for the \(k\)-th slice. The individual slice centroids and overall sigma matrix are used to compute space charge effects with a modified space charge model that takes into account the effective force on each slice centroid. The overall bunch centroids and overall sigma matrix are utilized for generating graphic output displays of the beam envelopes and centroid locations.

**Wakefield Optical Elements**

Three new "optical elements" have been added to TRACE 3-D to model the monopole, dipole and quadrupole wakefield functions. These elements are inserted into a beamline model immediately after each element that is responsible for generating a wakefield. The monopole wakefield changes the energy of the bunch slices, the dipole wakefield causes deflections of the transverse centroids of the slices, while the quadrupole wakefield effects the sigma matrices of the bunch slices in addition to the energy and transverse centroids. The three wakefield multipoles are expressed in terms of wake function strengths per unit length, \(W_0(s), W_1(s), W_2(s)\).

Each wakefield acts on a bunch over the length, \(L\), of the element responsible for generating the wakefield. The product of this length and the multipole strengths are used for computing the wakefield effects [6] and are modeled as second degree polynomials:

\[
L W_0(s) = p_0(1) + p_0(2)s + p_0(3)s^2,
\]

\[
L W_1(s) = p_1(1) + p_1(2)s + p_1(3)s^2,
\]

\[
L W_2(s) = p_2(1) + p_2(2)s + p_2(3)s^2.
\]

The three coefficients for a given multipole, \(p_0(1), p_0(2)\) and \(p_0(3)\), are user inputs for the corresponding wakefield optical element.

The effects on the energy and centroid of the \(k\)-th slice are given by [6]:

\[
\Delta E_k = -\sum_{i<k} n_i L W_0(<x>_i - <x>_k),
\]

\[
\Delta <x>_k = C_k \sum_{i<k} n_i L W_1(2<x>_i - <x>_k),
\]

with an expression similar to (20) for \(\Delta <y>_k\). The sigma matrix for the \(k\)-th slice is transformed with a \(R\)-matrix, with elements that differ from the identity matrix given by [2]:

\[
R_{21} = -R_{43} = q_1,
\]

\[
R_{23} = R_{41} = q_2,
\]

with

\[
q_1 = C_k \sum_{i<k} n_i L W_2(2<x>_i - <x>_k),
\]

\[
q_2 = C_k \sum_{i<k} n_i L W_2(2<x>_i - <x>_k),
\]

The \(q_1\) and \(q_2\) terms correspond to normal and skew quadrupole moments, respectively. The coefficient \(C_k\) appearing in (20), (23) and (24) is a function of the relativistic energy factor of the \(k\)-th slice, \(\gamma_k\), and is given by

\[
C_k = \frac{r_e}{r_e(M/m_e)} \gamma_k,
\]

where \(r_e\) is the classical radius of the electron, \(m_e\) is the electron mass and \(M\) is the particle mass.
Integration with the GUI

User defined optics elements, such as the wakefield elements described above, may be easily integrated into the S.P.A.R.C. GUI for TRACE 3-D using a new TableBuilder application. The TableBuilder is used to create customized data input windows called Piece Windows [5]. Custom Piece Windows for user defined elements provide the same functionality as other Piece Windows, including options for the choices of parameter units, including several "smart units" options, and lower and upper user guidance limits. The guidance limits are soft, that is, any parameter value may always be entered. The limits are utilized to provide the user with a visual alert when his or her input value may have impractical consequences.

<table>
<thead>
<tr>
<th>Element Parameters</th>
<th>Value</th>
<th>Units</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Term P0(1)</td>
<td>0.0050</td>
<td>uV</td>
<td>0.0000</td>
</tr>
<tr>
<td>Linear Term P0(2)</td>
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<td>uV/m</td>
<td>0.0000</td>
</tr>
<tr>
<td>Quadratic Term P0(3)</td>
<td>0.0000</td>
<td>uV/mm²</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

The TableBuilder for MacTrace™ and PowerTrace™ is used to create custom Piece Windows for data input.

Figure 1. Example of custom Piece Window for a wakefield element, created using the TableBuilder application.

Once a custom Piece Window such as that shown in Figure 1 has been generated, the graphic construction of beamlines that include the user defined elements is the same as for beamlines with any other optical elements [4,5]. The setting up of arrays and other input for TRACE 3-D is accomplished by the GUI and is transparent to the user.

Several other improvements to the GUI have also been implemented and a few more are under development in order to fully support the new TRACE 3-D capabilities. Several additional smart units options have been added to the Global Parameters [5]. For example the Beam Energy may be input in terms of the relativistic velocity (β), relativistic energy (γ), or particle momentum (in GeV/c), in addition to eV, keV, MeV or GeV. The radiofrequency may be entered as either a frequency or a wavelength, with several options for each. The S.P.A.R.C. expert rule system [4,5] provides all conversions and gives users feedback in any of the available units options for his input.

Other Enhancements

A few other optical elements have been added to TRACE 3-D as part of this work, and some additional parameters have been added to existing elements to support misalignment modeling. In particular, the rotate element has been modified so that it can model either rotations (yaw and pitch, as well as roll) or displacements of the beam axis. Roll and displacement parameters, including an option to generate random values, have been added to the quadrupole. An electrostatic quadrupole has been added to the program. We also note that together with a suite of other electrostatic elements (prisms, einzel lenses and acceleratortubes) developed as part of other work, versions of TRACE 3-D are available for studying a broad spectrum of bunched and continuous beam accelerator systems.

Summary

A new version of the TRACE 3-D code has been developed for modeling wakefield effects and similar phenomena related to variations of a beam bunch in the longitudinal direction. A number of new optical elements have been added to support the modeling of wakefields and misalignments. The new version of TRACE 3-D has been integrated with an enhanced version the S.P.A.R.C. GUI that allows users to customize the integrated TRACE 3-D / GUI program to meet individual needs.

Acknowledgements

The authors are indebted to Chris Babcock for assistance in incorporating changes to the GUI Global Parameter Pane and for modifications to existing Piece Windows. Portions of this work have been completed as part of Cooperative Research and Development Agreement (CRADA) number LA95C10203 between the Los Alamos National Laboratory and G. H. Gillespie Associates, Inc.

References

PRELIMINARY TEST OF $\pm \Delta F$ ENERGY COMPENSATION SYSTEM

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Abstract

The 1.54 GeV S-band linac for the Accelerator Test Facility (ATF) accelerates multi-bunch beam. The beam has 20 bunches of $2 \times 10^{10}$ electrons with 2.8 ns bunch spacing. When multi-bunch beam is accelerated in the linac, the beam has the energy deviation by transient beam loading. The 1.54 GeV S-band Linac is an injector of the damping ring (DR), and the energy acceptance of the DR is $\pm 0.5\%$. This means that the beam loading compensation system is necessary in the linac for a successful injection of multi-bunch into DR. The system consists of a compensating section in addition to a regular accelerating section. The accelerating structures of compensating section are operated with slightly different RF frequencies of 2856$\pm$4.327MHz. This paper describes the principle of the beam loading compensation system and the results of energy compensating experiment.

Introduction

For future linear colliders, one of essential technique to get a sufficient luminosity is the ability to accelerate multi-bunch beam with small bunch spacing. As the pulse length of a multi-bunch beam is shorter than the filling time of accelerating structures, the energy gain of successive bunches drops by approximately linear function due to a transient beam loading in the accelerating structures. The energy loss ($E_{bl}$) at time $t$ after the first bunch injection is

$$E_{bl} = \frac{r_0sL}{2} \left[ \frac{2\pi^2 - 2t - 1 - e^{-2\pi t}}{1 - e^{-2\pi t}} \right].$$

where $r_0$, $s$, $\tau_0$, $\tau_f$ are the instantaneous current of the beam and shunt impedance, the attenuation parameter and the filling time of the accelerating structures, respectively. The instantaneous beam current is expressed as

$$i_0 = \frac{eN_b}{\tau_p},$$

where $e$, $N_b$, and $\tau_p$ are $1.6 \times 10^{19}$C, the total number of electrons per bunch and bunch separation, respectively. There are many methods to compensate transient beam loading, such as $\Delta T$ method, $\Delta F$ method and so on. The $\Delta T$ method is to inject a beam before an rf pulse has filled in an accelerating structure. The $\Delta F$ method is to have one or more accelerator structures running at slightly higher and lower than fundamental frequency and roughly in 90 degree out of phase from the acceleration.

Principle of $\pm \Delta F$ Energy Compensation System

The $\Delta F$ Energy Compensation System (ECS) compensates for multi-bunch energy spread by keeping a bunch separation synchronized with an rf frequency. In this compensation system, compensating structures are installed between the regular accelerating structures. When a bunch train goes through the compensating structures driven at an rf frequency which is slightly higher and lower than the fundamental accelerating frequency, successive bunches of the train ride on a different phase of the accelerating field (see Fig. 1). Due to this phase difference, the energy gain of the successive bunches is different. As a result, the multi-bunch energy spread is compressed to a small value. When a bunch train enters the compensating structures of $+\Delta f$, the energy gain is lower for the bunch head and higher for the tail due to the fact that each bunch accelerates at a positive slope of the part of sinusoidal wave in the structure. To compensate for this single-bunch energy spread which is created in the compensating structures, two frequencies ($f-\Delta f$, $f+\Delta f$) are necessary in order to compensate it by both a negative slope and a positive slope.

![Fig. 1. Principle of the $\pm \Delta F$ energy compensation](image)

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This energy compensation system has a high flexibility for bunch population changes, the amount of compensation can be controlled by the input RF power applied to the compensation structures.

\[ \pm \Delta f \] Energy Compensation System in ATF

The 1.54 GeV S-band Linac of ATF accelerates a multi-bunch beam that consists of 20 micro-bunches with 2.8 ns spacing and the repetition rate of 25 Hz. After acceleration in the 1.54 GeV linac, the multi-bunch beam are injected into DR which generates extremely low emittance beams. The energy acceptance of DR is \( \pm 0.5\% \). As the multi-bunch beam with intensity of \( 2.0 \times 10^{10} \) electrons/bunch is accelerated in the 1.54 GeV linac and a bunch train is injected after an rf pulse has filled in an accelerating structure, the multi-bunch energy spread of a bunch train is evaluated to be about 9.6% peak to peak without AT and \( \Delta f \) compensation as shown in Fig. 2. Therefore, the beam loading compensation system is necessary in ATF for a successful operation of multi-bunch scheme. With the \( \Delta f \) energy compensation system, the multi-bunch energy spread can be reduced to 0.27% with beam intensity of \( 2.0 \times 10^{10} \) electrons/bunch.

![Energy Compensation System](image)

**Fig. 2. Evaluated beam loading in ATF linac**

**Experimental setup**

As shown in Fig. 3, the ATF rf system of the accelerator section consists of 8 regular rf units and 2 ECS rf units.

![Accelerator section](image)

**Fig. 3. Accelerator section of the ATF 1.54 GeV injector linac (LO-L16 regular sections, C1, C2 compensating sections)**

The regular rf units consists of an E3712 klystron, a pulse modulator, a two-iris SLED cavity, rf waveguides, two 3 m-long accelerating structures and rf dummy loads. The ECS rf unit is composed of a SLAC-5045 klystron, a modulator, and a 3 m-long accelerating structure. The accelerating structures for the energy compensation system are designed for two frequencies \( (f_0 \pm \Delta f) \). The rf pulse waveform from the two SLAC-5045 klystrons is rectangular with a width of 1.0 \( \mu s \).

**Timing system**

In contrast to the regular accelerating section where the bunches are accelerated onto the crest of the RF wave, in the compensation section the bunches enter a phase where a slope of the part of sinusoidal wave. That is, a small jitter results in large uncertainty in the energy gain of bunches. In this reason, a very stable accelerating rf signal is required.

In the ATF, the fundamental frequency is generated using a 1428 MHz master oscillator, and the other necessary frequencies are generated from this reference signal using frequency multipliers and dividers. All the components are synchronized to this master oscillator. The sideband frequency for the compensation was selected to be 4.327 MHz signal, twice the revolution frequency of the DR, and 1/660 of the accelerating frequency. This frequency was decided by the bunch number (20 bunches) and the DR revolution frequency. Two compensation signals \( (f_0 \pm \Delta f) \) are generated by mixing the fundamental (2856 MHz) and the sideband (4.327 MHz) signal in the special module. Phase jitter was measured by generating two signals of the same sideband and feeding them into a mixer. The result of this measurement was 1.7 ps jitter at FWHM (\( \sigma = 0.8 \) ps)[1][2].

**Measurement system of the beam energy**

The beam energy of each bunch was measured from the strength of the bending field and the beam position after the bending magnet of the beam transport line. The measurement of the beam position for each bunch was performed by using stripine type BPM. The multi-bunch signal from BPM was measured by the digital oscilloscope of 2.5 GHz sample. The energy difference in a bunch train was calculated from the horizontal beam position and the dispersion function \( (n) \) at the BPM position. In this measurement, the position resolution of the BPM is limited by a sampling resolution and speed of the digital oscilloscope. The position resolution is evaluated to be 22.5 \( \mu \)m from the measurement range of the oscilloscope, the signal amplitude and the coefficient of sensitivity of the BPM. This value is sufficient to measure the beam position for each bunch, as the position resolution is converted into the energy resolution of 0.003%.

The dispersion function at the BPM was measured and compared to the calculated value by the program "SAD"[3] in the beam test. The measured value was 14% lower than the calculated value. The discrepancy is small compared to the DR energy acceptance. In the beam test of the ECS, the dispersion function of calculated value by the program "SAD" was used.

The beam profile were observed by a profile monitor using an optical transition radiation (OTR). A fast gated camera which has ~3 ns gate width, is used for the OTR monitor. The beam energy spread of each bunch was measured
by the width (FWHM) of the profile at the beam transport line. The profile of each bunch was distinguished by changing the delay of the gated camera timing.

**Preliminary beam test of the ECS**

**Adjustment of RF phase for the ECS**

An adjustment of the RF phase for the ECS was performed by using the OTR monitor. At first, the gate timing of the OTR camera was set to the center of the bunch train. Then, the current of the bending magnet was adjusted that the bunch profile was seen on the center of the screen. An ECS phase was searched by a phase scan with 20 degrees step. Fig. 4 shows the beam energy dependence on the ECS phase. The optimum phase was decided from the result of a phase scan to find 90 degree apart from the accelerating phase.

![Fig. 4. ECS phase scan](image)

**The measurement of multi-bunch energy spread**

In this experiment, the multi-bunch of 23 bunches/pulse accelerated up to 1.16 GeV with intensity of $3.2 \times 10^{10}$ electrons/train. The bunch population of each bunch is shown in Fig. 5. After the adjustments of the ECS RF phase, the RF power of the klystrons were set to get a flat energy distribution for all bunches with 1.9 MW for $+\Delta f$ and 1.5 MW for $-\Delta f$. The result of ECS on/off is shown in Fig. 6. The energy of each bunch distributed in about 1.5% without ECS, where the calculated energy difference was 2%. The ECS could compress it to about 0.5%. The energy decrease of the bunch train head seems to come from a BPM miss-reading by the beam loss of the collimator in front of the BPM.

Fig. 7 shows a single-bunch energy spread of each bunch with $\pm\Delta f$ ECS and $+\Delta f$ only. The single-bunch energy spread with the $\pm\Delta f$ ECS was around 0.3% FWHM. When only $+\Delta f$ ECS is applied on increase of single-bunch energy spread is expected. Although, there is no significant difference in this low compensation voltage. The detail of the single-bunch energy spread measurement is presented in elsewhere[4].

![Fig. 6. multi-bunch energy spread](image)

![Fig. 7. Single-bunch energy spread](image)

**Summary**

The beam test of the ECS was performed by using 2856±4.327MHz structures in the ATF linac. When the calculated energy difference by the beam loading was about 2%, the ECS could compress it to 0.5% by using rf power of 1.9 MW for $+\Delta f$ and 1.5 MW for $-\Delta f$ with $3.2 \times 10^{10}$ total intensity.

**Acknowledgment**

The authors would like to acknowledge all the member of the ATF group and Mr. Morita of E-CUBE corporation for their useful discussion, cooperation and support. The authors also appreciate to Drs. T. Suda and H. Honma of photon factory division in KEK for the reason that they have readily lent us the pulse modulators for the ECS.

**References**


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RF AND BEAM DIAGNOSTIC INSTRUMENTATION AT THE ADVANCED PHOTON SOURCE (APS) LINEAR ACCELERATOR (LINAC)

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Abstract

A system of beam diagnostics and rf phase and amplitude measurement, based mostly on VXI, was implemented at the APS Linac and has now operated successfully for more than two years. Standardization of instrumentation among the various APS accelerators accounted for some of the non-VXI packaged equipment that was used. Equipment for which the optimum topology or location did not lend itself to VXI was also accommodated so as to yield the greatest stability, reliability, and flexibility.

The APS Linac instrumentation is described, and operational performance is discussed. Future plans, including an expansion to include a switchable spare klystron (which can be accommodated with only minor changes to the VXI-housed equipment) and a beam position monitor using frequency domain analysis to provide improved determination of positron position in a mixed-particle beam condition are also discussed.

Introduction


The VXI-based instrumentation includes rf phase and amplitude measurements and beam position monitors (BPMs), that use outboard down-conversion. Monitoring of beam current, Faraday cups, and slits is VME-based, following the APS standard. Loss monitors and average current monitors use other types of packaging. A fifth-harmonic cavity, used as a bunch monitor, was successfully tested but has not yet been set up for operational use.

Fluorescent screens and related image processing constitute a separately controlled subsystem and are discussed elsewhere [2,3].

Equipment Topology

The rf schematic for the APS linac is shown in Figure 1. Linac sectors are comprised of a klystron and associated accelerating structures. Three sectors incorporate SLED cavity pulse compression. The principal phase measurement is made at the SLED output or at the klystron output in sectors without SLEDs. Multiplexed phase measurements are available for other forward power samples, including at the input and output of each accelerating structure. Envelope detector channels are provided for almost all of these signals and for reflected power signals as well.

Each accelerating structure has its own loss monitor.

Fig. 1. The linac rf diagram, showing the division by klystron into five sectors.

There are three wall-current monitors in the linac. Two are located in the electron linac and the third is at the end of the positron linac.

Six BPMs are installed in the electron linac, one downstream of each accelerating structure and one in the diagnostic line following the electron linac analyzing magnet. Seven BPMs are installed in the positron linac, one downstream of six of the last seven accelerating structures and one in the diagnostic line following the positron linac analyzing magnet.

Equipment Description

The VXI data collection modules were designed by Los Alamos National Laboratory (LANL) [4] with upgrades accomplished collaboratively by LANL and Argonne National Laboratory (ANL). A common digital interface exists on all modules, while three types of on-card signal conditioning allow measurements of rf amplitude, rf phase, and beam position. Each channel digitizes a single measurement during each linac pulse. Each module can also be commanded by software to put analog signals onto either or both sets of designated local bus lines on the backplane.

Analog-to-digital conversion in all modules is done by a Datel SHM-49 hybrid track/hold amplifier and an AD574, 12-bit, monolithic analog-to-digital converter, yielding a 10-MHz bandwidth.

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The VXI data collection and conversion modules used for each type of measurement are described below.

**Phase Measurement**

A down converter module driving a vector detector module (VDM) produces two channels of I and Q waveforms and digital data. The VDM operates at 20 MHz and uses two insulated, ovenized, I/Q demodulator assemblies. Phase is calculated by software and can be plotted by on-line sweeping of the sampling time. A phase between -180° and +180°, with a resolution of 0.01°, is computed from measured I and Q data. The smaller in magnitude of I and Q is always used as the numerator in the computation to avoid losing precision near the sine wave maxima. Line-stretcher type phase shifters are included at the reference inputs of each sector's phase measuring modules. These phase shifters are set so that the phase reading of each sector can be set to approximately +90° at maximum energy conditions for electrons. There are two advantages to this choice. +90° is a point where phase is calculated as:

\[
\cos^{-1}\left(\frac{I^2}{\sqrt{I^2 + Q^2}}\right),
\]

where I is near zero and the I channel has a lower noise level than the Q channel. In addition, the readings for electrons at +90° and positrons at roughly -90° will not fall near the point of discontinuous readings located at ± 180°.

**Amplitude Measurement**

Envelope detector modules provide eight channels of diode-detected signals. Linearized values for each possible raw output value from the analog-to-digital converter, interpolated from calibration of 88 points per channel, are stored in an EEPROM.

**Beam Position Monitor**

A logarithmic amplifier electronics system is used with stripline BPMs to measure electron and positron beam positions at the APS linac. Stripline-type BPMs were chosen because they provide -5 dBm of peak signal from the 8-mA positron beam.

The electronics can be subdivided into two sections, a downconverter section and a logarithmic amplifier section. Both the external downconverter and the 70-MHz logarithmic amplifier BPM VXI module have eight channels to accommodate two sets of horizontal and vertical stripline signals.

The downconverter section consists of a 2.856 GHz-to-70 MHz downconverter followed by a 70-MHz bandpass filter and amplifier. The bandpass filter stretches the 30-ns pulse to around 200 ns and reduces its amplitude by some 13 dB. This 70-MHz signal is used as the input to a cascaded chain of logarithmic amplifiers consisting of two Analog Devices AD640 with their video bandwidths set to 7 MHz. Beam position is calculated from the relative stripline signal amplitudes. With the signal-to-noise ratio at the input to the logarithmic amplifier circuits approaching 75 dB, resolutions of 1 μm should be possible [5].

**Timing and Software Peak Detection**

A different trigger timing system than the one used at LANL is used for most measurements in the APS linac and improves resolution and jitter by more than an order of magnitude. The upgraded LANL modules allow any of the VXI backplane triggers to be directly selected, or the LANL default triggering system can still be used. A VXI trigger module, designed at ANL, contains a set of eight-bit programmable delay lines that can be used to select sample time in increments of 5 nanoseconds. A separate delay line controls each of the two ECL triggers and eight TTL triggers on the VXI backplane. Software peak detection by scanning is available for all signals. Time scans are automated and replace the hardware peak detecting circuits that are commonly used. A typical SLED waveform time scan is shown in Figure 2.

![Fig. 2. A typical SLED waveform timescan.](image)

**Non-VXI Diagnostics**

Wall current monitors are based on a design previously used at Fermilab [6]. The signals from current monitors, Faraday cups, and slits are processed with a VME-packaged, high-speed gated integrator [7].

The loss monitors use a design that is standard throughout the APS, in which a 500-V power supply energizes a 7/8-inch air-dielectric coaxial cable that is used as an ionization chamber. A signal processing chassis contains multiplexers, optical isolators, and current-to-voltage amplifiers. A voltage proportional to the average
beam loss in the monitored accelerating structure is digitized in a VME module [8].

Performance

The phase detection modules have achieved 0.1 degree average repeatability. Operating performance has supported closed-loop operation with as little as 0.5 degree dead zone.

Envelope detectors used in amplitude measurement have been repeatably calibrated to within 0.2 dB of a standard. Operational performance has been somewhat inconsistent, however, and errors of 0.5 dB have been reported. Some of this is due to trigger timing errors, and there is an ongoing effort to provide more specific timing for each signal.

Operational BPM resolution is acceptable at 53 μm, and loss monitor sensitivity is at least 4.2 pA/pC with 0.3 s minimum averaging time.

Future Plans

A system which will provide switching of a sixth klystron and modulator in place of any of the basic five is under design. Figure 3 is a layout of the most probable topology for accomplishing the switching. Additional waveguide bi-directional couplers are being added to the two sectors without SLEDs so that the principal phase measurement will be made at the input to each sector, independent of which klystron is actually driving that sector. SLEDed sectors are already compliant, as the measurements are made at the SLED output. As a result, only very minor changes to the phase measuring system will be required.

A new BPM system that gives information on the polarity of the charged particle producing the signal (electron or positron) has been developed, and will provide for much improved positron diagnostics capability [9]. The new design takes advantage of the fact that electrons and positrons have different phase relationships between odd and even order frequency components by detecting I and Q separately for fundamental and second harmonic components of the stripline signals. A prototype is under development.

Conclusions

The instrumentation has supported the successful operation of the APS Linac. Improvements in accuracy, resolution, and convenience of remote readout are continuing as needs are identified.

Acknowledgments

Work is supported by the U. S. Department of Energy, Office of Basic Sciences under the Contract W-31-109-ENG-38. We sincerely acknowledge the efforts of C. Gold, D. Jefferson, J. Stevens, and J. Hawkins, whose efforts in support of the linac instrumentation were essential to the successful results. We gratefully acknowledge D. Haid for graphics assistance.

Fig. 3. The mechanical layout for switching in the spare klystron.

References

A NEW ELECTRON GUN MODULATOR FOR THE ELETTRA LINAC

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Abstract

The ELETTRA Linac is equipped with a triode type electron source, capable to deliver up to 1 A beam current at 100 KeV electron energy. The first part of the Linac, named ELETTRA 100 MeV, is capable of delivering both relatively short electron pulses (2 ns for single bunch operation and 10-300 ns for multibunch operation), suitable for storage ring injection, and with a much longer pulse train for FEL operation. Until now the switching between the two operating modes required hardware settings on the gun modulator electronics, resulting in time loss and limitation in flexibility.

A completely new integrated electron Gun Modulator has been developed which supports both operating modes. Hereafter the new design architecture and the results of preliminary tests are presented.

Introduction

The first part of the ELETTRA Linac, the 100 MeV pre-injector, has been preliminary tested [1,2] to verify its capability of producing an electron beam burst in order to drive the IR/FIR FEL under development at Sincrotrone Trieste [3,4,5].

A complete description of the Trieste pre-injector Linac can be found in [6], in table 1 the expected FEL beam parameters are listed.

Up to now, we have operated the machine in the FEL mode mainly at 30 MeV with a 5 μs macropulse at 10 Hz repetition rate.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (MeV)</td>
<td>20 ± 75</td>
</tr>
<tr>
<td>Energy spread @ 75 MeV (%)</td>
<td>± 0.3</td>
</tr>
<tr>
<td>Macropulse repetition rate (Hz)</td>
<td>10</td>
</tr>
<tr>
<td>Macropulse length max. (μsc.)</td>
<td>10</td>
</tr>
<tr>
<td>Macropulse repetition rate (MHz)</td>
<td>20.8 ± 31.2</td>
</tr>
<tr>
<td>Macropulse length FWHM (μsc.)</td>
<td>10</td>
</tr>
<tr>
<td>Charge per macropulse (nC)</td>
<td>0.4</td>
</tr>
<tr>
<td>Peak Current (A)</td>
<td>37.5</td>
</tr>
<tr>
<td>Normalized Emissance rms (mm mrad)</td>
<td>62.5</td>
</tr>
</tbody>
</table>

In a first stage, due to hardware constraints, we were also obliged to work at a fixed macropulse repetition rate of 25 MHz, while a notable limitation for the maximum achievable beam macropulse width, 5 μs instead of the 10 μs expected, was caused by the poor performances of the PFN (Pulse Forming Network), which only provides an useful pulse length for the klystron up to 6 μs.

Anyway, up to May '96, the major constraints to continue the machine operation and tests in FEL mode has been derived from the very long time required in switching the machine set up from injection to FEL modes; in particular more than one hour was necessary to replace the Injection Gun Modulator with the FEL Gun Modulator, since a single unit supporting both operating modes was not available until that data.

Starting from the second half of '95 we have developed and assembled a new Gun Modulator Unit that can be operated both for the injection and for the FEL modes.

At the beginning of May '96 the beam test on the first prototype assembled on the Linac was started.

The New Gun Modulator Unit

The Trieste Gun is a standard thermionic Pierce triode, using a commercial planar cathode-grid unit, Thomson TH 306, with an emitting surface of 1.2 cm². The cathode-grid assembly is negatively HV referred with a low voltage grid bias for current interdiction.

In Fig.1 the emitted currents as a function of the negative grid bias for two different anodic voltage settings (60 and 75 kV) are reported. Due to HV power supply limitation, we could not extend our measurements beyond 50 mA. The reported data have been collected on keeping the grid negatively biased at 30 V and superimposing a continuous adjustable positive pulse.

![Fig. 1 Gun emission curves at 60 and 75 kV.](image)

In our case, to interdict the electron emission at 85±10 kV anodic voltage, a negatively bias on the grid of about -14 V is needed.

The new modulator unit combines on a special designed PCB the single bunch mode as well as the FEL mode.

At 10 Hz pulse repetition rate one can obtain a single 2 ns pulse for Storage Ring injection, or a frequency variable pulse train ranging up to 32 MHz, variable in steps of 2 ns, for FEL operation. In the second case the macropulse length can be continuously adjusted up to 30 μs keeping the repetition rate fixed at 10 Hz.

In Fig. 2 a block diagram of the pulser (a) and the pulse time sequences (b) are reported.
A synchronized trigger (the main trigger) is sent via a fiber optic link to the clock of a flip-flop circuit; the two flip-flop exits are suitably delayed (5 nsec) and logically combined (AND1-AND2) to trigger the two main pulser circuits, AV1 and AV2; these make use of two 2N2369 transistors operating in avalanche mode.

The two transistors are alternately fired at half of the selected operating microbunch repetition rate and an hybrid circuit, recombines the two pulse trains to pilot the cathode of the gun.

The main trigger is synchronized with the 500 MHz frequency of the machine. The jitter between the two pulse trains before the pulser AV1 and AV2 has been measured and found to be lower than ±0.5 nsec. No remarkable jitter increase was observed from the avalanche pulser or from transistor pairs which were differently matched.

The measured pulse to pulse amplitude stability seems to be acceptable (≤5%). Nevertheless, more work has to be performed and accurate measurements will be necessary to find the best operating conditions of the system.

In May '96 we have operated the machine with the new gun modulator in single bunch mode and in FEL mode with a micropulse repetition rate ranging from a few MHz up to 32 MHz. The macropulse beam current at the Linac exit has been measured to be higher than 100 mA.

In Table 2 the main beam parameters measured in May '96 compared with the previous measurements taken in '95 are reported.

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>March '95</th>
<th>May '96</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>30 MeV</td>
<td>30 MeV</td>
</tr>
<tr>
<td>Macropulse current</td>
<td>30 mA</td>
<td>≥100 mA</td>
</tr>
<tr>
<td>Horizontal emittance @ 30 MeV</td>
<td>3.38 mm mrad</td>
<td>4.22 mm mrad</td>
</tr>
<tr>
<td>Energy spread @ 30 MeV</td>
<td>≤±0.6%</td>
<td>≤±0.51%</td>
</tr>
</tbody>
</table>

### Conclusions

The preliminary tests performed on the first prototype of the new gun modulator has given encouraging results. Further improvements are now under consideration in order to increase the performance of the prototype.

We are considering the use of a wide band RF amplifier which should increase the peak current emitted from the gun. A new trigger scheme, with a 500 MHz programmable divider, is now under consideration in order to further reduce the pulse to pulse jitter and to improve the beam amplitude stability.

### Acknowledgements

The authors are grateful to all the Linac technical staff for the continuous help received.
References

POWER MODEL OF BIPERIODIC DAW CAVITY

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Abstract

A high power model of the biperiodic L-support DAW for
electron acceleration is fabricated and under test. Two 1.2m
long accelerating tubes are coupled by a bridge coupler, which
has an RF coupler, a vacuum port, and three frequency tuners.
Each end of the bridge-coupled tube set is terminated by a full-
cell endplate for the accelerating mode. The operating
frequency is S-band so that the DAW accelerating tube can
replace a conventional disk-loaded-waveguide accelerating
tube for high power tests. The mechanical design and the
measured parameters are described.

Introduction

An electron linac[1] has been installed at the Accelerator
Laboratory, Institute for Chemical Research, Kyoto
University. Its use is mainly intended as the injector for the
electron storage ring KSR [2,3], which is being assembled.
Three of 3-m disc-loaded wave-guides are installed as the
accelerator tubes, which are operated at 2857MHz. By
replacing one of the wave-guides with a new accelerating tube
with a higher shunt impedance and the higher accelerating
gradient, the output energy can be increased with the same
input RF power.

Design of Power Model

A cold model made of Aluminum was fabricated to study
the characteristics of the DAW structure with biperiodic L-
supports [4]. Based on the results from the cold model tests, a
high power model was designed and three units of the power
model have been fabricated.

Figure 1 shows the schematic drawing of the power
model. Because of the biperiodicity of the structure, one unit
of the power model contains a disk-ring and a unit frame with
two washers supported by L-supports. The unit frame is
reversible with 90° rotation. The unit frames and the L-
supports are made of chromium copper for the mechanical
strength. In order to have the cooling water channel, the
washer is divided into two OFC (Oxygen Free Copper) parts,
which are brazed together in a furnace. The L-supports are
bent pipes with the thickness and the diameter of 1mm and
6mm, respectively. Two washers and four L-supports are
brazed on the frame. Photo 1 shows the unit frame.

The disk-ring is inserted between two unit frames, where
the RF contact is achieved by 0.2mm hight knife edges on the
inner corners of the unit frames. The seam between two unit
frames will be welded together. The disk-ring is made of OFC,
and has four 2 mm x 2 mm evacuation grooves on the outer
surfaces that the space between the knife edges and the welded
seam is open to the inside. The whole assembly is covered by
a stainless steel pipe, and cooled by water jacket. Cooling
water comes from outside of the jacket pipe to the washers
through the pipes screwed on the frames and through the L-

Fig. 1 Schematic Drawing of the power model.

Photo 1 Unit frame of the power model.
supports. The other ends of the L-support-pipes on the outer surface of the unit frames are open to the water jacket. Two outlet ports are located on the outer surface of the stainless steel jacket pipe. The assembled accelerating tube has longitudinal symmetry with 90° rotation so that the direction can be reversed for an improvement of the electric field distribution.

Two of the accelerating tubes are coupled by a coaxial bridge coupler, which has an evacuation port and frequency tuners. The RF power is fed through the coupling slot on the coaxial bridge coupler. The spool in the bridge coupler is supported by four straight pipes connected to the body of the bridge coupler, so that the cooling water can go through the spool. The electric field distributions in the bridge coupler for the accelerating mode and the coupling mode are shown in Fig. 3 and Fig. 4, respectively.

**Low Power Test of Unit Frame**

Three of the power model units are fabricated for mechanical investigations. Each accelerating mode frequency is measured with two half cell endplates. The half cell endplates are made of Aluminum, so as not to distort the edges on the unit frame much. A unit frame is put between the half cell endplates, and the stack is pressed by six M8 bolts at the torque of up to 150 kg-cm (see Photo 2). The results are shown in Table I. The estimated Q-value by SUPERFISH is 21000, which does not include the power loss on L-supports. Although the surface of the washer, which is made of OFC as stated before, seems clean, the surface of chromium copper looks dark, which may be one of the reason of the low Q-value. The conductivities on the chromium copper and aluminum are assumed as 70% and 65% of that on copper, respectively, which may not be accurate enough for us to compare the absolute value of the Q-value.

![Coaxial bridge coupler](image)

**Photo 2** The configuration of the accelerating mode frequency measurement. The unit frame is put between the half-cell endplates, and the stack is pressed by six bolts.

**Table 1 Measured accelerating mode frequency and Q-value.**

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Frequency [MHz]</th>
<th>Q value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2860.167</td>
<td>14100</td>
</tr>
<tr>
<td>2</td>
<td>2860.887</td>
<td>13900</td>
</tr>
<tr>
<td>3</td>
<td>2859.385</td>
<td>13900</td>
</tr>
</tbody>
</table>

![The electric field plots for the accelerating mode.](image)

![The electric field plots for the coupling mode.](image)

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All the three units are stacked together with two aluminum alloy disk-rings inserted in between, and the accelerating mode frequency is measured as 2858.083 MHz.

The measurement of the coupling mode frequency is not as easy as the accelerating mode frequency, because of the termination problem. Strictly speaking, the measurement of even the accelerating mode frequency does not show the right biperiodic configuration, because the half cell endplate gives mirror symmetry, and then the configuration is quad-periodic. The L-supports do not perturb the accelerating mode much, and then the periodicity problem should not be serious on accelerating mode. The coupling mode frequencies are being evaluated combining with the cold model cells.

The electric field distributions are measured by the bead-pull perturbation method. The three-stacked unit frames are put between the cold model cells (see Photo 3). The measured electric field distribution for a configuration of eighteen accelerating gaps is shown in Fig. 5. The electric field distribution in the power models is smoother than that in the cold model, which shows the higher mechanical precision of the power model than that of the cold models.

**Conclusions**

We are accumulating the technical knowledge for building the high power structure through these experiments. Because the duty factor for this particular application is very low (less than $10^{-4}$), the heat problem may not be so serious. Simulation studies on the water flow, the heat transfer, and the thermal expansion are scheduled.

**Acknowledgment**

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**References**


DOUBLE-FEED COUPLER FOR THE LINEAR COLLIDER

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Abstract

Symmetrical electric field in a coupling cavity was obtained with a double-feed type coupler in which two irises couple to symmetrical TM₀,₀-mode. To simplify the structure, J-shaped waveguide was attached to the cavity for feeding the rf power through the two irises. Good field symmetry was verified by the perturbation method. The cavity was tested in maximum surface gradient up to 118 MV/m which was limited by a klystron performance and not breakdown limit. The field emission current was measured with Faraday cup and the microscopic field enhancement factor of 66 was obtained with Fowler-Nordheim plot and no critical discharge occurred. It was confirmed that the presented double-feed coupler is capable of handling high surface gradient more than 100 MV/m.

Introduction

In next generation linear colliders in the center of mass energy range of 300–500 GeV, high luminosity of 10^{33}–10^{34}/cm²/s is required[1]. To obtain high luminosity, it is necessary to accelerate electron beams maintaining its low emittance. One of the main reason to cause beam deflection and emittance growth is the asymmetrical field around the axis because of its coupling iris. A magnetic field component associated with this asymmetrical field kicks electron beam in transverse direction. To solve this problem, different types of double-feed coupler have been proposed and developed by SLAC[2][3] and DESY[4]. They have good symmetrical field but the structures are rather complicated because they use power divider. To simplify the structure, we developed a new type of double-feed coupler of which J-shaped waveguide was attached to the cavity as shown in Fig. 1.

Structure

In the structure shown in Fig. 1, rf power is fed by J-shaped waveguide through two irises, which are located at opposite symmetrical positions around the axis of the cavity. Rf characteristics were measured as listed in Table 1.

<table>
<thead>
<tr>
<th>Table 1. rf characteristics of the double-feed coupler.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant frequency</td>
</tr>
<tr>
<td>Coupling coefficient β</td>
</tr>
<tr>
<td>Unloaded Q</td>
</tr>
</tbody>
</table>

![Fig. 1. Double-feed coupler. J-shaped waveguide was attached to the cavity.](image1)

![Fig. 2. (a) Equivalent circuit model of the double-feed coupler. (b) simplified model.](image2)

Fig. 2. (a) Equivalent circuit model of the double-feed coupler. (b) simplified model.

The principle of the double-feed coupler is explained with an equivalent circuit model as shown in 2 (a). The parallel LCR resonator represents coupling cavity and the susceptance \( jB_1 \) and \( jB_2 \) are associated with the irises. Here, we assume no loss in the transmission line. The impedance \( Z(z) \) seen from an arbitrary position \( z \) to a short plane is given as:

\[
Z(z) = jZ_0 \tan \frac{2\pi}{\lambda_g} z
\]

where \( Z_0 \) is the characteristic impedance of the transmission line and \( \lambda_g \) is the guide wavelength. When the irises are
located at the position $z_i = (n + \frac{m}{2} + \frac{1}{4})\lambda_s$, the impedance $Z(z_i)$ and $Z(z_f)$ become infinite. The susceptance $jB_1$ and $jB_2$ looking from the rf source are equal because the distance between two irises is $n\lambda_s$. In this case, we can omit the impedance $Z(z)$ and simplify the equivalent circuit model from (a) to (b). Same power is fed in the cavity from each iris.

We chose the integers $m = 1$ and $n = 3$.

**Field Distribution**

The field distribution was obtained by the perturbation method with a dielectric bead (φ3.0, spherical, made by macor) as a perturbation object. To verify improvement of the field symmetry, it was compared with that in a conventional single-iris coupler cavity.

When a dielectric bead is used, the deviation of the resonant frequency $\Delta f$ is represented as:

$$\frac{\Delta f}{f_0} = \frac{k\varepsilon_r\chi_e|\vec{E}|^2}{4U} \Delta \tau$$

where $f_0$ is the resonant frequency of the cavity, $k$ the geometrical factor and equal to 3 in this case, $\varepsilon_r$ the dielectric constant in vacuum, $\chi_e$ the electric susceptibility, $\vec{E}$ the electric field, $\Delta \tau$ the volume of a perturbation object and $U$ the energy stored in the cavity. By moving the bead and measuring the frequency shift $\Delta f$, the field intensity is calculated from equation (2). The field distribution was measured by moving the bead from one iris to the other. The measured field distributions are shown in Fig. 3. The field symmetry in the cavity was better than that in the conventional single-iris coupler cavity.

**High Gradient Experiment**

In order to investigate the high power performance, high gradient experiment is performed. Maximum surface gradient, microscopic enhancement factor, momentum distribution of field emission current and vacuum level were measured. A layout of the experimental apparatus is shown in Fig. 4. A 5MW klystron is used as a power source which supplies rf power in the coupler cavity through a waveguide filled with SF6 gas. An rf window separates this waveguide to the other vacuum type waveguide.

Incident and reflected power were measured with Bethe-hole type coupler and these waveforms are shown in Fig. 5. The maximum surface gradient $E_{r,\text{max}}$ is given as the function of the incident power $P_{in}$ as:

$$E_{r,\text{max}} [\text{MV/m}] = 68\sqrt{P_{in} \text{[MW]}}$$

The incident power is limited by the klystron performance. In this case, the maximum power was limited up to 3.4 MW. The maximum surface gradient of 118 MV/m was obtained without any critical discharges. The break down limit seems considerably higher than this value.

---

**Fig. 4. Layout of the high gradient experiment.**

**Fig. 5. The waveforms of incident rf power and reflected rf power.**
Microscopic enhancement factor $\beta$ is obtained from the Fowler-Nordheim plot which is given as:

$$\log \left( \frac{\bar{j}_f}{E_{\text{F},\text{cutoff}}} \right) = \frac{-6.53 \times 10^9 \cdot \phi^{1.5}}{E_{\text{F},\text{cutoff}}} + \log \left( \frac{57 \times 10^{-12} \cdot \phi^{0.95}}{\phi^{1.5}} \cdot \beta^{2.5} \right)$$

where $\bar{j}_f$ is the field emission current, $\phi$ the work function. The field emission current was measured with Faraday cup FC-1 and the maximum surface gradient was given by equation (3). The microscopic enhancement factor of $\beta = 66$ was obtained from the Fowler-Nordheim plot as shown in Fig. 6.

Fig. 6. Fowler-Nordheim plot from which the microscopic enhancement factor of 66 is obtained.

Fig. 7. Momentum distribution of the field emission current in the coupler cavity.

The momentum distribution of the field emission current is shown in Fig. 7. The momentum was measured with the momentum analyzer magnet and the current value was measured with Faraday cup FC-2 in Fig. 4. As the momentum acceptance $\Delta P/P$ of the system was about 40%, the maximum momentum of the field emission current was estimated to be about 2.0 MeV/c. Then the calculated accelerating field in the cavity was above 60 MV/m.

Fig. 8. Mass spectrum of the residual gases. There was no critical difference between rf-on case and rf-off case. No critical discharge occurred.

The vacuum level of $1.53 \times 10^{-6}$ Torr was measured with B-A gauge. Mass spectrum of the residual gas was obtained by a residual gas analyzer as shown in Fig. 8. There was no critical difference between rf-on case and rf-off case. It shows that no critical discharge occurred.

Summary

Field symmetry was improved by adopting the double-feed type coupler. The high gradient experiment showed that it is capable of handling high surface gradient more than 100 MV/m. This type double-feed couplers have already been used for some accelerating structures at KEK.

Acknowledgment

The authors wish to acknowledge Prof. M. Yoshioka, Dr. T. Shintake and Dr. Y. Takeuchi for their continuous encouragement.

References

DEVELOPMENT OF
A FOLDED-COAXIAL RFQ LINAC FOR THE RILAC

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Abstract

A variable-frequency RFQ linac which will be used for a new injector of the RIKEN heavy-ion linac (RILAC) has been constructed. This paper describes the results of the performance tests as well as the design of the real structure. The RFQ, based on a folded-coaxial resonator with a movable shorting plate, accelerates ions with mass-to-charge ratios of 6 to 26 at up to 450 keV per charge in the cw mode. Low power tests of the resonator have shown that the power losses are 6 kW at 17.7 MHz and 26 kW at 39.2 MHz for the maximum intervane voltage of 33.6 kV. Stable operations have been achieved in the range of the intervane voltage from 10 kV to 40 kV. Acceleration tests in the cw mode have also been performed using several ion beams at various frequencies. The new injector system consisting of this RFQ and an 18-GHz ECRIS will be installed in the RILAC by the end of 1996.

Introduction

The RIKEN heavy-ion linac (RILAC) is rf frequency-tunable between 17 and 40 MHz[1], which allows us to accelerate various kinds of ions with mass-to-charge (m/q) ratios up to 28 in a wide energy range. A 450 kV Cockcroft-Walton accelerator with an 8-GHz electron-cyclotron resonance ion source (ECRIS) has been used as the injector of the RILAC.

Recently a new injector system of the RILAC has been constructed, which consists of an 18-GHz ECRIS and a variable-frequency RFQ linac, in order to meet growing demands for much more intensity of heavy ion beams in the RILAC. In this paper we describe some results obtained from the performance tests of the RFQ as well as the outline of the RFQ resonator.

RFQ Resonator

The RFQ resonator is based on a folded-coaxial structure[2]. The distinct features of this RFQ are that it can be operated in a low frequency region and the frequency range is quite large.

Figure 1 shows a schematic layout of the RFQ resonator. Horizontal vanes are held by front and rear supports fixed on the base plate. Vertical vanes are fixed on the inner surfaces of a rectangular tube which surrounds the horizontal vanes. This tube is supported by four ceramic pillars placed on the base plate. The lower stem is used only in high-frequency operations where it is in electric contact with both the conductor tube and the base plate, while it is detached from the tube in low-frequency operations. This stem was found to reduce the power consumption because it shares the rf electric current with the upper stem[3].

![Fig. 1. Schematic drawing of the RFQ resonator. The inner volume of the resonator is about 1700 mm (length) × 700 mm (width) × 1150 mm (height). The vane length is 1420 mm.](image)

The resonator is separable into upper and lower parts, as shown in Fig. 1. All the vanes are rigidly fixed in the lower part. The upper part containing the stem and the movable shorting plate can be removed as a unit. This separable structure permits accurate alignment of the vanes and easy maintenance.

The channels for water cooling are arranged based on the heat analysis. Water for the horizontal vanes is supplied through the front and rear supports of the vanes. That for the vertical vanes and the rectangular tube is provided through the inside of the upper stem. The total water flow is 155 l/min at the pressure of 7 atm. The resonator is evacuated by two turbo-molecular pumps (1500 l/s) on its both sides.

The vanes are three-dimensionally machined within the accuracy of ±50 μm. The vane parameters were determined by taking the results of a numerical simulation into account[4]. Misalignment effect on the beam transmission efficiency was also estimated[4].

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Performance Tests

Low Power Tests

The resonant frequency was measured as the first step of the tests. When the lower stem is out of the resonator, the resonant frequency varies from 17.7 to 36.2 MHz by changing the position of the shorting plate by a stroke of 790 mm. When it is used, the frequency varies from 30.2 to 39.2 MHz. This result is in good agreement with the MAFIA calculation.

Figure 2 shows the measured Q-values and shunt impedances. The corresponding MAFIA-calculation curves are shown in the figures as well. The shunt impedance $R_s$ is defined by $V^2/(2P)$, where $P$ is the rf power consumption and $V$ is the intervane voltage. As shown in the figure, the measured Q-values and shunt impedances with the lower stem are larger than those without the stem at above 30 MHz.

The MAFIA calculations overestimate the measured values by about 50%. This is considered to result from the fact that the calculation does not realistically treat the roughness of the wall surface and the imperfection of the electric contact.

The power losses estimated from the shunt impedances are 6 kW at 17.7 MHz and 26 kW at 39.2 MHz for the maximum intervane voltage of 33.6 kV in the cw operation.

![Fig. 2. Measured Q-values and the shunt impedances along with the MAFIA calculations. The closed circles and the solid curve represent the measured and calculated values, respectively, when the lower stem is detached from the conductor tube. The open circles and the dashed curve represent the measured and calculated values, respectively, when the stem is used.](image)

High Power Tests

High power tests was carried out with an rf power source based on an Einmac 4CW5000E, which has a cw power of 40 kW at maximum between 16.9 MHz and 40 MHz.

In the first stage of the tests we encountered a problem on the ceramics pillars. When the intervane voltage was above 25 - 30 kV, the pillars were broken by the heat due to the dielectric losses around the metal screws fixing the pillars to the conductor tube.

![Fig. 3 Schematic drawing of the improved ceramics pillar.](image)

This problem has been solved by adopting the structure of the pillars illustrated in Fig. 3, which consists of Al2O3 welded with copper-tungsten metal on its both sides. This welding is possible because both materials have similar values of the coefficient of the linear thermal expansion. After this improvement, the RFQ has been stably operated in the whole range of the acceleration voltage acceptable by the RILAC as shown in Fig. 4. The vacuum stays in a range of 1 - 3 x 10^-7 Torr at a pump head. No significant temperature-rise has been detected during the operation.

![Fig. 4. Specification of the RFQ linac. The abscissa and the ordinate represent the resonant frequency and the intervane voltage, respectively. The output energy, proportional to the intervane voltage, is also indicated. The hatched area shows the region where the RFQ has ever been operated in the cw mode. The accelerated ions are indicated by closed circles. The solid curves represent the acceleration condition of ions, each of which is indicated by the m/q-value. The dashed curve shows the maximum attainable voltage with the present power source (40 kW), which is estimated by the measured shunt impedance of the resonator.](image)
Acceleration Tests

Acceleration tests have been performed using ion beams from an 18-GHz ECRIS. The extracted beam from the ion source is focused by an Einzel lens and is bent by a bending magnet. The bending magnet also has a focusing function by the slant pole edges. The beam is focused again by a solenoid lens before entering the RFQ. There are two diagnostic boxes in the beam line. One is located between the bending magnet and the solenoid lens, which has a Faraday cup, two profile monitors, and two slits. The other is placed just after the RFQ, which has a profile monitor, a Faraday cup, two slits and an electrostatic deflector with a scanning wire probe.

The accelerated ions so far are $O^{3+}, 4+, 5+, N^{4+}, N^{4+}$, $A^{2+}, 3, 6, 8, 9, 11+, K^{+}, Xe^{12+}, T^{7}, 16, 17+$ at the frequencies of 17.7, 19.5, 26.1, 29.5, 32.8, 34.4, 36.8 and 39.2 MHz in the range of the intervane voltage of 17 - 35 kV. They are indicated by closed circles in Fig. 4. The maximum transmission efficiency, defined by the ratio of the beam current in the two Faraday cups, was 88 % with the beam intensity of 120 eμA.

The emittance of the input beam of $A^{8+}$ extracted from the ECRIS at 8.5 kV, measured at 1400 mm upstream of the RFQ. The transmission efficiency was 87 %. The ellipse indicates the emittance assumed in the vane design (145 π mm×mrad).

![Fig. 5. Emissite of the input beam of $A^{8+}$ extracted from the ECRIS at 8.5 kV, measured at 1400 mm upstream of the RFQ. The transmission efficiency was 87 %. The ellipse indicates the emittance assumed in the vane design (145 π mm×mrad).](image)

The emittance of the input and the output beam was measured by the profile monitors along with the slits[5]. The input beam emittance from the ion source is 150 - 300 π mm×mrad, which decreases as the extraction voltage and the charge states of the ion increase. An example of the measured results is shown in Fig. 5. On the other hand, the output beam emittance is almost independent of the acceleration condition and is in agreement with the PARMTEQ simulation.

The energy distribution of the output beam was measured by the electrostatic deflector (40 mm in gap and 200 mm in length) placed downstream of the RFQ along with the scanning wire probe. The beam energy was deduced from the beam position measured by the probe, and the voltage applied to the deflector. As shown in Fig. 6, the output energy decreases as the intervane voltage is reduced, which is well reproduced by the simulation. The energy spread of the output beam was also measured by the same device. The result is 2-3% at FWHM and is consistent with the PARMTEQ simulation.

![Fig. 6. Measured energy distribution (solid curves) and the PARMTEQ simulation (dashed curves). This measurement was done at the frequency of 17.64 MHz using $A^{2+}$ beam. The corresponding output energy is 350 keV/q. The numbers represented by Vn indicate the ratios of the intervane voltage to the standard value of 26.1 kV.](image)

Outlook

The new injector has been moved to the RILAC beam line in August 1996. Acceleration tests of the RILAC with the new injector will be completed by the end of this year.

The maximum extraction voltage of the 18-GHz ECRIS will be raised from 10 kV to 20 kV in the near future. New vanes are under fabrication so that the RFQ can accept the upgraded beams.

Acknowledgments

The authors are grateful to Dr. N. Tokuda and Dr. S. Arai at INS for the usage of the program for vane-cutting as well as for the fruitful information about the vane design. The resonator was fabricated by Sumitomo Heavy Industries, Niihamara Work, the rf power source by Denki Kogyo, and the ceramics pillars by KYOCERA Corporation.

References

KEY SYSTEMS OF AN 433 MHZ ION LINAC
FOR APPLIED PURPOSES

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Scientific Research Efremov Institute of Electrophysical Apparatus

Abstract

Commercial compact RF ion linac for different purposes is being designed and fabricated by the Efremov Institute since 1990. This report briefly describes key bloks of linac such as injection system, low energetical RFQ, drift tube resonators with output energy 10...15 MeV, RF system. Concept of their construction and technical realization is elucidated. Status of promised researches on creation of commercial RF ion linac in the Efremov Institute is presented.

Introduction

NPK LUTZ subdivision of the Efremov Institute is developing technology of production of ion 433 MHz linacs. Sample of such linac had tested under laboratory conditions. It is 1.8 MeV RFQ for H² ion acceleration. [1] A new RFQ cavity with output ion energy 2 MeV had been fabricated. For accelerating of ions up to 10...15 MeV, 2 MeV RFQ linac may be used as initial part of accelerator (IPA). It is proposed to accelerate particles from 2 up to 15 MeV in the drift-tube H-resonator. Protons and deuterons with such energy can be used for medical isotope production, elemental analysis of materials, in PET-system and other special purposes. Principles of building of key systems of such linac is given below.

Injection’s system

Injector includes system of ion obtaining and system of the beam formation and focusing. System of formation must provide adjusting of the output beam emittance to accelerator’s acceptance. Best accordance of the beam with accelerating tract may be achived if the ion beam has convergence to the axis and symmetry in xy-plane (z-the beam axis). System of the beam formation includes focusing lenses and sometimes accelerating gaps to accelerate the beam up to injection’s energy. Usually space charge of the beam is only partially compensated and there are necessary to have magnetic or electrostatic lenses to avoid excessive broadening of the beam along injector. In our case a preference was given electrostatic formation’s system. Compact linac’s injector includes SPS with extracting voltage 15...20 kV, bending magnet wich separates ion beam H² or D² from impurity and helps to form the beam phase volume, electrostatic LEBT system that focuses and accelerates ion beam up to 60 keV. Last system includes set of electrodes. Number, placement and potentials of electrodes are determined by required output beam parameters. There is code for computer designing of LEBT system. [2] Reasons and advantages of such choice are:
1. moderate currents and moderate space charges accordingly in compact linac allow using of the beams with decompensated charge;
2. absence of collective effects, beam plasma oscillations and beam instabilities along injector;
3. computations show that beam heating between source and first electrode of LEBT is small;
4. it is easy to provide low gas pressure at accelerating resonator’s input (near 5*10⁻⁷ Tor);
5. simplicity and reliability of construction.
Other properties of injections system are given in paper TPH82 of Linac96 Conference.

Accelerating structure

Usually 2 MeV 433 MHz RFQ is used as initial part of 10...15 MeV accelerator. RFQ as IPA in our case has some peculiarities. [3]
1. Accelerating gradient is high enough for RFQ. It is more then 1 MeV/m.
2. RFQ cavities are fabricated from AMT6 aluminium alloy and their inner surfaces are covered by copper with help of electroplating.
3. Vacuum housing is absent. Requiring vacuum may be provided by indium packings.
4. System of RF feeding allows to depress parasite modes and discussed below.

It is proposed to accelerate ions from 2 up to 10...15 MeV in the drift-tube resonator. Usually Alvarez structure is used as second stage of accelerator. Disadvantages of Alvarez resonators as part of industrial installation are complexity of tuning, necessity of special arrangements for alignment of drift-tubes, hardness of intensity cooling under big average power and, as a consequence, high cost of fabrication and operation. In additional of Alvarez cavity drift-tube holders cannot be very thick and structure has not high mechanical stiffness, it feels jabs and vibrations. Instead of Alvarez here is proposed structure with crossed transversal holders (CTH), that works on π-mode (its cross-section is shown on fig. 1). Electromagnetic field distribution for operating type oscillation is according to H(TE) mode [4]. Structure consists from separate cells, each of them include broad outer cilindrical ring. Inside of rings drift tubes are fastened on massive holders. Cells can revolve each relatively others
independently around longitudinal axis. Adjacent cells are oriented such that their holders are located at the right angle each to other (or nearly to this position). CTH-structure has high mechanical stiffness, may have intensive cooling and need not special arrangements for alignment. Its technology of fabrication is close to traditional technology waveguide’s fabrication. In our case CTH structure is aperiodical one, because alternate phase focusing (APF) is used and we need not magnetic lenses inside drift-tubes.

Tuning of CTH-resonator may divide on following operations conventionally:
- establishing of the identity of working type of oscillations;
- compensation of the field decreasing at edges of resonator;
- compensation of the field decreasing along resonator;
- compensation of field modulating in APF structure;
- obtaining of resonant frequency in resonator.

Such dividing of operations is conventional for irregular resonator. Identity of working type of oscillations is realization of base type of oscillations with minimal frequency and experimental obtaining of the field in each gap. There are always places of resonator, where field is absent, because cells have weak connection and structure can have ununiformities, for example, long drift-tubes. Therefore long resonator is tuned sequentially. It is divided on few parts and its length is increased step by step in process of tuning. It is convenient to begin tuning with terminal’s cells, placing holders under right angle and increasing angle’s changing when gaps and drift-tubes will decrease. Compensation of field decreasing on cavity edges is made by placing of tuning cross-like elements on faces of long drift-tubes. Such elements equal own frequencies of terminal’s cells and regular ones. Selection of tuning element’s sizes, their angular positions are determined by experiment. After preliminary tuning final levelling of the field was produced. Near gaps with big field’s amplitude angular shifts of cells are increased and near gaps with small field’s amplitude angular shifts are decreased. The tuning must take account that change of angle turn between cells creates change of field not only in gap between these cells but on entire tuned part of resonator. Therefore increasing of turn pair of cells must be accompanied by decreasing of angular shift of other part on this section. It is hardness that fields distribution is sensitive to the angular turns. Serious problem of multigap’s resonator is dividing of types oscillations and high sensitivity of field’s distribution to perturbation of cell’s own frequencies. In spite of this tuning of 59-gaps structure with operating frequency 866 MHz was made successfully. This resonator was 1/2 scaled model of 433 MHz cavity that is intended for acceleration of protons from 2 up to 10.6 MeV. Model had been fabricated from D-16 aluminium alloy. As result of final tuning irregularities of gap’s field were not higher then ±5% and distance between operating type oscillation and next parasite type one was 4.1 MHz. These results are good enough. Experimental data, obtaining under researching of 866 MHz resonators with 59 aluminium alloy, 6 copper cells and results of mathematical modelling had shown that shunt-impedance considered H-cavity is comparable or more then Alvarez cavity’s shunt-impedance for energetical diapason 2...15 MeV. Shunt-impedance will higher in few times, if proposed structure used for acceleration with constant phase, but not acceleration with help of APF. In this case for stabilization of radial motion in H-resonator must be used quadrupole lenses in the drift-tubes.

**RF system**

It is expedient to build up RF system multisectioned accelerator as separate amplifying lines. Dividing of RF power is made on low level. As output amplifier of line had been worked out endotron type device «Kiwi» of output pulsed power 450 kW and preamplifier of output power 2 kW. Functional scheme of endotron «Kiwi» is given on fig. 2.

Main characteristics of endotron are given in table 1.

<table>
<thead>
<tr>
<th>Table 1. Main parameters of device «Kiwi»</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
</tr>
<tr>
<td>Input pulse power</td>
</tr>
<tr>
<td>Output pulse power</td>
</tr>
<tr>
<td>Average power</td>
</tr>
<tr>
<td>Anode voltage</td>
</tr>
<tr>
<td>Length of pulse</td>
</tr>
<tr>
<td>Efficiency</td>
</tr>
<tr>
<td>Band of operating frequencies</td>
</tr>
</tbody>
</table>

In such type devices resonance circuits hook up to directly electrodes of grid operated tube inside vacuum volume. It allow to lower energy accumulated in scheme, active part of tube is used entirely and as result, total size of cascade are decreased significantly and broad band of operating frequencies is achieved. On the output of endotron ferrite circulator is installed to preserve device from overload when break-down in the cavity take place. RF system for accelerator cavity’s feeding must have enough high power feeder, have not break down problem and to favour eliminating of undesirable modes in cavity. Last problem take place for four-vane RFQ (or drift-tube H-resonator), these are used in our case.

Proposed feeding scheme is satisfying these requirements. As far as accelerated beam in RFQ is remaining unbunched on one third of the cavity’s length and is exiting wide spectrum of frequencies, methods of their difference may by not good enough. Here is proposed to use directional selective coupling. Method of directional selective coupling use field’s correlation in such regions where coupling is maximal at operating mode and vanishes at undesirable ones. [5] Feeding system’s scheme is shown on fig. 3. It contains directional couplers (DC), equal length’s feeders $l_1...l_4$ and $l_5$ to attain equal amplitudes of cophasal excitation at equal coupling loop’s spaces. In exact symmetrical case all mentioned undesirable modes except quadrupoles with even number of
longitudinal alterations are not exited. For exact symmetrical case only quadrupole modes with even number of longitudinal variations are exited and feeder-loop's matching on operating mode reveals in full decoupling of matched load m1, m2, m3. Coaxial hybrid ring briges are used for the couplers.

**Conclusion**

Here were considered peculiarities of key systems of compact 433 MHz RF linac. At present these and others blocks are working out or are operating as parts of laboratory’s installation. Creation of compact commercial machine may be ended during year or two under necessary financial support.

**References**


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**Fig. 1.** Cell of accelerating structure.

**Fig. 2.** Functional scheme of endotron.

**Fig. 3.** Scheme of feeding system.
ADVANCES AT NPK LUTS 433 MHZ ION LINAC


Scientific Research Efremov Institute of Electrophysical Apparatus

Abstract

There are presented intermediate testing results of 433 MHz compact linac which is being worked out by Linear Accelerator and Cyclotron Division (NPK LUTS) of the Efremov Institute for applied purposes. Technical parameters of 1.8 MeV ion RFQ are given. Results of measurements of vane voltage, beam current and energy under accelerator's testing are discussed. It supposed a new RFQ of 2 MeV output energy will be mounted at the nearest time.

Introduction

During last years Linear Accelerators and Cyclotron Division of the Efremov Institute is working out commercial RF ion linac for different applications.[1] Now had worked out, fabricated and researched injection's system, 433 MHz RFQ with 1.8 MeV output energy. RF system having endotron BM-105 as output cascade of power's amplifier. These blocks were mounted and installation had lasted. Brief description of accelerator's stand is given below.

Injection's system

Injector includes following main elements:
- SPS with Penning geometry of discharge chamber, source is placed inside of vacuum volume;
- Bending magnet, which has demountable poles face to form beam with energy up to 20 keV and to separate impurities;
- Electrostatic system of focusing and preacceleration up to 60 keV, that includes collection of electrodes with variable potentials.

Metalohydrate system of purification produces preliminary purification of hydrogen. Magnetic field of discharge chamber is formed by poles of bending magnet. Permanent magnets KC-37 type created an induction of magnetic field which must be 0.15 Tesla if H beam is produced. Magnitude of current and quality of obtained beam depend on relation of partial pressures of hydrogen and cesium in a source. Optimization of this relation allowed to obtain H- ion current 60 mA when discharge current was 190 A and discharge voltage was 140 V. Length of current pulse is 100 microseconds. Maximal current of H- ion was 100 mA. Injector's vacuum system has two turbomolecular pumps and supports pressure 5*10^-7 Torr near injector output. Measuring system allows to measure emittances in XX' and YY' planes and distribution of current's density in beam cross section. Results of measurements of normalized emittances are:

A. Regime without cesium: l=15 mA, E_{ax}=2.1*10^7 rad*m, E_{ay}=1.1*10^7 rad*m.
B. Regime with addition of cesium: l=40 mA, E_{ax}=3*10^7 rad*m, E_{ay}=2*10^7 rad*m.

Accelerating structure

Accelerating structure is four-chamber's RFQ. Its cross section is given on fig.1. Geometrical and physical parameters are given in table 1. First sample of RFQ was fabricated from aluminum alloy D-16. An accuracy of producing of vane modulation is 10...20 microns. Inner surfaces of cavity will be covered by copper using electroplating. Resonators tuning is effected in a step by step fashion with help of following operations:
1. field's symmetrization of cavities quadrants;
2. tuning of connection's elements;
3. check of symmetrization and procedure's repeating;
4. determination of electromagnetic axe of cavity;
5. measuring of longitudinal field's distribution.

Table 1. RFQ Specification.

<table>
<thead>
<tr>
<th>Accelerated particles</th>
<th>H^+ or H^-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>433 MHz</td>
</tr>
<tr>
<td>Input ion energy</td>
<td>60 keV</td>
</tr>
<tr>
<td>Output ion energy</td>
<td>1.8 MeV</td>
</tr>
<tr>
<td>Number of periods</td>
<td>220</td>
</tr>
<tr>
<td>Vane length</td>
<td>1552 mm</td>
</tr>
<tr>
<td>Total length</td>
<td>1590 mm</td>
</tr>
<tr>
<td>Pulse current</td>
<td>up to 60 mA</td>
</tr>
<tr>
<td>Beam Transmission at 40 mA</td>
<td>87%</td>
</tr>
<tr>
<td>Intervane voltage</td>
<td>98kV</td>
</tr>
<tr>
<td>Final sinchronous phase</td>
<td>30°</td>
</tr>
<tr>
<td>Phase beam length</td>
<td>40°</td>
</tr>
<tr>
<td>Average bore radius</td>
<td>3.5 mm</td>
</tr>
<tr>
<td>Minimal bore radius</td>
<td>2 mm</td>
</tr>
<tr>
<td>Output normalized emittance</td>
<td>10^-7 rad*m</td>
</tr>
<tr>
<td>Cavity RF power (without beam)</td>
<td>250 kW</td>
</tr>
<tr>
<td>Quality factor (for D16)</td>
<td>3800</td>
</tr>
</tbody>
</table>

As result of repeating of tuning cycle resonance frequency 433.3 MHz had been established. Dipole modes had eigenfrequencies 420.47 and 433.37 MHz respectively. Differences of magnetic field's amplitudes in cavity's quadrants were about ± 2%, inclination of electromagnetic axe to geometric one was less then 0.2°, and small shift field's axe took place.

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RF system

RF power system includes following fundamental units: master oscillator, preliminary cascade of amplification of power, final one, pulse source of anode supply, source filament supply, source of synchronizing pulses. Output amplifier is endotron type device BM-105. It's operating parameters are given in Table 2.

Table 2. BM-105 specifications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse output power</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>Pulse length</td>
<td>24 μsec</td>
</tr>
<tr>
<td>Efficiency of anode circuits</td>
<td>30%</td>
</tr>
<tr>
<td>Frequency's diapason</td>
<td>400...500 MHz</td>
</tr>
<tr>
<td>Pulse input power</td>
<td>1 kW</td>
</tr>
</tbody>
</table>

Really we used mode 433.3 MHz with pulse length 50...100 μsec. Output power is 500 kW if pulse length 100 μsec and output power is 365 kW if pulse length 130 μsec. Average power remains constant and it is equal to 6 kW.

Three of modulators of master oscillator, preliminary and output amplifier's cascades are fulfilled as circuits with full discharge of accumulating condenser and they are hooked up to the load via pulsed transformers. RF system have control systems of field's amplitude and frequency. Control systems compensate fast and slow deviations of field's frequency and amplitude. Four of RF power's lead-ins into RFQ cavity via hybrid ring suppress spurious dipole modes.

Working time of RFQ cavity under high level of power was about 120 hours. Cavity are served by six pumps HMT-0.25 type and magnitude of pressure they are maintained is $10^{-6}$ Tor. Power's level in the RFQ cavity was measured via brake radiation's spectrum of electrons. They are appeared as result field's and secondary emission. Results of measurements are represented on fig. 2. These measurements allow to estimate intervane voltage that depends on level of RF power in the cavity. 98 kV voltage corresponds to 250 kW of RF power.

Measurement of proton's energy

Time of work with beam was limited 30 hours. 10...15 mA beam was injected into RFQ cavity with 60 keV energy. Experimental procedure of proton's energy's measurement is based on gamma-radiation's monitoring of nuclear reactions Al(γ,γ)Si, Al(p,γ)AlMg. Sources Co-57 (122 keV), Cs-137 (662 keV), Mn-54 (843 keV), Zn-65 (511 keV and 1115 keV) and K-40 line of natural noise were used for spectrometer's calibration. Typical spectrum of γ-radiation is represented on fig. 3. Energy of accelerated protons is estimated on relation of 843 keV and 1368 keV partial γ-peaks.

Calculations show that beam energy is near 1.7 MeV. RFQ cavity, that is described here, was first experimental sample. It's surface was not polished and not covered by copper. On account of periodical RF break downs accelerator worked unstable and intervane voltage did not achieve nominal one with the beam presence. These factors and initial shift between beam and resonator axes did not allows to obtain output current in pulse more then 15 microamperes.

Perspectives

Now the new RFQ cavity with output energy 2 MeV had been fabricated from AMG-6 aluminium alloy. Such accelerator may be used for express analysis of materials. It may be analysis of a secondary radiation. For example, γ or X-ray analysis or analysis of radiation due to neutron activation. Other blocks of measuring complex: camera of interactions and measuring and process data system had been fabricated too. For accelerating H² ions from 2 up to 10...15 MeV, 2 MeV RFQ linac may be used as initial part of accelerator. It is proposed to accelerate particles from 2 up to 10...15 MeV in the drift-tube resonator. Protons and deuterons of such energies can be used for medical isotope production, elemental analysis of materials and other special purposes. Usually Alvarez structure is used as second stage of accelerator. Instead of Alvarez NPK LUTS proposes structure with crossed transversal holders (CTH), that works on π-mode (see fig. 4). Electromagnetic field distribution for working type oscillation is according to H(TE) mode. Samples of CTH-structure had fabricated, tuned and tested in the Efremov Institute.[2] Structure consists from separate cells, each of them includes broad outer cylindrical ring. Inside of rings drift tubes are fastened on massive holders. Cells can revolve each relatively others independently around longitudinal axe. CTH-structure has high mechanical stiffness, may have intensive forced cooling and need not special arrangements for alignment. It's technology of fabrication is close to traditional technology of waveguide fabrication.

Perspective of improving of RF system are considered in paper TPH81 of Linac 96 conference.

Conclusion

At present separate units of 2 MeV installation have been tested. At the next time a test of whole installation will be produced. To make a compact commercial linac, it is obvious that new injector and RF system should be made. These units are worked out now. Instead of endotron type BM-105 we will use device KIWI and compact preliminary amplifier.

References


Fig. 1. Cross-section of RFQ cavity.

Fig. 2. Energetical spectrum of brake radiation for 0.8, 0.4 and 0.25 nominal meaning of RF power.

Fig. 3. Energetical γ-spectrum of nuclear reactions by accelerated protons.

Fig. 4. Accelerating structure with crossed transversal holders.
SIMULATION ON THE EMITTANCE OF THE RF GUN INCLUDING THE SCHOTTKY EFFECT

Yongzhang Huang*, Yoshikazu Miyahara

Abstract
The applied electric field strength can affect the electron emission because of the Schottky effect. In the case of rf gun, this effect will cause the electron current varying with the phase of the rf electric field. Especially for the photocathode rf gun, the variation is so significant because of the strong rf field, that it cannot be neglected though the electron bunch is only a few pico-seconds long. The charge distribution within the bunch therefore becomes tilted. The emittance of this tilted bunch might be larger than that of the square bunch. The result seems to make the argument that further reducing the beam emittance by shaping the drive laser bunch both in radial space and in time structure be more challenging in the technology point of view. In order to produce a square charge distribution, the laser bunch would probably be required to be time-tilted.

Introduction
The so-called self amplified spontaneous emission might produce coherent radiation in the VUV and the soft x-ray regions with peak brilliance several orders higher than the third generation light sources. However, it demands very stringent qualities of electron beam. In order to meet the requirements, the photo-cathode rf gun injector is basically asked to produce the electron bunches with InC charge and 1rm-mrad normalized transverse emittance. With the adoption of the Carlsten’s emittance compensation scheme[1], the emittance growth due to the linear components of space charge forces can be recovered. The final emittance, thus, can reach about 1rm-mrad which is already shown in current simulation studies at SLAC[2] and DESY[3].

The emittance compensation technique has its roots in removing the linear correlation between the longitudinal and the transverse phase spaces. One can image that the compensation would be completely done if the correlation is completely linear. So that the charge distributions of electron bunches are necessary to be uniform in both longitudinal and transverse dimensions. In other words, any effects which can cause non-uniform charge distributions in both dimensions would increase the final emittance, because the resulted non-linear correlations cannot be removed by the Carlsten’s technique.

At the emittance level of 1rm-mrad, any small effects which would affect the charge distributions in the processes of emission and acceleration would make contributions to the emittance value. Among them, the drive laser bunch holds the most significant influence since it directly determines the charge distributions of emitted electrons. This effect has been studied in detail in the LCLS collaboration and a technical way has been pointed out. This way is to shape the drive laser bunch both transversely and longitudinally into a square bunch[4]. An emittance of less than 1rm-mrad is foreseen through this way. The other effects, such as the space charge force and the rf electro-magnetic force, are taken into account naturally in simulations.

Another effect caused by the Schottky effect, however, is lack of investigation in simulation as far as we know. The Schottky effect means that the accelerating field can increase the current emission because the field reduces the level of the cathode barrier. As the result of the time variety of the rf field, the emission current varies with the rf phase. Because of the strong rf electric field, this variation is so significant that it cannot be ignored though the electron bunch length is only a few pico-seconds. The charge distribution becomes tilted within the bunch. The emittance of this tilted bunch might be larger than that of the square bunch.

This paper will present our simulation results on the effect. The numerical model is simply described in Section 2. Section 3 is the main body of this paper and gives all simulation results. Finally, a summary is given in Section 4.

Numerical model
The beam dynamics is calculated using a pc-version of PARMELA[5]. The gun cavity is the LCLS type, 1.6 cell π-mode s-band cavity. In simulations, the Carlsten’s emittance compensation is adopted by using a solenoidal magnet. Its position and strength are optimized to obtain the minimum transverse emittance in down stream beam line. Figure 1 shows the schematic layout of the rf gun injector used in our simulations. In Section 3.1 and Section 3.2, the simulations include no accelerating structure. By comparison, the accelerating structure is added in simulations of Section 3.3. The maximum field strength of 140MV/m at cathode is assumed.

The emitted electron bunch is treated as a composition of a series of short gaussian pulses with identical standard deviation σ and different central positions. The rise and
falling time is simply taken as $2\sigma$, the main part of the bunch length is the time difference between the first and the last short gaussian pulses. By varying the height of each separated gaussian pulses, one can obtain an arbitrary shape of emitted electron bunch. The bunch contains 10,000 big particles in our simulations.

A small code based on above consideration is programmed to produce the bunch shape. Thus, the Schottky effect can be included in simulations. The photoelectron current can be described by,

$$J = aI \left( h\nu - \phi + b\sqrt{\beta E} \right)^2.$$  

Here, $J$ is the total electron current density, $I$ is the laser intensity, $h\nu$ is the photon energy, $\phi$ is the work function, $E$ is the electric field strength, $\beta$ is the field enhancement factor, and $b = \sqrt{e/4\pi\varepsilon_0}$, $a$ is a constant related to the material properties and surface conditions. Notice that this formula implies a linear growth in the photo emission due to the electric field term. However, the reality seems more complicated than the formula. A measurement[6] done at the BNL accelerator test facility showed a higher growth than the linear growth. So that we decided that the Schottky effect would be represented by scaling the BNL's experimental data into our simulations.

Simulations

Square drive laser bunch

To purify the problem considered, we assume that the drive laser bunch is a nearly square bunch in both transverse and longitudinal dimensions. The bunch radius is 1mm and the bunch length is 10 pico-seconds. Figure 2 shows the PARMELA output of the longitudinal bunch distributions at different positions: the cathode, the end of the first cell, the end of the second cell, and the position with the minimum emittance. The available minimum transverse emittance is 0.94\(\pi\)mm-mrad before the accelerating structure.

Comparing Figure 2a and Figure 2b, a bunching effect is found during the early acceleration stage. This bunching takes place through the normal mechanism of rf acceleration, so that it is strongly relative to the rf phase when the drive laser is triggered. At the phase operating for small emittance, the overall bunching amount is not large. It still can be seen, however, that the electrons are compressed a little more at tail part than at head part. This difference will in principle cause the non-linear space charge force induced emittance growth during behind path. However, the growth is rather smaller than that the other effects caused.

Schottky effect

The schottky effect is introduced into simulations while the drive laser is kept being square. Most other parameters in simulations are kept unchanged also. And those unchanged parameters are found very close to their optimized values for obtaining the minimum emittance. In order to see the minimum emittance value, it is necessary to vary the solenoidal field strength within a certain range. Figure 3 shows the PARMELA output of the longitudinal bunch distributions at the same positions as in Figure 2. It may be surprise to see how large is the current increase caused by the Schottky effect. The current distribution is finally alike a gaussian. The available minimum emittance of this tilted bunch is 1.00\(\pi\)mm-mrad which is by about 0.06\(\pi\)mm-mrad (or about 6%) larger than that of the square bunch case.

With down-stream acceleration

Since there is no further acceleration behind the gun cavity in the above calculations, the beam energy is not high enough to suppress the space charge forces. The emittance compensation has to be done rather rude in order to overcome the counterraction of space charge forces. As a result, the available minimum emittance is larger than that would be reached. Actually, the further acceleration can reduce the space charge forces. Therefore, it will help the emittance compensation taking its effect smoothly and achiev-
Figure 3: Phase spectrum of the electron bunch at different positions while the Schottky effect is included. acathode; bxexit of the first cell; cexit of the second cell; deminimum emittance position. The horizontal unit is in pico-second. The vertical unit can be think of the relative intensity. Note, that the head of the bunch is on the left side.

ing smaller emittance value. That is proved by simulation and the results are listed in the following table. A 3-meter long SLAC type constant gradient accelerating structure is adopted in our simulations. The accelerating gradient is assumed to be 14MV/m. One can learn that the Schottky effect causes an emittance growth of 0.05πmm-mrad, or a growth about 6%.

<table>
<thead>
<tr>
<th></th>
<th>Minimum emittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Schottky effect</td>
<td>0.88πmm-mrad</td>
</tr>
<tr>
<td>Schottky effect</td>
<td>0.93πmm-mrad</td>
</tr>
</tbody>
</table>

Summary

The influence of the Schottky effect on the beam emittance has been studied in this paper. Comparing with the influences of drive laser bunch shape, for example, the rise and falling time, it is a small effect. This is understandable since the schottky effect changes only the top part of the bunch charge distribution. The effect can be neglected in most cases, even the case in Figure 3 where a large field enhancement is taken account. However, it may worth keeping in mind when trying to achieve very small emittance values. As we already know that square drive laser bunch cannot produce square electron bunch since the Schottky effect, it may be necessary calling for a time-tilted laser bunch. Both the tilted laser and the schottky effect work together, a square electron beam can be produced.

References


STATUS OF THE DUAL-AXIS RADIOPHGRAPHIC HYDROTEST FACILITY

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Abstract

The Dual-Axis Radiographic Hydrodynamics Test (DARHT) Facility will employ two electron Linear Induction Accelerators to produce intense, bremsstrahlung x-ray pulses for flash radiography with sub-millimeter spatial resolution of very dense (attenuations > 10^5), dynamic objects. We will produce an intense x-ray pulse using a 19.75-MeV, 3.5-4 kA, 60-ns flattop electron beam focused onto a tungsten target. A 3.75-MeV injector with either a cold velvet cathode or a laser-driven photocathode will produce a beam to be accelerated through a series of 64 ferrite-loaded induction cells with solenoid focusing. Accelerator technology demonstrations have been underway for several years at the DARHT Integrated Test Stand (ITS) and results including beam energy, emittance, and Beam Break-Up (BBU) measurements are discussed here.

I. Introduction

To meet DARHT mission requirements we must produce a large x-ray dose (~ 1000 Roentgen one meter from the source) in short bursts (< 100-ns) from a very small source size (~1.2-mm equivalent diameter of a uniformly illuminated disk at 50% modulation). Detailed considerations of detector response, test object transmission and scatter, and the bremsstrahlung spectrum limit maximum electron beam energy to ~20-30-MeV. With this energy limit, the high dose and short pulse width specifications require high peak current because dose is related to total charge on the target and beam energy. The small source size requires the electron beam to be focused to ~ 1-mm diameter, thus requiring very good beam quality. Therefore, we have selected a Linear Induction Accelerator (LIA) for DARHT. This paper summarizes the principal accelerator systems installed on the Integrated Test Stand (ITS), which is the initial 5.75-MeV section of the first DARHT accelerator. Photoelectric cathode development, ITS electron-beam measurements, and facility construction status are also discussed.

II. Integrated Test Stand (ITS)

The ITS is shown in Fig. 1. It was first operated in 1991 with the purpose of developing and demonstrating the LIA advances required to meet DARHT performance specifications [1]. Over 30,000 pulses have been accumulated on the ITS, including the experiments reported here.

The relatively long, pulsed-power injector consists of a prime power supply that pulse-charges a glycol Blumlein that, in turn, discharges into a series of three transmission lines with impedance changes to step-up the voltage driving the diode [2]. The prime power source consists of a 3.0-μF capacitor bank charged to ~120-kV dc, and switched through the primary of a 1:15 Stangenes iron-core auto-transformer by a single air-blown spark gap. The glycol Blumlein consists of a 7.65-Ω inner line and a 7.3-Ω outer line and is pulse-charged to 1.5-MV in 4.6-μs. The Blumlein is switched with four, parallel, laser-triggered spark gaps (measured 1-σ jitter of 0.7-ns). The Blumlein contains an adjustable peaker and L-C filter, which shapes the initially sharp-rising pulse to a [1-cos(ωt)] shape with a 10-90% risetime of 20-ns. Three transmission lines in series transform the pulse from 1.5-MV to a maximum of 4-MV on the diode.

The vacuum diode consists of a 170-Ω liquid resistor load in parallel with the 181-mm A-K gap. Our typical 90-mm diameter velvet emitter is inset approximately 2-mm into the cathode-field-forming electrode and produces 4-kA at 3.75-MeV. The radial vacuum insulator is cross-linked polystyrene (REXOLITE 1722), 1.8-m in diameter and 0.35-m thick, with capacitive grading provided by the liquid resistor forming a radial wedge in parallel with six concentric aluminum grading rings embedded in the insulator. Although the injector insulator can operate up to 4-MeV, we typically run at 3.75-MeV to minimize emission from our cathode shroud.

The accelerator induction cells [3] for the ITS are assembled into an eight-cell "cell-block". Completion of the first DARHT LIA requires seven additional cell-blocks. Each cell has a 148.2-mm-diam. bore, 19.1-mm accelerating gap, 11 oil-insulated TDK PE16B nickel-iron-zinc ferrite toroids (237-mm ID, 503-mm OD, 25.4-mm thick), a low-dielectric constant (ε>2.5) cross-linked polystyrene insulator, a quadrupolar wound solenoid magnet with iron homogenizer rings [4], two cosine-wound dipole trim-magnets (to compensate for possible installation tilts of the solenoid magnet), and a cosine-wound quadrupole magnet.

Calculations of the magnetic field caused by pulsed-power currents fed into the cell via two radial lines located on either side of the cell showed a quadrupole field with an estimated gradient-length product of ~3-Gauss. The presence of the field was experimentally confirmed by observation of an asymmetric beam distribution downstream of the cell-block. Cosine-wound quadrupole magnets installed within the cell around the beamtube immediately downstream of each feedline
pair has eliminated the beam asymmetry that leads to emittance growth and a larger effective radiographic source size.

The Induction Cell Pulsed Power (ICPP) consists of four water-insulated, 11-Ω Blumleins with coaxial midplane-triggered switches operating in SF6 [2]. A single Blumlein is connected to two accelerator cells via four, Dielectric Sciences 2158, 44-Ω cables. Each Blumlein has a separate charging unit which uses two 1.4-μF Maxwell primary capacitors charged to 29-kV. Two EEE CX-1722 thyristors are used in parallel to switch the capacitors into a 1:11 Stangenes iron-core step-up transformer that charges the Blumlein to 250-kV in 5-μs. The Blumleins provide a 250-kV, 67-ns pulse to the cells with a 0.6%-rms variation over the beam pulse-width of 60-ns. Jitter (1σ) in the coaxial switches ranges from 0.8-1.2-ns over 1000 shots. Each Blumlein has an independent trigger unit housed in a separate oil-insulated steel enclosure that consists of two 30-nF, 70-kV primary capacitors switched by a EEE CX 1725 thyristor into a Stangenes 1:4 step-up autotransformer that drives a magnetic pulse-compressor which reduces the risetime of the required 200-kV trigger pulse to less than 10-ns into the trigger cable. This in turn results in a risetime of 20-ns at the Blumlein spark gap trigger electrode. Typical trigger system jitter is <275-ps (1σ) for any consecutive 100 shots.

III. Photoelectric cathode

We are investigating a photoelectric cathode as an alternative to our present velvet cathode to produce a lower emittance beam so that we may be less sensitive to possible emittance growth through the accelerator and have the possibility for a smaller radiographic source size. Due to the plastic insulators in our accelerator, we must operate the photoelectric cathode at vacuums of 10^-5-10^-6 Torr, thus prohibiting the use of alkali-metal compounds. We have recently reported on an electron-beam-pumped laser operating at ArF (193-nm) or KrF (248-nm) producing 3.5-J in 100-ns (35-MW) that has been used to illuminate a micro-machined aluminum cathode [5]. On a machine similar to the ITS injector we performed experiments at 2.75-MeV. Quantum efficiency was measured for ArF on micro-machined aluminum at 1×10^-3. Current densities of 100 A/cm^2 and total currents of 2-kA have been achieved. Beam temperature measurements are underway.

We have also reported recently on characterization of aluminum photocathodes as a function of temperature [6]. In our photocathode test stand an ArF laser is used to illuminate small-scale samples of candidate cathode materials that can be radiatively heated to 200°C. A 92% transparent tungsten wire mesh anode is located across a 6.7-mm A-K gap operating at 30-kV dc. We observe a factor of ~2.5 increase in emitted current density for a micro-machined aluminum cathode when it is heated to 150°C, indicating the possibility of extracting a 4-kA beam with less than a joule of incident ArF energy. A beam temperature measurement using a heated cathode will be completed to investigate cathode heating effects on beam quality. Using this same test stand we have also begun characterization of polycrystalline (predominantly <11,1,0>), boron-doped, hydrogen-terminated synthetic diamond films which may exhibit quantum efficiencies of ~1%.

IV. Recent ITS electron beam experiments

A. Emittance

To determine the emittance and the rms values of beam radius, r, and dr/dz, at the A-K gap, we measure the beam radius at z=1600-mm as a function of current in the anode magnet, centered at 537-mm (cathode location is z=0). The light from an OTR foil is captured with a 20-ns gated camera and the distribution is analyzed as a function of time and then fit with our envelope code know as "XTR" to extract the beam parameters in the A-K gap. XTR includes beam-potential depression, diamagnetic-field enhancement, and other high-current effects.

We tested our experiment by imposing an axial field of 65-Gauss on the cathode, which imparts angular momentum to the beam resulting in \( \psi_{rms}=BR^2/2mc = 0.233 \, \text{πcm-rad} \) for a cold, uniform-density beam with \( \text{R}=35\,\text{mm} \). The XTR-deduced result was 0.23 πcm-rad. Without the imposed field, we estimate roughly 10% accuracy and determine \( \psi_{rms} = 0.15 \, \text{πcm-rad} \) for our 4-kA, 3.75-MeV beam. This is adequately low to produce a spot radius on the target < 0.5-mm.

B. Measurement of Beam Break-Up (BBU)

Amplification of transverse beam motion in the accelerating gaps (BBU) must be sufficiently small to prevent smearing of the final focus spot as this would result in increased x-ray source size. We measured the transverse impedance of several different accelerating gaps [7] before choosing our final design. Our input beam has been measured to have low noise (< 20-μm displacement) near the dominant accelerating cell resonant frequency of 740-MHz. BBU calculations with a magnetic field varying from ~1.0-2.7 kGauss show that a 4-kA beam can be accelerated to 19.75-MeV with <10% spot size smearing.

We have measured BBU amplification as a function of frequency between 700-to-900-MHz by exciting beam oscillations (typically 0.1-mm) with a tunable rectangular box that was shock-excited by the beam. The amplitudes of the transverse motion were measured before and after the eight ITS cells for both horizontal and vertical orientation of the box. The gains were found to agree approximately with the code predictions with a transport magnetic field lower than nominal so as to not effectively damp the BBU motion (Fig. 2). The best agreements for the inferred cell transverse coupling impedance was within 20% of the measurements in ref. 7.

We have since observed that our beam produces a steady-state quadrupole magnetic field with an integrated gradient-length product of 30-Gauss when passing through the box. The response of the beam position monitors to the resulting elliptical beam is then significantly non-linear to centroid displacements. We are now repeating the BBU measurements with cosine-wound quadrupole magnets near the box. Also, we have connected a ~25-W external rf drive to the box to improve the reproducibility of the initial deflections.
C. Energy spread

We measure time-resolved beam energy distribution in a single pulse using a 60-degree spectrometer magnet to image a collimated portion of the center of the beam onto a Bicron 422 scintillator viewed with a streak camera. Fig. 3 shows a representative trace from the spectrometer measuring the beam extracted from the ITS injector. The beam has an energy of 3.783-MeV with an rms spread of 0.55%, or ±1% peak-to-peak, over 60-ns at this point. Tapering of the first injector transmission line and adjustments to the peaking section within the Blumlein will be used to flatten the large central bulge within this trace.

Fig. 2 Measured & calculated BBU gain thru ITS cell-block

![Graph showing BBU Gain vs Frequency](image)

Fig. 3 Injector energy spread with expanded scale

![Graph showing Energy vs Time](image)

V. Facility construction status

Fig. 4 shows an artist's rendition of the completed facility, showing two long halls for perpendicular accelerator installation with pulsed-power halls running alongside. Building construction is 30% complete with an estimated finish date of November 1997. The first radiographic experiments are scheduled for June 1999. Operation of the complete, dual-axis facility is expected by September 2001 and is paced by completion of the second accelerator. Prior to construction of the final machine, we will consider designs to deliver four sequential pulses with ~2MHz repetition rate.

![Artist's rendition of DARHT](image)

Conclusions

Our work since 1991 indicates that we will achieve the radiographic performance required by DARHT. The principal accelerator components have been tested on the ITS accumulating over 30,000 pulses. Measured beam characteristics have been well-predicted by our computational models and these have been extensively benchmarked and improved against ITS data. An alternative photocathode system is under development to generate a colder beam than our present velvet cathode, thus making us less sensitive to emittance growth and presenting the possibility of achieving a smaller radiographic source size.

Acknowledgments

Work performed under the auspices of the US Dept. of Energy.

References

Banquet Talk

Ed Knapp

Thursday, August 29, 1996
NEW DIRECTIONS IN SCIENCE.

Ed Knapp
Santa Fe Institute

The Santa Fe Institute was founded about 12 years ago by a group of scientists who, for one reason or another, had come to the conclusion that something was really very broken in the practice of science in the American university. Individual disciplines dominated the research agenda to the exclusion of almost all interdisciplinary work, and the research agendas of these disciplines were narrowing to an alarming extent. The Santa Fe institute was organized to be a entirely visiting institution, a place where people could come on sabbatical or for extended workshops and not be constrained to the rigid requirements of department life, or worry about publishing yet another unread paper to insure the proper number of refereed publications the tenure committee might require for permanent appointment. On the whole, this experiment has been quite successful, and I think that we can point to a number of cases where ideas generated in the give and take of interdisciplinary discussion have become almost mainstream in academic circles. Several of these are in the Social sciences, and today I would like to talk a bit about computer simulation, and the challenges we all face in introducing simulation techniques from the physical sciences into the realm of cultural and economic problems.

The cultural and economic sciences seem to be ready made for extensions of the Monte Carlo techniques so prevalent in the design and analysis of High Energy Physics and Accelerator experiments. These problems almost always consist of large aggregations of individuals or organizations which interact as time progresses in a sequence of encounters, with themselves or with their environment, leading to a statistical distribution of effects which can characterize the development of the system. But things are never as easy as they might seem.

Simulation is used in the Physical sciences to investigate the really hard problems where analytical methods cannot give adequate description to the interactions involved. In the case of particle accelerator physics, beam interaction and space charge effects are almost always handled via simulation techniques. Simulation is more prevalent in the design and analysis of high energy physics experiments, where Monte Carlo simulations of event signatures, spectrometer acceptance, and background rates are almost always required by the program committee before beam time is allocated. Simulations are often required in the analysis of the experimental results, again for geometrical acceptances as well as detector efficiencies, etc.. Of course, the most complex of the simulations in the physical sciences is probably in the codes which are used to design and analyze nuclear explosions, which combine particle transport with hydromagnetic and radiation effects in a extremely complex way.

Moving to the biological sciences, including ecology and evolution, we see a more complex system, and thus more difficulty in applying simulations accurately. In the Social sciences, the interacting entities can think, plan ahead, make mental models of their domain, evolve in time, learn, and in general introduce innumerable complications into the interactions. Social sciences such as economics, anthropology, organizational theory, psychology, and even philosophy and history may be amenable to simulation if we can only learn how to do it. The problem is learning how to do science with simulations such that meaningful insights emerge from the exercise, leading to deeper understandings of the problems, if not predictability as is the case in the physical sciences.

What are some of the characteristics of cultural or social investigations? Usually, the universe of the problem is made up of many "agents", e.g. individuals, firms, countries, villages, or similar. This is in analogy to the particles being transported in typical monte carlo simulations for particle physics. Collisions between agents and other agents or the environment occur as time unfolds, producing the dynamics of the situation. Typically, the fate of individual agents is "path dependent", history does count. At this point, analogies to the physical sciences become less clear. A major part of the environment in which social simulations unfold is generated by the actions of the agents themselves. This feedback, or coupling between individual and group behavior, is what makes such studies scientifically interesting, and often mathematically intractable. This can be said to capture the point where simplicity becomes complexity. The behavior of the entire assemblage of agents "emerges" in a highly nonlinear manner from the behaviors of the individuals. The agents themselves can be highly complex, and their interactions with the environment can modify their individual behaviors. To be realistic, in contrast to simulations in the physical sciences, agents must also be able to learn, modify behavior, and in general optimize their performance. Hierarchical stratification of organization should be possible in the simulation. There must be a mechanism for individuals to organize into groupings, for example families, firms, countries, etc. And finally, it is clear that the entire simulation is very path dependent, this is not only do to individual agents histories depending critically on chance encounters during the passage of time, but the emergence of a "world" is historically path dependent. Any simulation must allow "today", the sum of past evolution and emergence of a society, the sum of culture, superstitions,
myths, institutions, and the like must be insertable at certain points.

Making simulations with all of these features is a very tall order. Can it be done? The problems are much too important for science to duck - we must try even though it seems extremely daunting. The World in which we live is made of the collective decisions of millions of agents acting under the rules, both cultural and legal, set up by our organization of society. Can such a world be modeled using simulation techniques? It certainly has not been done yet - but just as in the physical sciences simulations are essential to experimental investigations, as computation becomes cheaper much more complex simulations of human organization and behavior will become important.

With this as background, I would like to describe a simple first attempt to bring this type simulation into the scientific arena. I will give in what follows some results from a study of the formation of financial markets by a simulation program which incorporates some of the features of social simulation mentioned above. This work has been done by a collaborative group of visitors at the Santa Fe Institute, and consists of Brian Arthur, an economist and demographer, John Holland, a computer scientist and psychologist, Blake LeBaron, an economist, Richard Palmer, a physicist, and Paul Taylor, a stock tracker.

A persistent puzzle in finance is why academic theorists and market traders should view financial markets is strikingly different ways. Standard economic theory assumes homogeneous investors who share rational expectations of an asset's future price, and who instantaneously and rationally discount all market information into this price. It follows that the market is efficient in that no opportunities are left open for consistent speculative profit, that technical trading (using patterns in past prices to forecast future ones) cannot be profitable except by luck, that temporary price overreactions -bubbles and crashes- reflect rational changes in assets' valuations rather than sudden shifts in investor sentiment. It follows too that trading volume is low or zero, and that indices of trading volume and price volatility are not persistent or serially correlated in any way. The market, in this standard theoretical view, is rational, efficient, and mechanistic. Traders, on the other hand, often see markets as offering speculative opportunities. Many believe that technical trading is profitable, that something definable as a "market psychology" exists, and that herd effects unrelated to market news can cause bubbles and crashes. Some traders and financial writers even see the market itself as possessing its own moods and personality, sometimes describing the market as "nervous", or "sluggish", or "jittery". The market in this view is psychological, less than efficient, and organic. From the academic viewpoint traders with such beliefs - embarrassingly the very agents assumed rational by the theory - are irrational, wrong, superstitious. From the traders viewpoint, the standard academic theory is unrealistic, alien, not borne out by their own perceptions. To quote one of the most successful traders, George Soros: "this efficient market theory interpretation of the way financial markets operate is severely distorted. It may seem strange that a patently false theory should gain such widespread acceptance."

Arthur et. al. Have constructed a simulation of a simple market, with features which make possible the study of some of the questions raised by this fundamental puzzle in economic science. In this market N agents decide on their desired asset distribution between a risky stock paying a stochastic dividend and a risk free bond. The individual agents formulate their expectations independently, but are identical in other respects. Except for the heterogeneity of agents, the market is neoclassical in all respects. Each trader has access to information on the state of the market in the form of time series of past and current prices and dividends. In the model they do not use the raw time series, but these data are summarized into a set of binary descriptors, which for example, could be the running average of the stock dividend, or the price trend for the last pre determined number of periods, or other statistical information generated from the raw price and dividend data stream. Using these descriptors the individual agents predict the price for the next period, and decide to buy or sell the stock depending upon their current position in the market. Descriptors are combined into hypotheses which are reinforced or discarded according to the success or failure of the individual hypotheses to accurately predict the price. Each agent has its hypotheses stored on a "genome", a bit string which encodes the present set of hypotheses with which the agent trades. This bit string is modified by the success or failure of the trades the agent performs, as well as is modified by mutation and crossover which brings new hypotheses to the action. A standard genetic programming approach is used for the evolution of strategies, as well as the discard of unsuccessful hypotheses. The price of the stock then varies according to the aggregate of the buy and sell orders presented. Further, hypotheses can be classified into classes, those which reflect fundamentals, (such as price to dividend ratios), and technical trading indicators, such as price trends.

Clearly, this model incorporates in a rudimentary way several of the criteria discussed for simulations in social situations. In incorporates learning, path dependence, and strong feedback where the agents generate their own environment. Arthur et al have conducted a series of experiments using this model, and have gained considerable insight into the observed behaviors of real markets in real world situations. First they investigated the operation of the market in the homogeneous rational expectations regime. As expected, if the hypotheses were limited to the calculation of fundamentals and bids were determined using this data only, the rational expectations model was replicated, price followed fundamentals very closely, and volume was low. Even small admixtures of technical hypotheses rapidly
converge back to the rational expectations result, and technical hypotheses tend to die out in the models used by the agents for trading. There clearly is a natural, weak attraction to the rational expectations model. As initial heterogeneity is increased, increasingly the market does not converge to the rational expectations regime. Instead, complex patterns form in the collection of beliefs, and the market falls into a regime that differs materially from the rational expectations behavior. Bubbles and crashes occur, and suggest that technical trading, in the form of buying or selling into trends, may have emerged in the market. Once into the rich psychological regime the volume increases substantially, and in other respects mimics very closely several of the statistical features of a real market which are not reproduced in the rational expectations regime. In particular, statistical correlations between price volatility and volume observed in real markets, called GARCH (Generalized Autoregressive Conditional Heteroscedastic time series) behavior is seen clearly. Other observations in the behavior of the market which track with the observations in real markets include the dynamics of recovery from dividend or price perturbations and the income distributions of participants in the market. And finally, it is clear that the environment for trading is bootstrapped by the individual traders. A very successful trader at one time, if frozen in its trading hypotheses, will do very poorly at a different time, as the environment has evolved around it into different competition. They have even seen strategies evolve to corner the market!!! It is clear that real stock markets operate in the rich psychological regime.

Thus it seems clear that for this case real insight into market behavior can be extracted from simple simulations of learning and adaptation of agents in a market environment. Clearly this simulation cannot be used for application into a real market to predict behavior - particular stock prices on the New York Stock Exchange for example. But as a tool for economics research simulations may be the wave of the future. No less a critic than Robert Solow, Nobel prize winner from MIT, has written in Science magazine that this type simulation may be the future in some aspects of economics research.

As should be apparent, programming these type problems is a very technical and demanding task. Even in the Physical sciences typical Monte-Carlo simulations are usually handled by utilizing library programs which take care of the graphical output, geometrical parameters, and so on. There are no equivalent libraries of programs available to the social scientist in consistent use at the present time, and up until recently each simulation was essentially started from scratch. About three years ago a team of visitors at SFI held a series of meetings to evaluate what was available to the community for applications of these kinds, and developed a set of goals for a programming language, or platform, which could be developed to support agent based simulations. Out of this effort a collaborative group of computer scientists and others have developed a programming platform called SWARM which is available to any group wishing to do simulations of this kind. This platform utilizes many individual pieces from the overall simulation community and also significant extensions in power not utilized previously. Interestingly, industry participation in this collaborative team has been significant, both in the input phase and in the implementation of actual code. Swarm is multi-agent software platform for the simulation of complex adaptive systems. In the Swarm system the basic unit of simulation is the swarm, a collection of agents executing a schedule of actions. Swarm supports hierarchical modeling approaches whereby agents can be composed of swarms of other agents in nested structures. Swarm provides object oriented libraries of reusable components for building models and analyzing displaying, and controlling experiments on those models. Swarm is currently available as a beta version in full, free source code form It requires the GNU C Compiler, Unix, and X Windows. More information about Swarm can be obtained from the World wide web,

http://www.santafe.edu/projects/swarm/.
Invited Talk Session FR1

Chairman: J. Alessi

Friday, August 30, 1996
HIGH LUMINOSITY MUON COLLIDER DESIGN

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Abstract
Muon Colliders have unique technical and physics advantages and disadvantages when compared with both hadron and electron machines. They should be regarded as complementary. Parameters are given of 4 TeV high luminosity $\mu^+\mu^-$ collider, and of a 0.5 TeV lower luminosity demonstration machine. We discuss the various systems in such muon colliders.

Introduction
The possibility of muon colliders was introduced by Skrinsky et al. [1], Neuffer [2], and others. More recently, several workshops and collaboration meetings have greatly increased the level of discussion [3, 4]. A detailed Feasibility Study [5] was presented at Snowmass 96.

Technical Questions
Hadron collider energies are limited by their size, and technical constraints on bending magnetic fields. Lepton (e$^+e^-$ or $\mu^+\mu^-$) colliders, because they undergo simple, single-particle interactions, can reach higher energy final states than an equivalent hadron machine. However, extension of $e^+e^-$ colliders to multi-TeV energies is severely performance-constrained by beamstrahlung. The luminosity $\mathcal{L}$ of a lepton collider can be written:

$$\mathcal{L} = \frac{1}{4\pi E} \frac{n_\gamma}{2r_0\alpha} \frac{P_{\text{beam}}}{\sigma_y} n_{\text{collisions}}$$

where $\sigma_y$ is the average vertical (assumed smaller) beam spot size, $E$ is the beam energy, $P_{\text{beam}}$ is the total beam power, $\alpha$ is the electromagnetic constant, $r_0$ is the classical radius, and $n_\gamma$ is the number of photons emitted by one bunch as it passes through the opposite one. If this number is too large then the beamstrahlung background of electron pairs and other products becomes unacceptable.

As the energy rises, the luminosity, for the same event rate, must rise as the square of the energy. For an electron collider, $n_{\text{collisions}} = 1$, and, for a fixed background, we have the severe requirement:

$$\frac{P_{\text{beam}}}{\sigma_y} \propto E^3$$

In a muon collider there are two significant changes: 1) The classical radius $r_0$ is now that for the muon and is 200 times smaller; and 2) the number of collisions a bunch can make $n_{\text{collisions}}$ is no longer 1, but is now related to the average bending field in the muon collider ring, $6 \text{T}$, it is 900.

In addition, with muons, synchrotron radiation is negligible, and the collider is circular. In practice this means that it can be much smaller than a linear electron machine. The linacs for the 0.5 TeV NLC will be 20 km long. The ring for a muon collider of the same energy would be only about 1.2 km circumference.

There are, of course, technical difficulties in making sufficient muons, cooling and accelerating them before they decay and dealing with the decay products in the collider ring. Despite these difficulties, it appears possible that high energy muon colliders might have luminosities comparable to or, at energies of several TeV, even higher than those in $e^+e^-$ colliders.

Parameters
The basic parameters of a 4 TeV $\mu^+\mu^-$ collider are shown schematically in Fig. 1 and given in Table 1 together with those for a 0.5 TeV demonstration machine based on the AGS as an injector. It is assumed that a demonstration version based on upgrades of the FERMILAB machines would also be possible.

Figure 1: Schematic of a Muon Collider.
Table 1: Parameters of Collider Rings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C of m Energy (TeV)</td>
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</tr>
<tr>
<td>Beam energy (TeV)</td>
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<tr>
<td>Beam γ</td>
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<tr>
<td>Repetition rate (Hz)</td>
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<td>Muons per bunch (10^12)</td>
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<tr>
<td>Luminosity (cm^{-2}s^{-1})</td>
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</tr>
</tbody>
</table>

Components

Proton Driver

The proton driver is a high-intensity (four bunches of 2.5 x 10^{13} protons per pulse) 30 GeV proton synchrotron, operating at a repetition rate of 15 Hz. Two of the bunches are used to make μ^+’s and two to make μ^-’s. Prior to targeting the bunches are compressed to an rms length of 1 ns.

For a demonstration machine using the AGS [6], two bunches of 5 x 10^{13} at a repetition rate of 2.5 Hz at 24 GeV could be used.

Target

Predictions of nuclear Monte-Carlo programs [7, 8, 9] suggest that π production is maximized by the use of heavy target materials, and that the production is peaked at a relatively low pion energy (∼100 MeV), substantially independent of the initial proton energy.

Cooling requirements dictate that the target be liquid: liquid lead and gallium are under consideration. In order to avoid shock damage to a container, the liquid could be in the form of a jet.

Pion Capture

Pions are captured from the target by a high-field (20 T, 15 cm aperture) hybrid magnet: superconducting on the outside, and a water cooled Bitter solenoid on the inside. A preliminary design [10] has a Bitter magnet with an inside coil diameter of 24 cm (space is allowed for a 4 cm heavy metal shield inside the coil) and an outside diameter of 60 cm; it provides half (10 T) of the total field, and would consume approximately 8 MW. The superconducting magnet has a set of three coils, all with inside diameters of 70 cm and is designed to give 10 T at the target and provide the required tapered field to match into the decay channel.

Decay Channel and Phase Rotation Linac

The decay channel consists of a periodic superconducting solenoidal (5 T and radius = 15 cm). A linac is introduced along the decay channel, with frequencies and phases chosen to decelerate the fast particles and accelerate the slow ones; i.e. to phase rotate the muon bunch.

Figure 2 shows the energy vs ct at the end of the decay channel.

![Energy vs ct of muons at end of decay channel with phase rotation; muons with polarization P > 1/3, -1/3 < P < 1/3, and P < -1/3 are marked by the symbols ‘+’, ‘-’ and ‘-‘ respectively.](image)

The selected muons have a mean energy 150 MeV, rms bunch length 1.7 m, and rms momentum spread 20 % (95 %, εL = 3.2 eVs). The number of muons per initial proton in this selected bunch is ∼0.3.

Polarization Selection

If nothing is done then the average muon polarization is about 0.19. If higher polarization is desired, some selection of muons from forward pion decays (cos θ_d → 1) is required. This can be done by momentum selecting the muons at the end of the decay and phase rotation channel. A snake [11] is used to generate the required dispersion. Varying the selected minimum momentum of the muons yields polarization as a function of luminosity loss as shown in Fig. 3. Dilutions introduced in the cooling have been calculated [12] and are included. A Siberian snake is also required in the final colliding ring.

Ionization Cooling

For the required collider luminosity, the phase-space volume must be greatly reduced; and this must be done within the μ lifetime. Cooling by synchrotron radiation, conventional stochastic cooling and conventional electron cooling are all too slow. Optical stochastic cooling [13], electron cooling in a plasma discharge [14] and cooling in a crystal lattice [15] are being studied, but appear very difficult. Ionization cooling [16] of muons seems relatively straightforward.

In ionization cooling, the beam loses both transverse and longitudinal momentum as it passes through a material medium. Subsequently, the longitudinal momentum can be restored by co-
herent reacceleration, leaving a net loss of transverse momentum.

Figure 3: Polarization vs $F_{loss}$ of muons accepted; the dashed line shows polarization as selected before cooling; the solid line gives polarization after cooling.

The equation for transverse cooling (with energies in GeV) is:

$$\frac{d\epsilon_n}{ds} = -\frac{dE_\mu}{ds} \frac{\epsilon_n}{E_\mu} + \frac{\beta_\perp (0.014)^2}{2 E_\mu m_\mu L_R},$$

(3)

where $\epsilon_n$ is the normalized emittance, $\beta_\perp$ is the betatron function at the absorber, $dE_\mu/ds$ is the energy loss, and $L_R$ is the radiation length of the material. The first term in this equation is the coherent cooling term, and the second is the heating due to multiple scattering. This heating term is minimized if $\beta_\perp$ is small (strong-focusing) and $L_R$ is large (a low-Z absorber).

Energy spread is reduced by placing a transverse variation in absorber density or thickness at a location where position is energy dependent, i.e. where there is dispersion. The use of such wedges can reduce energy spread, but it simultaneously increases transverse emittance in the direction of the dispersion. It thus allows the exchange of emittance between the longitudinal and transverse directions.

Cooling System The cooling is obtained in a series of cooling stages. In general, each stage consists of three components with matching sections between them:

1. a FOFO lattice consisting of spaced axial solenoids with alternating field directions and lithium hydride absorbers placed at the centers of the spaces between them, where the $\beta_\perp$'s are minimum.

2. a lattice consisting of more widely separated alternating solenoids, and bending magnets between them to generate dispersion. At the location of maximum dispersion, wedges of lithium hydride are introduced to interchange longitudinal and transverse emittance.

3. a linac to restore the energy lost in the absorbers.

In a few of the later stages, current carrying lithium rods replace item (1) above. In this case the rod serves simultaneously to maintain the low $\beta_\perp$ and attenuate the beam momenta. Similar lithium rods, with surface fields of 10 T, were developed at Novosibirsk and have been used as focusing elements at FNAL and CERN [17].

The emittances, transverse and longitudinal, as a function of stage number, are shown in Fig. 4. In the first 10 stages, relatively strong wedges are used to rapidly reduce the longitudinal emittance, while the transverse emittance is reduced relatively slowly. The object is to reduce the bunch length, thus allowing the use of higher frequency and higher gradient rf in the reacceleration linacs. In the next 7 stages, the emittances are reduced close to their asymptotic limits. In the last 3 stages, using lithium rods, there are no wedges and the energy is allowed to fall to about 15 MeV. Transverse cooling continues, and the momentum spread is allowed to rise. The total length of the system is 750 m, and the total acceleration used is 5 GeV. The fraction of muons remaining at the end of the cooling system is calculated to be 55%.

Figure 4: Normalized transverse and longitudinal emittances as a function of section number in the model cooling system

Acceleration Following cooling and initial bunch compression the beams must be rapidly accelerated to full energy (2 TeV, or 250 GeV). A sequence of recirculating accelerators (similar to that used at CEBAF) could be used but would be relatively expensive. A more economical solution would be to use fast pulsed magnets in synchrotrons with rf systems consisting of significant lengths of superconducting linac.

For the final acceleration to 2 TeV in the high energy machine, the power consumed by a ring using only pulsed magnets would be excessive and alternating pulsed and superconducting magnets [18] are used instead.

Collider Storage Ring After acceleration, the $\mu^+$ and $\mu^-$ bunches are injected into a separate storage ring. The highest possible average bending field
is desirable to maximize the number of revolutions before decay, and thus maximize the luminosity. Collisions occur in one, or perhaps two, very low-β* interaction areas.

**Bending Magnet Design** The magnet design is complicated by the fact that the μ’s decay within the rings (μ⁻ → e⁻νeνμ), producing electrons whose mean energy is approximately 0.35 that of the muons. These electrons travel toward the inside of the ring dipoles, radiating a fraction of their energy as synchrotron radiation towards the outside of the ring, and depositing the rest on the inside. The total average power deposited, in the ring, in the 4 TeV machine is 13 MW. The beam must therefore be surrounded by a ≈ 6 cm thick warm shield [19], which is located inside a large aperture conventional superconducting magnet.

The quadrupoles can use warm iron poles placed as close to the beam as practical, with coils either superconducting or warm, as dictated by cost considerations.

**Lattice** In order to maintain a bunch with rms length 3 mm, without excessive rf, an isochronous lattice, of the dispersion wave type [20] is used. For the 3 mm beta at the intersection point, the maximum beta’s in both x and y are of the order of 400 km (14 km in the 0.5 TeV machine). Local chromatic correction is essential. Two lattices have been generated [21, 22], one of which [22], after the application of octupole and decapole correctors, has shown to have an adequate calculated dynamic aperture.

Studies of the resistive wall impedance instabilities indicate that the required muon bunches would be unstable if uncorrected. In any case, the rf requirements to maintain such bunches would be excessive. BNS [23] damping, applied by rf quadrupoles [24], is one possible solution, but needs more careful study.

**Muon Decay Background**

Monte Carlo study [25, 19] indicated that the background, though serious, should not be possible. Further reductions are expected as the shielding is optimized, and it should be possible to design detectors that are less sensitive to the neutrons and photons present.

There would also be a background from the presence of a halo of near full energy muons in the circulating beam. The beam will need careful preparation before injection into the collider, and a collimation system will have to be designed to be located on the opposite side of the ring from the detector.

There is a small background from incoherent (i.e. μ⁺μ⁻ → e⁺e⁻) pair production in the 4 TeV Collider case. The cross section is estimated to be 10 mb, which would give rise to a background of ≈ 3 10⁶ electron pairs per bunch crossing. Approximately 90% of these, will be trapped inside the tungsten nose cone, but those with energy between 30 and 100 MeV will enter the detector region.

**Conclusion**

- Considerable progress has been made on a scenario for a 2 + 2 TeV, high luminosity collider. Much work remains to be done, but no obvious show stopper has yet been found.

- The two areas that could present serious problems are: 1) unforeseen losses during the 25 stages of cooling (a 3% loss per stage would be very serious); and 2) the excessive detector background from muon beam halo.

- Many technical components require development: a large high field solenoid for capture, low frequency rf linacs, multi-beam pulsed and/or rotating magnets for acceleration, warm bore shielding inside high field dipoles for the collider, muon collimators and background shields, etc. but:

- None of the required components may be described as exotic, and their specifications are not far beyond what has been demonstrated.

- If the components can be developed and the problems overcome, then a muon-muon collider could be a useful complement to e⁺e⁻ colliders, and, at higher energies could be a viable alternative.

**Acknowledgment**

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**References**


ADVANCED RF POWER SOURCES FOR LINACS

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Abstract

In order to maintain a reasonable over-all length at high center-of-mass energy, the main linac of an electron-positron linear collider must operate at a high accelerating gradient. For copper (non-superconducting) accelerator structures, this implies a high peak power per unit length and a high peak power per RF source, assuming a limited number of discrete sources are used. To provide this power, a number of devices are currently under active development or conceptual consideration: conventional klystrons with multi-cavity output structures, gyrokystrons, magnetrons, sheet-beam klystrons, multiple-beam klystrons and amplifiers based on the TEL principle. To enhance the peak power produced by an rf source, the SLED rf pulse compression scheme is currently in use on existing linac's, and new compression methods that produce a flatter output pulse are being considered for future linear colliders. This paper covers the present status and future outlook for the more important rf power sources and pulse compression systems. It should be noted that high gradient electron linac's have applications in addition to high-energy linear colliders; they can, for example, serve as compact injectors for FEL's and storage rings.

1. Overview

In this report we consider the current status of pulsed high power rf sources for linac's with copper (non-superconducting) accelerating structures. The desired peak output power from these sources is driven in large part by the requirements of electron-positron linear colliders which are currently under active design and development at various laboratories around the world. Some basic rf-related parameters for these machines are given in Table 1. This table is based on data contained in the December, 1995, report of the International Linear Collider Technical Review Committee [1]. This report is primarily concerned with the details of linear collider designs at 500 GeV center-of-mass (c.m.) energy; upgrade paths to 1 TeV c.m. are only briefly considered. However, we have selected the 1 TeV parameters because particle physicists strongly urge that the collider designs should include the potential for an upgrade to reach this energy. Two of the machines in Table 1 (JLC-X and VLEPP) propose upgrades to 1.0 TeV c.m. simply by doubling the active accelerator length. In the other three designs a higher accelerating gradient, with a correspondingly greater power demand from the rf source, is proposed for the upgrade. In addition to the linear collider designs shown in Table 1, two other designs have been proposed which are based on the two-beam accelerator approach: CLIC at CERN and the Two-Beam NLC proposed by LBNL and LLNL as an alternative rf power source for the NLC. Although the drive beam of a two beam accelerator is capable of producing copious amounts of rf power at good efficiency, we will consider only discrete rf sources here.

Although phase-locked oscillators have been proposed as possible rf sources for powering linear colliders, we consider only amplifiers here because of their higher gain and greater stability. Among the potential candidates for a high power microwave amplifier, klystrons, gyrokystrons and magnetrons have demonstrated the capability to produce power in the 3-17 Ghz frequency range at a level of interest for linear colliders. Details concerning current performance of these devices are presented in Sections 2 and 3 of this report.

RF pulse compression, using passive microwave components, can enhance the peak power from a microwave tube by a factor of 2-1/2 to 5 or so with reasonable efficiency. Current pulse compression methods are discussed in Section 4. Some future possibilities for pulse compression, including the use of loaded delay lines to reduce delay line length and the use of active switching to increase power gain and efficiency, are discussed in Section 5.

Looking to the longer-range future, there is interest in how to reach energies well beyond the 1 TeV energy provided by the designs in the Technical Review Committee Report. To reach higher energies within a reasonable overall accelerator length, a higher accelerating gradient will be needed. Significantly higher gradients can only be achieved by increasing the rf frequency. Some scaling relations for the variation of rf power requirements with frequency and gradient are given in Section 6. As an example, by extrapolating 11.4 GHz technology to 34 GHz, a 5 TeV collider could be built with an unloaded gradient of 250 MV/m and an active structure length of about 30 km. However, the required peak rf power is about 800 MW per meter at a pulse length of about 60 ns. Even with rf pulse compression, it will be difficult to obtain the required power from a conventional round-beam 34 GHz klystron. Some limitations on the power that can be reached by round-beam klystrons, and how this maximum power output might scale with frequency, are also discussed. Some possible microwave devices that might provide power adequate to drive a 5 TeV collider at 34 GHz are described in Section 7.

2. Klystrons

The workhorse of the world’s high power klystrons at S-band is the SLAC 5045 klystron [2] currently in use as the power source for the SLC. Approximately 240 of these tubes have been in use on the SLAC linac for about 10 years. Some of these tubes have now accumulated over 65,000 hours of operating time. The specifications for the 5045 klystron, the mean time to failure, and some of the failure modes together with the number of tubes that have failed in each mode over a ten-year period, are given in Table 2. An outstanding feature of the 5045 klystron its reliability and long lifetime. To be successful in a linear collider application, where several thousand tubes are used, a klystron will need to approach the reliability and lifetime of the 5045.

A 150 MW S-band klystron for powering the DESY S-band linear collider (SBLC) has been designed and engineered at SLAC [3]. Table 3 gives the design specifications and the performance of the first two prototype tubes. The design philosophy for these tubes followed a conservative approach.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>SBLC (DESY)</th>
<th>JLC-C (KEK)</th>
<th>JLC-X (KEK)</th>
<th>NLC (SLAC)</th>
<th>VLEPP (BNF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Frequency (GHz)</td>
<td>3.0</td>
<td>5.7</td>
<td>11.4</td>
<td>11.4</td>
<td>14.0</td>
</tr>
<tr>
<td>Accelerating Gradient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unloaded/Loaded (MV/m)</td>
<td>42/36</td>
<td>58/47</td>
<td>73/58</td>
<td>85/63</td>
<td>100/91</td>
</tr>
<tr>
<td>Dark Current Capture Gradient (MV/m)</td>
<td>16</td>
<td>31</td>
<td>61</td>
<td>61</td>
<td>75</td>
</tr>
<tr>
<td>Peak Power per Meter at Structure input (MV/m)</td>
<td>49</td>
<td>97</td>
<td>100</td>
<td>145</td>
<td>120</td>
</tr>
<tr>
<td>Klystron Peak Power (MW)</td>
<td>150</td>
<td>100</td>
<td>135</td>
<td>75</td>
<td>150</td>
</tr>
<tr>
<td>Klystron Pulse Length (μs)</td>
<td>2.8</td>
<td>2.4</td>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Repetition Rate (Hz)</td>
<td>50</td>
<td>50</td>
<td>150</td>
<td>120</td>
<td>300</td>
</tr>
<tr>
<td>Pulse Compression Type</td>
<td>SLED</td>
<td>SLED</td>
<td>DLDS</td>
<td>BPC</td>
<td>VPM</td>
</tr>
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<td>Compression Ratio</td>
<td>=3.5</td>
<td>5.0</td>
<td>2.0</td>
<td>4.0</td>
<td>4.6</td>
</tr>
<tr>
<td>Compression Gain (%)</td>
<td>2.0</td>
<td>3.5</td>
<td>1.95</td>
<td>3.5</td>
<td>3.3</td>
</tr>
<tr>
<td>Compression Efficiency (%)</td>
<td>=60</td>
<td>70</td>
<td>98</td>
<td>87</td>
<td>73</td>
</tr>
<tr>
<td>RF System Efficiency (%)</td>
<td>23</td>
<td>26</td>
<td>31</td>
<td>34</td>
<td>40</td>
</tr>
<tr>
<td>Number of Klystrons</td>
<td>4900</td>
<td>6200</td>
<td>6900</td>
<td>9500</td>
<td>2800</td>
</tr>
<tr>
<td>Active Length (km)</td>
<td>29</td>
<td>22</td>
<td>18</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td>Wall Plug Power (MW)</td>
<td>285</td>
<td>200</td>
<td>220</td>
<td>190</td>
<td>115</td>
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</table>

Table 2
The SLAC 5045 Klystron

<table>
<thead>
<tr>
<th>Specification</th>
<th>Design</th>
<th>Performance I</th>
<th>Performance II</th>
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<tbody>
<tr>
<td>Operating Frequency</td>
<td>2856 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Voltage (kV)</td>
<td>350 kV</td>
<td>535</td>
<td>536</td>
</tr>
<tr>
<td>Beam Current (A)</td>
<td>414 A</td>
<td>700</td>
<td>720</td>
</tr>
<tr>
<td>Micropervance (A/cm²)</td>
<td>2.0</td>
<td>1.8</td>
<td>1.83</td>
</tr>
<tr>
<td>Output Power (MW)</td>
<td>67 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repetition Rate (Hz)</td>
<td>3.3 μs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>180 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Cavities</td>
<td>46 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cathode Loading (A/cm²)</td>
<td>53 db</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area Convergence</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Time to Failure (h)</td>
<td>≈ 50,000 hrs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cause of Failure (403 tubes: 1984-1994)</td>
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<td></td>
<td></td>
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<tr>
<td>Window failure</td>
<td>89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gun ceramic</td>
<td>82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unstable or low rf output</td>
<td>68</td>
<td></td>
<td></td>
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<tr>
<td>Arcing</td>
<td>57</td>
<td></td>
<td></td>
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<tr>
<td>Gassy</td>
<td>46</td>
<td></td>
<td></td>
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<tr>
<td>Vacuum Leak</td>
<td>24</td>
<td></td>
<td></td>
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<tr>
<td>Low Emission</td>
<td>16</td>
<td></td>
<td></td>
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<tr>
<td>Water Leak</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faulty parts</td>
<td>7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3
SLAC/DESY 150 MW S-Band (2998 MHz) Klystron

<table>
<thead>
<tr>
<th>Specification</th>
<th>Design</th>
<th>Performance I</th>
<th>Performance II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Voltage (kV)</td>
<td>55</td>
<td>535</td>
<td>536</td>
</tr>
<tr>
<td>Beam Current (A)</td>
<td>150</td>
<td>700</td>
<td>720</td>
</tr>
<tr>
<td>Micropervance (A/cm²)</td>
<td>3</td>
<td>1.8</td>
<td>1.83</td>
</tr>
<tr>
<td>Cathode Loading (Max A/cm²)</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area Convergence</td>
<td>40.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Power (MW)</td>
<td>60</td>
<td>150</td>
<td>156</td>
</tr>
<tr>
<td>Repetition Rate (Hz)</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Electronic Eff. (%)</td>
<td>&gt;40</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Gain (db)</td>
<td>62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output circuit</td>
<td>1 cell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Focusing type</td>
<td>Solenoid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solenoid Power (kW)</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Window Type</td>
<td>TE₁₁, pillbox</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. Windows per Klystron</td>
<td>4</td>
<td></td>
<td></td>
</tr>
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### Table 4
SLAC X-Band (11.4 Ghz) Klystrons

<table>
<thead>
<tr>
<th></th>
<th>XLT-4</th>
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<th>X5011</th>
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<tr>
<td></td>
<td>Design</td>
<td>Achieved</td>
<td>Design</td>
<td>Achieved</td>
</tr>
<tr>
<td>Gun</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Voltage (kV)</td>
<td>440</td>
<td>450</td>
<td>465</td>
<td>480</td>
</tr>
<tr>
<td>Beam Current (A)</td>
<td>350</td>
<td>190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microcervance (A/cm²)</td>
<td>1.2</td>
<td>1.15</td>
<td>0.6</td>
<td>0.65</td>
</tr>
<tr>
<td>Cathode Loading (A/cm²)</td>
<td>8.75</td>
<td>7.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area Convergence RF</td>
<td>125</td>
<td>140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Power (MW)</td>
<td>50</td>
<td>75</td>
<td>50</td>
<td>62</td>
</tr>
<tr>
<td>Pulseswidth (µs)</td>
<td>1.5</td>
<td>1</td>
<td>1.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Repetition Rate (Hz)</td>
<td>180</td>
<td>120</td>
<td>180</td>
<td>60</td>
</tr>
<tr>
<td>Electronic Eff. (%)</td>
<td>52 (sim)</td>
<td>48</td>
<td>63 (sim)</td>
<td>60</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>&gt;50</td>
<td>55</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Output circuit</td>
<td>4 cell TW</td>
<td>5 cell TW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Focusing Type</td>
<td>Solenoid</td>
<td>PPM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solenoid Power (kW)</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. Windows per Klystron</td>
<td><strong>TE₀₋₁-TW</strong></td>
<td><strong>TE₀₋₁-TW</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There are two additional programs for the development of high power klystrons for linear collider service. At KEK, a klystron is being developed in collaboration with Toshiba for the X-band JLC collider. The first tube achieve the performance shown in Table 5 at short pulse lengths, but could not sustain higher power levels or longer pulse lengths due to breakdown in the single output gap. To reduce the field level, the klystron has been redesigned with a 4-cell TW circuit; this new tube is currently under test.

### Table 5
Parameters for the KEK/Toshiba and BINP/VLEPP Klystrons

<table>
<thead>
<tr>
<th></th>
<th>KEK/Toshiba</th>
<th></th>
<th>BINP/VLEPP</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design</td>
<td>Achieved</td>
<td>Design</td>
<td>Achieved</td>
</tr>
<tr>
<td>RF Frequency (GHz)</td>
<td>11.4</td>
<td>14</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Output Power (MW)</td>
<td>135</td>
<td>96/50</td>
<td>150</td>
<td>60</td>
</tr>
<tr>
<td>Pulseswidth (µs)</td>
<td>0.75</td>
<td>0.10.2</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Repetition Rate (Hz)</td>
<td>150</td>
<td>100</td>
<td>300</td>
<td>2</td>
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<tr>
<td>Microcervance (A/cm²)</td>
<td>1.2</td>
<td>1.2</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>Electronic Eff. (%)</td>
<td>45</td>
<td>33</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>Beam Voltage (kV)</td>
<td>600</td>
<td>620</td>
<td>1000</td>
<td>1000</td>
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<tr>
<td>Cathode Loading (A/cm²)</td>
<td>13.5</td>
<td>13.5</td>
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<td>5</td>
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<tr>
<td>Output Circuit</td>
<td>4-cell TW</td>
<td>single gap</td>
<td>14-cell TW</td>
<td></td>
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<tr>
<td>Gain (dB)</td>
<td>53-56</td>
<td>75</td>
<td>75</td>
<td>90</td>
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<tr>
<td>Focusing Type</td>
<td>SC</td>
<td>Solenoid</td>
<td>PPM</td>
<td>PPM</td>
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<td>Solenoid/Cryogenic Power (kW)</td>
<td>1</td>
<td>40</td>
<td>40</td>
<td>40</td>
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<tr>
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<td>TE₀₋₁-TW</td>
<td><strong>TE₀₋₁,-2</strong></td>
<td><strong>TE₀₋₁,-2</strong></td>
<td></td>
</tr>
</tbody>
</table>

in which existing 5045 technology was extended to higher beam currents and rf power densities. In the first tube an 8.56 GHz oscillation proved troublesome. In the second tube, two copper drift tubes were replaced by stainless steel drift tubes. The second klystron processed quickly and showed no instabilities.

Table 3 gives design and performance parameters for two X-band klystrons designed and built at SLAC (see [4] for an overview of the X-band klystron program at SLAC). Four klystrons in the XL series [5] have been produced. XL-1 and XL-2 have 3-section standing-wave output circuits and the other two tubes have four-cell traveling-wave outputs. The first three tubes produced the specified 50 MW at 1.5 µs but were troubled by instabilities unless the focusing strength was increased at the cost of reduced efficiency. Several design changes were incorporated in XL-4, including adjustments in the spacing and tuning of the bunching cavities, fabrication of the last three drift tubes from stainless steel, and coating the output circuit with titanium nitride. This klystron has produced 50 MW at 1.5 µs and 120 pps at a beam voltage of 400 kV with 43% efficiency; at a somewhat shorter pulse width (1.1 µs) it has reached 75 MW at an efficiency of 48%. It is essentially free of oscillations, pulse-shortening or missing pulse phenomena that have been observed in all previous X-band klystrons built at SLAC.

The second column in Table 4 shows design parameters [6] and achieved performance for the first Periodic Permanent Magnet (PPM) focused klystron built at SLAC. This tube has produced over 60 MW at 0.6 µs with an efficiency of 60%. At a pulse length of 1.2 µs it has reached the design power output of 50 MW at somewhat lower efficiency. Although the output rf pulse is stable, a complex phenomenon takes place as a function of drive power which is not yet fully understood. In any case, this is the only klystron of this design that will be built. The program effort will be directed to the design of a 75 MW PPM tube with a microcervance of 0.75.

3. **Magnicons and Gyroklystrons**

A magnicon is a scanning-beam microwave amplifier in which a rotating electron beam interacts synchronously with a rotating TM-mode in a cylindrical output cavity. It is capable of high efficiency, and has been proposed as an alternative to klystrons for powering linear colliders. At the Budker Institute of Nuclear Physics (Novosibirsk), a 7 Ghz magnicon has produced 30 MW at 35% efficiency [9]. The efficiency was limited by an oversized electron beam diameter (4 vs 3 mm). At the Naval Research Laboratory, an 11.4 Ghz magnicon is under design with a simulated output of 58 MW at 58% efficiency [10]. By using the TM⁺⁻ mode in the output cavity, this magnicon also acts as a frequency doubler from 5.7 to 11.4 Ghz. The space efficiency in a magnicon it is necessary to keep the beam diameter (e.g. = 2 mm in the NRL design) small relative to the rf wavelength. It will be difficult therefore
to achieve high power in a magnetron at a frequency which is substantially higher than the 11 GHz of the NRL design.

Gyrokystrons, having extended annular beams, are capable of producing high rf power at high frequencies. The most extensive work on the development of high power gyrokystrons has taken place at the University of Maryland. In past experiments, 27 MW at 9.9 GHz has been produced with an efficiency of 32%, and 32 MW at 19.7 GHz (2nd harmonic) at an efficiency of 29%; the pulse length was about 1 μs (see references in [11]). A new gyrokystron testbed has recently been completed with a higher power modulator capability (800A at 500 kV). A coaxial gyrokystron is now under construction which will eventually reach a simulated output power of 160 MW at 17.1 GHz (2nd harmonic) at an efficiency of 41% [11]. Use of a single-stage depressed collector could increase this efficiency to 55%.

4. RF Pulse Compression

An rf pulse compression system can enhance the peak power output from a microwave tube by trading reduced pulsewidth for increased peak power. The power gain is given by the compression ratio, R, in pulsewidth times a compression efficiency which takes account of intrinsic losses (e.g., reflected power, resistive (copper) losses, and the effect of a non-flat output pulse. Pulse compression reduces the burden on the rf power source and helps to match the modulator pulse length] to the accelerator structure filling time. It is especially important at higher frequencies where the structure filling time, which scales as ω−1/2, is short and the production of peak rf power is more difficult. A pulse compression system always involves an energy storage element of some sort to delay or transfer energy from the early portion of the rf pulse into the compressed output pulse.

The first large-scale pulse compression system for an accelerator application was the SLED scheme, implemented on the SLAC linac in the late 1970’s. Using a pair of TE015 cylindrical cavities (Qω=1×105) as energy storage elements, SLED produces a power gain of about 2.7 with a compression efficiency of 62% (R = 4.4). A distinguishing feature of the SLED compression method is a 180° phase reversal in the klystron drive, which triggers the release of the energy stored in the high Q cavities. Two cavities and a 3 db coupler are used so that the energy reflected and emitted from the cavities will not return to the klystron but will be directed into the transmission line to the accelerator.

Because the SLED output pulse has a shape which is dominated by the exponential decay of energy in the storage cavities, it is poorly adapted for powering a linear collider with long bunch trains. The pulse shape problem can be solved by replacing the two storage cavities with shorted delay lines. In this scheme, called SLED-II, the delay line length (in travel time) is equal to one-half the desired output pulse length. The power gain is optimized by adjusting the reflection coefficient of an iris at the entrance to the delay lines. Assuming lossless components, the power gains (and efficiencies) for a SLED-II system with compression ratios of 4, 5 and 6 are 3.44 (86%), 4.0 (80%) and 4.5 (75%).

A program has been in progress at SLAC for a number of years to develop the necessary components for a high power SLED-II pulse compression system. To keep losses low, overmoded TE01 circular waveguide is used for the SLED-II delay lines and for power transmission over distances greater than a meter or so. A low loss (3/4%) mode converter [12] has been developed which makes it possible to couple efficiently to the circular guide from standard WR90 rectangular guide. This so-called “flower petal” mode converter also makes it possible to manipulate rf power using relatively simple rectangular waveguide components. For example, a 90° bend is constructed from a mitered rectangular waveguide bend and two mode transducers.

A complete SLED-II compression system has been implemented on the NLC Test Accelerator at SLAC, and tested at both low and high power [12]. The measured efficiency of the SLED-II system was 68% at R=6 (power gain of 4.05). The intrinsic Q for the delay lines (12.07 cm diameter) was measured to be 1.05×108, which is 76% of theoretical. This corresponds to a roundtrip power loss of 1.5% for a delay of 225 ns. The power transmission system connecting the SLED-II compressor to the NLCTA injector consists of 20 m of 7.4 cm diameter circular waveguide, two 90° bends and mode converters at each end. The measured one-way loss is 5.8%. The system is currently delivering an output power of about 150 MW; this power level is still increasing as the injector accelerating structures continue to process, and is expected to reach about 200 MW.

5. Future Possibilities for Pulse Compression

Several possibilities exist for improving pulse compression systems beyond SLED-II. First of all, the intrinsic inefficiency of a SLED-II system translates to a 30-40 MW increase in ac wall plug power for a 1 TeV collider. The Binary Pulse Compression (BFC) scheme, which compresses by a factor of R=2n, is inherently 100% efficient, but unfortunately needs a total delay line length of (R-1)Tp, where Tp is the output pulse length. This can be compared to a lengthTp for a SLED-II system.

Two ways have been suggested for reducing the delay line length for a BFC scheme. In the DLDS (Delay Line Distribution System) scheme proposed at KEK, the rf is sent up-stream toward the gun for one-half of the delay, and the transit time of the returning beam provides the other half. This reduces the length of delay line pipe by about a factor of two (see [1] and [8] for more details on DLDS). A second method being considered for reducing delay line length is to replace the lines by a chain of N coupled resonators, where N is of the order 3 to 10. Larger values of N will give a flatter pulse and greater pulse shape efficiency. For a delay of one microsecond, a Q on the order of 106 is required for good transmission efficiency. This can be achieved in a TE01m-mode cavity on the order of 1.5 m long, but because of the high mode density coupling to parasitic modes is a problem. Active R&D on such loaded delay lines is underway at SLAC and elsewhere.

Use of an active device to switch the effective reflection coefficient of the iris at the entrance to the delay lines can improve the efficiency and power gain of a SLED-II system. Such a switch, based on changing the conductivity of a silicon wafer with a laser beam, is under investigation at SLAC [13].

6. Limitations on Klystron Power

If all dimensions of an accelerating structure are scaled in proportion to the rf wavelength λ, the energy stored per unit length varies as Uₘ = G²λ², where G is the accelerating gradient.
Therefore, assuming a fixed repetition rate and ratio of pulse length to filling time, the gradient and the total machine energy can be increased in direct proportion to the rf frequency while maintaining a fixed active structure length and ac power. It is interesting to note that the gradient for capture of an electron at rest (dark current capture threshold) is also proportional to frequency \( G_{\text{d}} = 1.605 \text{ MV}/\lambda \). Operational difficulties, such as the interference of dark current with beam position monitoring, can also be expected to scale with \( G_{\text{d}} \). While the dark current capture threshold does not impose an absolute limit on accelerating gradient, it is dangerous to assume it can be exceeded by too wide a margin. Values of \( G_{\text{d}} \) are listed in Table I for the various collider designs.

The accelerators listed in Table I were not designed with any particular frequency scaling law in mind. However, there is a consistent trend toward higher gradients at higher frequencies. If the unloaded gradients for the 500 GeV c.m. designs (not listed) are plotted vs. frequency, they fall roughly on a straight line parallel to and 35% above the line \( G_{\text{d}} = 0 \). If we extrapolate this trend to 34 GHz (12 times SLC), we obtain an unloaded gradient of 250 MV/m. This frequency and gradient can serve as the basis for a 5 TeV linear collider design with a reasonable length (= 30 km of active structure) and ac power (= 250 MW).

The peak rf power required per meter of structure length scales as \( U_{\text{p}}^2 / f \), \( -G_{\text{d}}^{1/2} \). Assuming an NLC accelerating structure with somewhat higher group velocity \( (v_g/c = 0.09) \) scaled to 34 GHz, the peak power per meter will scale to \( 800 \text{ MW/m} \). In a scenario using a 3-stage BPC compression scheme and two 0.6 m accelerating structures per klystron, the peak klystron power required would be 150 MW. We consider next the limitations on obtaining this kind of power from a 34 GHz microwave source.

It is well known that the efficiency of conventional round-beam klystrons depends on the microperveance, \( K_{\text{m}} \). This dependence is not sharply defined, but the expression \( \eta = 0.75 - 0.17 K_{\text{m}} \) gives approximate efficiencies for the X-band klystrons simulated at SLASS (assuming modest future improvements). To obtain an overall rf system efficiency of 50%, a klystron with an efficiency in the range 65–70% is needed. To achieve such efficiencies, the microperveance will need to be in the range 0.3–0.6. Assuming a beam voltage of 500 kV, the maximum output power will be in the range 35–70 MW.

Another limitation is klystron power depends on the acceptable cathode loading per square centimeter, \( I_b \), the maximum area convergence ratio \( A_i \), (dictated by the gun optics) and the need for good coupling to the beam in the rf gaps (maximum beam radius \( \lambda/8 \)). Putting these factors together, the maximum output power is \( P = \eta V_{\text{b}} I_b A_i \pi (\lambda/8)^2 \). The maximum area convergence is limited by the beam convergence: \( A_i = 150 I_{\text{b}} \lambda \) [14]. For \( I_b = 8 A/cm^2 \), a beam voltage of 500 kV and a microperveance in the range 0.3–0.6, the maximum klystron power is in the range 180–40 MW at 34 GHz.

7. RF Sources for 34 GHz

In the previous section it was found that efficiency and cathode loading and area convergence considerations limited the power of a conventional klystron to about 40 MW at 34 GHz. Four such beams packaged together in the same vacuum envelope could produce the desired 150 MW. Such a multibeam klystron having common rf cavities but separate PPM-focused beam tubes has indeed been proposed [14]. Klystrons using a sheet beam, essentially equivalent to many round beams in parallel, are also capable (in simulations) of producing 150 MW at 34 GHz with good efficiency [15].

As discussed in Sec. 3, gyroklystrons are capable of producing high power at high frequency. At the University of Maryland, a coaxial-circuit gyroklystron frequency doubled to 34 GHz has been designed which produces an power output of 150 MW at a simulated efficiency of 42% [16]. A single-stage depressed collector can increase this to 56%.

Another annular-beam device capable of delivering high power output at high frequencies is the ubitron FEL proposed by McDermott et al. [17]. Using a TE_{00} -mode coaxial cavity with PPM focusing, it produces a simulated output power of 250 MW at 11.4 GHz with an efficiency of 50%.

References

A number of papers relevant to high power rf sources and pulse compression systems for linacs are presented at the recent meeting on Pulsed RF Sources for Linear Colliders (RF96), April 8–12, 1996, Shonan Village Center, Hayama, Japan. In the following, a reference to RF96 indicates a paper to be published in the proceedings of this conference.

ROLE OF LASERS IN LINEAR ACCELERATORS

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Abstract
While time-dependent electromagnetic fields using microwave technology have been exploited for decades in acceleration and manipulation of charged particle beams, modern lasers stand poised to be exploited for these purposes with great promise. The advent of compact sub-picosecond terawatt lasers has renewed the interest in phenomena that involve scattering or collective interaction of lasers with relativistic particles for various purposes such as diagnostics and control of beams, ultra-high gradient particle acceleration, laser-driven high brightness particle sources, etc. We will give examples of laser-linac interaction already in use or being contemplated in such areas as TeV-scale gamma-gamma colliders, laser monitoring of beams, laser injectors and prospects for laser acceleration of particles.

I. Introduction
The microwave technology at frequencies up to tens of GHz has been the work horse for particle accelerators since World War I and II. Powerful radio frequency (rf) electromagnetic energy sources — such as tetrodes and klystrons, with a great deal of flexibility in amplitude, phase and frequency control — have been the drivers of particle storage and acceleration in circular and linear accelerators. Along with such versatile power sources came the necessity to control and manipulate particle beams via rf electromagnetic fields to a high degree of precision. The rf and beam feedback systems, bunch-rotating and Landau rf cavities, etc. — all have been employed successfully to benefit collider operation. As the science and technology of rf sources and devices progressed, the demands on the spectral purity of rf components for accelerator applications rose precipitously. This has been so in order to assure a high degree of stability and control of the beam.
Progress in technology allows us today to contemplate going beyond the GHz microwave rf technology to mm-wave and even THz radiation sources and eventually to the state-of-the-art short pulse high power compact lasers. Many of these technologies are ready to be exploited in charged particle handling devices. In this article, we will restrict ourselves to various possibilities with lasers only, and even that as it applies to possibilities with linear accelerators alone, leaving untouched the multitude of possibilities with storage rings and circular colliders.
The development of compact high power, short pulse, efficient lasers is a fast moving technology [1]. Peak powers well above multiple terawatts have been demonstrated and routinely used in the so-called Table Top Terawatt (T³) solid state lasers, based on the Chirped Pulse Amplification (CPA) technique. Current research is focused on further increase of peak power (multiple Joules of energy in sub 100 fs pulse length) as well as increasing the repetition rate beyond 1 Hz to a kHz and beyond. This latter aspect of high repetition rate as well as the phase, amplitude and jitter control of T³ lasers is very relevant for particle accelerators. Fortunately, we benefit from the laser developments driven by the demands for coherent control needed for research in fields such as ultrafast phenomena in solids, chemistry of liquid and gas phases and many biological studies.
These intense lasers are well-known to have high electric and magnetic fields. Investigations are under way throughout the world to explore possibilities to exploit such intrinsic ultrahigh electromagnetic fields by coupling these lasers appropriately to a particle beam for net longitudinal acceleration and for other beam manipulations [2–3]. Such coupling can be produced in free space in presence of suitable boundaries and apertures; or in free space without boundaries via nonlinear higher order mechanisms and in presence of magnetic fields; or via direct coupling to a suitable macroscopic medium like a plasma. However, just as in today's microwave technology involving beam manipulation over fractions of 'm'ss' in time-scales of 'picoseconds' at frequencies of GHz, one would have to invent techniques and learn to manipulate and control signals and particles at optical wavelengths of 'microns', in time-scales of 'femtoseconds' and at frequencies of 'THz' in order to take advantage of today's lasers.
Lasers can be scattered off a relativistic electron beam and the frequency up-shifted photons can be used directly for various scientific applications. One such use of lasers in linear accelerators is in the realm of colliders where a linear γ–γ or photon-photon collider provides an attractive complement to high energy TeV scale electron-positron collisions. This is discussed in Section II. The intrinsic coherent transverse focal volume of a laser is typically much smaller than that of a particle beam. Thus lasers could act as ideal microprobes of particle beam phase space for purposes of diagnostics. This is discussed in Section III. One particular aspect that makes lasers unique is their ultrashort pulse duration (100 fs or shorter) which makes time-resolved measurements of emittance over short beam slices possible. The intrinsic high field of lasers allow us to contemplate their use in particle acceleration and various beam manipulations. This is discussed in Section IV. Finally the tunability and short pulse nature together with the ability to synchronize lasers to sub-ps level make them ideal drivers for particle injectors to linear accelerators. Various possibilities are under investigation and are reported in Section V. Section VI concludes with an outlook.
II. Photon-Photon Colliders

The LEP and the SLC have been successful in doing precise spectroscopy of the W and Z. However, we understand the technical and fiscal constraints of large circular lepton colliders owing to limits imposed by the synchrotron radiation. Hence, there is increasing interest world-wide in TeV scale linear colliders involving electrons and positrons. Such colliders are seen as complementing the multi-TeV hadron colliders of the future, such as the LHC.

It has also been recognized that in order to maximize the reach to accessible high energy physics frontier, it is important and reasonable to explore the technical possibility of at least two interaction points (IPs) at these colliders: one for normal electron-positron collisions and a second one for collisions of hard photons on hard photons, electrons on hard photons and electrons on electrons. This second IP is commonly referred to as the Gamma-Gamma Collider arm of a linear collider — a term dubbed after an international workshop on the topic in Berkeley in 1994 [4]. High energy photons i.e. gamma rays for these collisions are most effectively produced via Compton backscattering of focused laser beams by the high energy electron beams of the linear collider. The high energy photon beams are then brought into collision with opposing electron or photon beams. Since one does not need positrons for the Compton conversion, the possibility of electron-electron collision exist as well. With suitable laser and electron beam parameters, a luminosity of electron-photons and photon-photon collisions comparable to that of the electron-positron collisions can be achieved. In addition, the polarization of the high energy photons can be controlled via polarization of the laser and the electron beams. With high luminosity and variable polarization, the photon-photon and electron-photons collisions at TeV energies will significantly enhance the discovery potential and analytic power of a TeV linear collider complex.

Yet another important reason to consider photon-photon collisions is the limitations imposed by radiative effects of the macroscopic beam electromagnetic fields. Charged particles get bent severely by the macroscopic electromagnetic field of the opposing colliding beam, leading to copious emission of what is known as ‘beamstrahlung’ photons, characterized by the Y parameter — a classical measure of average radiated photon energy in units of beam particle energy. The effect also leads to a large energy spread, σB, in the colliding beams. If the number of particles per colliding bunch is too large, the beamstrahlung photons can produce coherent pairs, causing concern about electromagnetic and hadronic backgrounds in the detector. Typically, the conventional wisdom in collider design is to stay below Y-0.3 limit in order not to be limited by the radiative effects. However, as one reaches up to higher energies of 5 TeV in the center-of-mass and beyond with luminosities above 10^{35} cm^{-2} s^{-1}, conventional choices for the radiative effects lead to unrealistic values for critical collider parameters e.g. a total site power well above a gigawatt, etc. We are thus forced to consider colliders with radiative parameters in the unconventional regime of Y>>0.3 and large σB. The “γ-γ” collisions (instead of direct e^+e^- collisions) via Compton conversion offer an alternative paradigm to collider physics, with no limitation from beamstrahlung or coherent pair production. The issues to be addressed are rather different: the development of suitable laser technology, the feasibility of the laser-beam and γγ interaction point geometry and the complementarily of the physics.

A preliminary but rapidly evolving conception of such a composite and integrated linear collider complex is being considered by the international linear collider community at present and is shown in Figure 1 [5]. The required laser peak powers — about a Joule in a picosecond or a 100 mJ in 100 femtoseconds — have already been achieved in today’s state-of-the-art Ti: Lasers. And there is significant promise of enhanced repetition rate operation of these lasers to match the particle beam collision frequency for luminosity considerations. Investigations on both conventional lasers and Free Electron Lasers (FELs) towards this goal are underway at present [5].

![Fig. 1 A linear collider configuration with electron-positron, photon-photon, electron-photon, and electron-electron collisions.](image)

III. Lasers as Micro-probes

The TeV-scale electron-positron -gamma linear colliders envisioned today would require beam spot sizes of nanometers at the final focus of the collisions. For controlling the collisions and maintaining the luminosity, it is critical that one is able to measure and monitor such ultra-small spot sizes. Lasers have already been employed in this task successfully at the SLC at SLAC [6].

The principle of small spot-size measurement at the SLC is illustrated in Figure 2 (a) below. An interference fringe or standing wave pattern is created by direct and reflected near-infrared laser beams orthogonal to the electron beam. The relativistic electron beam is scanned across the waist of the fringe pattern. The pattern created by the Compton-scattered photons at a detector along the beam’s...
forward direction has intensity oscillations as a function of beam position during scanning, as shown in Figure 2 (b) for the SLC. The result contains information about the beam size, resulting in a measure spot size of 70 nm!

![Diagram of electron beam and interference fringes](image)

Fig. 2 (a) and (b) Final spot size measurement at the SLC via Compton Scattering across laser interference fringes.

While monitoring and control of beam spot sizes are important, the longitudinally time-resolved measurement of beam phase-space characteristics are even more critical. Development of this kind of techniques will become increasingly necessary for diagnosing electron bunches in future accelerators. Since the transverse coherence volume of lasers is typically much smaller than that of a particle beam, the laser beam can act as an optical microprobe of a finite region of the beam transverse phase space and with the advent of femtosecond lasers, all this can be achieved in a time-resolved manner over femtosecond slices of many samples of a beam.

X-rays produced by Thomson scattering of a short terawatt laser pulse (40 mJ, 100 fs long) off a 50 MeV electron beam at 90° have already been shown to be an effective diagnostic to measure transverse and longitudinal density distribution of the electron beam with subpicosecond time resolution at the Beam Test Facility at LBNL [7]. Near-infrared (800 nm) laser pulses, were focused onto the electron beam waist, generating x-rays in the forward direction with energies up to 30 keV (Figure 3 (a)). The transverse and longitudinal electron beam dimensions have been obtained by measuring the intensity of the x-ray beam, while scanning the laser beam across the electron beam in space and time (Figure 3 (b)). The electron beam divergence or transverse momentum distribution has been obtained through intensity and size measurement, followed by a deconvolution of spatial and spectral characteristics of the scattered x-ray beam, thus completing the full transverse phase-space characterization of the electron-beam in steps of femtoseconds over its entire 20 ps duration.

![Diagram of Thomson scattering phase-space diagnostic set-up](image)

Fig.3 (a) and (b) Thomson scattering phase-space diagnostic set-up (a) and phosphor image of scattered x-rays (b).

### IV. Laser-Plasma Acceleration

It is well known that lasers have inherently high electric and magnetic fields, that can potentially be harnessed for compact ultra-high gradient linear accelerators. There exists the possibility of acceleration via lasers in free space in presence of suitable boundaries or via nonlinear higher order mechanisms or via direct coupling of lasers to a plasma-like medium [2–3]. Among experimental results to date on laser-driven acceleration of electrons in a plasma, the UK (RAL) experiment is the most recent (1996). It has demonstrated the highest gradient (100 GV/m) and produced beam-like properties in the accelerated electrons with $10^7$ electrons @ 40 MeV ± 10% with a normalized emittance of $\epsilon_x<5\pi\text{mm}\cdot\text{mrad}$ [8].

I would like to remind the readers of two important aspects that will critically determine the future of laser acceleration schemes. First, just as today's microwaves from klystrons are suitably guided by linac waveguide structures without diffraction for efficient coupling to a charged particle beam, we will have to learn how to focus strongly (in order to achieve high electric field intensities) and simultaneously guide short pulse high energy lasers over long macroscopic
distances of cms without diffraction in order to use them for particle acceleration. Second, one would have to master the relative amplitude, phase and frequency control of lasers similar to that exhibited by today’s rf control level, but scaled to laser frequencies.

An artist’s impression of a staged and modular laser wakefield accelerator, compared and contrasted to its present-day microwave linac analog, is depicted in Figure 4 [9]. Such a scheme depends on the success of propagating and guiding intense laser pulses in hollow plasma channels at high power densities of the order of \(10^{18}\) W/cm\(^2\) over several hundred Rayleigh lengths. I would like to mention here the important results obtained at Maryland [10], where lasers focussed to \(10^{14}\) Watts/cm\(^2\), have been propagated up to 70 Rayleigh lengths. Much progress has also been made in the context of pulse train generation and control in today’s table-top terawatt lasers, thanks to applications in coherent wavepacket control for studies in chemistry. One has the capability today of tailoring a sequences of up to eight or ten pulses, varying in strength, phase and width from a short pulse laser.

![Image](https://via.placeholder.com/150)

**Fig. 4** Conventional microwave linac (a) with klystrons and metallic waveguides vs. conceptual laser-plasma linac (b) with lasers and plasma guides.

A state-of-the-art \(T^3\) - laser with improved repetition rate (10TW, 300 fs, 10 kHz) will provide 3 J of laser energy per pulse at a wavelength of 1 µm. If one aims at a 1 meter stage with energy gain of 10 GeV, one needs a plasma 1 meter long, with a density of \(10^{17}\) cm\(^{-3}\) accommodating 300 Rayleigh lengths. The accelerating wakefield wavelength will be 100 µm, the channel radius 30 µm, the acceleration gradient of 10 GV/m, with channel density variation of a 50% from center to the edge. In this scenario, one laser creates the necessary plasma acceleration structure via guiding, the other creates the wakefield for acceleration.

The required plasma channels need further study in order to overcome diffraction and to decouple the transverse gradient from that of the accelerating wake. Many similarities exist between linac structures and hollow plasma guides. These need to be quantified and better understood.

Synchronization of laser and electron pulse from stage-to-stage in Figure 4 demands sub-ps laser synchronization scheme. There are various injection and synchronization schemes under study at present as mentioned in Section V.

Should the guiding, staging and controllability issues be worked out, there is hope that wakefields excited in plasmas by a suitably shaped laser pulse will have the necessary characteristics for particle acceleration to ultrahigh energies, based on rather reliable simulations available today [11].

**V. Laser Injectors**

Lasers are beginning to play a crucial role in injectors of high quality (i.e. low emittance and high phase-space brightness) electron beams to linear accelerators. RF photoinjectors, where electrons packed tightly in phase-space are produced from a photocathode surface properly embedded in a high electromagnetic field inside a radio frequency cavity and subjected to short pulse laser irradiation for photo-emission, have been under intensive development in the past decade. Normalized particle beam emittances close to 1 π mm-mrad have been achieved. Such optically switched rf photoinjectors are optimal candidates as injectors for FELs and future colliders based on metallic traveling waveguide linear accelerators. The promise and R&D of rf photoinjectors is described elsewhere in detail [12].

As we have discussed before, some of the high gradient acceleration concepts using lasers as drivers envision using a high density (\(10^{19}–10^{19}\) cm\(^{-3}\)) plasma as an accelerating structure over the short time duration of a picosecond or so (2–3). For possible future high gradient linear accelerators based on laser-driven plasmas, it is probably more natural to consider a photoinjector that is based on a plasma, rather than on a rf cavity made up of conducting metallic structures. Thus emerges the concept of LILAC — Laser Injected Laser ACcelerator, proposed by D. Umstadter [13]. In LILAC, one laser pulse drives a wakefield in the plasma and another ejects and injects background plasma electrons, thus employing an all-optical synchronized injection and acceleration (Figure 5).

In laboratory experiments, a terawatt-peak-power laser beam was focused into a gas jet and an electron plasma wave was observed to create and accelerate a naturally collimated beam of electrons in a 10 fs slice to relativistic energies (up to \(10^9\) electrons, with an energy distribution maximizing at a MeV and a physical (unnormalized) total geometric transverse emittance of 1 π mm-mrad and electric field gradient of 2 GV/cm) [13].

Yet another laser-based, ultra-cold optical injector scheme is based on interaction of subcyclic optical pulses with a thin plasma film (10 nm in thickness) [14]. The resulting chirp introduced in the electron phase space of the plasma distribution leads to a compressed ultracold electron bunch with a potential normalized emittance of \(10^{-4}\) π mm-mrad in a bunch shorter than a nm. It is important to note however that such a short bunch will radiate coherently (N\(^2\) radiation) in soft x-ray and longer wavelengths.

Finally, Pellegrini [15] has proposed a FEL solution to the injection into a plasma-based accelerator. Such
accelerators typically demand an injector pulse as long as a tenth of the plasma wake wavelength and a normalized emittance less than $1 \pi$ mm-rad for focusing into an optical channel. The scheme is based on using the same laser to drive the plasma accelerator and to seed a FEL modulation into the injected beam from a rf photoinjector. The FEL, thus phase-locked to the plasma wave will provide both longitudinal and transverse focusing and a train of synchronized bunches.

![Diagram of LILAC concept](image)

**Fig. 5** The LILAC concept: one pulse drives a wakefield and another injects electrons.

**VI. Outlook**

There is significant promise of the usefulness of lasers in the monitoring, control and manipulation of charged particle beams. The time is ripe to begin exploiting today's lasers and even guide its future development for this purpose.

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**References**


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[9] The author is indebted to T. Tajima for fruitful discussions on conceptualizing Figure 4.


[15] The author is indebted to C. Pellegrini for bringing this work to his attention.
Invited Talk Session FR2

Chairman: G.A. Loew

Friday, August 30, 1996
STATUS OF ALPI AND RELATED DEVELOPMENTS OF SUPERCONDUCTING STRUCTURES

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Abstract
This talk treats of three main topics, namely:
I) the status of the Superconducting Linac ALPI;
II) the strategies put into action in order to push up the resonator performances;
III) the design and prototype work directed to the construction of a new positive ion injector for our Linac.

Since the beginning of 1995 several beams have been successfully accelerated with the ALPI Linac injected by the XTU-Tandem, especially in the medium-light mass region using Pb-plated and Nb-coated resonators.

The machine, warmed up several times since 1993, does not exhibit significant Q-degradation at high field. The difficulty of transferring the high Q- performances of the Nb based resonators from test bench conditions into the machine environment is discussed with some detail. The most challenging work now under way in Legnaro is the construction of two Superconducting RFQ’s which will boost the velocity of the ions produced by an ECR source and pre-accelerated through a 350 kV platform from beta 0.01 up to beta 0.035. The design work and the key choices of the manufacturing process will be presented.

Introduction
In 1989, after a couple of years of preliminary R&D in RF superconductivity, a long term project, named ALPI was initiated at the Laboratori Nazionali di Legnaro (LNL) aiming at extending the nuclear physics activities grown in the eighties around the 16 MV XTU tandem. The goal of the programme was to design and construct, through the development of the necessary expertise, heavy ion machines based on superconducting technologies which would allow to reach and overcome the nucleus-nucleus interaction barrier of any stable beam-target nuclear system.

Following the pioneering work at ANL [1](Argonne, USA), SUNY at Stony Brook [2](New York, USA), Weizmann Institute of Science [3](Rehovot, Israel) and later at Maine [4], we decided to construct and install a superconducting linac based on a large number (initially 93) of independently phased lead plated Quarter Wave Resonators (QWR’s), thus boosting the energies of the XTU tandem beams up to 20 MeV/A (for sulphur isotopes)[5].

The availability of a 16 MV tandem with single and double stripping capability makes the use of a superconducting linac as a post accelerator extremely effective, allowing high intensities (10-30 pA) onto the target for medium-light beams like e.g. sulphur, chlorine and nickel and a reliable use of medium-heavy ions up to iodine with intensities of few pA.

A positive ion CW-mode injector for ALPI linac has been designed in order to produce heavy ion beams of convenient energy and intensity. Beside improving the performance of the LNL accelerator complex for the light and medium heavy ion species, the new machine will allow to produce and accelerate also isotopes which are either rare or inadequate for typical tandem negative ion sources (see fig. 1, and fig. 2).

The new injector, named PIAVE [6], includes a 14.4 GHz ECR source installed on a high voltage platform (350 kV), two 80 MHz superconducting RFQ’s and two ALPI-like cryostats containing 8 bulk niobium 80 MHz QWR’s. The particular configuration of LNL accelerator complex (XTU tandem, PIAVE and ALPI) will then allow to feed two out of the three experimental halls with completely independent beams at the same time bringing, in the near future, the total amount of available beam time over 6000 hours per year.

Experience with ALPI
Although the machine is prepared to host up to 93 QWR’s, our present operating experience is limited to forty-eight 160 MHz accelerating cavities and three out of the five buncher stations [7].

Two more cryostats housing “medium β” type resonators (β=0.11) are ready for the installation.

The whole linac was meant, originally to consist only of lead plated QWR’s. The development of bulk Nb (β=0.055) and Nb sputtered (β=0.14) QWR’s reduced the number of cavities needed to reach the design performances of the linac to 93 cavities (β=0.055) of the machine already in an advanced stage of construction was delayed because of unexpected problems connected with the resonator unlocking induced by pressure fluctuations in the liquid helium reservoir of the cryostats. We believe the problems to be now fixed (see later on).

According to the experiment requirements, the accelerated ion species cover the mass range between 30 and 90 with specific energies up to 13.4 MeV/A [8]. The corresponding maximum accelerating voltage reached by the linac is 20.5 MeV/q with an average resonator gradient of 2.65 MV/m. The beam intensity onto the target in most cases ranges between 1 and 3 pA (up to 5 pA on the case of 20).

The majority of the experiments was devoted to the spectroscopy of very exotic nuclear states by means of the 4π multi-array detector named GASP, which needs a quasi-dc time structure of the beam. Only in few cases the beam was injected with a 5 MHz prebunched structure obtained with the double-drift double-frequency buncher (5+10 MHz), chopper and phase detector assembly [8]. In those cases where neutrons and γ-rays were discriminated through time of flight techniques, a direct measurement of the dark current between pulses less than 10^-4 with respect to the bunched portion of the beam was obtained.

In our experience the dc-bunching operation mode (160 MHz bunching) even proved to speed up the setting up of the machine, to require no interventions on accelerator components for days and to preserve the usual transmission and final quality of the beam. In fact once the resonators of the low energy leg of the machine are correctly phased, the particles outside the separatix are mainly lost in the internal “U-bend”.

In routine operation about 30% of the dc-beam injected in the machine is transported to the target. This average value results from the bunching efficiency (45%) and the total transmission of the machine including injection and extraction lines (70%).

The periodicity adopted for our machine (triplet-cryostat-diagnostics-cryostat) which allows us to monitor the beam every two cryostats, has been found very effective for the setting up of the periodical focussing Therefore we are confident to routinely reach 90% transmission, as demonstrated in some cases with sulphur and nickel beams.

The availability of beams for experiments strongly depends on the reliability of the cryogenic system. In the last eighteen months, in fact, 19% of the scheduled beam time was lost because of faults of the screw-compressors and damages of “cold box” turbines caused by power failures in occasion of strong storms. Faults occurring in other linac subsystems (pulsing, diagnostics) caused another 6% of machine shutdowns.
Fig. 1. Layout of the ALPI accelerator complex

Fig. 2. Performances of the ALPI complex in the configurations XTU-tandem (15MV)-ALPI and new injector(8MV)-ALPI. Two stripping configurations are considered when using the tandem as injector: gas(T)-foil(T) (both inside the tandem) and gas(T)-foil(outside the tandem). For the new injector (high energy curve) stripping is done before injecting ALPI. For comparison the performances of the XTU tandem alone (16 MV) are also plotted. The figures on the plots indicate beam intensities onto the target.

**Expertise on Superconducting QWR’s at LNL**

In 1987, at the beginning of our experience, we decided to develop two gap resonators, geometrically simple, very stable against mechanical vibrations and suitable to cover the ion velocity range of interest for experiments.

Within the R&D program we defined the following priorities:

1. Feasibility studies and tests (dynamics and electrodynamic investigations) of QWR’s in which the straight inner conductor ends in a hemisphere [9]. This geometry reduces peak surface electrical fields, facilitates the coating processes (lead plating and Nb sputtering), simplifies the construction of bulk niobium resonators and makes either seamless (by drilling a copper rod) or vacuum brazed OFHC copper cavities feasible[10] (see fig. 3).

2. Fixing up of a recipe for electroplating with a reduced number of process steps. Electroplating is a low cost treatment which can be used as a first approach in the development of new superconducting structures which exhibit complicate geometries.

3. Transfer of CERN experience in the sputtering process from the 350 MHz e-cavities to the QWR’s. This ambitious goal was originally conceived as a long term program aiming at the upgrading of the Lead plated resonators.

4. Improving of the manufacturing technologies of bulk niobium QWR’s.

**Lead plated resonators**

Our experience in lead plated resonators is supported by the high number (120) of successful plating cycles performed so far and by the sixty working resonators produced for the linac [11].

The good reliability and reproducibility of the plating process allowed us to restrict the laboratory quality test during the mass production to only 15% of the total number of resonators in preparation. Normally these resonators do not suffer from severe multipacting.

In the last two years the machine was warmed up three times forcing us to recondition it from scratch. In the worst case (cryostat opening) the cure of the multipacting did not take longer than 6 hours per cavity following twelve hours of baking of the resonators at 350 K with the cryostat shields at 60-70 K. Through the assistance of a semiautomatic computer control procedure the whole linac multipacting conditioning was performed in about 60 hours.
prototyping work which allowed us to fix a reliable recipe for the sputtering process [14]. The guidelines of the prototyping work were:

1. Optimization of the resonator copper base avoiding sharp corners in the internal surfaces and any hole in the outer conductor with the exception of the beam ports. Coupler and pick-up antennas were moved to the tuning plate placed at the bottom of the resonators.
2. Careful design of the Nb cathode in order to get a uniform deposition rate in every area of the resonator with particular attention to the high current zone.
3. Fixing up of the polishing of the OFHC copper substrate and its best vacuum conditions before sputtering.
4. Definition of the cathode preparation ("cathode training").
5. Fixing up of the multiple stages sputtering procedure.

The best results on test bench show high Q performances (2x10^10) at low field level and accelerating gradients of 6.9 MV/m at 7 W of dissipated power (see fig. 4).

Fig. 4. The best Q performances reached at LNL on bench test with the different QWR's installed in the linac.

These resonators are nearly multipacting free (1-2 hours of conditioning is enough) and with clean assembly conditions they exhibit weak field emission. When field emission appears too strong a rinsing with high pressure (200 bar) de-ionized water is sufficient to reduce the x-ray emission at the usual level.

The resonators installed in the accelerator sustain accelerating fields in excess of 4 MV/m at 7 W of dissipated power. It should be noticed that such resonators were produced with an anomalous sputtering process (at floating bias voltage), and suffered from vacuum leaks and dust contamination during installation [15].

**Bulk-Nb QWR's**

Prototypes of QWR's with β=0.055 (f=80 MHz), β=0.11 (f=160 MHz) and β=0.165 (f=240 MHz) have been developed in these years at LNL [16]. Extensive bench tests showed the excellent Q-performance of such cavities (Qv in excess of 10^9) which sustain accelerating fields of 5 MV/m with a power dissipation of 1 W (see fig. 4).

The 80 MHz resonators were chosen for the "low-β" section of the linac and for the high velocity part of the new injector (β≥0.035). The weight of such 1 m long resonators is very close to that of the β=0.11, f=160 MHz copper bases allowing the use, for the cryostats, of the same basic design as in the medium and high β sections of the machine.

When the 80 MHz resonator is working inside a normally noisy environment, its amplitude and phase are easily locked up to field levels of 6 MV/m within the usual self-sputtered loop configuration by widening the resonant bandwidth (resonator overcoupling). On the contrary, if the pressure in the liquid

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**Keeping the linac resonators at 300 K either in high vacuum (range 10^2 mbar) or in dry Nitrogen overpressure (1200 mbar) does not affect the multipacting conditioning time. On the contrary a wrong procedure in warming up of the resonators can strongly influence the multipacting phenomenon in the subsequent conditioning. The cavities must be steadily kept at a higher temperature than the cryostat shielding. If the shield temperatures, due to cryogenics faults, drifts over 120 K with the resonators still at a temperature close to 4.5 K, the whole multipacting conditioning has to be repeated.**

Field emission is cured in the machine by using the following complementary methods: "gentle" RF power processing both in high vacuum and controlled He gas atmosphere (4×10^-3 mbar) and the usual RF high power processing by means of 1 kW RF amplifiers. While the latter method is manually applied to single resonators exhibiting severe electron loading, "gentle" RF processing is managed by the RF control program, pulsing the 100 W amplifier output signal for a duration of 400 ns with a duty cycle of 20%.

The results of such field emission treatment are very encouraging. After every warming up of the machine the previous Q-performances were promptly recovered for all the resonators.

The accelerating field at 7 W dissipated power was improving with time through subsequent conditioning stages, from the initial average value of 2.4 MV/m to the present 2.7 MV/m.

More in details, 62% of the resonators exceeds the average field value of 2.6 MV/m, 27% of them exhibits a value in the range 2.6-2.8 MV/m and the remaining 11% shows values slightly lower than 2 MV/m.

Lead-tin plated resonators have been preferred in some laboratories because of their stability against oxidation and hydroxidation processes which makes even air storage possible [12]. As an alternative, since approximately same BCS losses are expected for both lead and lead-tin coatings, we pursued the goal of making lead films oxygen and humidity resistant through passivation processes [13].

**QW-Niobium sputtered resonators**

In June 1995, the first cryostat housing four Nb coated QWR's produced via DC biased diode sputtering was installed in the machine. This represented the final goal of a very intense

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helium reservoir of the cryostat feeding the resonator, is oscillating, as in our case, by \( \pm 50 \) mbar, this locking method is not longer efficiently applicable, because of frequency drifts up to 50 Hz. These drifts are normally in the range of 1-2 Hz per minute and can be recovered within a window of few Hz by means of a computer program which, in response to the phase error signal, drives the fine tuning mechanism.

In order to respond essentially to the excitation of the 42 Hz mechanical resonant mode of the cavity, a fast tuner (an externally controlled reactance VCX) is going to be used in combination with the slow tuner. The fast tuner consists of an inductive coupler connected by means of a 50Ω coaxial line to a variable capacitance located outside the cryostat. The system is designed in such a way that a tuning range of 400 Hz MV² m⁻³ (i.e., 25 Hz at 4 MV/m accelerating field, which appear to be more than needed in our case) can be obtained with only 1 W dissipated by the tuner at 4.2 K, and about 8 W dissipated at 100 K. The advantage of having easy access to the electronic components is clear, as well as the fact that relatively low power lines and feed-throughs are needed.

Furthermore, in order to lower the Q of the 42 Hz mechanical resonance, minor and simple mechanical modifications, mainly involving the flange holding the resonator, are still under development.

The new injector PIAVE

The energy plots as function of the beam mass number (see fig. 2) well illustrates the specific function of the new injector in the ALPI complex:

1. It makes acceleration of heavy nuclei (A\( \geq 130 \)) feasible.
2. It increases the beam intensity onto target by a factor 10 or more for medium-heavy and medium-light nuclei. For heavy beams intensities are estimated to be around some \( \mu \)A.
3. It extends the use of ALPI to the rare and costly isotopes.

The new injector preserves the CW operation mode of the ALPI linac and the beam qualities typical of the tandem accelerator.

The crucial requirement of high beam quality is already fulfilled at Argonne National Laboratory where a superconducting linac capable of accelerating very slow ions (\( \beta = 0.009 \)) is in full operation since few years [17].

The novelty of our design consists in employing for the first acceleration stage (0.0095≤β≤0.035) two superconducting RFQ's resonating at 80 MHz following the original idea of I. Ben'zi [18]. The rest of the acceleration up to \( \beta = 0.045 \) is provided by eight 80 MHz bulk niobium QWR's (\( \beta_w = 0.05 \)) housed in two cryostats.

The layout of PIAVE injector is shown in fig 4.

The beam, produced by a 14.4 GHz ECR source standing on a 350 kV high voltage platform [19] is analyzed and transported to the new injector through a matching line which contains an achromatic "U-bend" vertically tilted by 20 deg. The beam emerging from the pre-accelerating column is, in fact, 5 m higher and horizontally displaced by 1.8 m with respect to the new injector beam axis.

The longitudinal phase space matching at the SRFQ input is met by means of a room temperature double drift and double frequency (80-160 MHz) buncher operating at moderate voltage (V<4 kV) with an efficiency close to 60%. To increase the pulse to pulse time interval to 200 ns for time-of-flight experiments and isomeric nuclear state investigations, a 5 MHz buncher is foreseen on the high voltage platform downstream the source extraction voltage.

Downstream the RFQ transverse focussing in the QWR accelerating section is accomplished with two quadrupole doublets to compensate for the strong RF defocussing forces active at these low \( \beta \) values. Then the beam enters the linac through an achromatic "L-bend" of the ALPI type and the longitudinal matching is obtained with two room temperature bunchers placed in the beam waists before and after the "L-bend".

The design parameters of the RFQ's are presented in table 1. The frequency is fixed at 80 MHz which seems the best compromise between beam dynamics and resonator size requirements.

The major constraints for the RFQ design, dictated by the superconducting nature of the cavities, are: the maximum electric surface field \( E_s (25 \text{ MV/m}) \) and the maximum stored energy \( U \) (5 J). This last value is imposed by the RF power needed to keep the resonator locked within the required frequency window of \( \pm 10 \) Hz.

Due to the high costs of a superconducting structure and associated cryostat, big emphasis was given to the maximization of the average acceleration \( E_s \); this was pursued bunching the beam outside the SRFQ's and keeping the modulation factor \( m \), \( k_R \) (average aperture over modulation wavelength) and interwave voltage \( V \) relatively large [20].

Once fixed \( k_R \) and limited \( m \) in a certain range, with the reported condition on \( U \) and \( E_s \), both \( R_s \) and resonator length are determined according to \( \beta \). Since both \( V \) and \( R_s \) are proportional to \( \beta \), problems in the RFQ design are soon met as \( \beta \) approaches values around 0.035. This velocity is high enough to accelerate with QWR's.

The longitudinal emittance growth during the first stage of acceleration and the transverse mismatch between the two resonators are kept under control constructing a rather long first RFQ, with moderate values of \( R_s \) and \( V \), and a shorter second one with higher \( R_s \), \( V \) and \( E_s \), values. This configuration allows to shape the first 22 cells of the SRFQ 1 as an adiabatic bunch compressor where the synchronous phase \( \varphi \) decreases linearly from -40 deg down to -18 deg. At the same time the modulation is increased with a law which preserves the specified acceptance.

In the second RFQ \( \varphi \) is kept constant at -8 deg and both transverse and longitudinal emittances are well within specifications. The vane shaped four-rods resonators [21] are going to be fabricated in high RRR (250) Nb and will be fully immersed in a liquid He-bath at 4.2 K. Electrodes and stems are hollow structures which allow the liquid-He to get in close contact with all the current loaded surfaces of the resonator. Three mm thick Nb walls are well suited to dissipate the power losses estimated with M.A.F.I.A. code (magnetic field ≤300 Gauss). The present resonator design comes out from the results of extensive M.A.F.I.A. simulations combined with detailed investigation on the mechanical stability of the resonator made with the I.D.E.A.-S code.¹

Our aim was, in fact, to push the frequency of the lowest vibration mode as high as possible (f=130 Hz) and to try to avoid any environmental perturbation exciting it. In this way we keep the resonator locked in the usual self excited loop scheme by enlarging the bandwidth up to 20 Hz. Any slow frequency drift is corrected by a slow tuner driven by a feedback mechanism which acts in response to the phase error signal.

The SRFQ's are designed to be realized in bulk niobium sheets e-b welded. The problems related to theirs construction are presently tackled with the realization of a stainless steel model. The aim of the prototype construction is to check the required jigs, the rough tuning procedure, the welding feasibility and the mechanical stability of the structure, compared with the computer simulations.

¹ IDEAS-S Finite Element Modeling, Structural Dynamics Research Corporation, 2000 Eastman Drive, Milford, OH 45150, USA
Table I SRFQ’s parameter list

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio Frequency</td>
<td>80 MHz</td>
</tr>
<tr>
<td>Input Energy</td>
<td>41.2 keV/u</td>
</tr>
<tr>
<td>Output Energy</td>
<td>578 keV/u</td>
</tr>
<tr>
<td>Average acceleration</td>
<td>2.16 MV/m</td>
</tr>
<tr>
<td>Max. Surface E field</td>
<td>25 MV/m</td>
</tr>
<tr>
<td>Max. surface B field</td>
<td>295 G</td>
</tr>
<tr>
<td>Max. stored energy/RFQ</td>
<td>≤4 J</td>
</tr>
<tr>
<td>Acceptance</td>
<td>≥0.9 mm mrad (norm.)</td>
</tr>
<tr>
<td>Output emittance</td>
<td>≤0.7 ns keV/u (norm.)</td>
</tr>
</tbody>
</table>

Conclusions

In the last few years at LNL have been introduced many innovations in the fabrication of QRW’s with the result of obtaining high performing resonators at moderate costs. The SCALPI linac is working according to the experiment needs and it is going to reach the expected 35 MV in the near future.

A challenging new injector based on SRFQ’s has been recently funded and it is expected to be in operation in three years from now.

Acknowledgments

The results presented in this paper have been possible for the invaluable efforts of the colleagues of the LNL accelerator division.

References


*The values are referred to a mass to charge ratio of 8.5 e.g. $^{28}_{\text{Si}}^{16}$.
SUPERCONDUCTING STRUCTURES FOR HIGH INTENSITY LINAC APPLICATIONS

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Abstract

The state of the art of superconducting radio frequency structures for particle acceleration is shown, with special reference to the suitability of the available technology for high current linear accelerators. It will be demonstrated that the basic requirements for these applications can be met today and the limitations will be discussed.

1. Introduction

The pioneering work for the application of superconducting (SC) radio frequency (RF) accelerating structures in accelerators was done at Stanford with an electron recirculating machine [1]. Since then many projects have been realized and have shown the feasibility of SC RF. Prime examples were apart from the mentioned machine, the heavy ion accelerators at Argonne [2] and Saclay [3]. Many of these machines have worked for several years and have paved the way for a wider use of SC RF in high energy accelerators. For electron acceleration, SC structures were used for S-DALINAC [4] and in the past years SC cavities have been successfully installed and used in large electron storage rings in the TRISTAN collider at KEK [5], and HERA [6] at DESY. The two biggest SC installations today are the recirculating electron accelerator CEBAF [7] with 169 m, and LEP2 with presently 245 m of active length installed. LEP upgrading will be completed in 1998 with 272 SC cavities covering an active length of 462 m, and giving nominally 2.7 GV.

In the past the main arguments for using SC cavities were the low RF losses, allowing a "cheap" RF installation. This is exploited particularly for heavy ion accelerators.

SC RF allows higher gradients to be achieved at reasonable RF power than normal conducting (NC) structures. This was first used in TRISTAN, then HERA, CEBAF and now in LEP. The upgrade of LEP with additional copper cavities is not possible merely because of space and prohibitive electricity cost, not to mention the large transverse impedance, which would severely limit the current.

The high gradient application is being intensely explored for large number production by TESLA[8], where 20 km of SC structures running at 25 MV/m will be required.

Recently new applications emerged for high current storage rings. One example is the upgrade of CESR [9], where SC cavities allow the transverse impedance to be kept minimal due to the small number of cavities with a large beam aperture, running at high gradient of up to 10 MV/m. Work is also going on at KEK for KEKB [10], where beam currents above 1 A are planned. A single cell cavity has been tested up to 11.7 MV/m.

The high stored energy in SC cavities is exploited in several applications: The extreme of beam loading is being studied for CLIC, where the high stored energy of SC resonators is used to accelerate the very intense bunches of the drive beam, about 50 % of the stored energy is taken by each pulse [11]. The acceleration system for LHC [12] with its circulating proton beam of 0.5 A, is based on SC cavities, mainly for reasons of stored energy.

A new field is presently being studied with growing interest: The use of SC cavities in high current linear accelerators for neutron sources, nuclear waste transmutation, accelerator driven reactors, etc. in the 1-1.5 GeV range [13-16]. This paper summarizes the state of the art in superconducting structures, especially results obtained in series production, and performance in accelerator operation. It will be shown that many components required for high intensity linacs are already available and limitations will be discussed.

2. Basics of RF superconductivity in accelerators

2.1. Losses

A very important feature of RF superconductivity is the fact that even in the superconducting state, the surface resistance does not vanish. The unloaded Q-value $Q_0$ of any cavity is proportional to $1/R_s$, where $R_s$ is the surface resistance of the material. $R_s$ of SC cavities is given by [17]:

$$ R_s = A \cdot \left( \frac{2 \cdot \pi \cdot f}{T} \right)^2 \cdot \frac{\alpha_T}{T} + R_{RES} \quad (1) $$

where $T$ is the operating temperature, $f$ the RF frequency, $T_e$ the critical temperature (for Nb 9.2 K, for Pb 7.2 K) and $\alpha$ is a material dependent constant which is about $2.5 \times 10^{24}$ for Nb. For frequencies below 10 GHz $\alpha$ is near 1.85.

The first part is given by the BCS theory, the second part, the residual resistance $R_{RES}$ depends on the state of the surface, material impurities, etc.

The operating temperature has to be chosen as a function of frequency and acceptable cryogenic losses. As (1) shows, the BCS part of $R_s$ increases with frequency, therefore a lower operating temperature is desirable for high frequencies. This has to be weighed against the efficiency of cryogenic cooling plants. For the 12 kW plants at LEP a power factor of 225 W at room temperature per W at 4.5 K has been measured [18], for 1.8 K operation 1 kW per W can be expected [19]. For LEP2 cavities at 352 MHz, 4.5K operation is adequate, CEBAF cavities operating at 1.5 GHz are cooled to 2K. Usable Q-values at nominal fields are typically $1 \times 10^9$ for Nb cavities, for Pb they are about a factor 10 lower.
2.2. Limitations

The theoretical limitation of accelerating field, given by the critical magnetic field strength is 50 MV/m for typical Nb high beta structures and 30 MV/m for quarter wave resonators [20]. In practice other factors limit the performance below these values:

Q-degradations leading to increased power deposition into the He can be caused by: trapped magnetic fields, surface defects and contaminations, local hot spots, which might even lead to a quench.

As an example, a curve of unloaded Q_n as a function of accelerating field measured on a sputter coated Cu/Nb LEP cavity is shown in fig 1.

![Graph showing Q-value as a function of accelerating field](image)

Fig. 1.: Example of the unloaded Q-value of a LEP cavity as function of accelerating field $E_a$.

The design parameters for LEP are a $Q_0$-value of $3.4 \times 10^8$ at the nominal accelerating field of 6 MV/m. The drop in $Q$ in this case at 7.5 MV/m is attributed to the onset of field emission. The operating field is chosen below this field with some safety margin. Many cavities produced show no such field emission up to above 8 MV/m.

3. Low beta structures

This is a very busy field of research and development. A comprehensive review is given by [21]. Modern applications mainly concentrate on coaxial resonators of the quarter- or half-wave length type with the beam passing on a diameter. So far, most work was directed towards applications with very low ($\mu$A) beam currents. In Argonne resonators were developed for high current (80 mA), high brightness ion beams, which went as far as cold RF testing of the resonators. In a half wave resonator made for a beta of 0.12, accelerating fields of 18 MV/m were achieved in cw operation at 355 MHz, (with some electron loading). The energy gain was 1.26 MV. Other prototype resonators for this purpose were developed and tested, a quarter wave resonator at 400 MHz and a "spoke resonator" operating at 850 MHz. Two examples are shown in fig 2.

![Diagram of resonators](image)

Fig 2: $\lambda/4$ resonator and $\lambda/2$ resonators developed for low beta, high current structures. From [22-23].

For the International Fusion Materials Irradiation Facility (IFMIF) deuterion acceleration modules for 125 mA from 8 to 40 MeV (beta 0.06 to 0.14) are being studied using $\lambda/2$ resonators [14].

Quarter wave structures operating at ATLAS provide gradients of up to 6 MV/m for low beta.

All these devices have only been operated with low RF power. For a beam current of 100 mA, a synchronous phase of 20 degrees from the crest, the above mentioned resonator would transfer 118 kW per structure to the beam, a value which is well within the reach of power couplers today. High power operation and vibration problems still need to be studied.

4. High beta structures

4.1. Structures

All high beta accelerators being conceived today make use of the elliptical cell shape as shown in fig 3 in the case of LEP, with small modifications.

![Diagram of LEP structure](image)

Fig 3: Structure of LEP SC cavities for beta = 1

Usually several cells are coupled together via the beam aperture and operated in $\pi$-mode. This structure type is chosen because it is basically free of multipactor. The number of cells per cavity varies: for the CESR upgrading single cells (500 MHz) are chosen, the LEP2 (352 MHz) and HERA (500 MHz) cavities have 4 cells, TRISTAN uses 5 cells (500 MHz). Tuning is always done by elastic longitudinal deformation.
For lower beta acceleration development is going on in Wuppertal for [13], where the same elliptical shape is being studied for acceleration of particles in the range of beta from 0.37 to 0.91. These cavities have 5 cells of 1/2*β*λ length, a design field of 10 MV/m and a frequency of 700 MHz. Their r/Q values have been calculated to vary from 86 to 539 Ω/cavity. A detailed mechanical design is still to be done, and the multipacting properties need to be checked. Similar work is being done in Los Alamos [15].

4.2 Performance in large scale applications

Large scale experience only exists with structures for beta=1. The operational parameters used in accelerators are:

TRISTAN: 32 5-cell cavities are installed (508 MHz), max. average gradient in operation: 4.7 MV/m, typical operating gradient: 3-3.8 MV/m

HERA: 16 4-cell cavities installed (500 MHz), usable gradient > 4 MV/m, power limited to < 100 kW/cavity, typically running at 2.6 MV/m presently.

CEBAF: 338 5-cell cavities, (1500 MHz), total active length 169m, gradient > 5 MV/m average, wide distribution of cavity performance with peak of distribution at 7 MV/m, some cavities go as high as 14 MV/m

LEP2: Presently 144 4-cell cavities installed, (352 MHz), total active length presently 245 m, operating gradient: 5.5-6 MV/m. All 272 cavities will be installed by 1998.

SC RF technology in large scale accelerator applications is very well established today.

5. Technology

5.1. Cavities and cryostats

High beta cavities are made of sheet material, half shells are spun and electron beam welded together. Two technologies exist: solid Nb and Nb sputtered in a thin film onto a copper substrate. The latter was developed at CERN and is being successfully used for the series production of LEP2 cavities, where so far over 1000 m² of superconducting surface have been produced. For low beta structures solid Nb and Nb bonded to copper via various methods are widely used, some laboratories use lead coated copper. The welding of Nb or Cu is usually done with electron bombardment. The cleaning and assembly procedures are very delicate. An example is given in [24]. The cavities are usually immersed in a bath of liquid He. All exposure of the internal surface to air has to be done in a dust free environment, in a clean room of typically class 100 or better, which requires an appreciable technological effort, considering that LEP 4-cavity modules are 12 m long. For space and cryogenic economy several cavities are housed in one common cryostat, in TRISTAN and HERA there are two, in LEP four, for CEBAF, ESS and TESLA eight cavities per cryostat are used.

The technology is very well developed for series production; LEP cavities are bought from industry fully assembled and are accepted according to their RF specifications.

5.2. Power couplers

One of the most critical and limiting items for high current applications is the power coupler. For cavities running at 6 MV/m, a beam of 100 mA requires about 560 kW/m to be transferred to the beam (synchronous phase assumed 20 deg). All couplers in operation for high power transfer are built either as coaxial lines with capacitive coupling to the cavities or as waveguide coupler in the case of CESR. The vacuum seal is done via brazed ceramic windows, some designs use a cold and a warm window.

5.2.1. Coaxial couplers: The CERN design is shown in fig 4.

Coaxial lines are prone to multipactor [25], which can usually be conditioned. Experience at CERN showed, however, that after some time of operation multipactor reappeared, which was attributed to recondensed gas (couplers bridge the full temperature range from the cavities to room temperature). Applying a positive DC bias voltage of +2500 V to the inner conductor permanently suppressed multipactor. The design value for this coupler is a power transfer of 120 kW under matched conditions. It has been tested on a cold cavity up to 200 kW transferred power, limited only by field emission in the test cavity, and conditions have been reached in cold tests, which correspond to 450 kW of transferred power [26].

5.2.2. Waveguide couplers: The design developed at Cornell uses ceramic discs in the waveguide as vacuum seal, the coupling is done directly from the waveguide to the cut-off tube on the cavity. This window has been tested in warm tests up to 250 kW traveling wave and 125 kW standing wave power, in a beam test with a cold cavity a maximum of 155 kW was transferred to the beam.

5.3. Higher Order Mode (HOM) couplers

Superconducting structures have high Q values also for the modes excited by the beam. They can harm beam stability and they can reach amplitudes above breakdown field due to the long memory of the cavities. The effects of these modes on high intensity beams, especially their influence on beam halo still needs to be studied. All storage rings are equipped with higher order mode couplers, which are usually built as antennas with an incorporated high pass filter rejecting the fundamental frequency component. At TRISTAN they work with beam currents of 4-4.5 mA, giving HOM power of 200
Proton linacs are under discussion with 1.0 GeV energy and 100 mA beam current. This beam power of 100 MW makes the problem of efficient power transfer into the beam a prime issue. Using numbers from LEP give the wall plug powers shown in Table 1 for 10 mA and 100 mA total current for the NC and the SC systems.

This is under the following assumptions:

- Stable phase angle: 20 deg.
- Accelerating gradient Cu cavities: 2.35 MV/m
- Accelerating gradient SC cavities: 6 MV/m
- Cryogenic efficiency: 225 W/W
- Waveguide losses: 5%
- Klystron efficiency: 65%
- Static losses of cryostat (incl. warm gas return): 180 W/4-cell module

For the 100 mA case, the RF power per 4-cell LEP cavity is 940 kW, which could be handled with 2 or 4 couplers per cavity. This is for beta=1 structures, but the arguments are valid for lower beta structures. The actual parameters such as number of cells per cavity and RF frequency have to be optimized.

For pulsed operation the advantage of SC cavities becomes smaller, because the cavity filling time may become an appreciable fraction of the pulse length. The RF power increases accordingly. In the case of ESS this is about 6.3%, in [14] 14% are quoted.

The high gradient leads to higher stored energy in the cavities. This can be an advantage for smaller beam loading effects and for efficiency. LHC and the CLIC drive beam facility make use of this.

7. Features specific to SC cavities

7.1. Beam loading

SC cavities can not directly replace Cu structures. There are important differences in beam loading, and especially the transient behavior in case of RF trips or beam loss needs attention. Because the unloaded Q values are in the order of $10^6$, the power couplers have to be strongly overcoupled to provide optimum power transfer to the beam. For LEP cavities the loaded Q for 50 mA operation would be $Q_u = 4.5 \times 10^3$. This leads to big reflections in case of current fluctuations and strong beam loading effects. In case of RF trips, the peak reflected power is 4 times the forward power without beam for a given voltage. In case of a beam loss, the power arriving at the power coupler would drive the cavities to twice the nominal accelerating field. A fast RF control is therefore required to avoid damage.

7.2. Field oscillations

SC cavities are built like large bellows, and they can mechanically oscillate. The high Q-values make their fields and phases very sensitive to mechanical vibrations. Experience at LEP revealed several sources of field oscillations.

<table>
<thead>
<tr>
<th></th>
<th>10 mA</th>
<th>100 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cu system</strong></td>
<td>81 kW / MV</td>
<td>217 kW / MV</td>
</tr>
<tr>
<td><strong>SC system</strong></td>
<td>18 kW / MV</td>
<td>154 kW / MV</td>
</tr>
</tbody>
</table>

Table 1: Wall plug power calculated for LEP2 parameters (352 MHz)
7.2.1. Oscillations related to cryogenic conditions. Field oscillations up to 40 % peak-peak have been observed in some cavities, which can be attenuated by changing the Liquid He level or the operating pressure in the He tank.

7.2.2. Effects due to Lorentz forces. The SC cavities deform mechanically due to the forces on the walls from the electromagnetic fields. The frequency change resulting from this is proportional to the square of the field amplitude.

Lorentz forces can lead to a coupling between electromagnetic energy in the cavities and mechanical oscillations. It can be shown, that if the cavities are tuned to frequencies below their resonance, the system becomes unstable and starts to oscillate at a mechanical resonance of the cavity. In LEP operation this occurs in the presence of beam, because the tuning system compensates the effect of the beam by detuning the cavities towards the dangerous direction. This problem is solved for the time being in LEP by detuning the cavities, such that at maximum current and maximum field, the cavities are driven at or near their resonance.

In pulsed applications, Lorentz force detuning causes a movement of the cavity walls in each RF pulse, which can continue during the whole length of the pulse. Phasing schemes have been invented to solve this problem, however, their practical feasibility with several cavities driven in parallel from the same RF source, needs to be demonstrated.

In LEP the residual field oscillations can still be as high as 10%, a fast RF feedback on the vector sum is being implemented, to keep the fields of each group of 8 cavities constant.

8. Challenges of superconducting RF

Quite sophisticated technology, requiring heavy infrastructure and skilled personnel is required for production and also for maintenance, including cleaning facilities, chemistry, clean room etc. This and the operation at cryogenic temperatures, makes turn-around time in development long and even minor repairs can become quite time consuming. Extreme discipline and professionalism is required. Fast repair, especially of activated material is certainly difficult with techniques presently available. The e-folding time for decay of activated Nb is ~1 month, as compared to 13 hrs. in Cu.

9. Conclusion

It has been shown that SC RF structures are available for reliable operation in accelerators. Nowadays, gradients of around 6 MV/m have been achieved for high beta applications. Structures for heavy ion accelerators have been in continuous use for several years. All the other components required have been or are being developed for high current circular accelerators: RF power couplers have been used to transfer up to 250 kW via a SC cavity and fields in couplers equivalent of 400 kW power transfer have been achieved, and development is going on in many laboratories. HOM couplers have been tested in storage rings up to several kW power.

RF superconductivity bears the potential of substantial savings in investment, especially infrastructure, and also in operating cost of the RF system due the higher gradient and the more efficient power transfer to the beam. The large beam aperture is advantageous to both reduced beam losses and transverse impedance.

The know how and the technical infrastructure needed for development work and follow-up of production are available in several large laboratories today.

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Postscript

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