EW DEVELOPMENTS IN
ARTICLE ACCELERATION TECHNIQUES

PROCEEDINGS
Editor: S. Turner
Vol. 1

ECFA–CAS/CERN–IN2P3–IRF/CEA–EPS WORKSHOP
held at
Orsay, France
29 June – 4 July 1987
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ABSTRACT

A Workshop organised jointly by the European Committee for Future Accelerators (ECFA), the CERN Accelerator School (CAS), the Institut National de PhysiqueNucléaire et de Physique des Particules (IN2P3), the Institut pour la Recherche Fondamentale/Commissariat à l'Energie Atomique (IRF/CEA) and the European Physical Society (EPS) was held at the Laboratoire de l'Accélérateur Linéaire (LAL), Orsay, from 29 June to 4 July 1987. Its purpose was to review current experimental and theoretical developments in charged-particle accelerator techniques and to address problems related to future very-high-energy machines.

These proceedings contain the great majority of the papers presented at the Workshop, the corresponding questions and answers, and the round-table discussion. The principal topics were semi-conventional high-frequency linacs, transformer acceleration mechanisms, acceleration using plasma, \(e^+e^-\) sources including low-emittance production and preservation, final focus and interaction point, and other new ideas. Among the latter were open accelerating structures, crystal X-ray accelerators, ferroelectrics, and acceleration using lasers.
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FOREWORD

In 1982 the European Committee for Future Accelerators (ECFA) in collaboration with the Rutherford Appleton Laboratory (RAL) organised a Workshop in Oxford on "The Challenge of Ultra-high Energies". Two years later, with the help of the CERN Accelerator School (CAS) and the Istituto Nazionale di Fisica Nucleare (INFN), ECFA ran a Workshop on "The Generation of High Fields" which took place in Frascati. The present Workshop on "New Developments in Particle Acceleration Techniques" is the third one in this series. It was held at the Laboratoire de l'Accélérateur Linéaire (LAL) d'Orsay, and was organised by ECFA together with CAS, the Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), the Institut pour la Recherche Fondamentale/Commissariat à l'Energie Atomique (IRF/CEA) and the European Physical Society (EPS). This series of meetings is complementary to the American series held in Los Alamos 1982, Malibu 1985 and Madison 1986.

Research into new particle acceleration techniques extends from conventional accelerator physics into the fields of lasers and plasmas. It was the purpose of the Orsay meeting to bring together physicists from these different disciplines and to give them the opportunity to discuss the latest progress in new or conventional acceleration methods including particle sources, RF power sources, focalisation and interaction regions and to try to define the most promising areas for further study. Attendance at the Workshop was truly international; of the 150 participants about a quarter were from the USA while Australia, Canada, China, Finland, Japan and USSR were all represented by one or more participants, CERN Member States participants making up the rest. There was also a good balance of participants among the different disciplines.

After a short introduction by G. Coignet, the opening address was given by M. Davier, Director of LAL-Orsay. The meeting then started with a few invited talks. Ch. Llewellyn-Smith presented the physics motivation for higher energies, underlying the rich rewards expected when constituent particles collide at energies around 1 TeV. The major domains of activity in new acceleration techniques, going from the nearly conventional methods to the more futuristic ones were reviewed by H. Henke, S. Aronson and J.L. Bobin. Then R. Palmer stressed the importance of parameter interdependence and the implication for any type of acceleration method. J. Seeman and R. Sheppard presented a status report on SLC, which can be considered as the first practical test for linear colliders. Finally, C. Rubbia underlined the importance of the complementary approaches, that is $\sqrt{s} = 1$-2 TeV electron-positron colliders and $\sqrt{s} = 20$-40 TeV proton-proton colliders. He also stressed that luminosity $L$ is as important as centre-of-mass energy $\sqrt{s}$, i.e. $L > 10^{33}$ cm$^{-2}$ s$^{-1}$ is needed in both cases. The importance of parallel development of new detectors able to cope with such a luminosity was also highlighted.
During the main part of the meeting, the morning sessions were devoted to the presentations of individual contributions and their discussion, while the afternoons were reserved for the activities of the five Working Groups (see programme hereafter). The final session was used for summary reports from the conveners of each of the Groups and for a concluding round-table discussion chaired by K. Johnsen.

At the meeting, a variety of new experimental results were presented. In addition, from the studies performed during the recent years, it now appears that a better understanding of the problems is emerging. All this leads to the belief that "semi-conventional linac" schemes are the way to go to build tomorrow's e⁺e⁻ colliders. Work in this direction is presently proceeding with the √s = 2 TeV CERN Linear Collider (CLIC) and with the √s = 1 TeV Stanford Collider (SC) projects. These studies have stimulated worldwide work on the design of power sources such as superconducting RF cavities, gyrotrons, relativistic klystrons, lasertrons, etc. Electron gun development is under way and solutions are getting close to fulfilling the needs of the semi-conventional linacs. Positron sources, on the other hand, were barely touched at this meeting but further developments would certainly be worthwhile. The required emittances can be provided by damping rings but these are coming to their limits and new ideas were put forward at the meeting which seem to have much merit. Near-conventional quadrupole systems seem to be adequate for achieving the final focus at the interaction point but alternative devices may be necessary to achieve the ultimate goal. General theoretical studies continue to explore the problems of parameter interdependence, scaling laws, multibunch operation, final focus and interaction region.

The Workshop also confirmed the flourishing programme on more futuristic approaches. The wakefield transformer has recently achieved particle acceleration, and for the switched pulse linac effort is concentrated on developing triggered switches. Many groups work both experimentally and theoretically on plasma based accelerators, plasma beat-waves, plasma wakefield, wakeatron, etc. Although these schemes presently look more suitable for the after-tomorrow multi-TeV colliders, proof of principle experiments are going on, and important steps in understanding the fundamental problems are being made. A more immediate output of these plasma schemes could be to use the very strong fields they generate to focus the beams at the interaction point. Other new ideas for acceleration, still at the conceptual stage, were also presented.

Finally, it was underlined on many occasions that it is urgent to develop novel instrumentation related to the specific problems of these new linear colliders. For example, measurements of beam spatio-temporal dimensions, beam emittances, component alignment and associated feedback systems, all need attention.

The above arguments are developed in detail in over 60 papers presented in these proceedings, the relatively high number amply demonstrating the current keen interest in this field. Despite an extremely tight deadline in order for the proceedings to be published while the subjects presented are still topical, the vast majority of the state-of-the-art talks and those topics presented only to the Working Groups have been written up.
In addition very convenient summaries of the information presented have been prepared by the conveners of each of the Working Groups and these appear at the beginning of each section of these proceedings. Some very novel acceleration concepts are also included in the section entitled "New Ideas". An attempt has also been made to transcribe from tape recordings the comments made after each of the oral presentations and during the concluding round-table discussion. However, caution is necessary with the latter since, in the time available, it has not been possible to check all of the statements with their author.

On behalf of the Organising Committee we thank the sponsors of this meeting ECFA, CAS/CERN, IN2P3, IRF/CEA and EPS, and also Thomson CSF, Alsthom and Compagnie Générale d'Electricité. Special acknowledgements are due to the conveners for guiding with enthusiasm the work and discussions in their Groups and for providing so quickly a synthesis of the results achieved. The speakers, scientific secretaries and participants and especially the authors of the papers presented here also deserve our thanks. In particular we acknowledge the efforts of J. Buon, P.J. Bryant, J. Le Duff and of the senior secretaries Jacqueline Boratav, Nicole Mathieu and Suzanne von Wartburg, and our hosts at Orsay, all of whom ensured that the meeting ran so smoothly. Finally, a special word for Barbara Strasser who corrected or typed all of the proceedings.

G. Coignet  Chairman of the Workshop
S. Turner  Editor
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## Working/Discussion Groups

**Subject**

- Semi-conventional high-frequency linacs
- Transformer acceleration mechanisms
- Acceleration using plasma
- $e^+e^-$ sources, low emittance production and preservation
- Final focus and interaction point

**Conveners**

- W. Schnell, A. Sessler
- T. Weiland, P. Wilson
- R. Evans, T. Katsoulea
- J. Le Duff, C. Pellegrini
- P. Chen, B. Montague
### State-of-the-art Talks

#### SUBJECT

**Semi-Conventional Linacs**
- Conventional power sources for colliders
- Beam dynamics issues in big linear colliders
- RF pulse distortion in travelling wave linac structures
- Parameter choice for linear colliders in multibunch operation
- A study of tolerances for low emittance damping rings

**Transformer Acceleration Mechanisms, Lasertron and Sources**
- The wake-field transformer experiment at DESY
- Hollow beam gun
- Hollow beam measurements
- Computer simulations for the DESY wakefield transformer experiment
- Model measurements for the switched power linac
- SLAC lasertron
- Lasertron experiments and high-gradient structures in Japan
- Accelerator R & D at Orsay
- Ribbon lasertron: RF power source for TeV linac colliders
- New idea for laser production of very high electron densities
- Los Alamos high-brightness electron injector
- High current density photoemission from metals in nano and picosecond pulses

**Plasma Acceleration**
- UCLA beat-wave accelerator programme
- Beat-wave acceleration experiments at INRS-Energie
- Plasma beatwave experiment at RAL
- CO₂ laser-REB interaction: beatwave acceleration
- Interaction experiments in long & homogeneous plasmas at the GRECO ILM
- Theoretical work at UCLA on plasma accelerators
- Theoretical results on laser acceleration of particles
- Limitations due to Brillouin and modulation instabilities for the beatwave accelerator
- Spatio-temporal energy cascading in the beatwave accelerator
- The charged particle acceleration by HF-wave field in plasma

**Final Focus, New Ideas, Technology**
- The nature of beamstrahlung
- Applications of high power, intense beams to electron acceleration
- Ferroelectrics in accelerator physics
- Gyrotron
- Physics of relativistic klystrons
- High-gain FEL's at short wavelengths
- Cost optimization of induction linac drivers of linear colliders
- Plasma lenses for focusing particle beams
- A diffraction radiation model for energy losses for a simple geometry

**SPEAKER**

- M. Allen
- R. Ruth
- G. Geschonke
- J. Claus
- P. Krejcik
- T. Weiland
- W. Bialowons
- F. Decker
- P. Wilhelm
- J. Knott
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**CLOSING ROUND-TABLE DISCUSSION**

**LIST OF PARTICIPANTS**

**705**
OPENING ADDRESS

M. DAVIER
Laboratoire de l'Accélérateur Linéaire - Orsay - France

Let me warmly welcome all of you at Orsay on the campus of our university. We are extremely honoured to host this workshop and we find this particularly fitting since research on and with accelerators has always occupied a large part of the activities at Orsay since the very beginning, some 30 years ago.

In 1956, Frédéric Joliot and Irène Joliot-Curie installed here the Institute of Nuclear Physics and a 200 MeV synchrocyclotron was built. It is still in use, accelerating protons and light ions. At nearly the same time, the construction of the electron linac was undertaken under the leadership of Hans Halban. It was built in steps, eventually to reach an energy of 2.3 GeV, the largest linac before SLAC went into operation. This was the start of LAL, the Laboratoire de l'Accélérateur Linéaire. Some more accelerators are to be found at Saclay only a few kilometers away: the 2 GeV Saturne synchrotron and a 600 MeV electron linac with good duty cycle. A large concentration of expertise therefore exists in this area.

Such an environment has played an important role for accelerator development and research - we are getting closer to the subject of this workshop! Let me illustrate this with our best example: the development of the technique of e⁺e⁻ storage rings.

This goes back to 1962-63. The idea started in Frascati where the small 200 MeV ring ADA was build under Touschek, Amman, Bernardini and others. The injection scheme was still rather primitive: with only one beam line and an internal target to produce the positrons, it was necessary to flip the entire storage ring by 180° around a horizontal axis to fill with both beams. It was hard to store more than a few hundred particles and since the Orsay linac could be used as a more efficient injector, it was decided to move ADA here (Fig. 1) and a very fruitful collaboration started. Beams with larger intensities (~ 10⁷ particles) were stored and the first interesting measurements could be made: determination of bunch size, observation of beam-beam bremsstrahlung, measurement of the emission of synchrotron radiation. These were the heroic days of e⁺e⁻ rings. I was then an undergraduate in the lab, and many fascinating stories on the experiment were going around, as for example the naked-eye observation of the synchrotron radiation of a single electron left circulating in the ring. People also learned that despite a good vacuum some dust was left inside the vacuum chamber, as evidenced by a sudden loss of the beam when flipping the ring around!

In the meantime, it was decided under the leadership of Pierre Marin to build here a larger machine, ACO, which could really be used to produce hadrons for the first time in
e⁺e⁻ annihilation (Fig. 2). The beam energy of 550 MeV was ideal to cover the light vector mesons. ACO has been a very successful machine. The achieved luminosity in excess of $10^{32}$ sounds terrific, but we should remember with modesty that luminosity used to be expressed in units of cm⁻² h⁻¹ in those early times!

Going bigger, the next machine was DCI with 1.6 GeV beam energy (Fig. 3). A daring scheme was to be used: colliding 4 bunches simultaneously (e⁺e⁻ against e⁺e⁻) from 2 rings so that the space charge limit could be overcome. This turned out to be very hard to operate and could never be used successfully. Sometimes, clever ideas on paper do not work in practice. Accelerator physics still remains an experimental science.
Now these storage rings are used for synchrotron radiation research. A new machine specially optimized for this purpose, Super ACO, is just being commissioned in the LURE laboratory.

Let me also mention that LAL in collaboration with CERN has taken a major part in the design and the construction of LIL, the LEP linear injector (Fig. 4).

Since this workshop is devoted to new acceleration techniques, I will come to a close in mentioning our on-going work at LAL on new RF sources and on testing the limits of accelerating structures. More futuristic schemes are contemplated, as for example at the nearby Ecole Polytechnique where strong expertise is found in laser and plasma physics.

I hope I have convinced you this is a good place to hold your Workshop. Many results will be presented and I trust interesting new ideas will be discussed. They are badly needed for the next generations of accelerators.

Have a good week here and a successful Workshop!
Fig. 3: The 1.6 GeV DCI storage ring (Photo LAL-Orsay)

Fig. 4: LIL, the LEP linear pre-injector (Photo CERN)
INVITED PAPERS
HORIZONS OF HIGH ENERGY PHYSICS

C.H. Llewellyn Smith
Department of Theoretical Physics, 1, Keble Road, OXFORD, OX1 3NP, England.

ABSTRACT
A review is given of the present state of particle physics, of what can be expected from machines now being constructed and of how future machines may contribute to further progress.

1. INTRODUCTION

Talks by theoretical particle physicists at accelerator meetings traditionally begin with a review of the state of the art and then go on to consider how future machines may contribute to further progress. I shall follow this pattern but I shall pause in the middle to ask questions about the utility of the exercise:

i) Should we believe it at all? There is, after all, no shred of evidence for any theoretical idea since QCD - which is now fifteen years old - so perhaps theory is not a helpful guide.

ii) At the other extreme, could it be that we are now near the end and no longer need experiment? This is apparently the view of some of the new generation of string theorists who stick Dirac's dictum that "it is more important to have beauty in one's equations than to have them fit experiment" on their walls and seem to believe that future progress will be driven by pure thought rather than experiment.

iii) Could it be that the "new physics expected at or below 1 TeV", which is so frequently invoked as an argument for building further machines, could be found and exhausted at SLC, LEP, HERA and the Tevatron?

iv) Finally, at the other extreme, could these machines find nothing, which would make further machines essential but very hard to sell to the public?

2. THEORY - WHERE WE STAND

2.a The Standard Model: Open Questions and Possible Answers

The Standard Model, which describes matter in terms of quarks and leptons whose interactions are governed by the unified electroweak theory, QCD and Einstein's theory of gravity, is at present consistent with all the data. In those cases in which we are able to work out its consequences they fit quantitatively and there is no reason to doubt that it works in other cases also. Nevertheless, the standard model can at best be an effective, phenomenological, theory. It has too much arbitrariness and too many parameters, albeit quantities such as the fine-structure constant and the ratio of the masses of the electron and proton which, in the past, were thought of as "fundamental constants" rather than as parameters, and Einstein's theory of gravity is inconsistent
with quantum mechanics. In seeking a better model to replace the standard model, we can work from the "bottom up", attempting to improve its shortcomings, or from the "top down", attempting to construct a final "theory of everything in one step".

Table 1
Problems in the Standard Model

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Solutions</th>
<th>Relevant Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavour</td>
<td>&quot;Horizontal&quot; group</td>
<td>More quarks and leptons?</td>
</tr>
<tr>
<td></td>
<td>Compositeness</td>
<td>Masses, mixings</td>
</tr>
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<td></td>
<td>Topology for d&gt;4</td>
<td>Rare decays?</td>
</tr>
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<td>Unification</td>
<td>Pre-GUT</td>
<td>&quot;Horizontal&quot; bosons?</td>
</tr>
<tr>
<td></td>
<td>GUT</td>
<td>Structure?</td>
</tr>
<tr>
<td></td>
<td>Super GUT/String</td>
<td>W', Z'?</td>
</tr>
<tr>
<td>Mass</td>
<td>Higgs+SUSY</td>
<td>Nucleon decay?</td>
</tr>
<tr>
<td></td>
<td>Technicolour</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 contains the standard list of problems and shortcomings of the standard model. On hearing of the discovery of the muon Rabi apparently asked "who ordered that?" and we must ask the same question about the tau, the strange quark, the charmed quark etc. Possibly the different families of quarks and leptons are joined in a single representation of a large "horizontal" group. Possibly they are themselves composed of more elementary objects. Maybe, as discussed later, flavour is a consequence of the topology of extra hidden dimensions of space-time. Experiments which may cast light on this problem include searches for more quarks and leptons, accurate measurements of masses and mixings (which will also cast light on the problem of the origin of mass), searches for rare decays such as μ→eγ mediated by "horizontal" gauge bosons, searches for the "horizontal" gauge bosons themselves, and searches for substructure.

Given the semi-successful unification of electromagnetic and weak interactions in SU(2) × U(1), it is natural to ask whether these interactions may be more completely unified, for example in a left-right symmetric group, whether, more ambitiously, they may be unified with the strong force in a grand unified theory and, finally, whether there is a super grand unified theory of all the forces, including gravity. Larger groups necessarily imply the existence of more gauge bosons which can mediate new interactions. Clearly we should look for these extra gauge bosons experimentally and also for rare processes that they might mediate, such as nucleon decay which is predicted by grand unified theories.

The last problem is the problem of mass. How can the W and the Z be symmetry partners of the photon and yet have masses that are at least 26 orders of magnitude greater? The standard answer is through the Higgs mechanism which implies the existence
of at least one Higgs boson, which should be sought experimentally. However, as will be
discussed below, it is difficult to understand how the conventional Higgs mechanism could
work unless there is an underlying supersymmetry in nature, which would imply the
existence of relatively light supersymmetric particles which can be sought in future
experiments. An alternative possibility is that masses are generated through
"technicolour" in which case techni-particles should show up at around 1 TeV.

I shall now discuss the mass problem in more detail since it has an associated energy
scale which suggests that it may be resolved by experiments in the relatively near future.
I shall then explain why I think that supersymmetry deserves to be taken seriously, before
turning to the present state of superstring theory, which is the current great white hope
of advocates of a "top down" approach.

2.b The Schizophrenic Problem of the W Mass

The problem of the W mass has two aspects. First, why is the W not massless, like the
photon? Second, given that it does have a mass, why is it not very much larger? The
first problem may be approached from a theoretical and from an empirical point of view.
Theoretically, gauge bosons have only two degrees of freedom and hence two polarization
states. While this is true for the massless photon, a massive spin-1 particle, such as
the W, must have three polarization states, since we can go into its rest frame and
orientate its spin in three possible directions. The question is then, how did the W
acquire its third, longitudinal, polarization state? There are three possible answers.
First, the longitudinal W could be a component of an additional elementary field - the
Higgs field; in this case, at least one extra field must remain as a separate observable
particle - the Higgs boson. Second, the longitudinal W could be a bound state of a
techniquark and an antitechniquark bound together by a new, very strong, technicolour
force. Third, perhaps the W is not a gauge boson at all.

Empirically, the problem can be seen by calculating the scattering amplitude for
longitudinally polarized W bosons. The amplitude grows rapidly with energy and violates
perturbative partial wave unitarity at an energy of 1 TeV in the centre of mass (assuming
standard gauge theory vertices; with any other vertices, the violation occurs at a lower
energy). This implies one of two things. Either perturbation theory fails and
longitudinal Ws become strongly interacting at 1 TeV, in which case new phenomena, such as
resonances, would show up; this would occur in technicolour theory. Or there is an extra
perturbative contribution due to Higgs boson exchange. If $M_H$ is less than 1 TeV,
perturbative unitarity would hold at all energies. If, on the other hand, $M_H$ is large
compared to 1 TeV, there would be a region between 1 TeV and $M_H$ at which perturbation
theory would fail and longitudinal Ws would be strongly interacting. In any case,
experimental study of the scattering of longitudinal Ws up to and beyond 1 TeV is
essentially guaranteed to cast light on the origin of mass. It must be stressed, however,
that the problem could be solved by experiments at much lower energy e.g. by the
discovery of a Higgs boson with a mass of, say, 10 GeV in the decay of Z.
If the W mass is generated by the Higgs mechanism, we then face the problem that the mass scale associated with the Higgs field and hence the mass of the W contains quantum corrections $\delta M_W - gM_X$, where $M_X$ is the largest mass scale in the problem e.g. the mass of the X boson in a grand unified theory or the Planck mass in theories in which gravity is incorporated. If this were correct, it would only be possible to understand the observed mass of the W by invoking incredibly accurate, and highly artificial, cancellations between the quantum corrections and the zeroth order value of the mass. The only way out of this dilemma seems to be to invoke supersymmetry. According to supersymmetry every particle (P) has a superpartner (\tilde{P}) whose spin differs by half a unit, i.e. every boson has a supersymmetric fermionic partner, and every fermion has a supersymmetric bosonic partner. These partners contribute to the mass of the W with opposite signs so that the correction to the mass of the W may be written

$$\delta M_W = g \sum_i (M_{P_i} - M_{\tilde{P}_i})$$

If we exclude large cancellations and make the very reasonable requirement that $\delta M_W < M_W$, then the mass splitting between each particle and its superpartner must be less than or of order 1 TeV.

2.c Supersymmetry

In the paragraph above we introduced supersymmetry (SUSY) as a way to solve the hierarchy problem of the co-existence of widely different mass scales $M_W$ and $M_X$. This rather technical route to SUSY may obscure the other, very powerful, arguments for taking SUSY seriously:

i) SUSY unifies fermions and bosons, and thus abolishes the distinction between constituents of matter and carriers of forces.

ii) Supersymmetric theories are less divergent than ordinary theories. A divergence usually indicates that a theory is only an effective theory, the cut-off characterising the range of validity of this theory. The fewer the divergences, the closer the theory is likely to be to an ultimate theory.

iii) The generators of SUSY transformations, which have a fermionic character as they change fermionic states into bosonic states and vice versa, satisfy an anti-commutation algebra: the anti-commutator of two different SUSY charges is a translation. A theory in which SUSY acts locally, allowing different SUSY transformations at different points in space and time, is therefore invariant under local translations which are part of a general coordinate transformation. As a result, local SUSY can naturally be unified with gravity.

iv) According to a rather general theorem, SUSY is the last possible symmetry of the S-matrix. It would seem to me very peculiar if nature made use of the other
symmetries (internal symmetries, gauge symmetries and Poincaré invariance) and not of
supersymmetry. Likewise, it would seem to me odd for there to be elementary particles
with spin-\(\frac{1}{2}\) (the electron etc.), spin-1 (the photon, W and Z), and spin-2 (the
graviton) and not also with spin-0 and three halves, as there are according to SUSY.
These arguments, especially the last, suggest that we should take SUSY very seriously.

The bad news is, first, that known fermions do not have the right properties to be the
SUSY partners of known bosons, so that it is necessary to make the apparently extravagant
supposition that there is a SUSY partner for every known particle waiting to be discovered
somewhere below 1 TeV, and second that SUSY is hard to hide, or spontaneously break to use
the usual description, as must be done in order to break the degeneracy between particles
and their superpartners. The least contrived models which work invoke the existence of a
set of shadow particles, whose only coupling to the known particles is through gravity,
and the assumption that SUSY is broken in the shadow world thus:

```
Our World                     "Shadow World"
-----------------------------
-----------------------------
only coupled by gravity
- transmits SUSY breaking.
```

2.d Superstrings

In superstring theory particles are replaced by open strings or closed loops with
dimensions of order \(10^{-33}\) cm and tension (T) of order the Planck mass. Particles
correspond to the different modes of excitation of these strings. String theories provide
the first consistent quantum theory of extended objects. As in classical theories, where,
as pointed out by Lorentz, the divergence of the electromagnetic mass of the electron
would be eliminated if the electron is an extended object, it turns out that the
replacement of particles by extended strings reduces the divergences - perhaps removing
them entirely.

The version of the string theory which is most likely to be relevant to the real world
is the super (Fermi-bose) string. It was noticed many years ago that this theory has a
remarkable property in the limit that the tension \(T\rightarrow\infty\). In this "rigid" limit only the
massless modes of the string remain at finite energy and they behave as point-like
particles. It turns out that there are spin-1 massless modes with exactly the
interactions of gauge bosons and spin-2 massless modes with exactly the interactions of
Einstein's graviton. It was this discovery that led to the idea that the string describes
gravity, among other things, and that T is governed by the Planck mass (originally the
string had been introduced as a model of soft hadronic process, T being governed by the
Regge slope). Despite this remarkable property, the string fell out of fashion because it
was thought to be riddled with quantum inconsistencies or anomalies, and because, even at
the classical level, the theory is only consistent in 10 space-time dimensions. The recent dramatic revival of interest was due to the discovery by Green and Schwarz that the theory is anomaly free if it has an internal symmetry group SO(32) or E(8) × E(8).

Anomaly free versions of the superstring theory are probably completely free of divergences and are the first, and only known, consistent theories of quantum gravity. They therefore deserve to be taken extremely seriously although the prediction of nine space and one time dimensions is apparently wrong. This problem is "solved" by assuming that the extra six space dimensions curl up, or "compactify", to sizes of order 10⁻³⁵ cm so that we are unaware of their existence, just as a two-dimensional sheet of paper might curl up to form a drinking straw which would appear one-dimensional to a being only able to resolve distances large compared to its radius. Whether or not this compactification occurs is a dynamical question whose answer is unknown. If, however, we assume that it occurs and make several other quite plausible, phenomenologically motivated, assumptions, it turns out that the E(8) × E(8) symmetry (which is preferred to SO(32) because the latter is unable to accommodate chiral fermions after compactification to four dimensions) would break down to E(6) × E(8) on compactification and that particles governed by E(6) would only interact with those governed by E(8) through gravity. Assuming that SUSY is spontaneously broken in the E(8) sector, and recognising that E(6) (with SU(5) and SO(10)) is one of the possible grand unified theories, we find that we have recovered the supersymmetry theory constructed previously working from the bottom up! This is encouraging: although a lot of phenomenological assumptions were built in, the result could have been an unacceptable grand unified theory. If we develop the theory further and try to make contact with physics well below the grand unified scale, it turns out to be quite possible - although not inevitable - that it predicts extra vector bosons, quarks and leptons with masses of order $M_W$ or a few times $M_W$.

One attractive feature of the compactified string theory is that it provides a possible mechanism for understanding the origin of flavour. The six compactified dimensions are in general able to support several massless modes, the exact number depending on their topology. The different flavours would be associated with the different excitations in the hidden dimensions.

3. IS THEORY A GOOD GUIDE FOR EXPERIMENT - AND VICE VERSA?

We shall address these questions by considering the highlights of the last 50 years of particle physics, some of which are listed in Table 2. Cleaned retrospectively of wrong experiments and wrong theoretical ideas, we see that the subject has progressed rather logically and that there has been an intimate interchange between theory and experiment: theory has been rather successful in anticipating discoveries but it has almost always been driven very directly by experimental results. It is true that theory has not been particularly successful in predicting what will be achieved by experiments at new machines - the exceptions being the discovery of the anti-proton and the W and Z. The present
### Table 2

Some Highlights in Particle Physics (discoveries in boxes were anticipated theoretically)

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiments at the Energy Frontier</th>
<th>Experiments below the Frontier</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1940</td>
<td>$\mu$, $\pi$, K</td>
<td></td>
<td>Renormalization of QED</td>
</tr>
<tr>
<td>1950</td>
<td>Resonances P-Violation</td>
<td>P-Violation V-A</td>
<td>Yang-Mills</td>
</tr>
<tr>
<td></td>
<td>$\nu_e \neq \nu_\mu$</td>
<td>Resonance Spectroscopy CP Violation</td>
<td>SU(2)×U(1)</td>
</tr>
<tr>
<td>1960</td>
<td>Deep inelastic Neutral currents</td>
<td></td>
<td>QCD</td>
</tr>
<tr>
<td></td>
<td>Charm [J]</td>
<td></td>
<td>GUTs??</td>
</tr>
<tr>
<td></td>
<td>Gluon $\gamma$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>$W$, $Z$</td>
<td></td>
<td>Superstring??</td>
</tr>
</tbody>
</table>

The situation is without historical precedent however. Until we knew the nature of the strong and weak forces, we could only work on the assumption that experiments at higher energies/shorter distances would lead to new insights. Now we can be much more confident that this is the case since we have a theory which works perfectly but is only valid up to 1 TeV.

The answer to the question of whether theory can progress without experiment seems to be yes and no. The idea of local gauge invariance could certainly have been introduced much earlier. The implementation of this idea in SU(2)×U(1) and QCD could not, however, have been anticipated by more than a few years since the former required the knowledge that weak interactions have a V-A structure while the latter could not have preceded the discovery of quarks and of colour. Likewise, the idea behind the quark model could have been anticipated — indeed it was anticipated by Fermi and Yang in the early 1950s and later developed by Sakata. The quark model itself, however, could not have preceded the accumulation of spectroscopic data in the late 1950s and early 1960s. This suggests that while there is no natural time scale for new ideas, experimental information sets the pace for finding how nature may use them. The question is, then, whether we have enough experimental clues to construct a final theory now — presumably based on the superstring.

Famous utterances such as Kelvin's remark, just before the discovery of the electron, that "there is nothing to be discovered in physics now: all that remains is more and more precise measurement", show how easy it is to imagine that we have all the evidence we need. Nevertheless it is not obviously ridiculous to think that we have the necessary facts to establish the "theory of everything". For the first time since Kelvin's day we have a phenomenological theory that apparently fits all the facts. It may be that, just as the discovery of the strong and weak forces sabotaged the programme of seeking a theory...
of all forces which unifies electromagnetism and gravity, quite new phenomena await discovery – but there is no hint of this and, indeed, the success of hot big bang cosmology speaks against it. It therefore seems to me not inconceivable that the superstring will eventually be confirmed as the theory but I cannot imagine being convinced that it is correct without experimental exploration of the new physics that it is supposed to predict at or below 1 TeV.

4. COULD NEW MACHINES NOW UNDER CONSTRUCTION TEACH US ALL, OR NOTHING?

I have sketched possible discovery limits for LEP 200, Hera and the Tevatron in Figure 1.

Possible discovery limits for LEP 200, HERA and the Tevatron. The bars (-) represent present limits; the future limits will depend on what luminosity is achieved. Both present and future limits are more or less model dependent. Here t = the top quark, l = new leptons, H = the standard Higgs boson, q = a scalar quark, g = the gluino, i = a scalar lepton, W' = a heavier W and Z' = a heavier Z. The dashed lines for H at the Tevatron represent the hope1) of seeing \( H \rightarrow \tau^+ \tau^- \) if \( M_H < 2m_t \). HERA will set a limit of order 180 GeV on the sum \( m_q + m_{\tilde{q}} \).

The most likely particles to exist are, in decreasing order of probability, the top quark, the Higgs boson and supersymmetric particles. The success of SU(2)\( \times U(1) \) requires the mass of the top quark to be less than 250 GeV. Personally I would expect the Higgs boson to have a mass of order \( M_W \) or perhaps \( G_{\tilde{q}} = 300 \) GeV and I would guess that if supersymmetric particles exist their masses might be in the same range. Experiments at the machines now under construction will therefore explore a significant part of the region in which new particles might lie but by no means all of it. It is therefore
possible that we will learn nothing from these experiments. At the other extreme, it seems to me very unlikely that we will learn everything. If the Higgs boson is discovered, then it will be odds on that supersymmetric particles exist also. Although some may be found, it is difficult to imagine that we will be able to understand the full spectrum of supersymmetric particles without going to higher energy.

5. EXPERIMENTS AT FUTURE COLLIDERS

5.a Preliminary Remarks

In this section I shall make some remarks about physics at new colliders. I shall neither enter in much detail nor attempt to present a systematic survey since the subject has recently been explored in very great depth [2] and, in any case, I reviewed the already very large literature only a year ago [3]. I shall concentrate on $e^+e^-$ and pp machines since a purpose built ep machine is unlikely to be proposed as the first to explore a new region (the physics that can be done with ep machines is considered in [2, 3]).

5.b Electron Positron Colliders

The natural unit in which to measure electron positron annihilation cross-section is

$$
\sigma_{\text{point}} = \sigma(e^+e^- \rightarrow \mu^+\mu^-) = \frac{87 nb}{1 \gamma} \frac{1}{[E_{\text{CM}}(\text{GeV})]^2}
$$

I shall assume that future machines will achieve luminosities

$$
L \geq (\sigma_{\text{point}}^{-1})/\text{day} = 1.3 \times [E_{\text{CM}}(\text{TeV})]^2 \times 10^{32}\text{cm}^{-2}\text{sec}^{-1}.
$$

Good physics could be done with such luminosity although, as we shall see, higher values are needed for some purposes and are highly desirable. Bearing in mind that the world record to date is

$$
L = 5 \times 10^{31}\text{cm}^{-2}\text{sec}^{-1},
$$

this is a formidable requirement, but I would imagine that there is a limit of social acceptability not far below this luminosity which any future machine would have to exceed - I certainly cannot imagine a machine which would only produce one muon pair per year being approved. It might, however, be sensible to consider constructing machines with much lower luminosity if there were firm reasons to expect new phenomena which would lead to larger cross-sections [3] e.g. a new Z or electron sub-structure.

A machine with the luminosity above could discover new quarks and leptons with masses up to, perhaps, 80% of the beam energy. It could search for the tail of a $Z'$ with $M_{Z'}$ up
to about 4 times the centre-of-mass energy and for direct contact interactions between quarks and leptons with a scale \( \Lambda \) up to about 45 times the centre-of-mass energy. The search for supersymmetric particles, however, would require higher luminosities [2] due to the fact that the asymptotic cross-section for the production of spin-0 particles is one quarter of that for spin-\( \frac{1}{2} \) particles, the slower (\( s^2 \)) turn on at threshold, and the different signature: in order to reach 80% of the beam energy, luminosity of perhaps 5 or 10 times (\( s^2 \))\(^{-1} \) would be required.

The search for Higgs bosons is also highly luminosity dependent. The detailed studies reported in [2] lead to the conclusion that experiments at an electron-positron collider with a centre-of-mass energy 2 TeV and a luminosity of \( 10^{33} \) cm\(^{-2}\)sec\(^{-1} \) would lead to the discovery of a Higgs boson with a mass up to 0.6-0.8 TeV, while the region up to 1-1.2 TeV could be explored with a luminosity of \( 10^{34} \) cm\(^{-2}\)sec\(^{-1} \). Such heavy Higgs bosons would be sought as resonances in the WW invariant mass spectrum in ell ell WW[ZZ]. If the mass is of order 1 TeV or more, a broad enhancement would be seen, rather than an obvious

\[ \text{Fig. 2} \]

Differential cross-sections \( \frac{d\sigma}{d\tau} \) for “hard” sub-processes at sub-energy \( \sqrt{s} \) with typical strong interaction cross-sections \( \hat{s} = 10^{-2}/s \), where \( \tau = \hat{s}/s \). The solid curves are for glue-gluon induced processes at \( \sqrt{s} = 2, 20 \) and 40 TeV; the dashed curve for a uu induced process in pp collisions [u\( \bar{u} \) in p\( \bar{p} \)] at \( \sqrt{s} = 20 \) TeV and the dotted curve for a u\( \bar{u} \) induced process [uu in p\( \bar{p} \)] at \( \sqrt{s} = 20 \) TeV. With \( L = 10^{33} \) cm\(^{-2}\) sec\(^{-1} \) a process with this cross-section would generate 1 [10] event(s) per day in a bin with \( \Delta \tau = 0.01 \) for \( \frac{d\sigma}{d\tau} = 10^{-3} \) nb[10\(^{-3}\) nb] and this might represent a discovery limit, depending on the signature.
resonance, since the width increases like $M_h^3$ and exceeds the mass for masses above 1.44 TeV - in which case the Higgs boson would hardly be a particle. As discussed in section 2, if a light Higgs boson is not found, study of the scattering of longitudinally polarised $W$s and $Z$s for invariant masses above 1 TeV will be the way to decide whether there is a very heavy Higgs boson - possibly out of experimental reach - or whether the W mass is generated in some other way, such as by technicolour. It seems that this will require [4] electron-positron colliders with energy of 5 TeV or more and luminosities of $(\sigma_{\text{point}})^{-1}$ or more.

5.3 Proton-proton Colliders

The most important feature of pp collisions is that the constituent quarks and gluons whose interactions we wish to study carry only a small fraction of the beam energy. If we consider the production of a given final state by a "hard" constituent interaction at invariant mass $M$ with a cross-section $\sigma = 10^{-7}/M^2$, which is typical for a strong process, and convolute this cross-section with the quark/gluon distributions, we obtain the overall cross-section showing in Figure 2. Figure 2 shows the well-known fact that gluon-gluon collisions are much more probable than quark-quark collisions and that quark antiquark collisions occur as frequently in pp as in p\bar{p} collisions, except, in both cases, for the highest values of $M$. The point to which I wish to draw attention is that, for any plausible luminosity, the discovery limit $M_{\text{max}}$ is well below the kinematic limit and can be increased by increasing the luminosity as well as, or in addition to, increasing the energy. For energies of order 20 TeV and luminosities of order $10^{33} \text{cm}^{-2} \text{sec}^{-1}$, a factor of 2 in energy increases the discovery limit by the same amount (about 60%) as a factor of 15 in luminosity assuming that the extra luminosity can be used. It is important to realise that it is not known whether detectors can be built that will operate at $10^{33}$, except for special purpose detectors, as the conditions will be quite different from any encountered to date; for example, at the SSC with $L=10^{33}$ an average of 1.4 in elastic events will be generated at each bunch-bunch crossing, i.e. (every 16ns) with an average multiplicity of order 60. Further detector development is therefore very important in order that the potential of pp colliders can be exploited, but meanwhile when we see discovery potentials quoted that are based on a luminosity of $10^{33}$ we should look critically at what has been assumed about the detectors.

If the discovery limit for a particular process is rate limited, and if the cross-section scales ($\sigma = 1/E^2 f(M/E)$), then the $L$ dependence of the limit and the $E$ dependence are related; if the limit behaves approximately as $E^p$, then it will vary as $L^{(1-p)/2}$. If, on the other hand, the discovery is background limited, the advantage of increasing $L$ may be less relative to the advantage of increasing $E$ because the signal may increase more rapidly with energy than the background. In my talk at the Berkeley Conference [3] I reported discovery limits in the form constant $\times L^{0.8}$ which I obtained by making fits to the results in reference 5. Comparing those fits with the results obtained in reference 2, which were based on detailed detector simulations, I find that I erred on the side of optimism. Nevertheless it is clear that the LHC with $E_{CM} = 17$ TeV can probe
the 1 TeV region although the SSC with $E_{CM} = 40$ TeV would obviously do better. For example, with $L = 10^{33}$ experiments at the LHC should discover a Higgs boson with a mass below 0.6 TeV while at the SSC 1-1.2 TeV should be in reach. The Higgs boson will be sought in $WW$ scattering in the sub-process $qq'^q'WW$. In order to overcome the QCD background, it will be necessary for both $W$s to decay leptonically unless the outgoing quarks ($q'$) could be tagged, in which case the much more copious hadronic decays could be used. This would extend the reach for finding the Higgs boson and might also make it possible to make quantitative studies of the scattering of longitudinal $W$s at centre-of-mass energies above 1 TeV at the SSC, a process which is on the edge of observability without tagging [6].

5.4 Summary and Comparisons

Electron-positron colliders provide a clean unbiased way to search for new phenomena up to an energy of order the beam energy. Luminosity of at least $(\text{point})^{-1}$ will be desirable and substantially higher luminosity would be preferable. Flexibility in energy which does not compromise the luminosity would also be desirable since the cross-sections for new phenomena tends to peak not far above the threshold before decreasing.

Proton-proton machines such as the LHC and SCC will allow us to explore the region beyond 1 TeV. If the reach for the most likely discoveries increases like $E^{0.65}$, as claimed in ref. 3, the SCC will go 70% beyond the LHC for the same luminosity. We should not infer that the SCC is 70% better. If nothing new inhabits the extra region, the advantage will be relatively small (cf Serpukov and the PS and AGS), but if there are new phenomena the SCC may be qualitatively better (cf SPEAR and ADONE). The simple scaling law associates an $L^{0.17}$ behaviour with a reach which grows like $E^{0.65}$. If true, a 25-fold advantage in luminosity could compensate for the lower energy of the LHC relative to the SCC. In practice, however, increased luminosity could only compensate for the lower energy up to a point given the difficulties of doing experiments at very high luminosity. The relative advantage of energy and luminosity is the subject of continuing work by the CERN long-range planning group. Preliminary results on looking for $H\to ZZ$ with both $Z$s decaying to mu-pairs at $L=5 \times 10^{34}$cm$^{-2}$sec$^{-1}$, suggests that the reach would only be extended up to 0.85 TeV and show that whereas the signal would increase by a factor of 8 in going to the SCC the background would only increase by a factor of 2.

In order to compare the capabilities of electron-positron and proton-proton colliders, we can appeal either to history (Fig. 3) or to the recent study carried out in Europe (Fig. 4). Figure 3 shows that since 1970 proton-proton machines have had an advantage of about a factor 10 in centre-of-mass energy over electron-positron colliders but I believe that it would generally be conceded that their contributions to physics have been of similar importance. This factor of 10 was borne out by the European study, whose results are summarised in Fig. 4. It shows that a 2 TeV electron-positron collider (CLIC) would have a similar discovery potential to the LHC. This figure also shows that these machines have complementary capabilities. The reach of $e\bar{e}$ colliders clearly grows
A version of the Livingston plot (due to Kjell Johnsen) for fixed target synchrotrons and colliders.

linearly (provided the luminosity grows like $E^2$), so if indeed CLIC and LHC are roughly comparable and if also the reach of pp colliders grows as $E^{0.65}$, then the SSC will be comparable to an $\bar{e}e$ collider with $E_{CM} = 3.5$ TeV while the Eloisatron (a hypothetical pp collider with a centre-of-mass energy of 200 TeV) would be comparable to a 10 TeV $\bar{e}e$ machine.

6. CONCLUDING REMARKS

The theoretical arguments for expecting that there are new phenomena, at or below 1 TeV, associated with the origin of mass, are very compelling. It will be necessary to explore these new phenomena experimentally: despite the euphoria of some string theorists, pure thought will not be enough. It is possible that experiments at SLC, LEP, HERA and the Tevatron will discover nothing. It is also possible, and perhaps more likely, that they will unveil the eagerly anticipated "new physics at or below 1 TeV" but it seems most unlikely that they will exhaust it. Any direct information about this physics would point the way to the most fruitful avenues for future exploration. Meanwhile the R and D programme is clear - work is needed on linear electron-positron colliders and also on detectors for high luminosity proton-proton machines.
Fig. 4
Summary of the possible discovery limits for 12 different processes, compiled by Amaldi\(^2\), for a) pp collisions with \(E_{\text{cm}} = 16\ \text{TeV}, L = 10^{33}\ \text{cm}^{-2}\text{sec}^{-1}\) (LHC), b) ep collisions with \(E_{\text{cm}} = 1.5\ \text{TeV}, L = 10^{32}\ \text{cm}^{-2}\text{sec}^{-1}\), and c) e\(\text{e}^-\) collisions with \(E_{\text{cm}} = 2\ \text{TeV}\) (CLIC) with "low" \(L = 10^{32}\ \text{cm}^{-2}\text{sec}^{-1}\) and "high" \(L = 4 \times 10^{33}\ \text{cm}^{-2}\text{sec}^{-1}\). For compositeness the scale has been divided by ten e.g. CLIC with high L is expected to reach \(\Lambda = 100\ \text{TeV}\) with the usual definition of \(\Lambda\). See Ref. 2 for further details.
References

1. G. Alverson et al. FERMILAB-conf. 87/51, to be published in Proc. 1986 Snowmass Study on Physics of the SSC.


4. M.C. Bento and C.H. Llewellyn Smith, Nucl. Phys. B289, 36, 1987. We overlooked the dangerous background from e+e→WZ,WWZ, pointed out and analysed in ref. 2, but we are hopeful that this background can be suppressed e.g. by using the fact that the signal [background] is dominated by longitudinal [transverse] Zs that have a sin²θ*[cos²θ*]

decay distribution which should be easy to exploit in the decays Z→Ee,WW (we considered WW→ZZ scattering with one Z decaying to charged leptons - we actually included ττ and forgot to exclude cases in which the other Z decays to νE; our rate estimates are therefore over optimistic by a factor of two).


Discussion

H. Hora, University of New South Wales

Since this conference is a meeting of conventional high energy physics laser and plasma experts, I would like to make a comment on your question on "mass of particles". Today's techniques can provide such high laser intensities in a focus that electrons and ions (relativistically) oscillate with an energy above several GeV and pair production (e-, p-) will occur. You cannot distinguish the particles by their mass. This state corresponds to the temperatures above $10^{12}$ K (GeV) where the Gresner-Stöcker or Hagedorn models limit the state of matter [1]. The study of this "proto-matter" with particles undistinguished by mass and merging the fermion-boson properties [2] may be a further interesting topic apart from the usual accelerator technology.


P. Chen, SLAC

Would you please comment on the non-uniquess of the internal symmetry group in superstring.

Reply

It is true that there seem to be two groups in the superstring. The choice is simply made because one of them does not allow you to have left-handed weak interactions. But this is the disturbing thing, if you think that the theory should lead you to a theory which somehow fixes itself. This is rather unsatisfactory.
RF LINACS AND POWER CONVERSION

H. Henke
CERN, Geneva, Switzerland

ABSTRACT

The main choices for a high-gradient, high-energy electron linac are presented. These are: the accelerating structure; the beam-induced effects and possible cures; the radio-frequency parameters; the power converters; and the pulse compression devices. Today's possibilities for a superconducting linac are briefly mentioned and compared with the standard, heavily pulsed, normal conducting linac. Finally, the inherent advantages of two-beam linacs and proposals for their realization are given.

1. INTRODUCTION

The aim of this paper is to report on the actual status and the prospects of creating high accelerating fields using conventional methods. I will therefore restrict myself to describing very high-energy linacs and devices which are capable of generating accelerating fields of 50 to 200 MV/m in an efficient way.

A first choice has to be made between two different types of accelerating structures: travelling-wave (TW) and standing-wave (SW). The TW structure delivers a constant accelerating voltage after one filling time, and it represents a matched load for the power source, but it requires an output with an absorber for the leftover power. In the SW case, the voltage builds up exponentially and about 23% of the incident energy is reflected, but it does not require any output load. In practice, the handicap of reflected energy can be more than compensated for by using irises with smaller diameter and nose cones, thus increasing the stant impedance by 25% to 40%, in comparison with a TW structure. As a consequence, it is not obvious whether a TW or SW structure is better suited for efficient acceleration. The choice has to be made by looking at other issues such as operation, costs, and ease of fabrication.

Owing to the necessary mode separation, a SW structure consists of only a few coupled cells, typically five, whereas a TW structure is one order of magnitude longer. The cell-to-cell coupling in the SW case is small, about 1%, and the structure is more sensitive to errors that have arisen during the manufacturing stage (this can only be overcome by using complicated coupling devices). The main drawback for high-gradient applications is, however, the high ratio of peak to average field, which is 1.6 times more in a π-mode SW structure than in a TW structure. Equally decisive may be a small iris opening causing high transverse wake fields, especially for high-frequency structures. Taking these arguments into account it is probable...
that future high-gradient linacs will use TW structures, with the exception of superconducting cavities which will be of the SW type.

After a short discussion of reasons why one would like to use a high operating frequency, this paper addresses the problems of the beam-induced fields and possible cures. Then it is pointed out why the situation is very different for a superconducting RF.

Microwave power tubes are briefly mentioned, especially their expected performance at high frequencies. No matter which tube turns out to be the best, the required very high peak power will probably need a subsequent pulse compression device as well as a large number of power sources. An alternative solution may be one of the different two-beam devices presented at the end of this report.

2. PRINCIPAL DESIGN PARAMETERS [1]

As mentioned in the Introduction, TW structures are likely to be the solution for high-gradient, normal conducting linacs. In that case, sections can have constant cross-section (constant impedance, CI), where the field decays exponentially with the distance from the input; or they can be of constant gradient (CG) type, where the cross-section changes so that the field stays constant. The latter case reveals a few, although minor, advantages [2]. The RF dissipation is constant over the length, thus facilitating the cooling task remarkably. The ratio of peak to average field strength is smaller and the energy gain slightly higher. The structure is less sensitive to frequency deviations and less subject to transient effects. It is also less susceptible to multibunch beam break-up. These advantages must be weighed against the more complicated construction.

For ease of calculation, in the following we will assume a CI structure. However, the conclusions drawn apply also to a CG structure. Then the acceleration field decays exponentially as

\[ E(s) = E_0 \, e^{-as} \]  

(1)

whereas the stored energy \( W'(s) \), the dissipation \( P'_d(s) \), and the power flow \( P(s) \) decay with \( 2a \) (\( s \) is the coordinate along the structure, and the prime means per unit length). Shunt impedance \( R' \) and quality factor \( Q \) are defined as

\[ R' = E(s)^2/P'_d(s), \quad Q = \omega W'(s)/P'_d(s) \]  

(2)

The group velocity \( v_g \), equal to the energy velocity \( v_E \), follows from

\[ v_g = v_E = P(s)/W'(s) \]  

(3)
as

\[ v_g = \frac{\omega}{2\alpha Q} \tag{4} \]

after the use of \( P_d'(s) = -dP(s)/ds = 2\alpha P(s) \) and Eq. (2). Then the filling time,

\[ T_f = \frac{1}{v_g} \tag{5} \]

is the time a wave front needs to travel through a section of length \( l \).

The total voltage of the accelerator of length \( L \) follows from integrating Eq. (1):

\[ V = \frac{1}{L/1} \int_0^1 E(s) ds = E_0 L (1-e^{-\tau})/\tau, \quad \tau = \alpha l. \tag{6} \]

Combining Eqs. (2) to (5), one finds the peak and average RF power, for a given voltage gain \( V \) over a length \( L \):

\[ \hat{P}_{RF} = P_0 (L/1) = \left( \frac{V^2}{2R' L} \right) \tau / (1-e^{-\tau})^2, \tag{7} \]

\[ \overline{P}_{RF} = \hat{P}_{RF} T_{rep} f_{rep} = \left( \frac{V^2 Q f_{rep}}{\omega R' L} \right) \tau^2 / (1-e^{-\tau})^2, \tag{8} \]

where we assumed a square pulse of duration \( T_f \) and a pulse repetition frequency \( f_{rep} \). The energy transfer efficiency

\[ \eta_t = \frac{\overline{P}_{RF}}{\overline{P}_{RF}} = \frac{(Ne\omega R' L/QV)(1-e^{-\tau})^2}{\tau^2} \tag{9} \]

gives the fraction of the RF power which is transferred into beam power, \( \overline{P}_b = NeVf_{rep} ; \overline{P}_{RF} \), and \( \eta_t \) are shown in Fig. 1 as a function of \( \tau \), the attenuation per section. The attenuation \( \tau = 1.25 \) gives the minimum peak power, a working point often used in the past when accelerators were limited by the peak power available. Modern high-energy linacs have to be built with small average consumption, even at the expense of an increased peak power. At SLAC the point chosen is \( \tau = 0.57 \), and \( \tau = 0.25 \) may be the extreme operational point for a 1 TeV linac such as, for instance, the one proposed for CERN [3].

Let us now examine the frequency dependence of the different quantities. For constant \( E_0 \) and \( \tau \) we find

\[ W', P \propto \omega^{-2}, \quad P_d', Q \propto \omega^{-1/2}, \quad R' \propto \omega^{1/2}, \]

\[ v_g \propto \text{const}, \quad \alpha \propto \omega^{3/2}, \quad T_f, l \propto \omega^{-3/2}, \tag{10} \]

and consequently

\[ \hat{P}_{RF} \propto \omega^{-1/2}, \quad \overline{P}_{RF} \propto \omega^2, \quad \eta_t \propto \omega^2. \tag{11} \]
Equation (11) shows the strong dependence of the average power on the frequency, whilst savings in peak power can only be made when going to frequencies of at least one order of magnitude higher than the standard 3 GHz.

Although the accelerating fields in future linacs will probably be determined by the available peak power rather than by breakdown, it is still desirable to choose a high frequency where the breakdown limit is high. The breakdown formula for a short RF pulse is [4]

$$E_b(T_p) = E_b[1 + 4.5/T_p^{1/4}]$$,  \(12\)

where \(E_b\) is given by the Kilpatrick formula for CW operation,

$$f = 1.643 \times 10^{-3} E_b^2 e^{-8.5/E_b}$$.

Here \(E_b\) is in units of MV/m, \(T_p\) is in \(\mu s\), and \(f\) is in GHz. For high fields \((E_b \gtrsim 20 \text{ MV/m})\) and short pulses \((T_p < 20 \text{ \(\mu s\)})\) the quantities scale as

$$E_b \propto f^{1/2}, \quad T_p \propto f^{-3/2}, \quad \text{and therefore } E_b(T_p) \propto \omega^{7/8}.$$ 

This result is plotted in Fig. 2, which gives the limiting field due to breakdown and to surface heating. A SLAC breakdown measurement [5] is given for comparison.
3. **WAKE FIELDS [6-8]**

The co-travelling electromagnetic fields of a bunch are scattered at the surrounding chamber and act back on the beam. Longitudinally scattered fields lead to energy loss and energy spread. The transverse components deflect particles and may cause emittance blow-up or even beam loss. For highly relativistic beams these fields can be calculated by neglecting the back action on the exciting charge during the passage through a certain component, i.e. the scattered fields are taken into account as external fields. Also, we are not interested in the fields at a fixed point, but in the force acting on a co-travelling charge over a certain interval:

\[
\vec{W}(\tau) = \frac{1}{Q} \int \frac{Z_2}{Z_1} \left[ \vec{E} + \vec{v} \times \vec{B} \right](q_2, \varphi_2, z, \tau) \, dz.
\]

The position of the exciting charge is \( q_1, \varphi_1 \) (in cylindrical coordinates) and of the probing charge, \( q_2, \varphi_2 \). The latter travels at \( t = z/v + \tau \), i.e. a distance \( \tau v \) behind the first. The components of \( \vec{W} \) are called wake potentials. They are normalized with respect to the amount \( Q \) of the exciting charge; Figure 3 shows the wake potentials for a 30 GHz disk-loaded guide [9]. The longitudinal wake has a discontinuity at \( \tau = 0 \) followed by a smooth part which gives the short-term, non-resonant effect. Then the wake starts to oscillate, as a result of the superposition of long-term resonant effects. The exciting charge 'sees' half the value of the wake which it creates immediately behind itself. The transverse wake potential behaves in a similar way, except for \( \tau = 0 \), where the electric and magnetic forces cancel each other and the wake is zero.

For a given structure geometry, the longitudinal and transverse wake potentials per unit scale with frequency as

\[ W_L = \omega^2, \quad W_T = \omega^3 \]  \hspace{1cm} (14)

![Figure 3](image_url)

**Fig. 3** a) Longitudinal and b) transverse wake potential of a point charge travelling in a disk-loaded guide.
and can therefore be detrimental in the case of a high frequency. Figure 4 demonstrates these effects, taking as an example a 30 GHz 1 TeV linac [9]. Figure 4a shows the superposition of the longitudinal wake potential and the accelerating voltage. The r.m.s. bunch length is 0.3 mm, and a phase difference of 14° is introduced between the bunch centre and the RF. (The phase difference is required for adequate Landau damping, see next section). This results in a 6.6% decrease of the accelerating voltage and a 5.9% energy spread. In Fig. 4b the transverse shape of the bunch is drawn at the end of the linac. For this purpose the bunch is cut into slices longitudinally, and the dots indicate the transverse position of the centroids of the slice. As can be seen, the 'tail' of the bunch is blown up by a factor of 800.

4. CURES AGAINST WAKE-FIELD EFFECTS

As pointed out in the above section, it would be preferable to use a frequency that is typically one order of magnitude higher than 3 GHz in order to save RF power. But the question is, Can we still cope with the much larger wake-field effects?

4.1 Structure geometry and bunch length

The longitudinal wake fields scale with the iris opening $2a$ and the r.m.s. bunch length $\sigma_z$ as

$$W_L \propto \frac{1}{a}, \frac{1}{\sigma_z} \quad \text{for} \quad a/\lambda = 0.1, \ldots, 0.3, \quad a/\lambda = 0.01, \ldots, 0.05, \quad (15)$$

but the shunt impedance also goes like

$$R' = \alpha^{0.8}. \quad (16)$$
So, increasing $a$ does not help. Increasing $\sigma_z$ brings the wake fields down, but it also makes it harder to decrease the energy spread within the bunch stretching over a larger fraction of the sinusoidal RF voltage. In general, there is not much to be done against the longitudinal wake fields. The transverse wake fields scale as

$$W_T \propto a^{-2.8},$$

(17)

and opening up the beam hole helps a lot.

The dependence on $\sigma_z$ is more complicated. The transverse wake field $W_T$ is small for very short bunches $\sigma_z \leq 0.01\lambda$, shows a maxima for intermediate bunch lengths, and goes slowly down for $\sigma_z \geq 0.1\lambda$. The short bunches cause a high $W_L$ and are difficult to make. The long bunches are unacceptable owing to their large energy spread. Thus one will normally fall into the range where the transverse wake is highest.

4.2 Strong focusing

Since the transverse wake force is proportional to the transverse offset, one obvious and necessary requirement is to focus the beam as much as possible. But a very strong focusing system is also very sensitive to quadrupole displacements. In the example of a 30 GHz, 1 TeV linac [9], the allowable quadrupole displacement jitter is about 0.1 μm.

4.3 'Flat' beams

Slightly relieved tolerances follow in the case of a slotted iris (proposed by R. Palmer of BNL). In the direction of the slot the transverse wake is small. Thus the focusing can be made weaker, whilst the emittance is small. Perpendicular to the slot, the large wake field requires a small $\beta$-function but the emittance can be made larger. As a result, the tolerances are relieved by a factor of 1.5 to 2 in both planes without any loss in luminosity.

4.4 Landau damping [7, 10]

The use of an energy spread along the bunch in order to inhibit blow-up was first described in Ref. [10]. If the 'tail' of the bunch has a lower energy than the 'head' it will advance in betatron phase. On the other hand, the sign of the wake-induced kicks is such as to cause the 'tail' to lag behind the 'head'. So one effect can compensate the other, and any blow-up can, in principle, be suppressed by choosing the right energy spread. This is called Landau damping. Figure 5 shows the transverse bunch shape with damping, as compared with Fig. 4b without damping, again for the example of a 30 GHz, 1 TeV linac [9]. The 'head' particles, oscillating freely and with an amplitude corresponding to adiabatic damping, are out of phase, so that their wakes more or less cancel out. The core of the bunch is damped even more by constructive complicity of the wakes. The energy spread, which is
Fig. 5 Transverse offset of the bunch at the end of the linac in the case with Landau damping, compared with Fig. 4b without damping.

necessary for damping, is 0.5% and 2% for $\sigma_z/\lambda = 0.01$ and 0.03, respectively.

4.5 RF focusing [11]

As pointed out by R. Palmer, the transverse focusing may by achieved by transverse RF fields in the structure. An RF structure with slotted irises has the property that a passing charge 'sees' only a magnetic field in the direction of the slot and is therefore focused. In the perpendicular direction it 'sees' the focusing magnetic force plus a defocusing electric force of twice the magnitude. The effective focusing gradient has been calculated [11] as

$$G = \frac{\dot{E}}{c_0 \lambda} \sin \varphi,$$

with $\dot{E}$ being the peak accelerating gradient; $\lambda$ is the RF wavelength and $\varphi$ is the RF phase angle measured backwards from the top. Such a cavity forms an RF quadrupole of the same peak focusing strength as a conventional quadrupole with 0.6 T pole-tip field, if $E = 100$ MV/m, $\lambda = 1$ cm, and the quadrupole aperture is 1.2 cm. The advantages of an RF focusing system are:

i) the savings that can be made in precision-permanent magnets;

ii) the accelerating cavity, now forming the focusing system, may be used to observe a beam-induced higher mode signal for automatic control;

iii) the focusing acts within the bunch scale, i.e. parts of the bunch with different phase angle $\varphi$ are focused differently, and the spread in betatron oscillation, necessary for Landau damping, is introduced without a large energy spread; the spread in the betatron wave number is

$$\Delta k_{B}/k_B = + \cot \varphi_0 \pi \sigma_z/\lambda = +9\%,$$

for $\sigma_z/\lambda = 0.01$, $\varphi_0 = 20^\circ$ at the bunch centre;
iv) the spread [Eq. (19)] is more than one order of magnitude larger than is achievable through an energy spread. So the focusing strength itself can be reduced, and relieved alignment jitter tolerances are to be expected.

5. STRUCTURE CHOICE [1, 12]

There are many different slow-wave structures capable of accelerating electrons. A few are shown in Fig. 6. In general, they can be classified into forward-wave structures, where group and phase velocities are of the same sign, and backward-wave structures, where group and phase velocities have opposite signs.

Nearly all existing high-energy electron linacs are of the disk-loaded waveguide type (DLG). Even though other structures may present some advantages, such as higher shunt impedance, none of them has so far proved to be as practical as the DLG. High shunt impedance is obtained typically with small beam apertures and/or high group velocities. Small beam apertures yield large transverse wake fields, which is certainly detrimental to our aims (see sections 3 and 4). Group velocities that are higher than necessary require larger distances between feeds, i.e., higher peak power, for efficient operation. No matter which measures are taken to widen the beam aperture and to reduce group velocity, they always reduce the shunt impedance until only a slight advantage, or none at all, remains. Moreover, most structures result in a more complicated fabrication and therefore in

![Diagram](image)

*Fig. 6 Different slow wave structures for electron linacs.*
higher costs. This is especially true for high-frequency structures where mechanical considerations, for instance cooling and fabrication, play a vital role.

For the above-mentioned reasons, the DLG is certainly a good candidate for very high energy linacs. Additionally, it has been proved that it can be built at 35 GHz and that it can stand very high accelerating gradients [13]. The experiment was done with a seven-cell fully equipped $2\pi/3$ mode cavity. The input power was 3.1 MW, resulting in a peak field of 380 MV/m in the input cavity and 190 MV/m average accelerating field.

Apart from the standard DLG special structures, a DLG with a slotted iris or a 'muffin-tin' might be used for specific tasks such as RF focusing. Or, if the urge for multibunch operation becomes overwhelming, one might think of using structures where higher modes are heavily damped, as in the 'open' DLG shown in Fig. 6.

6. **SUPERCONDUCTING LINACS [14-16]**

Nearly all that has been said in the preceding sections is not valid for superconducting (SC) linacs:

i) SC cavities prefer CW or quasi-CW operation since the filling time is typically 100 ms.

ii) Standing wave cavities are more suitable owing to the small number of coupled cells per unit, no need for a return power-line, and no transient fields.

iii) Low frequencies are preferred since

$$Q_0 \propto \omega^{-2}, \quad (R/Q) \propto \omega, \quad P_d \propto \omega.$$  \hspace{1cm} (20)

Another argument in favour of having low frequencies is that this would keep the number of feed lines per unit length as small as possible, which is desirable because they are by far the most expensive parts. Thirdly -- and this is especially important for SC cavities with their long 'memory' -- the shunt impedances for beam-excited higher modes are smaller.

A lower frequency limit is given by the cost per unit length and by the transverse dimensions. A compromise is at present thought to lie between 1-2 GHz.

Why could an SC approach be attractive in preference to copper structures at the same frequency?

First, the quality factors are extremely high; today they are typically $Q_0 \geq 3 \times 10^9$. Theoretical work indicates values of $Q_0 \approx 10^{12}$ for Nb$_3$Sn at 1.8 K and 350 MHz. Owing to the high Q-values, the stored energy is not dissipated rapidly. Typical time constants are around 100 ms and are much larger than the bunch repetition time. This means that the stored energy has not to be supplied in a short time and that no very high peak power sources
are needed. The delivered RF power goes completely into the beam, the
dissipation being negligible.

Secondly, an SC cavity has high accelerating gradients: 5 to 10 MV/m
are achieved routinely, 30 MV/m is something of a record. Again, the
theoretical predictions are much higher: 60 MV/m for Nb and 100 MV/m for
Nb₃Sn, leaving room for development.

Thirdly, higher-order modes can be damped 10⁵ times as fast as the
fundamental mode is dissipated. So multibunch operation is possible. The
repetition rate and the duty cycle can be made very small.

Fourthly, the geometry adopted -- by now almost universally -- is a
simple spherical or elliptical shape (see Fig. 7). This allows easy
fabrication from sheet metal, and good surface treatment. The electrical
peak surface field is only about twice as high as the average accelerating
field (the magnetic peak surface field to the average accelerating field is
30-40 G per MV/m). Multipacting is largely suppressed.

Fifthly, the iris opening is much larger than for normal conducting
cavities. This allows couplers to be placed at the cavity ends (beam tubes)
and fabrication tolerances to be relaxed. But the main advantage is that
higher modes are less excited and can be more easily damped.

Although SC cavities are today a well-understood technique, there is
still much room for development. The main field-limiting effect is thermal
breakdown due to surface defects. This can be improved by increasing the
thermal conductivity λ. Commercially available Nb has a thermal conductivity
of about 30 W/mK. A 150 W/mK has been achieved with a yttrification method
at Cornell University [17]. Sputtering Nb or Nb₃Sn on Cu, with λCu = 460
W/mK, is expected to reduce thermal breakdown considerably. Additionally, it
would allow tube-cooling instead of bath cooling, thus simplifying
fabrication and reducing costs. Work is going on in order to obtain clean
and defectless surfaces, and to improve further the surface inspection, the
cryostat design, and the shaping and welding techniques. High-temperature
annealing will be developed and should improve the surface by degassing and
homogenization of bulk material.

Cornell University [15] has worked out the parameters for a 1 x 1 TeV
collider. The frequency was chosen to be 3 GHz. The repetition rate of 20 Hz

Fig. 7 Schematic view of a five-cell superconducting cavity and its
cryostat module.
with a duty cycle of 1% results in an RF pulse of 500 μs duration. One hundred bunches of $5 \times 10^{10}$ particles are within one pulse with 1.5 km spacing. The quality factor is taken to be $3 \times 10^9$ and the accelerating field 30 MV/m.

The relative optimistic value for the accelerating field in the Cornell example shows at the same time the weak point of today's SC linacs: a 30 MV/m accelerating gradient still needs a 40 + 40 km length for a 1 TeV collider! It should, however, permit a luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$ with relatively modest RF power. Another serious problem is the cryogenic input power. Assuming an R/Q of 1500 Ω/m for the cavity, static cryogenic losses of 1 W/m, and a cryogenic efficiency of 0.1%, the cryogenic input would be 200 MW.

7. **RF POWER GENERATION**

The creation of accelerating gradients around 100 MV/m requires a very high peak RF power in copper structures. In conventional generators the peak power is limited by voltage breakdown, the cathode current density, and the cathode area. The ultimate breakdown limit is considered to be 500 kV and the upper current density limit is determined by the space charge. 'Child's Law' tells us that the highest possible current density between two parallel, closely spaced electrodes is given by

$$J_{SC} [A/cm^2] = 2.3 \times 10^{-6} \left(\frac{V_0 [V]}{d [cm]}\right)^{3/2},$$

where $V_0$ is the voltage and $d$ is the spacing. The limit follows when in a steady-state flow the space-charge field just cancels the external field. The cathode area is related to the wavelength and therefore scales as $\lambda^2$.

The impressive progress in the past has been achieved by playing with these fundamental parameters. The voltage has been increased as much as possible by shortening the pulse. The cathode area was enlarged and the beam compressed afterwards. Even the RF cavities interacting with the beam became larger by overmoding them. Nevertheless, the basic limitation that the peak power is proportional to $\lambda^2$ remains.

7.1 **Klystrons**

The 'workhorse' in accelerator technology is still the classical klystron. Its modular construction allows each part to be optimized in a very efficient way. The cathode system is optimized for high current and high beam energy. The RF part -- cavities and drift tube -- is separated and grounded. The collector (also independent) is at or near ground.

This principle allowed tubes to be built which reached 150 MW at 3 GHz for 1 μs [18]. The supply voltage was 450 kV. The tube operated with 51% efficiency and a saturation gain of 59 dB.
From these results it seems possible to envisage a supertube at 9 GHz (M.A. Allen, J.M. Paterson, SLAC). A very short pulse of 80 ns duration, and a 1 MV supply voltage obtained by magnetic compression, would yield 700 MW output power.

Instead of increasing the voltage, attempts are also being made to increase the cathode and beam area. This will lead to sheet-beam or ring-beam klystrons (Fig.8) [19]. Development is also going on to increase even further the already high efficiency by an adiabatic RF extraction with a series of output cavities.

Finally, there is a proposal [20] for a quasi-continuous array of rather small tubes, instead of going through the acrobatics of generating extremely high peak power and then redistributing it. Instead of a sheet beam there is an array of beamlets and output cavities, so-called 'klystrinos', each of which is connected to individual or double accelerator cavities (Fig. 9). These klystrinos would operate at a high frequency,
around 11 GHz, with short pulse duration of the order of 100 ns. The power needed is about 13 MW out. Fifty times more klystrons than large klystrons are necessary for a 325 x 325 GeV collider. Indeed, this may be frightening. However, when viewed against the difficulties and cost of building the large klystrons with pulse compression systems, it may not be all that formidable.

7.2 Gyroklystrons [21]

The principle of a gyroklystron (see Fig. 10) is very similar to the one of an ordinary klystron. The difference is that the longitudinal bunching is replaced by an azimuthal bunching. An annular hollow beam is compressed magnetically, thus giving the electrons a radial velocity. This in turn makes the electrons gyrate at the cyclotron frequency in an axial solenoidal magnetic field. The beam then enters an input cavity driven in an axis-symmetric TE mode, where the azimuthal electric field provides a modulation in the cyclotron frequency,

$$\omega_c = \frac{e}{m}(\beta_0/\gamma).$$

(22)

Electrons which are accelerated will lag behind in the gyrating phase, and those which are decelerated will advance (see Fig. 11a). A subsequent drift tube will allow an azimuthal bunching to take place. In the output cavity the bunches, now all in phase, will again drive an axis-symmetric TE mode (Fig. 11b).

The advantages of such a device are:

1) a magnetron-type, annular cathode with a large area;

![Fig. 10 Schematic view of a four-cavity gyroklystron.](image1)

![Fig. 11 Gyration electrons in interaction with the electric field of a) input RF cavity and b) output RF cavity of a gyroklystron.](image2)
ii) a high-voltage capability;

iii) an oversized beam pipe and overmoded cavities breaking the strict relation between interaction area and $\lambda^2$.

The problems arise from the oversized RF part where higher modes have to be suppressed, and from the less stable situation concerning the azimuthal bunching. The efficiency, typically between 35 and 45%, is lower than for a klystron (50 to 65%). This is a consequence of the azimuthal bunching, where the longitudinal energy cannot be completely transferred into azimuthal energy.

An experimental tube is under construction at the University of Maryland [22]. The design is for a 10 GHz tube at a peak power level of 30 MW. The supply voltage is 500 kV, and the pulse duration will be between 1 and 2 $\mu$s. Once the tube works successfully, it seems relatively straightforward to scale to output powers of several hundred megawatts.

7.3 Lasertrons

Progress in the field of laser-driven optical cathodes has initiated studies of directly modulated emission at high frequency. A photocathode is illuminated by an RF-modulated laser. The bunches are accelerated to high voltage and immediately passed through an RF output structure to produce microwave power (Fig. 12). Since the photocathode emits only while illuminated, only a d.c. power supply or a quite simple modulator is needed, leading to a very compact design. The efficiency should be very high. Computer simulations predict about 70%. Hopefully one can make use also of the very high current densities of photocathodes, which are several hundred A/cm$^2$ as compared with the 20 A/cm$^2$ of a thermonic cathode.

However, these potential advantages do not come for free. Photocathodes are far more sensitive to degradation by residual gas. The cathode activation requires various alkali metals and is difficult to achieve. Finally, the laser itself is a complex system and is not easy to modulate at a high frequency.

Such lasertrons are being developed at SLAC [23] and in Japan [24]. The SLAC experiment uses a 400 kV d.c. voltage. It is planned to have an RF power of 35 MW at 3 GHz during 0.3 to 1 $\mu$s. Initially, a GaAs cathode will

![Diagram](image)

**Fig. 12** Conceptual drawing of a lasertron (Ref. [24]).
be employed in a UHV vacuum of \(10^{-10}\) Torr. The Japanese tube (Fig. 12) has already produced 1.6 kW RF power at 3 GHz. At the moment it is limited by breakdown at 30 kV supply voltage. The design values are very similar to the SLAC ones.

7.4 Oscillators

Different oscillating devices have proved to be capable of creating very high peak power in the range of gigawatts. Backward wave oscillators are reported [25] with output powers in the range from 100 to 1000 MW at 10 GHz. At the MIT [26], a magnetron has produced 1.7 GW at 3 GHz with a conversion efficiency of 35%. The pulse duration was 30 ns. A review paper [27], lists virtual cathode oscillators which have produced up to 3 GW. However, these devices tend to have rather low efficiencies and produce a broad bandwidth output.

Although different oscillators have demonstrated the high-power levels required for high-gradient accelerators, they have yet to demonstrate the necessary stability and reliability. To achieve a stable phase, the oscillators have to be operated as amplifiers by injection locking. Practical experience with injection locking of magnetrons indicates that the locking power must be of the order of -15 dB with respect to the output power, which means that a tube delivering 1 GW output needs 32 MW locking power.

8. PULSE COMPRESSION SYSTEMS

A very good review article [28] has recently been published. Here I only want to give a short introduction to three RF pulse compression schemes.

8.1 SLED

The SLAC energy doubler (SLED) scheme came into being as a result of measurements on superconducting cavities. It was observed that the power radiated from a cavity that is heavily overcoupled approaches four times the incident generator power immediately after the generator has been switched off. A further increase by a factor of 2 can be gained if the RF source is reversed in phase rather than simply switched off.

Normally the power radiated from the cavity travels backwards to the generator. In the case of SLED, however, the waveguide system is broken, and a 3 dB coupler/dual-cavity assembly (shown in Fig. 13a) is inserted. After the RF pulse is turned on, the fields in the cavities build up and a wave of increasing amplitude is radiated from the cavity ports. The two emitted waves add at the accelerator port of the 3 dB coupler, whilst they cancel at the klystron port. In addition to the wave radiated from the cavities, there is a direct wave from the klystron which is opposite in phase.
Fig. 13  a) Schematic view of the SLED microwave network and b) the pulse-forming process (Ref. [28]).

The net field at the accelerator input starts with a negative value equal to the direct wave, goes through a phase reversal, and grows to a value determined by the difference between the final radiated wave and the direct wave (Fig. 13b). One accelerator filling time before the end of the RF pulse, the phase of the direct wave is reversed. Now, the emitted and the direct wave add at the accelerator, since the emitted wave cannot change instantaneously. Following the phase reversal, the fields in the cavities decrease rapidly as the cavities try to charge up to a new field level of opposite phase. The energy compression to levels that are 2.5 to 3.2 times higher than the klystron pulse is accomplished with an efficiency of 65%.

8.2 BPM

A device which increases RF power in steps of a factor two is the binary power multiplier (BPM). I will explain its operation by a single stage as shown in Fig. 14. The output of a low-level driver is divided by a 3 dB coupler $H_d$ to drive two high-power klystrons $K_a$ and $K_b$. The pulse duration determined by the klystron modulators $M_a$ and $M_b$ is set to twice the compressed pulse length. The biphase modulator $\phi_b$ codes the output of klystron $K_b$, whilst the phase shifter $\phi_v$ ensures the exact phase between the klystrons. In the diagram, a plus sign indicates zero phase and a minus sign indicates a phase shift of 180°. The time is in units of the compressed pulse length. The outputs of the two klystrons are connected to a 3 dB hybrid. Its properties are such that if the phase between the two inputs is zero the combined power appears at terminal $O_1$, and when the phase is 180° the combined power appears at $O_2$. Terminal $O_1$ is connected to a delay line D whose time delay is one unit. After one time-unit the phase of klystron $K_b$ is changed by 180° by means of the modulator $\phi_b$. As a consequence, during the second time-unit the combined output of the two klystrons appears at terminal $O_2$. As the output of terminal $O_1$ is delayed by one unit, the two outputs of the terminals appear simultaneously at terminals 1 and 2. The duration of each pulse is one unit and the peak power is double the output of one klystron. To obtain 2n power multiplication, we place n stages in tandem. The efficiency per stage can be brought to about 90%.
8.3 SES

A third technique, based on an active switch at the high-power side, is the switched energy storage (SES) scheme (Fig. 15a). A storage cavity is connected to the accelerating structure via a $\lambda/2$ long waveguide stub. Thus the short circuit at the end of the stub is transformed to the centre of the accelerator feed-line (Fig. 15b), yielding a very low coupling between the cavity and the accelerator. When the switch is fired, the short circuit at the end of the stub is moved by $\lambda/4$, which now transforms into an open circuit at the feeding-line centre (Fig. 15c), and produces a heavy coupling between cavity and accelerator. For the switching mechanism, a low-pressure plasma discharge has been proposed. This scheme has the potential of a high-power multiplication.

Fig. 14 Diagram of a single-stage binary pulse multiplier (Ref. [28]).

Fig. 15 a) Schematic view of the switched energy storage device; electric field envelope in the coupling section with b) switch off and c) switch on (Ref. [28]).
9. TWO-BEAM ACCELERATORS (TBAs)

To create a 100 MV/m accelerating gradient in a copper structure, one needs typically 300 MW/m peak RF power at 3 GHz or 100 MW/m at 30 GHz. For the generation of these high-power levels, two different lines of development are being pursued: one is in the range from 3 to 11 GHz, with newly developed klystrons or eventually gyroklystrons or lasertrons followed by a pulse compression system; the other is aiming for the range between 20 and 35 GHz. In this latter range, high-power tubes are not available, nor are they expected to be available in the near future. Additionally, the required repetition rates for a collider will be high (in the kilohertz range), and the short accelerating sections, of length $\alpha \omega^{-3/2}$, result in a high number of generators. A 1 x 1 TeV collider, for instance, needs 30,000 generators of 33 MW each when the gradient is 100 MV/m, the operating frequency is 30 GHz, and a section is 0.33 m long.

Instead of tens of thousands of power sources, it has been proposed to use a distributed RF source running parallel to the main linac (Fig. 16). The RF is generated in a periodical arrangement of decelerating units and transferred to the main linac. The energy lost by RF radiation generation is replenished periodically in reacceleration units. Deceleration and reacceleration is done adiabatically so that the distributed RF source is in a steady state. This is the concept of a TBA.

![Fig. 16 Schematic drawing of a two-beam accelerator.](image)

9.1 The original TBA [13, 29]

In the original proposal for a TBA, the RF generation was done with a continuously operated free-electron laser (FEL), i.e. the decelerating units, consisting of single-pass FEL units, created radiation travelling over the whole length of the linac. Conventional induction accelerating units were foreseen for the reacceleration of the beam (Fig. 17).
Fig. 17 Conceptual drawing of a two-beam accelerator which transfers energy from an FEL to a high-gradient linac.

The FEL and the main accelerating structure have been tested at LLNL/LBL. A 10 kA 3-4 MeV beam from an induction linac powered an FEL section. The wiggler, 3 m in length, was tapered. The output radiation was at 35 GHz with a peak power of up to 1.8 GW. As already mentioned in section 5, an accelerating gradient of 190 MV/m was reached with the FEL-generated RF in a seven-cell DLG.

Amongst the problems encountered in this scheme are the control of the RF phase, the inhibition of a side-band instability, and the long-distance transport of a relatively low-energy beam -- subjects of paramount importance. The reason for the low beam energy is the synchronous condition in the wiggler,

$$\lambda_{RF}/\lambda_w = [1 + (93.4 B_w \lambda_w)^2]/(2\gamma^2)$$, \hspace{1cm} (23)

with the wiggler field $B_w$ in tesla and the wiggler period $\lambda_w$ in metres. So the choice of $\gamma$ cannot be too high if one wants $\lambda_{RF} = 1$ cm for reasonable wiggler parameters. This typically limits the beam energy to a few tens of MeV.

A modification of this scheme has been proposed elsewhere [30]. There the induction accelerator has been replaced by a 350 MHz superconducting linac.

9.2 The relativistic klystron [31, 32]

The basic difference between a relativistic klystron and the original TBA, is that the FEL is replaced by a beam-cavity interaction, as for normal klystrons. A bunched beam passes through a succession of tuned decelerating
cavities, each of which extracts only a small portion of the beam power. The cavity may be a simple single-cell cavity, for low power, or an overmoded cavity or a TW structure for high power. Again, the energy lost is replenished by an induction accelerator.

The advantage of interaction cavities is that the mechanism is simple and well understood, as compared with an FEL. The RF phase automatically comes out right, and the main problem remaining is the long-distance transport of the beam—the beam which has a relatively low energy in order to make full use of the high efficiency of the induction linac.

9.3 The two-stage RF linac [33]

The two-stage RF scheme (Fig. 18) represents a kind of synthesis of different ideas about TBAs, the aim being to eliminate weak points. It employs a high-energy drive-beam, around 5 GeV, in order to minimize problems of phase stability and beam transport. The reacceleration cavities are low-frequency (350 MHz) superconducting devices, assuring high efficiency. The RF generation units are 30 GHz TW structures. Their group delay is equal to the superconducting RF period, thus keeping the RF energy flow constant between drive-beam bunches. The main linac consists of high-frequency (30 GHz) disk-loaded waveguides.

The choice of a low-frequency drive linac and a high-frequency main linac has several advantages. First, the main linac needs reduced RF power as pointed out in section 2. Secondly, the 'transformer ratio', i.e. the ratio of the gradient in the main linac to that in the drive linac, is proportional to the ratio of the frequencies:

$$\frac{E_{\text{main}}}{E_{\text{drive}}} = \frac{\omega_{\text{main}}}{\omega_{\text{drive}}}. \quad (24)$$

Thirdly, the low-frequency superconducting cavities have high Q-values and are operated in CW. The generators can be large (1 to 2 MW) high-efficiency klystrons of proven design. Owing to the CW operation, the repetition rate can be very high, around 6 kHz, and is determined by injector considerations only.

![Diagram](image_url)

Fig. 18 Two-stage accelerator with superconducting CW drive linac and a microwave main linac (Ref. [33]).
The time structure of the drive beam is relatively complicated, and shown in Fig. 19a. The basic cycle, determined by the repetition rate, is 166 µs. Then, four 350 MHz RF periods of 2.86 ns are needed to make up the 11.2 ns filling time of a main accelerating section. Since the charge required in one driving bunch is quite high, $4 \times 10^{12}$ electrons, it probably has to be split into a number of bunchlets spaced at the high-frequency RF period of 33 ps. These bunchlets 'see' a linearly increasing decelerating voltage in the RF generating structure, as shown in Fig. 19b. In order to match this voltage loss with the reacceleration, the bunchlets have to be placed on the rising slope of the sinusoidal reaccelerating field.

![Diagram of bunch structure and voltage](image)

**Fig. 19** a) Bunch structure in the drive linac and b) the matching of the decelerating and drive voltage for the device of Fig. 18.

Table 1 gives some possible parameters for a 1 TeV two-stage linac which would allow a luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$ in the collider mode. The first column is for an accelerating gradient of 6 MV/m in the superconducting reacceleration cavities, corresponding to the present-day performance. The second column reflects the enormous improvement which can be expected from an increase to 15 MV/m which is likely to occur during the coming years. The third column, finally, refers to the high-gradient superconducting case plus multibunch operation in the main linac. Multibunch operation allows a higher RF-to-beam efficiency and permits higher gradients.
Table 1
Parameters for a 1 TeV two-stage linac

<table>
<thead>
<tr>
<th></th>
<th>(MV/m)</th>
<th>80</th>
<th>160</th>
<th>445</th>
</tr>
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<td>Main linac, 30 GHz:</td>
<td>Active length (km)</td>
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<td>6.25</td>
<td>2.24</td>
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<tr>
<td>Drive linac, 350 MHz:</td>
<td>Accelerating gradient (MV/m)</td>
<td>6</td>
<td>15</td>
<td>15</td>
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<tr>
<td></td>
<td>Quality factor</td>
<td>$5 \times 10^9$</td>
<td>$5 \times 10^9$</td>
<td>$5 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>Cryogenic input power (MW)</td>
<td>33</td>
<td>67</td>
<td>186</td>
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<tr>
<td></td>
<td>Active length (km)</td>
<td>2.5</td>
<td>0.8</td>
<td>2.24</td>
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<tr>
<td></td>
<td>R upon Q (Ω/m)</td>
<td>270</td>
<td>270</td>
<td>270</td>
</tr>
</tbody>
</table>

* * *

REFERENCES

C. Pellegrini, BNL

1) The new high temperature superconductors might be able to support an accelerating field in the range of 500 MeV/m; if this is true a linac of this type would be a very good candidate for a collider. We have to support work in this area.

2) I would like to remark that there is no reason to stop at frequencies of 30 GHz. Still higher frequencies, in the range of 300 to 600 GHz, offer advantages in terms of average power needed for a given luminosity. At these frequencies one can use open accelerating structures. The design of these structures needs more study, but they offer some interesting possibilities, for instance reduced transverse wake fields. Also good power sources, namely the FEL, exist in this frequency range.

Reply

1) So, let us hope that filamentation and $\mu$-wave loss problems can be mastered, that surface coatings make these materials usable in vacuum and that the reported high critical fields can be repeated under operational conditions.

2) You are right, many parameters lead us to higher frequencies. But the transverse wake-field scales like $w^3$ and can be reduced by only a factor 2-3 in open structures. Further I see problems in the excitation and especially in phase control.

H. Hora, University of New South Wales

You mentioned the lasertron and the vacuum problems for the cathodes which may be overcome by using ultra-violet laser pulses [1]. Since you gave a very positive view about the lasertron and the problems with FEL's, I would like to ask what are the essential differences because I could see an ideal and intensive microwave source in the FEL.


Reply

In the case of the lasertron the problems arise from the cathode technology and the high DC fields in short gaps. Relatively long rise times, beam dynamics and cathode coating have to be improved.

FELs, in fact, may be a very good microwave source apart from their clumsiness. But depending on the application, phase locking, phase slippage and control and creation of sidebands may cause serious problems.
NON-RESONANT FIELD GENERATION

S. H. Aronson
Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT
Production of fields for particle acceleration by pulse technology is reviewed. Special attention is focused on several recently proposed schemes for generation of very high gradients, both in metallic structures and plasmas. Ongoing and planned experimental activities in these areas are discussed.

1. INTRODUCTION
At present there are many schemes under discussion, study, and development for acceleration of particles to very high energy. It is useful in some circumstances to adopt a taxonomic approach to this broad and varied field; that is, to classify the schemes into families within which common acceleration mechanisms are used. This approach has the virtue of making the field somewhat more comprehensible; more importantly it may help identify common virtues or defects and simplify the study of new species in a rapidly evolving field.

The task of the present paper is to explore a particular class of schemes grouped under the rubric "non-resonant" or "pulsed" field generation. The common feature is that the accelerating field is produced with one pulse (or a few pulses) of electromagnetic energy, rather than a long train of pulses, such as a many-wavelength burst of RF energy.

In section 2 we discuss briefly the virtues (and defects) of pulsed field generation in generic terms. In section 3 a number of such schemes currently under investigation are introduced and grouped according to their method of generating pulses and their method of coupling the pulsed field to the accelerated particles. In subsequent sections the various schemes are presented in more detail with emphasis on present status and future possibilities.

2. ADVANTAGES AND DISADVANTAGES OF NON-RESONANT FIELD GENERATION
Schemes employing very short pulses of energy share (in general) the following advantageous features:

a) Less heat is built up in structures. Kroll's paper in the Proceedings of the Malibu Conference [1] shows how this effect goes with the number of wavelengths in a pulse train, with $N = 1/2$ corresponding to a single pulse, as from a switched-power source. For $N$ large the achievable accelerating field at the melting limit decreases with the square root of $N$.

b) Very high peak power can be available with modest stored energy. Typically the maximum accelerating fields are found along the beam axis. Accelerating gradients in the GeV/m range (on paper) result.

c) For very short pulses HV breakdown occurs at very high fields.

d) Power switching can in principle be very efficient, allowing the possibility of systems with reasonable overall efficiency.
Many of the acceleration schemes falling in this class suffer from the following kinds of difficulties:

a) Various mechanical tolerances are often very tight in order to suppress unwanted field components: colinearity and homogeneity of laser and particle beams, symmetry of structures and switches, etc. Analogous problems occur in schemes where the structure is replaced by a plasma.

b) Good relative timing of power pulses and accelerated beam (i.e., low jitter) is required. This is sometimes automatic; for example a beam pulse switches the power, but in general good timing between different events or components must be imposed.

c) Problems (for example with instabilities or unwanted wake fields) may be worse with the wide-bandwidth inherent in short-pulse operation than in resonant power systems.

d) Many schemes put rigorous demands on laser systems: short pulse lengths, high repetition rates and very high peak power is required [2].

3. CLASSIFICATION OF NON-RESONANT FIELD GENERATION SCHEMES

In the present paper we will review the concepts for pulsed-power systems listed below. The list is not exhaustive, but perhaps representative of the efforts on-going at present:

1. Wakefield Accelerator (with off-axis driving beam) [3]
2. Wakeatron [4]
4. Induction Linac [6]
6. Switched-Power Linac [8]

These pulsed-power concepts can be grouped into sub-classes according to the Table below:

<table>
<thead>
<tr>
<th>Source of Pulse</th>
<th>SWITCH</th>
<th>PARTICLE BEAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupler or Transformer</td>
<td>Induction Linac</td>
<td>Wakefield Accelerator</td>
</tr>
<tr>
<td>Metal Structure</td>
<td>Switched-Power Linac</td>
<td>Wakeatron</td>
</tr>
<tr>
<td>Plasma</td>
<td></td>
<td>Plasma Wakefield Accelerator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Collective Implosion Accelerator</td>
</tr>
</tbody>
</table>

Table 1
Classification of non-resonant field generation concepts
We choose here as characteristics the method of producing the electromagnetic pulse and the means of coupling the pulse to the accelerated beam. In sections 4 through 6 we discuss the concepts grouped in the three filled elements of Table 1.

4. INDUCTION LINAC AND SWITCHED-POWER LINAC

a. In an induction linac (see Fig. 1) an accelerating electric field along the axis is produced by a time-varying magnetic flux around the axis. In the figure, the switch produces a pulse in the (primary) circuit penetrating the magnetic core; the beam is in effect the secondary winding and sees an accelerating voltage across the gap in the beam tube.

This is certainly the oldest new idea in non-resonant acceleration considered in this paper. The history is discussed briefly in Ref. 6. And although one can in principle concatenate induction acceleration units to reach high energies, it is not practical for this application. On the other hand, it is well-suited for the acceleration of very high-current beams. Table 2 gives a typical example.

![Sketch of the Induction Linac](image)

**Fig. 1** Sketch of the Induction Linac

**Table 2**

<table>
<thead>
<tr>
<th>FXR Induction Linac</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
</tr>
<tr>
<td>Beam Current</td>
</tr>
<tr>
<td>Pulse Length</td>
</tr>
<tr>
<td>Pulse Energy</td>
</tr>
<tr>
<td>Rep. Rate</td>
</tr>
<tr>
<td>No. of Modules</td>
</tr>
<tr>
<td>Module Voltage</td>
</tr>
<tr>
<td>Total length</td>
</tr>
<tr>
<td>Avg. Gradient</td>
</tr>
</tbody>
</table>

b. The switched power linacs considered here employ radial transmission lines to couple the pulsed field to the accelerated beam [9]. The idea has been discussed by Willis [8] over the last several years in the context of small-scale high-gradient structures. Figure 2 shows a schematic picture of one cell of a switched-power linac.
Fig. 2 A switched-power linac section using a radial transmission line

Several workers are pursuing linacs along this line, the principle difference among them being the switch technology. Willis and collaborators [7] are studying the use of vacuum photodiodes. Villa [10] would use very high-pressure gas switches; Melissinos and Morou [11] and Takeda [12] are developing solid state switches. All the switches mentioned above are triggered with very short laser pulses (on the order of 10 psec or less).

Very short pulses are necessary in order to achieve high field without suffering breakdown. The particle bunches to be accelerated are short compared to the field pulses and have very small transverse dimensions for luminosity considerations in a high energy linac. Thus the structure can have quite small dimensions, but large transformer ratios. Table 3 gives typical parameters of the Willis version; these are not very different from those of the other schemes mentioned above:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius</td>
<td>120 mm</td>
</tr>
<tr>
<td>Inner radius</td>
<td>1 mm</td>
</tr>
<tr>
<td>Gap (= disk thickness)</td>
<td>2 mm</td>
</tr>
<tr>
<td>Photocathode capacitance</td>
<td>20 pF</td>
</tr>
<tr>
<td>Pulse length</td>
<td>10 ps</td>
</tr>
<tr>
<td>Charging voltage</td>
<td>80 kV</td>
</tr>
<tr>
<td>Stored energy</td>
<td>64 mJ (16kJ/km)</td>
</tr>
<tr>
<td>Switchable power</td>
<td>6.4 GW</td>
</tr>
<tr>
<td>Radial enhancement</td>
<td>12</td>
</tr>
<tr>
<td>Gap field</td>
<td>0.6 GV/m</td>
</tr>
<tr>
<td>Average gradient</td>
<td>0.3 TeV/km</td>
</tr>
</tbody>
</table>

A number of R&D projects now under way must succeed in order for a version of this scheme to be developed into a practical high energy linac. Most critically, a switch that is fast, efficient and rugged must be demonstrated. Work on the vacuum photodiode switch at BNL and at Orsay will be reported at this Workshop. In the BNL work a gold-plated tungsten wire photocathode (DC surface field = 60 MV/m) has produced about 10 kA/cm² at photo-efficiencies of 10⁻³. Simulations [13] indicate that narrow field pulses can be formed and that stored energy can be extracted with reasonable efficiency.
The solid state switch under development at LLE (Rochester) [11] is also making progress. A prototype switch 2 mm long has held 37 kV DC (under oil) and been switched in less than 100 psec [14]. More recently, the Rochester group has reported the observation of voltage enhancement on a radial line structure built on a 3" diameter silicon disk, the peripheral switch being activated by a short-pulse IR laser [14]. This is an encouraging step toward the realization of switched-power linacs.

Many other technological issues need to be resolved. In order to minimize deflecting fields on the beam a high degree of symmetry is needed in the structure, implying tight construction and alignment tolerances and uniformity of the switching around the circumference. Model measurements of the radial line under way at CERN [15] and also to be discussed here indicate that higher multipoles of the azimuthal field distribution at the periphery are the center. Also, measured enhancement factors fit very well with the predictions of analytical calculations [16] and numerical simulations [17].

From a system efficiency point of view it is required that the switch have high gain (switched energy >> laser energy) and high efficiency (switched energy = stored energy). These considerations may determine the choice of switch technology (assuming more than one type of switch works at all!).

c. Before leaving this box in Table 1 we note the existence of two other ideas, one employing radial line transformers and the other based on laser/photodiode switches. Although not strictly speaking pulsed power devices, they were inspired by the work on switched power linacs at BNL and CERN mentioned above.

Caspers et al. [18] have suggested synthesizing a high-field pulse at the center of a radial line by feeding an appropriately phased set of frequencies at the periphery. It appears possible to select frequencies which sum to a very short high-field pulse at a predetermined repetition frequency, with relatively low fields everywhere in the structure at other times. One would like to use superconducting structures to minimize losses; it is hoped that one could exceed the critical field in the superconductor without quenching if the high-field pulses are sufficiently short. Much work needs to be done on the ideas and techniques upon which this scheme is based.

Palmer [19] has taken over the laser/photodiode switch of Willis’ switched power linac to produce a power source, called the Microlasertron. Here one has a linear array of photocathode wires at the appropriate spacing in a resonant cavity. Illumination of the cathodes with short laser pulses fills the cavity with CW power at the wavelength determined by the geometry of the photodiode array. Table 4 lists possible parameters of a Microlasertron producing about a gigawatt at a wavelength of 6 mm.

Table 4
Microlasertron Sample Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage supplied</td>
<td>50 kV</td>
</tr>
<tr>
<td>Gap</td>
<td>.5 mm</td>
</tr>
<tr>
<td>Laser pulse</td>
<td>.9 psec</td>
</tr>
<tr>
<td>Photocathode</td>
<td>40 wires, 40 cm² total area</td>
</tr>
<tr>
<td>Charge/pulse</td>
<td>8.8 nC/cm² (10% of sp. chg. limit)</td>
</tr>
<tr>
<td>RF field</td>
<td>150 MV/m</td>
</tr>
<tr>
<td>Cathode peak i</td>
<td>10 kA/cm²</td>
</tr>
<tr>
<td>Power output</td>
<td>.78 GW</td>
</tr>
</tbody>
</table>
5. WAKEFIELD AND WAKEATRON ACCELERATORS

a. This class of concepts shares with those described above the use of a metallic structure to couple the field pulse to the accelerated beam. In this case, however, a beam of particles rather than a switch is used to generate the fields.

The wakefield accelerator under study at DESY [3] employs a radial line transformer similar to the switched power linac. The periphery of the line is excited by the passage of a hollow driving beam and the wakefield pulse propagates inward to the axis of the structure. The transformer ratio of the structure provides the gain. Figure 3 shows the features of the DESY experiment.

b. The use of a radial line to provide gain in the DESY scheme is one way to beat the "wakefield theorem" [20] which limits the transformer ratio to 2 under certain conditions. Other ways around the limit involve tailoring the length or profile of the driving beam bunches. An application of this approach is found in the Wakeatron of the ANL group [4], shown schematically in Figure 4.

The driving beam in this case is a short proton bunch. The length of the driving pulse is the critical parameter in producing a transformer ratio greater than 2. A typical example from Ref. 4 has 100 GeV protons in a gaussian bunch with $\sigma = 3\text{mm}$, giving a transformer ratio of 10 and (with $3 \times 10^{11}$ protons and the structure geometry given in the figure) a gradient of 80 MeV/m. It is claimed that the use of protons can make the scheme cost effective and efficient. Protons also (by virtue of their mass) have a high frequency of oscillation about the point of zero energy loss; this so-called "mixing" in the driver bunch averages the energy loss over all the particles in the driver bunch and leads to the large transformer ratios.
Tests of the Wakeatron concept are planned for this year in the ANL Advanced Accelerator Test Facility [21].

6. PLASMA WAKEFIELD AND COLLECTIVE IMPSION ACCELERATOR

a. The plasma wakefield accelerator [5] replaces the metallic structure of the wakefield schemes discussed above with a low-density plasma. The passage of a driving bunch excites plasma waves; longitudinal electric fields in the waves accelerate the particles in a trailing bunch. Again, the wakefield theorem applies and recent work [22] confirms that proper shaping of the driving pulse can produce higher transformer ratios.

Experimental work on the plasma wakefield concept is being carried out by a Wisconsin-Argonne group [23] at the ANL Test Facility mentioned above. Figure 5 shows the plasma source to be used in the UW/ANL experiment. Table 5 lists some of the relevant plasma parameters. Accelerating gradients on the order of 100 MeV/m appear possible. However, there are difficulties analogous to the ones mentioned for the structure-based ideas. Here one may have (instead of high manufacturing tolerances) hard-to-meet requirements on plasma formation (uniformity, reproducibility) and instabilities in the beam/plasma system. Shaping the longitudinal profile of the driving pulse requires development as well but will not be studied in the initial ANL experiments.

---

Fig. 4 Schematic representation of the Wakeatron

Fig. 5 Sketch of the UW/ANL Plasma Source
Table 5

Plasma Source Characteristics

density $10^{12}$-$10^{14}$/cm$^3$
plasma wavelength 3 - 30 mm
axial mag. field 400 - 800 G
interaction length 10 - 20 cm
arc voltage < 100 V
arc current < 50
neutral pressure < 2 mTorr

b. A somewhat different idea, the so-called Collective Implosion Accelerator [24], shares with the previous wakefield scheme the use of a plasma to couple the power pulse to the accelerated beam. Here, however the plasma is created by a short laser pulse as depicted in Figure 6. The steps in this somewhat complicated scenario are as follows:

i. A shaped electron pulse ionizes the gas in the accelerator structure and ejects ionization electrons leaving an ion column on axis. This electron "charging pulse" may be preceded by an ionizing laser pulse.

ii. A short (1 psec) laser pulse following the sharply cut off tail of the charging pulse ionizes gas in a wide region around the ion wake. The ionization electrons rush in toward the wake; the radial current pulse produces an azimuthal magnetic field pulse which in turn induces an axial electric field.

iii. A short bunch of electrons trailing the laser pulse is accelerated by the implosion-created electric field.

![Diagram of Collective Implosion Acceleration Process](image)

Fig. 6 Depiction of the Collective Implosion Acceleration Process

In order to achieve the parameters which appear possible on paper a number of foreseeable difficulties (and no doubt some unforeseen ones) must be dealt with: Colinearity of all laser and particle beams with the structure is necessary to avoid strong transverse forces. Plasma instabilities may be present as in other plasma-based schemes. It is clear that positron acceleration will at least be different, if not harder, than electron acceleration.
6. SUMMARY

In the preceding few sections we have listed and described briefly a number of current schemes for acceleration with pulsed or non-resonant fields. Many schemes have been left out, and among the ones included the status of R&D is widely varying from speculation and calculation on one end to extensive hardware testing on the other. I leave induction linacs, a widely applied technology, out of this R&D spectrum.

A number of problems faced by most if not all of the schemes presented here have not been discussed. These relate more to the collider application than to the proof-of-principle in each case. These include high repetition rate capability of the devices and wall plug efficiency of a large system. In most of the cases considered these issues are somewhat premature, since many questions of technical feasibility have to be dealt with before the systems questions can be attacked in a meaningful way.

REFERENCES

1. N. M. Kroll, Proc. Workshop on Laser Acceleration of Particles (Malibu, 1985), AIP No. 130, p. 296 [Referred to as "Malibu, 1985" below.]
DISCUSSION

B. Zotter (CERN): The oldest and most advanced scheme using pulsed power acceleration is VLEPP in Novosibirsk, which is actually looking for project money at present. Was it left out for lack of information?

I apologize for this oversight. Unfortunately, the latest information I had available was the VLEPP status report communicated by Amaldi to the 1981 Lepton-Photon Symposium in Bonn. I am not familiar with its current status.

T. Katsouleas (UCLA): A comment and question on your discussion of the Fundamental Wakefield Theorem limiting the transformer ratio of symmetric bunches to $R=2$: This theorem follows from Maxwell’s Esq. and the principle of linear superposition. The second assumption can be relaxed. for non-linear plasma waves we have recently found that $R$ can be greater than 2 for symmetric bunches. Might the same possibility exist for structure-based wakefield devices (if driven to non-linear amplitudes)?

Thank you for pointing out this new result. In the case of structure-based devices, the Wakeatron uses symmetric proton bunches and achieves $R>2$, although this is a different issue. To my knowledge no one has studied the case of a structure-based device with non-linear amplitudes; it is not obvious to me that the plasma result you quoted would apply, but I would need to give it more thought.

H. Henke (CERN): 1. Could you comment on the dispersive medium in the radial line? Doesn’t it increase the bunch length if it is passive? 2. What is the shunt impedance of the synthesized pulse scheme of Caspers?

1. I am afraid I don’t have details on the Takeda scheme presented at Madison; I don’t know how to provide a medium in the line which compresses the pulse.

2. I have the following information from Caspers on an URMEL calculation of a line with outer radius 250 mm, hole radius 2.5 mm and 10 mm gap: The shunt impedance in the frequency range 0.4 to 4. GHZ changes from 0.023 to 0.064 Megohms; from 4. to 8. GHZ it remains fairly constant in the range 0.065 – 0.071 Megohms.
LASERS AND PLASMAS IN PARTICLE ACCELERATION

JL Bobin
Université Pierre et Marie Curie, Paris, France.

Abstract

Longitudinal electron waves in plasmas are considered for charged particle acceleration. Such waves can be driven to very high amplitudes either by resonant beating of two lasers or in the wake of a relativistic charged bunch. Acceleration dynamics are presented. The growth and saturation of the plasma wave are investigated when two lasers are made to beat or a single laser is beating with a wiggler. The role of the relativistic detuning, its possible compensations, the influence of the Raman cascade, are successively reviewed. Other problems deal with bunching, beam loading, focusing. A comparison is made among state-of-the-art lasers to check their suitability to this new application.

1. Introduction

The challenge accelerator builders are facing can be stated as follows:

accelerate along straight lines
- electrons
- up to energies over 1 TeV
- in a machine the size of which compares with that of present day devices
- with a luminosity $10^{34} \text{cm}^{-2} \text{s}^{-1}$.

To reach that goal, new concepts were devised in the past few years, some of which make use of plasmas and laser plasma interaction.

In plasmas, matter is already ionized, then the breakdown and surface heating limitation associated with acceleration in vacuo disappear. Furthermore plasmas are able to propagate large amplitude longitudinal electron waves (Langmuir waves), in which charged elementary particles can be accelerated and focused. Two methods were proposed to drive such waves: i) resonant beating between 2 electromagnetic (laser) waves [1]; ii) wakes [2]. Theoretical, numerical and experimental investigations are being done on both processes. This paper is aimed at presenting significant results and at discussing a few relevant problems. It is organized as follows: the first part, Sections 2 to 7, is a review of the fundamentals: concepts and results which are nowadays well established. The second part is devoted to problems which have been investigated in the past few years: Sections 8 to 10 deal with plasma physics, Sections 11 and 12 with beam bunching and focusing and Section 13 with lasers.
2. Electron acceleration in a longitudinal plasma wave

Assume a longitudinal electron wave propagates with a well defined amplitude and phase through a cold plasma in the z direction. Denoting by \( E_\omega \) the field amplitude, by \( \omega_p \) the frequency, by \( k_0 \) the wavenumber and by \( \phi_0 \) an initial phase, the relativistic equation of motion for an electron is

\[
\frac{dv}{dt} = -\left(\frac{e}{m_0}\right)(1-v^2/c^2)^{3/2}E_\omega \sin(k_0z-\omega_p t + \phi_0),
\]  

(2-1)

where \( m_0 \) is the rest mass. The equation is better rewritten in terms of the Lorentz factor

\[
\gamma = 1/(1-v^2/c^2)^{1/2}
\]

(2-2)

and with the similarity variable

\[
\xi = k_0 z - \omega_p t
\]

(2-3)

One then gets the differential system

\[
\frac{d\gamma}{dt} = -\left(\frac{eE_\omega}{m_0c}\right)(1-1/\gamma^2)^{1/2}\sin(\xi + \phi_0)
\]

\[
\frac{d\xi}{dt} = c\gamma(1-1/\gamma^2)^{1/2} - \omega_p
\]

(2-4)

from which is derived the \((E,\gamma)^*\) phase space representation displayed in Fig. 1.

![Fig. 1 \(\gamma,\xi\) phase plots. a) acceleration of trapped electrons, b) acceleration of passing electrons.](image)

The figure shows that the following can be accelerated to high energies: i) electrons with trapped trajectories and initial low energy, ii) electrons with sharply defined initial phase on passing trajectories associated with velocities greater than the phase velocity of the wave

\[
u_p = \omega_p/k_0.
\]

(2-5)
3. Acceleration energy and length

The first-order ordinary differential equation in \( \frac{dy}{d\xi} \) resulting from (2-1) is readily integrated to give

\[
ck_0 y - \omega_p (y^2 - 1)^{1/2} - ck_0 y_0 \cdot \omega_p (y_0^2 - 1)^{1/2} = (eE_0/m_0c)(\cos \xi - \cos \theta_0).
\]

(3-1)

The maximum value of the second factor in the right hand side is 2. It corresponds to the largest \( \Delta \gamma \) along a passing trajectory which assuming that both \( y_0 \) and \( \gamma \) are much greater than 1, is

\[
\Delta \gamma = \gamma - y_0 = (2eE_0/m_0c\omega_p)\sqrt{1-\beta_0^2} = (1-1/\gamma^2)^{1/2} = \omega_p/c \theta_0.
\]

(3-2)

The maximum energy that an electron may acquire in the process is then

\[
W_A = m_0c^2 \Delta \gamma \approx (4eE_0/m_0c\omega_p)m_0c^2\gamma_R^2 = 4eE_0\gamma_R c/\omega_p.
\]

(3-3)

Now, there exists an absolute maximum for the plasma wave amplitude: density perturbation equal to the background density, the so called wavebreaking condition. An equivalent statement is: all electrons in the plasma are trapped in the wave. In a reference frame moving with the phase velocity (henceforth called * moving frame *), most of the plasma electrons are traveling with a velocity \( -\omega_p/c \theta_0 \). They will be trapped provided the potential energy in the wave is at least equal to their energy \( \gamma_R m_0c^2 \). Integrating the Poisson equation over half a wavelength and noting that the particle number in a wavelength is a relativistic invariant as well as the longitudinal field, one finds the condition:

\[
2eE_0\gamma_R/k_0 = m_0\gamma_R c^2 \quad \text{i.e.} \quad E_0 = m_0c\omega_p/e.
\]

(3-4)

Substituting in (3-3), the upper limit for the electron energy turns out to be:

\[
W_{A\text{max}} = 2m_0c^2 \gamma_R c^2.
\]

(3-5)

In the moving frame, electrons are accelerated over at most half a wavelength. Since there is no phase locking, electrons in the wave are to be decelerated whenever they propagate beyond that distance. The corresponding acceleration length \( l_A \) in the laboratory frame is given by

\[
W_A = eE_0 l_A \quad \text{hence} \quad l_A = 2\gamma_R c/\omega_p.
\]

(3-6)

The length of the accelerating plasma column should not exceed \( l_A \) and the extension of the bunches along the z axis has to be less than a small fraction (e.g. \( 1/10^6 \)) of the wavelength \( 2\pi/k_0 \). After (3-3) and (3-6) the accelerating gradient is in general

\[
W_A/\gamma_A = 2eE_0 = cm_0\omega_p(n/n_0)
\]

(3-7)
where \( n \) is the amplitude of the density perturbation. The upper limit is

\[
(W_A/k)^{\text{max}} = m_0 c w_p
\]

(3-8)

In all cases, \((W_A/k)\) is proportional to the square root of the background plasma density.

The main limitation in the process comes from the acceleration length which results from wave particle dephasing. For given plasma and laser conditions, it puts an upper boundary on the energy a particle may acquire in a single pass. Such an effect can be overcome by superimposing on the plasma wave a uniform magnetic field whose direction is perpendicular to the wave-vector. Thus the particle velocity has a transverse component (Fig. 2). This slightly reduces the longitudinal component which can be kept equal to the phase velocity \( u_R \). An obvious analogy with surfing, inspired the word "surfatron" coined for this situation [3]. Let \( x \) be the coordinate parallel to the transverse component of the velocity. When phase locking occurs, the accelerated particle velocity tends to

\[
v_x = (c^2 - u_R^2)^{1/2}, \quad v_z = u_R,
\]

(3-9)

while its energy increases indefinitely according to

\[
d\gamma/dz \sim (e\phi/m_e c) x_R
\]

(3-10)

where \( B \) is the applied magnetic field. The particle travels at an angle \( \theta \) with respect to the wave vector.

Fig. 2 Particle and wave propagation in the surfatron
4. The resonant beat wave

When two electromagnetic waves act on an electron, the \( \mathbf{v} \times \mathbf{B} \) force has longitudinal components with the frequency \( \omega_1 - \omega_2 \). When this difference is equal to the plasma frequency \( \omega_p \), an electron plasma wave is resonantly driven. It is then shown [4] that the longitudinal electric field obeys the forced oscillator equation

\[
\frac{d^2 E}{d\xi^2} + \omega^2 E = -2(e/m_e)A_1 A_2 \cos \xi \tag{4-1}
\]

where \( A_1 \) and \( A_2 \) are the vector potentials of the laser waves. The solution of this equation has an amplitude unphysically growing to infinity, with a phase locking at \( \pi/2 \). The actual amplitude is expected to saturate, thanks to various possible processes: pump depletion, wave-breaking, relativistic oscillatory motion of the electrons in the wave, cascading towards lower frequencies by Raman scattering, collisional or Landau damping... Let \( \Gamma \) be some phenomenological damping coefficient. Accounting for relativistic electron oscillations results in a negative nonlinear cubic term added to the left hand side of (4-1) with a phenomenological coefficient \( \alpha \). Finally one gets a Duffing's equation

\[
\frac{d^2 E}{d\xi^2} + \Gamma \frac{dE}{d\xi} + (1-\alpha E^2)E = -2(e/m_e)A_1 A_2 \cos \xi \tag{4-2}
\]

whose solutions are investigated analytically or numerically [5]. An example is given in Fig. 6: it shows, in the absence of damping, that the amplitude varies periodically on a slow time scale: nonlinear period. There is no phase locking and numerical simulations have evidenced some turbulence creeping in after the first maximum [6]. This leads to the use of short laser pulses whose duration does not exceed the nonlinear period.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig3.png}
\caption{Longitudinal plasma wave amplitude: growth and saturation by relativistic detuning (cubic term in (4-2)).}
\end{figure}
5. Accelerator prospects

The accelerating gradient i.e. the relativistically invariant longitudinal electric field in the wave is simply related to the relative electron density perturbation \( n/n \)

\[
E = c(m_e n_e/e_p)^{1/2} (n/n)
\]  

(5-1)

where \( n_e \) is the unperturbed plasma density. Introducing the interaction parameter

\[
\lambda = (e/m_c c)^2 (E_1/\omega_1)(E_2/\omega_2)
\]  

(5-2)

and the Lorentz factor \( \gamma_R \) associated with \( u_R \), one gets for the energy in the laboratory frame that an electron may acquire

\[
W_A = 2m_e c^2 \gamma_R^2 (16 \lambda/3)^{1/3}.
\]  

(5-3)

Note that the phase velocity \( u_R \) is equal to the group velocity of the laser waves with mean frequency \( \omega_g = (\omega_1 + \omega_2)/2 \), and

\[
\gamma_R = \omega_g/\omega_p.
\]  

(5-4)

From (5-3) and (3-6) an effective accelerating gradient is derived

\[
W_A/\gamma_A = m_e c u_p (16 \lambda/3)^{1/3}.
\]  

(5-6)

The above results are valid provided one has

\[
(16 \lambda/3)^{1/3} \leq 1
\]  

(5-7)

the equality sign corresponding to wavebreaking. A quantitative summary is presented in Table 1: the data, laser intensities, acceleration energies and lengths refer to wave-breaking conditions. They represent absolute maxima.

High laser frequencies associated with low-density plasmas yield data of interest to high-energy physicists. However, maintaining the required beam intensity over long distances might seem unrealistic, even in the case of self focusing.

On the other hand, low frequency lasers irradiating high density plasmas provide comparatively modest accelerations but over very short lengths. Such conditions correspond to actual experiments on laser plasma interaction being done in many laboratories. Since all numbers shown in Table 1 obey scaling laws, this means that results relevant to particle acceleration can be easily obtained in present day experiments. Foreseeable accelerators are likely to be made of a number of stages built according to the intermediate part of Table 1.
Table 1

<table>
<thead>
<tr>
<th>Laser wavelength (μm)</th>
<th>10</th>
<th>1</th>
<th>0.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity (Wcm⁻²)</td>
<td>1.3x10¹⁵</td>
<td>1.3x10¹⁷</td>
<td>2x10¹⁸</td>
</tr>
<tr>
<td>Electron density (cm⁻³)</td>
<td>10¹⁵</td>
<td>10 GeV</td>
<td>1 TeV</td>
</tr>
<tr>
<td></td>
<td>10¹⁶</td>
<td>1 GeV</td>
<td>100 GeV</td>
</tr>
<tr>
<td></td>
<td>10¹⁷</td>
<td>100 MeV</td>
<td>10 GeV</td>
</tr>
<tr>
<td></td>
<td>10¹⁸</td>
<td>10 MeV</td>
<td>1 GeV</td>
</tr>
<tr>
<td></td>
<td>10¹⁹</td>
<td>100 MeV</td>
<td>1.6 GeV</td>
</tr>
</tbody>
</table>

Now, the main limitation in the electron energy comes from the existence of an acceleration length due to phase slippage. The "Surfatron" may be thought about as a way to increase the acceleration length. Since the interaction parameter need not be as high, another advantage of the surfatron is the reduction of the required laser intensity.

6. Laser wiggler beat wave and the I.F.E.L.

This last point deals with another severe limitation of the ordinary beat-wave i.e. the necessity of tremendously high laser intensities over large distances. An alternative scheme was proposed to set up beat waves with a moderate laser intensity [7]. As it is well known in the free electron laser, beating can be obtained between an electromagnetic wave (ω₁, k₁) and a spatially alternating magnetic field ("wiggler" with maximum field B₂, frequency ω₂=0 and wave-number k₂). In the presence of a relativistic electron beam (driving beam), doing so inside a plasma may induce the growth of a longitudinal wave with frequency ω₁ and phase velocity

\[ \nu_k = \omega_1/(k_1 + k_2). \]  \hspace{1cm} (6-1)

There exists a divergence for χ₀ at the cutoff
\[
\omega_p^2 = 2c\omega_1 k_1 - c^2 k_2^2. \tag{6-2}
\]

The problem of the saturation of the longitudinal wave is the same as before and is dealt with by the same methods. It turns out that when \(\omega_1\) is much greater than the cutoff value, the acceleration length is a fraction of the wiggler wavelength. Matching the acceleration length to the wiggler size requires conditions close to cutoff which will be holding in the following. Taking into account the relativistic correction, yields an energy and an acceleration length:

\[
W_A = 2m_0 c^2 ((\omega_p^2 / \omega_1^2)) \gamma R^2 \gamma^R (16 \Lambda/3)^{1/3}, \quad \Lambda_A = 2\gamma R^2 c / \omega_1. \tag{6-3}
\]

The interaction parameter is

\[
\Lambda = (e/m_0 c^2)(E_1/\omega_1)(B_2/k_2) \tag{6-4}
\]

where \(B_2/k_2\) can easily be made a large number. As it is clear from the data presented in Table 2 moderate laser intensities are indeed sufficient if one wants to build up a proof-of-principle experiment using state-of-the-art wigglers.

### Table 2

**ACCELERATION BY LASER-WIGGLER BEAT WAVE IN A PLASMA**

(Wiggler: \(\lambda_2 = 10\) cm, \(l_A = 1\) m, \(B_2 = .6\) T)

<table>
<thead>
<tr>
<th>LASER TYPE</th>
<th>CO₂</th>
<th>Nd</th>
<th>KrF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (\mu)m</td>
<td>10</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>Intensity (\text{Wcm}^{-2})</td>
<td>(5 \times 10^{10})</td>
<td>(5 \times 10^{12})</td>
<td>(8 \times 10^{13})</td>
</tr>
<tr>
<td>Plasma density (\text{cm}^{-3})</td>
<td>(2 \times 10^{15})</td>
<td>(2 \times 10^{16})</td>
<td>(8 \times 10^{16})</td>
</tr>
<tr>
<td>(\gamma R)</td>
<td>(5.40)</td>
<td>(1.7 \times 10^{3})</td>
<td>(3.4 \times 10^{3})</td>
</tr>
<tr>
<td>(W_A) (\text{GeV})</td>
<td>0.6</td>
<td>2.3</td>
<td>7</td>
</tr>
</tbody>
</table>

The laser wiggler beat wave in presence of an electron beam is also able to accelerate charged particles directly thanks to the ponderomotive potential (Inverse Free Electron Laser as proposed by C. Pellegrini [8]). Indeed, in the right hand side of the equation of motion,

\[
d\gamma / dt = (e/m_0 c^2) c (1-1/\gamma^2)^{1/2} \partial \Phi / \partial z + (e^2 / 2m_0 c^2 \gamma) \partial \mathbf{A}^2 / \partial t \tag{6-5}
\]

the forcing term can also be considered as an equivalent longitudinal electric field whose amplitude is

\[
E_{eq} = 2(e/m_0 c)(\omega_1/c) \Lambda_A A_2 = 2(\omega_1 m_0 c/e \gamma) \Lambda \tag{6-6}
\]
and whose periodicity is the same as that of the driven plasma wave if any. The field \( E_q \) is proportionnal to \( \Lambda \) whereas, \( E_0 \) goes as \( \Lambda^{1/3} \). (6-5) reduces to

\[
\frac{dy}{dt} = \left( \omega_p / \omega_0 \right) \Lambda \sin \xi_v
\]

\[
\frac{d\xi}{dt} = c(k_x + k_y)(1 - \gamma_x^2)^{1/2} - \omega_1
\]

(6-7)

which is readily integrated to give the maximum increase in \( \gamma \)

\[
\Delta \gamma = \left( 4\Lambda \omega_1 / c k_z \gamma_0 \right)^{2/3} - \gamma_0.
\]

(6-8)

This is to be compared with the similar expression obtained with the longitudinal \( E \) field in presence of a plasma

\[
\Delta \gamma = 4\left( \omega_p \gamma_0 \right)^{2/3} \omega_1 \gamma_R \sqrt{16 \Lambda / 3}.
\]

(6-9)

It turns out that the \( \Delta \gamma \) are equal for a critical value \( \Lambda_c \) which is exceedingly large. For \( \Lambda < \Lambda_c \), \( E_0 \) is larger than \( E_q \). As shown by the two examples of figure 7, the presence of a plasma greatly enhances the accelerating power of the I.F.E.L. Since the \( \Lambda^{1/3} \) dependance results from the same saturation mechanism via relativistic detuning, the 2 laser beat wave scheme also rates better than the inverse free electron laser for electron acceleration, at least with the available and predictable laser intensities.

![Diagram](image)

Fig. 4. Energy gain, of an electron in the I.F.E.L. (lower curves) and by laser wiggler beating in a plasma (upper curves). a) CO\(_2\) laser, b) Nd laser.
7. Wakefields

An electric charge travelling with a relativistic velocity through a plasma induces a wake of electrostatic oscillations. Consider first the case of a point charge \( q \) with velocity \( u_0 \) close to \( c \). The corresponding charge density reads in cylindrical coordinates around the direction of \( u_0 \):

\[
\rho_q = q\left( \frac{6r}{2\pi} \right) \delta(z-u_0t).
\]  
(7-1)

The equation for electron density oscillations is then

\[
\frac{\partial^2 n}{\partial t^2} + \omega_p^2 n = \left( e\mu_0/m \right) \delta_q = \left( q\omega_p^2/eu_0 \right) \left( \frac{6r}{2\pi} \right) \delta(z-u_0t)
\]  
(7-2)

whose solution is a Green's function

\[
n = \left( \frac{q\omega_p}{eu_0} \right) \sin\omega_p(t-z/u_0)Y(t-z/u_0) = n_0 \sin\omega_p(t-z/u_0)Y(t-z/u_0)
\]  
(7-3)

where \( Y(t-t') \) is Heaviside's step function. Using Poisson's equation, the corresponding electric field is found. Its longitudinal component is \( (\omega_0 \sim c) \)[9]

\[
E_z(r,z) = -\frac{qk^2}{2\pi e_0} K_0(kr)Y(t-z/c)\cos\omega_p(t-z/c) - E_{\omega z} Y(t-z/c)\cos\omega_p(t-z/c)
\]  
(7-4)

where \( k = \omega_p/c \) and \( K_0(kr) \) is a modified Bessel function.

In the case of an extended driving bunch, \( q(r,z) \), an integration of \( E_z \) has to be performed over the spatial domain occupied by the charges. Let for instance \( \lambda(\xi) \) be a linear density along \( Oz \) \((\xi=z-ct)\). Then

\[
\int_{-\infty}^{\xi} \lambda(\xi') \cos(k\xi')d\xi'
\]  
(7-5)

Taking e.g. \( \lambda(\xi) \) as a half period of \( \sin(k\eta) \), a resonant term is found in the integral which tends to \(-\langle \pi/2k \rangle \sin(k\xi) \) as \( k \to k \). The electric field amplitude is strongly dependent upon the shape of the driving bunch. In [10] an optimum "doorstep" bunch is found with the peak density at the trailing edge. In [9] a numerical investigation was made of the bunch shape influence on the electric field showing a maximum whenever the length of the bunch is an integer multiple of the wavelength \( 2\pi c/\omega_p \). Now, the driving bunch with length 1 and maximum particle density \( n_{\text{max}} \) undergoes a retarding electric field whose mean value \( \langle E_{\text{rel}} \rangle \) is approximated by some coefficient \( \mu \) times the maximum \( E_{\text{rel}} \). An Important parameter is the transformer ratio \( R \). In a one dimensional situation there is no on axis divergence of \( E_{\omega z} \) and

\[
R = E_{\omega z}/E_{\text{rel}} = \mu k (n_{\text{max}}/n_p).
\]  
(7-6)

The value of \( R \) is a measure of the efficiency of the wakefield as an accelerator. It is worthwhile to
note that wakefield effects were observed long ago when passing molecular ions through thin metal foils [11].

Part II: Problems

8. Growth and saturation of the plasma wave: compensation of the relativistic detuning

It was shown in [12] that a properly chosen initial detuning towards higher frequencies can compensate the progressive detuning towards lower frequencies induced by the negative cubic term in the Duffing equation (4-2). Cancellation occurs when the field amplitude is to pass through its first maximum which is then enhanced by a factor up to \(1.6\). Now, in experiments [13], the electron density increases with time: a linear approximation was used to account for this effect. Subsequently, a moderate increment was found to provide further enhancement of the longitudinal field amplitude. Since the beat wave growth is a convective process, such a model might also apply to spatially inhomogeneous plasmas.

Replace, in the Duffing's equation, the constant eigenfrequency squared, by a function of the similarity coordinate \(\xi\):

\[
d^2E/d\xi^2 + \Gamma dE/d\xi + [f(\xi) - \alpha E^2]E = - F \cos \xi.
\]  
(8-1)

\(f(\xi)\) is chosen in order to mimic the spatial or temporal variations of the electron density, and \(F\) is the amplitude of the external force. Setting

\[Y = dE/d\xi,\]
(8-2)

the modified Duffing's equation is rewritten

\[
dY/d\xi = - \Gamma Y - [f(\xi) - \alpha E^2]E - F \cos \xi.
\]  
(8-3)

(8-2) and (8-3) form a non autonomous differential system of the first order to be solved computationally by means of a centered finite difference scheme [14]. In all runs, \(F=1\) and \(\alpha=.001\). As in [13], assume there is no damping and choose a linear \(f(\xi)\):

\[f(\xi) = 1 + K \xi \quad \text{(i.e. electron density increasing linearly with time).}\]
(8-4)

The results are shown on figure 5. When \(K\) is varied, a sharp transition is observed for a critical value \(K_c\) slightly above \(0.0077\), better seen on the graph of figure 6a: first maximum of the E field
amplitude versus K. Other plots on figure 6 correspond to increasing damping coefficients. The transition is very steep at low damping, much smoother when the damping is comparatively high. This is typical of a fold catastrophe of the kind exhibited by the ordinary Duffing's equation [15].

The influence of the damping was investigated in longer runs. The chosen value for $K$, i.e. .001, corresponds to a small enhancement of the first maximum. Without damping, the average value of the amplitude is then steadily increasing, whereas a strong damping is found to smooth out the oscillations of the amplitude. When $f(\xi)$ is different from linear (e.g. a parabolic variation), the outcome is quite similar.

Detuning due to the non-linearities can be compensated in a different way. Indeed one can act on the driving frequency [16]. Since short laser pulses are needed, one or both of the beating wave might be produced after some compression technique thus exhibiting a time varying frequency: chirped pulse. The dynamics of the electric field are now described by another modification of the Duffing's equation viz.

$$\frac{d^2E}{dt^2} + \Gamma \frac{dE}{dt} + (1 - \alpha \xi^2)E = - \frac{F \cos[g(\xi)]}{E}$$

(8-5)

where $g(\xi)$ is a function chosen to model the time dependence of the driving frequency. A solution with a linear $g$ is displayed on figure 7. Again, a catastrophic transition is observed.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Evolution of the plasma wave amplitude for a linearly increasing density without damping. Curve labelled R is the reference: neither damping nor relativistic detuning. In curves labelled 0 to 8, $K$ increases from .0070 to .0078.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.png}
\caption{a) $\Gamma = .001$: first maximum of the amplitude vs $K$; b) $\Gamma = .01$: 1st, 2nd and 3rd maxima; c) $\Gamma = .025$: 1st and last maxima; d) $\Gamma = .05$: maximum vs $K$.}
\end{figure}
9. Growth and saturation of the plasma wave: the Raman cascade

A single laser wave is able to undergo forward Raman scattering whenever its intensity is greater than a threshold which depends upon damping mechanisms. The effect goes both ways: either a photon gives rise to a plasmon and a photon with a lower frequency (scattering on the Stokes side) or the photon recombines with a plasmon to produce a photon with a higher frequency (scattering on the antistokes side). Each of the two laser waves participating in the beat wave may be scattered either side. This cascade can be described by a system of coupled first order differential equations dealing with the complex amplitudes of the modes involved.

The relevant equations were set up by Karttunen and Salomaa [17]. Here the similarity variable $\xi$ is of a temporal nature and the equations read for each E.M. mode labelled $j$:

$$\frac{dA_j}{d\xi} = (\omega_j/\omega_0)(-A_{j-1}A_p + A_{j+1}A_p^*) \quad (9-1)$$

where $\omega_j$ correspond to the impinging laser wave with the higher frequency and $A_p$ is the amplitude of the plasma mode which in turn satisfies the equation

$$\frac{dA_p}{d\xi} + [(f(\xi) - 1 + \alpha |A_p|^2)A_p = \sum_j A_j A_{j-1}^*]. \quad (9-2)$$

In the left hand side of (9-2) are added terms dealing with the relativistic detuning and its compensation by a time varying density. A single term only is present in the right hand side of the
equations dealing with the modes at both ends of the cascade. These equations are solved numerically for a finite number of modes, usually 30.

Significant results are shown on figure 8. Energy cascading towards the lower frequencies improves the quantum efficiency of the beat wave. However, the phase shifts by $\pi$ every time one of the E.M. waves goes to zero. The conservation of coherence is then questionable. Introducing the relativistic detuning with a large coefficient changes drastically the dynamics. A nonlinear period shows up, the detuning dominates the process. A linear compensation enhances the saturation level of the generated longitudinal plasma wave whilst the electromagnetic spectrum spreads over all allowed modes. This is accompanied by a locking of the relative phase between the two pump waves and the plasma wave. In case of an overcompensation, the relative phase increases indefinitely, the spreading of the spectrum is limited and the plasma wave saturates at a lower level: a kind of steady state takes place.

Fig. 8. The Raman cascade. a) without relativistic detuning nor compensation; b) with relativistic detuning, no compensation; c) relativistic detuning, linear compensation; d) overcompensation of the relativistic detuning.
10. Plasma creation

In the past few years, preliminary experiments have been set up in order to study the plasma wave resulting from the resonant beating of two lasers and the subsequent electron acceleration. The plasma has to be fairly uniform, reasonably long and easily usable as a target for focused laser beams. The experiments so far were successful, evidencing plasma waves with longitudinal electric fields in the range $0.3\text{ to } 2\text{ GeV/m}$ [18], and injected electrons being accelerated from $0.64\text{ MeV}$ to about $2\text{ MeV}$, however with a large energy spread [19].

The workhorse is the molecular CO$_2$ laser; many lasing transitions are allowed. It is possible to easily select two of them in such a way that the frequency difference matches given plasma densities in the range $10^{15}$-10$^{17}$ cm$^{-3}$. Plasma creation in such a range can be obtained either through the use of laser (gas breakdown, irradiation of solid surfaces), or in electrical discharges. Table 3 states the advantages and drawbacks of various methods which were proposed to create plasma suited to electron acceleration.

### Table 3
METHODS FOR GENERATING PLASMAS

<table>
<thead>
<tr>
<th>Density (ecm$^{-3}$)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>By Lasers</strong></td>
<td></td>
</tr>
<tr>
<td>Gas breakdown</td>
<td></td>
</tr>
<tr>
<td>In quiet gas</td>
<td>$10^{15}$-$10^{17}$</td>
</tr>
<tr>
<td>In gas jets</td>
<td>$10^{16}$-$10^{17}$</td>
</tr>
<tr>
<td>Interaction with solid surfaces</td>
<td>$10^{16}$-$10^{20}$</td>
</tr>
<tr>
<td>Interaction with thin foils</td>
<td>$10^{16}$-$10^{20}$</td>
</tr>
<tr>
<td><strong>By Electrical Means</strong></td>
<td></td>
</tr>
<tr>
<td>B-pinches</td>
<td>$10^{15}$-$10^{17}$</td>
</tr>
<tr>
<td>High pressure arcs</td>
<td>$10^{16}$-$10^{17}$</td>
</tr>
<tr>
<td>Low pressure discharges</td>
<td>$10^{13}$-$10^{14}$</td>
</tr>
</tbody>
</table>
11. Bunching, beam loading

A specific feature of the longitudinal electron plasma wave as an accelerating structure, is the small wavelength, typically 100 μm. As in ordinary cavities, particles to be accelerated have to be gathered into bunches the length of which should be much smaller than the wavelength.

Then one can imagine an accelerating device with several stages. In the first one, an electron beam with a uniform longitudinal density and velocity \( u_x \) is bunched within a quarter period and half wavelength of the plasma wave (\( \gamma, \xi \) space representation on figure 9, a and b). After energy filtering, high energy bunches are injected with proper phasing into successive stages (figure 9c). An initially spatially uniform monoenergetic electron beam with an energy well above trapping is slightly bunched with a global energy loss: this is the regime which prevails in free electron lasers (figure 9d).

![Graphs](image)

**Fig. 9** Electron behaviour in \( \gamma, \xi \) phase space. a) initial state of a completely trapped electron beam; b) bunching of the trapped electrons of fig. a; c) acceleration of a bunch of passing electrons; d) behaviour of a high energy electron beam: slight bunching and global energy loss, free electron laser regime.
Now, a particle or a bunch accelerated in a longitudinal plasma wave induces a wakefield which can be calculated as in section 7. For an infinitely thin charge in a one dimensional situation

$$E_z = \frac{a}{\epsilon_0} \psi(t-z/c) \cos \omega_p (t-z/c) \quad (11-1)$$

which to be compared to the field in the wave $E_\nu$, it turns out that the two are equal when the number of elementary charges (e.g. electrons) per unit surface to be accelerated is [24]

$$N_{\text{max}} = \frac{c (\epsilon_0 \psi_0 / \nu_0)^{1/2}}{r_0}$$

where $r_0$ is the background density in the plasma and $r_\nu$ is the amplitude of the density oscillation (both per unit area). When these charges are properly phased with respect to the plasma wave there is no more oscillation behind them. (11-2) indicates the maximum permitted beam loading in plasma wave acceleration. The energy transfer from the wave to the bunch is then 100% efficient. However there is a 100% energy spreading inside the bunch. To cope with this drawback, arrangements of smaller bunches were investigated [24]. It was also found [25] that bunch shaping might improve the energy transfer.

12. Beam focusing

When a relativistic point charge propagates through a plasma, the electric field in the wake has a transverse component which is readily calculated after (7-4), using the Panofsky-Wenzel theorem [26]. Electric field lines form a 2 dimensional pattern which is schematically shown on figure 10.

Fig. 10 Electric field lines in the 2-dimensional wake of a point charge
The transverse component of the electric field is thus able to alternately focus and defocus a bunch of particles to be accelerated. Regions in the wake extending over a quarter wavelength are both accelerating and focusing. This is a very attractive property.

Focusing is also encountered in the resonant beat wave whenever the laser beams have a suited transverse structure: ideally a cylindrical symmetry with an intensity decreasing monotonically from the axis. Assuming a parabolic transverse profile for the longitudinal electric field amplitude

\[ E_z = E_{20} (1-r^2/r_0^2), \]  

and since the electric field is irrotational, it has a transverse component whose amplitude is

\[ |E_r| = \lambda r |E_{20}|/\pi r_0^2 \]  

where \( \lambda \) is the wavelength of the plasma wave. \( E_r \) and \( E_z \) are in quadrature so that the plasma wave is both accelerating and focusing over a spatial quarter period only just as in wakefields.

Preliminary evaluations of the above focusing properties are very promising. TeV electrons could be focused 4 meters after passing through plasmas 25cm long, a considerable improvement with respect to conventional magnet techniques.

Another focusing process uses the azimuthal magnetic field produced by a strong cylindrical current with uniform density. Metal " lenses " of this type are well known [27]. Strong focusing needs currents which would blow off the metallic conductor. A self pinched plasma can be maintained during a sufficient time with a fairly uniform current density [28] and prove effective as a focusing " lens ".

13. Requirements for lasers

Besides the energy, particle accelerators should provide a sufficient number of expected events thanks to a high luminosity. This parameter proportional to the repetition rate a convenient value of which is 1 kHz, a requirement the laser should mandatorily match.

A high energy particle accelerator is obviously expensive. Routine operation is also costly. It is important that the machine be as efficient as possible. To this end, the overall laser efficiency has to be over 10%.
The beat wave mechanisms outlined in Sect. 4 leads to further requirements on wavelength, power, and pulse duration. Equations (3-7) and (5-4) show: 1) that the electric field $E_0$ in the plasma wave which determines the acceleration gradient increases as the square root of the plasma density; 2) that the Lorentz factor $\gamma_R$ associated with the phase velocity is proportional to $\omega_e/\omega_p$. One wants high values for both $E_0$ and $\gamma_R$ which imply a dense plasma and consequently a small laser wavelength.

High laser powers are also needed. First, in beat wave generation the saturation amplitude, and hence the acceleration energy $W_A$, turns out to scale as $(\xi \lambda)^{3/2}$. This constraint is somewhat relaxed in the "surfatron" and laser wiggler beat wave schemes. However, considering the values in Tables 1 and 2, it appears difficult to match the focal volume of an optical system to the acceleration length. Now, light self-focusing was evidenced in numerical simulations [29]. The mechanism which comes from either ponderomotive or relativistic effects, provides a high intensity over long distances. In both cases the laser power (not the intensity) has to exceed a wavelength dependent threshold.

Finally, it was shown in Sect. 8 that the pulse duration should not be larger than a few nonlinear periods. In practice, this condition leads to 1-50 ns pulses.

The above requirements: high repetition rates over long periods of time (days or months), 10% efficiency, short wavelength, high power and picosecond pulses, look rather contradictory. No existing laser meets all of them, as can be seen in Table 4.

**Table 4**  
STATE-OF-THE-ART LASERS AND ACCELERATOR REQUIREMENTS

<table>
<thead>
<tr>
<th>LASER</th>
<th>$\lambda$ (µm)</th>
<th>SMALL $\lambda$</th>
<th>PICOSECOND PULSES</th>
<th>ENERGY</th>
<th>REP. RATE</th>
<th>EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{CO}_2$</td>
<td>10</td>
<td>No</td>
<td>Possible</td>
<td>Proven</td>
<td>Possible</td>
<td>Proven</td>
</tr>
<tr>
<td>HF</td>
<td>2</td>
<td>No</td>
<td>No</td>
<td>Possible</td>
<td>Possible</td>
<td>Proven</td>
</tr>
<tr>
<td>Nd</td>
<td>1</td>
<td>Yes</td>
<td>Proven</td>
<td>Proven</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>KrF</td>
<td>0.25</td>
<td>Yes</td>
<td>Questionable</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
</tr>
</tbody>
</table>

The KrF laser exhibits some appealing features. The main issue is how to efficiently extract the pump energy with picosecond pulses, a so far unsolved problem. Angle multiplexing as used in
Inertial Fusion is conceivable. But, in recombining the beams, one should be very careful about coherence which is essential in driving the plasma wave. Table 5 gives after J.J. Ewing [30], the main properties of both a KrF and a CO\(_2\) laser designed for a 10 TeV electron accelerator. The latter is well suited for proof-of-principle demonstrations as shown by preliminary experiments in the U.S. (U.C.L.A.) and Canada (I.N.R.S.).

<table>
<thead>
<tr>
<th></th>
<th>CO(_2)</th>
<th>KrF</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_2-\lambda_1)</td>
<td>1(\mu)m</td>
<td>37(\AA)*</td>
</tr>
<tr>
<td>Plasma electron density</td>
<td>(10^{17})cm(^{-3})</td>
<td>(4 \times 10^{18})cm(^{-3})</td>
</tr>
<tr>
<td>(N_R)</td>
<td>10</td>
<td>68</td>
</tr>
<tr>
<td>(l_A)</td>
<td>0.6 cm</td>
<td>3.8 cm</td>
</tr>
<tr>
<td>Power for self-focusing</td>
<td>0.47 TW</td>
<td>21 TW</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>3 ps</td>
<td>3 ps **</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>1.4 J.</td>
<td>63 J.</td>
</tr>
<tr>
<td>Total length</td>
<td>660 m</td>
<td>104 m</td>
</tr>
</tbody>
</table>

* feasible by Raman shift in H\(_2\)     ** DREAM!

14. Conclusion

Acceleration of elementary particles in laser plasma interaction has been demonstrated on a very small scale: 1 GeV/m over 1mm only. It is considered seriously by high energy physicists as a very promising way to reach energies beyond a few TeV. However the subject is still in its infancy. The accelerators of the next generation will be designed and built by extrapolating known and reliable techniques. This leaves about 20 years from now: 1) to investigate all the physics relevant to laser-driven acceleration of particles in plasmas; 2) to design laser sources suited to the job. If one looks back at the progress in the physics and the technology of high-power lasers designed for Inertial Fusion, one sees an increase in power by 6 orders of magnitude over the past 20 years. This is indeed a remarkable achievement. There is no doubt that, provided the demand and the motivation exist, a similar evolution will occur: by A.D. 2007, laser properties could be close enough to the requirements of accelerator physics, in time for a future generation of machines.
References

22. F. Amirafroff, E. Fabre, C. Labaune these proceedings.
27. F. Mills, private communication.
Discussion

C.J. McKinstrie, LANL

The formula for the nonlinear frequency shift of a large-amplitude Langmuir wave depends on relativistic nonlinearities inherent in the nonrelativistic fluid equations. The magnitude and sign of this frequency shift has been the subject of some controversy in the literature. This controversy has been resolved by W.B. Mori (Workshop on Interaction and Transport in Laser Plasmas CECAM, Orsay, p. 123 (1985)) and so Langmuir-wave saturation is now well understood.

Reply

I agree.

B. Zotter, CERN

Is there the same energy limitation for a plasma IFEL due to synchrotron radiation as in the normal IFEL?

Reply

No, because the gradients are orders of magnitude higher in a plasma IFEL. The electron wavelength can be made shorter than a wiggler wavelength. No study of the limitation was done so far.

P. Chen, SLAC

Are there also Raman cascading processes in your laser-wiggler beat-wave idea?

Reply

No, because the plasma wave frequency is essentially equal to the laser frequency. Only harmonic operation is possible in this anti-Stokes side with a very low efficiency.
THE INTERDEPENDENCE OF PARAMETERS FOR TEV LINEAR COLLIDERS

R. B. Palmer
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and Brookhaven National Laboratory, Upton, New York 11973

ABSTRACT

Burt Richter, at SLAC, has called for a design of a 0.5 + 0.5 TeV $e^+e^-$ collider with a luminosity of at least $10^{33}$ cm$^{-2}$ sec$^{-1}$. In order to find whether such a machine is possible, I have collected here approximate formulae for many of the relations governing the design of a linear collider. It must be emphasized that these are often only approximate relations whose accuracy is not expected to be better than about 10%, and in some cases may be worse. Units throughout will be meter-kilogram-second (mks) unless otherwise stated. Given these relations, their interdependence is studied and parameter choices made. A self-consistent solution is found that meets Richter's specification and does not involve any exotic technologies.

1. DAMPING RING

1.1 Emittance

It is assumed that electrons and positrons are obtained from damping rings, and that these are of the continuous wiggler type [1,2]. It is assumed that the phase advances per cell are sufficiently small and that straight sections are sufficiently short so that a smooth approximation ($\beta$ constant) can be used. All bending magnets in the ring consist of at least one inward bend and one outward, so that the average bending field ($B_d$) is less than the local fields $B_d$ in the magnets. I define

$$\langle B_d \rangle = \alpha_1 B_d$$

$$F_m = \text{fraction of ring filled by dipoles}$$

$$\zeta = \text{vertical/horizontal emittance due to mixing.}$$

The emittances both vertical and horizontal are damped by the emission of synchrotron radiation with a time constant [3]:

$$r_{x,y} \approx \frac{8.3}{J_{x,y} \frac{1}{B_d^2 \gamma F_m}} \quad \text{(mks)} \quad (1)$$

where $J_x, J_y$ are the partition functions [3], usually $J_x \approx J_y \approx 1$.

The horizontal ($x$) emittance does not reduce to zero, however, but to an equilibrium value. At high energies this value is set by the effect of quantum fluctuations:

$$\zeta \varepsilon_{xn} \approx 2.2 \times 10^{-10} \frac{1}{J_x + \zeta J_y} \beta_x B_d \frac{\gamma^2}{Q_x^2}$$

$$\zeta \varepsilon_{yn} = \zeta \varepsilon_{xn}$$

(2)

where $\zeta$ is a mixing parameter, $\beta_x$ is the average function ($\beta_x = R/Q_x$), and $Q_x$ is the tune of the ring.

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At lower energies intrabeam scattering sets an equilibrium emittance \([4]\):

\[
\epsilon \approx \frac{1.2 \times 10^{-10}}{B_d} \left[ \frac{N}{\epsilon n \gamma F_m Q \zeta (J_x + \zeta J_y)} \left( \frac{\beta_z}{\beta_y} \right)^{1/2} \right]^{1/2} ,
\]

\[
\epsilon_n = \zeta \epsilon, \\
\epsilon_n = \epsilon \frac{dp}{p} \sigma_z .
\]

(3)

We note from the different \(\gamma\) dependencies that there must be an optimum \(\gamma_0\) for which \(\epsilon = \epsilon_n\) (see Fig. 1).

![Normalized emittance vs energy](image)

**Fig. 1.** The normalized emittance of a sample ring, as a function of operating electron energy. As \(E\) is varied the ring is varied to keep the bending field \(B_d\), the focussing field \(B_q\) and the tune \(Q\) fixed. At low energies the emittance is dominated by intrabeam scattering, at high energies by quantum fluctuations.

\[
\gamma_0 \approx 2.1 \times 10^{-7} \left[ \frac{N (B_q/B_d)^{1/2}}{\epsilon n B_d^{1/2} \zeta (J_x + \zeta J_y)^{1/2} F_m k_1^{1/2}} \right]^{4/9} \left( \frac{1}{\epsilon n} \right)^{2/3} ,
\]

(4)

where

\[
\beta_z = k_1 \gamma^{1/2} \approx k \left( \frac{a \gamma}{B_q F_q} \right)^{1/2}
\]

\(a = \) quadrupole aperture \\
\(B_q = \) quadrupole pole tip field (\(\approx 1.5\) Tesla) \\
\(F_q = \) fraction of ring full of quads (\(\approx .2\)) \\
\(k_1 = .14\), for a lattice scaled from the SLAC damping ring.

When contributions from both quantum fluctuations and intrabeam scattering are comparable, then the equilibrium emittance is given [4] by
\[ \varepsilon_{en}(\text{equil}) = \frac{1}{2} \left[ \varepsilon_{en} + \left( \frac{1}{2} \varepsilon_{en}^2 + 4 \varepsilon_{en}^2 \right)^{1/2} \right], \] (6)

thus for \( \varepsilon_{en} = e \varepsilon_{zn} \)

\[ \varepsilon_{zn}(\text{equil}) \approx 1.6 \varepsilon_{zn} . \] (7)

Actually a minimum equilibrium is obtained at a \( \gamma \) somewhat below that given by Eq. (4) and it is a reasonable approximation to use

\[ \varepsilon_{zn} \approx 1.4 \varepsilon_{zn} . \] (8)

The wiggle is assumed to consist of a sufficient number of inward and outward bends, so that the contribution to the emittance from the rate of change of dispersion is negligible. This condition requires the maximum wiggler pole length \( \ell_w \) to satisfy

\[ \ell_w \ll \ell_w^{\text{max}} = \sqrt{\frac{8}{F_m}} \frac{\beta_z \rho}{R} , \] (9)

where \( \rho \) is the bending radius in a wiggler and \( R \) is the average machine radius. In these examples I assume \( \ell_w = 1/3(\ell_w^{\text{max}}) \) and the contribution to the equilibrium emittance is then less than 1/9.

1.2 Other Requirements

The impedance requirement for stability is taken to be:

\[ \frac{Z}{n} \leq \frac{(2\pi)^{3/2}}{\sqrt{\alpha \sigma_p^2}} \frac{\sigma_z}{\varepsilon e N} , \] (10)

where

\[ n = \frac{R}{\sigma_z} , \] (11)

\[ \alpha \approx \left( \frac{\beta_z}{R} \right)^2 = \frac{1}{Q^2} . \] (12)

Note that the approximation for the momentum compaction \( \alpha \) also requires condition [Eq. (9)].

Other relations are:

\[ \sigma_p = \frac{\Delta p}{p} \approx \frac{2}{J_z} 1.1 \times 10^{-5} (\gamma B)^{1/2} , \] (13)

Dispersion \( \eta \approx \frac{\beta_z^2}{R} , \) (14)

Sextupole length \( F_s \approx \frac{F_s}{4\eta} , \) (15)

acceptance \( \varepsilon_{zn} \approx 6 \times 10^{-4} \gamma R \frac{Q_y}{Q_z^2} , \) (16)

\[ \text{RF Volts/turn} \ U \approx 3.2 \times 10^6 \gamma \left( \frac{R \sigma_p}{\sigma_z} \right)^2 , \] (17)

where \( h \) is the harmonic number of the RF,

\[ \text{energy loss/turn} \ V = 5.78 \times 10^{-9} \frac{\gamma^4}{\alpha^2 R F_m} . \] (18)
2. ACCELERATION

2.1 Acceleration Cavity

I assume that acceleration takes place in a $2\pi/3$ disk-loaded-structure as used in the SLAC linac, but following Z. D. Farkas [5], I allow the group velocity to depart from that of the SLAC structure. Since the group velocity is a function of the iris aperture divided by the wavelength, we can choose these parameters separately and use an approximate fit to Farkas' calculation using the program TWAP [5] (see Fig. 2a):

$$\beta_g = \frac{v_g}{c} \approx \exp \left\{ 3.1 - 2.4 \left( \frac{\lambda}{a} \right)^{1/2} - 0.9 \left( \frac{a}{\lambda} \right) \right\}.$$  \hspace{1cm} (19)

The normalized corrected elastance is given approximately by (see Fig. 2b),

$$s_{at} \approx 5.7 \times 10^{10} \beta_g^4 \text{ (VmC}^{-1}) \hspace{1cm} (20)$$

This normalized and corrected elastance is related to the unnormalized elastance by

$$s_{at} = s_t a^2,$$  \hspace{1cm} (21)

where $s_t$ is defined by

$$s_t = \frac{\mathcal{E}_a^2}{w_f},$$ \hspace{1cm} (22)

$\mathcal{E}_a$ is the average accelerating field in a section and $w_f$ is the energy, assuming no losses, needed to generate that acceleration. This energy is not the same as that required ($w$) to fully fill the section because since the particle and fields are moving down the section at finite velocity, the length of the required field pulse is less than that of the section. Thus

$$w_f = \frac{w}{(1 - \beta_g)},$$ \hspace{1cm} (23)

and

$$s_t = \frac{s}{(1 - \beta_g)}.$$ \hspace{1cm} (24)

where the uncorrected elastance, as defined by D. Farkas is

$$s = \frac{\mathcal{E}_a^2}{w}.$$ \hspace{1cm} (25)

Note also that $s$ is related to the loss parameter defined by P. Wilson: [6]

$$k_0 = \frac{s}{4}.$$ \hspace{1cm} (26)
Fig. 2. Parameters of a SLAC-like accelerating cavity as a function of the group velocity \( v_g/c = \beta_g \). (a) the iris radius \( a \) divided by wavelength \( \lambda \); (b) the normalized corrected elastance \( S_{st} \); (c) the attenuation time constant \( T_0 \) in \( \mu \text{sec} \), for \( \lambda = 10.5 \text{ cm} \); (d) the peak RF field in the cavity \( \ell_{pk} \) divided by the average accelerating field \( \ell_a \); (e) the outer cavity radius \( b \) divided by the iris radius \( a \); (f) the relative peak rf power. In each case the line is obtained from I. D. Farkas [5] and the dots are for the approximation used here.

When losses are included, the energy needed is increased. If the attenuation time of the RF pulse, passing down the section, is defined as \( T_0 \), then for a section of length \( L \) the energy required for the same average acceleration will be:

\[
\omega_{RF} = \frac{\omega_f}{\eta_p} = \omega_f \frac{T^2}{(1 - e^{-\tau})^2},
\]

where \( \eta_p \) is the section efficiency, and

\[
\tau = \frac{L}{T_0 v_g} = \frac{T}{T_0}.
\]

This is for a uniform structure (i.e., \( \ell_a \) falling off along its length). Note that as \( \tau \to 0 \), \( \omega_{RF} \to \omega_f \) but the peak power per unit length goes to \( \infty \).
The attenuation time $T_0$ is given approximately by (see Fig. 2c):

$$T_0 \approx 42 \times 10^{-6} \left( 1 + 1.29 \beta_y^{1.5} \right) \lambda^{1.5}, \quad (28)$$

also (see Figs. 2d and e):

$$\frac{\xi_{pk}}{\xi_a} \approx 2 + 6.0 \beta_y, \quad (29)$$

$$\frac{b}{a} \approx 1.04 + 0.29 \ln \left( \frac{1}{\beta_y} \right) + 0.068 \left[ \ln \left( \frac{1}{\beta_y} \right) \right]^2, \quad (30)$$

where $\xi_{pk}$ is the maximum field within the structure and $b$ is the inside radius of the cavity. In all cases the length of a cell is assumed to be $\lambda/3$.

All of the above approximate relations were obtained by fitting curves shown in Farkas and Wilson’s paper [5].

2.2 Focussing in the Linac

Assuming a symmetric FODO structure, the average strength of the focussing is given by

$$\langle \beta_z \rangle = \left( \frac{\sin \mu \frac{E}{\mu} \frac{2a_q}{B_q F_q}}{c} \right)^{1/2}, \quad (31)$$

where $\mu$ is the phase advance per half cell (taken as $45^\circ$), $B_q$ is the pole tip field (taken as 1.5 Tesla), $F_q$ is the fraction of linear length devoted to quadrupoles, and $a_q$, the aperture of the quad, is taken to be $1.2 \times a_{av}$. Normally, $a_{av}$ is the iris radius, but if the iris is elliptical with radii $a$ and $b$:

$$a_{av} = \frac{1}{\left( \frac{2}{a^2} + \frac{2}{b^2} \right)^{1/2}}, \quad (32)$$

which is the radial distance at $45^\circ$.

3. EMITTANCE PRESERVATION

3.1 Transverse Wake Fields

The transverse wake field $W_t$ depends on the geometry of the cavities. As a function of the length $z$ along the bunch, the wakefield is observed [6] to have an initial linear rise:

$$\text{for } z \ll a: \quad W_t(z) \approx 6.64 \times 10^{10} \frac{z}{a^{2.5} \lambda^{5}}, \quad (33)$$

and a maximum of

$$\text{at } z \approx a: \quad W_t(z) \approx 3.28 \times 10^{10} \frac{1}{a^{2.2} \lambda^{8}}. \quad (34)$$
Fig. 3. The scale invariant transverse wakefield \((a^3 W_t)\) as a function of the distance \(z\) divided by the iris radius \(a\) for (a) \(a/\lambda = .105\) (as for SLAC), and (b) \(a/\lambda = .2\)

For values of \(W_t\) at \(z/a < 1\), a reasonable fit to the form of \(W\) [at least for the SLAC geometry (see Fig. 3)] is obtained if we take:

\[
W_t = \frac{1}{\left(\frac{1}{4 W_t^2} + \frac{1}{2 W_t}\right)^{1/2}}.
\]

(35)

The approximation is seen to be reasonable in the region \(z < a\).

In the case of an elliptical iris with dimensions \(a\) and \(b\), I assume the same form as given above with the substitution of \(a\) or \(b\) according to whether we are calculating \(W_t\) in the \(x\) or \(y\) directions.

3.2 Landau Damping

I assume that transverse wake effects are effectively controlled by Landau damping [7], providing an energy spread \(\Delta E\) is maintained between the front and back of the bunch where, in the two bunch approximation:

\[
2 E recognised approx \approx \Delta E \approx \frac{e}{4} N W_t (2 \sigma_x) \beta^2, \tag{36}
\]

where \(N\) is the number of particles per bunch, \(\beta\) the focusing strength in the linac and \(W_t(z)\) is the wake field potential. Both \(W_t\) and \(\beta\) are allowed to be different in the vertical and horizontal directions, but chosen so as to give the same required \(\Delta E\). For tolerance reasons that will appear below, I assume

\[
\beta_{x,y} \propto \ell^{1/3}, \tag{37}
\]

thus

\[
\sigma_p \propto \ell^{-1/3}, \tag{38}
\]

where \(\ell\) is the length along the linac. If not specified, \(\beta\) and \(\Delta E\) are given for the end of the linac — i.e., at full energy.
I will assume that the momentum spread $dp/p = \sigma_p$ required for Landau damping is maintained until the end of all acceleration, but then removed prior to the final focus by an acceleration section of length $\ell_v$ operating at a phase advance of 90°. The length required is

$$\ell_v = \frac{\sigma_p p \lambda}{2 \pi \xi_s \sigma_z}$$  \hspace{1cm} (39)$$

where $p$ is the final momentum, $\lambda$ the wavelength, $\xi_s$ the accelerating gradient and $\sigma_z$ the rms bunch length.

3.3 Tolerance Problems

A severe tolerance problem comes from the effects of the finite momentum spread and strong focussing needed to Landau damp the transverse wake field effects. From R. Ruth I take the required rms alignment for phase advance per cell $\psi$, to be [8]:

$$\langle dy \rangle = \sigma_y \sqrt{\frac{2}{N_q}},$$  \hspace{1cm} (40)$$

where

$$\sigma_y = \sqrt{\frac{\beta(\ell) \xi_y}{\gamma(\ell)}}$$  \hspace{1cm} (41)$$

and $N_q$, the number of quadrupoles, is

$$N_q = \int_0^L \frac{2d\ell}{\beta(\ell)\psi},$$  \hspace{1cm} (42)$$

and from Eq. (36) we have

$$\sigma_p \propto \frac{\beta(\ell)^2}{\gamma},$$  \hspace{1cm} (43a)$$

so

$$\langle dy \rangle \propto \frac{\gamma^{1/2}}{\beta(\ell)^{3/2}}.$$  \hspace{1cm} (43b)$$

We see that unless the $\beta$ is reduced at lower $\gamma$, the tolerances get tighter at lower $\gamma$. However, the quadrupole tip fields needed to obtain a given $\beta$ also fall with $\gamma$ [from Eq. (31)].

$$\beta(\ell) \propto \left(\frac{\gamma a}{B_q}\right)^{1/2},$$  \hspace{1cm} (44a)$$

so it is not difficult to assume, for instance:

$$\beta(\ell) \propto \gamma^{1/3} \propto \ell^{1/3},$$  \hspace{1cm} (44b)$$

which gives

Tolerances: \hspace{1cm} $\langle dy \rangle = \text{constant}$.
Landau: \( \sigma_p \propto \gamma^{-1/3} \),
Focus B: \( B_q \propto \gamma^{1/3} \).

Then from Eq. (42),
\[
N_q = 1.5 \left[ \frac{2L}{\beta_{\text{max}} \psi} \right] ,
\]
\[
\langle dy \rangle \approx 1.63 \frac{\beta_{\text{max}}}{\sigma_p_{\text{max}}} \left( \frac{\epsilon_n}{\gamma L \psi} \right)^{1/2}.
\]

This tolerance concerns the alignment and steering precision within the linac. If all components were truly aligned to this accuracy, it would meet the requirement, but it can also be met by an appropriate combination of alignment and corrective steering that is somewhat less severe.

Another interesting quantity is the change in phase advance \( \Delta \phi \) over the momentum spread integrated along the full accelerator. If this quantity is small compared to 1, then the dispersive errors due to misalignment appear at the end as a single lateral dispersion that could in principle be measured and corrected.
\[
\Delta \phi = \int_0^L \frac{\sigma_p(\ell)}{\beta(\ell)} \, d\ell ,
\]
\[
= \frac{1.5}{\beta(\text{max} E)} L \frac{\sigma_p(\text{max} E)}{\beta(\text{max} E)} .
\]

A tolerance of a different kind concerns the allowable random movement of components from pulse to pulse. Fixed misalignments can often be corrected, but random movements cannot. The most severe restriction is on random motion of the linac focusing quadrupoles. For 90° phase advance per cell:
\[
\langle dx \rangle, \langle dy \rangle, \approx \frac{2}{5} \frac{\sigma_{x,y}}{\sqrt{N_q}} ,
\]
where \( N_q \) is the number of quadrupoles from Eq. (42) or (45).

3.4 **Longitudinal Wakes**

The *Longitudinal wake* for very short bunches tends towards a constant that is dependent only [9] on the iris aperture ‘\( a \)’:
\[
z \ll a : \quad W = 1.78 \times 10^{10} \frac{1}{a^2} .
\]

For the elliptical case, I assume
\[
z \ll a : \quad W = 1.78 \times 10^{10} \left( \frac{0.5}{a_x^2} + \frac{0.5}{a_y^2} \right) .
\]

For bunches of length of the order of ‘\( a \)’ one finds [9]:
\[ z \approx a : \ 2W = 1.25 \times 10^{10} \left( \frac{1}{z} \right)^{1/2} \frac{1}{a} \left( \frac{1}{\lambda} \right)^{1/2}. \]  

(50)

And for the elliptical case I assume

\[ z \approx a : \ 2W = 1.25 \times 10^{10} \left( \frac{1}{z} \right)^{1/2} \left( \frac{5}{a_x} + \frac{5}{a_y} \right) \left( \frac{1}{\lambda} \right)^{1/2}. \]  

(51)

For intermediate values of \( z \), a reasonable fit to the SLAC case is obtained (see Fig. 4):

\[
W_2(z) = \left( \frac{1}{\frac{1}{1W^3} + \frac{1}{2W^3}} \right)^{1/3}.
\]  

(52)

Fig. 4. The scale invariant longitudinal wakefield \( a^2 W_2 \) as a function of the length \( z \) divided by the iris radius \( a \) for (a) \( a/\lambda = .105 \) (as for SLAC), and (b) \( a/\lambda = .2 \)

To properly obtain the momentum spread produced in a bunch by the longitudinal wake, one should perform integrations of the wake potentials over the charge distribution of the bunch [6]. The effects are relatively complex:

1) There is an average energy loss of the bunch (zeroth order).

2) There is a greater loss to the back of the bunch compared with the front (first order).

3) If the bunch is long there is a significant second order term with the rate of change of momentum falling at the back.

4) There is a significant third order term that arises if the bunch is Gaussian rather than uniform in current density.

Since all these are significant, the minimum number of sub-bunches that we can use to approximate the whole is four. I use four equal bunches: two at \( \pm 1.4\sigma_z \) and two at \( \pm 2\sigma_z \). (These give correct \( \sigma_z \) and \( \langle |z| \rangle \).) The energy losses of the four bunches are then:
\[ V_1 = \frac{Ne}{4\xi_a} \{W(0)\} , \]
\[ V_2 = \frac{Ne}{4\xi_a} \{W(0) + W(1.2\sigma_z)\} , \]
\[ V_3 = \frac{Ne}{4\xi_a} \{W(0) + W(4\sigma_z) + W(1.6\sigma_z)\} , \]
\[ V_4 = \frac{Ne}{4\xi_a} \{W(0) + W(1.2\sigma_z) + W(1.6\sigma_z) + W(2.8\sigma_z)\} . \]

These values are compared with a full integration in Fig. 5.

Fig. 5. The longitudinal wakefield generated momentum spread generated in a Gaussian bunch passing through a SLAC-like structure. The smooth line is a calculation by P. Wilson [6]. The dots represent the results of the four-bunch approximation used here. These points have been normalized to the P. Wilson calculation.

The average slope gives a \( \Delta p \) at 1\( \sigma \) of
\[ 1\sigma_p = 0.2(V_3 - V_2) + 1.4(V_4 - V_1) . \]  (54)

The half spread due to the second order effect is:
\[ 2\sigma_p = \frac{(V_2 + V_3) - (V_4 + V_1)}{4} , \]  (55)

and the half spread from third order:
\[ 3\sigma_p = \frac{0.87(V_2 - V_3) + 0.13(V_4 - V_1)}{4} . \]  (56)

The first and second of these effects can in principle be cancelled by the RF. The first order effect
being cancelled by a phase shift in the RF given by

\[
\tan \phi_{\text{cor}} = \frac{1}{2\pi} \frac{1}{\sigma_p} \frac{\lambda}{\sigma_z} .
\] (57)

However, some momentum spread is required for Landau damping so that the phase required at the end is, instead, given by

\[
\tan \phi_{\text{cor}} = \frac{1}{2\pi} \left(1 \frac{1}{\sigma_p} - \frac{\sigma_p}{\sigma_z} \text{Landau} \right) \frac{\lambda}{\sigma_z} .
\] (58)

The net second order momentum spread, including the RF is

\[
2\sigma_p (\text{total}) = 2\sigma_p - \frac{1}{2} \left(\frac{2\pi \sigma_z}{\lambda} \right)^2 .
\] (59)

For the purposes of designing the final focus system, I assume that the first order term is fully cancelled by the RF and use:

\[
\sigma_p (\text{focus}) = \left\{ 2\sigma_p (\text{total})^2 + 3\sigma_p^2 + \epsilon \sigma_p^2 \right\} ,
\] (60a)

where

\[
\epsilon \sigma_p = \frac{\epsilon_m}{\gamma \sigma_z} ,
\] (60b)

which is the contribution to the momentum spread from the finite longitudinal emittance in the damping ring.

4. FINAL FOCUS

The parameters for the final focus are obtained by scaling one of two designs provided by K. Brown [10]. In both cases the minimum \( \beta^* \) is calculated for a given momentum spread assuming no chromatic correction. The value of \( \beta^* \) that can be obtained with chromatic correction is less than \( \beta^*_0 \) by a factor \( S \)

\[
\beta^* \geq \frac{\beta^*_0}{S} .
\] (61a)

\( S \), in a design similar to that in the SLC is expected [10] to scale:

\[
S = \frac{S_0}{\sigma_p} \approx \frac{0.04}{\sigma_p} .
\] (61b)

This relation gives a factor of eight for \( \sigma_p = \pm 0.5\% \) as is obtained for the SLC.
Fig. 6. Final focus lens designs used (a) for solutions requiring a round focal spot and (b) for solutions requiring a flat beam.

The two designs used are shown in Fig. 6. The triplet is used for the symmetric case and the doublet for all asymmetric cases. The scaling involves the modification of all length dimensions by one factor and all transverse dimensions by another. We define scale factors \( f^* \) and \( a^* \). \( a^* \) is the aperture in the first quadrupole, and the 'ideal' focal length is \( f^* \):

\[
f^* = \left( \frac{a^*}{B^*} (B\rho) \right)^{1/2},
\]

\[
(B\rho) = \frac{E/e}{c}.
\]

\( B^* \) is the pole tip field in the first quad, \( E/e \) is the beam energy in electron Volts, and \( c \) is the velocity of light.

For any magnet system we can now express the performance in terms of these scaling parameters, \( a^* \) and \( f^* \), and of invariant constants \( (T_z, T_y, A_x, A_y \text{ and } L) \). The constants depend on the details of the magnet system considered.

Given \( f^* \) and \( a^* \) for any magnet system scaled from the original design (all longitudinal distances scaled with \( f^* \), all transverse distances scaled with \( a^* \), all pole tip fields the same) then we can write

\[
\beta_{0x,y}^* = T_{x,y} \cdot 2\sigma_p \cdot f^*,
\]

\[
\hat{\theta}_{z,y} = \frac{a^*}{A_{x,y} f^*},
\]

\[
\ell_1 = L f^*.
\]

where \( \ell_1 \) is the free space before the first quad, \( \hat{\theta} \) is the maximum angular acceptance, \( \sigma_p \) is the rms \( dp/p \) momentum spread. The definitions are such that for an 'ideal' focusing system that can focus in both directions (such as a lithium or plasma lens) \( T \approx A \approx L \approx 1 \).
Combining Eq. (63) with Eq. (61), one obtains:

$$\beta_{z,y}^* = \frac{(T_{z,y} A_{z,y})}{S_0} \frac{E/e}{c} \frac{\theta_{z,y}^*}{B^* \sigma_y^2}.$$  \hspace{1cm} (66)

Values for $T_{z,y}$ and $A_{z,y}$ for the two focus designs given are:

<table>
<thead>
<tr>
<th></th>
<th>Triplet</th>
<th>Quadrupole</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_x$</td>
<td>2.96</td>
<td>7.2</td>
</tr>
<tr>
<td>$T_y$</td>
<td>2.96</td>
<td>1.1</td>
</tr>
<tr>
<td>$A_x$</td>
<td>4.3</td>
<td>3.6</td>
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<tr>
<td>$A_y$</td>
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<td>2.0</td>
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<tr>
<td>$L$</td>
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</tr>
<tr>
<td>$T_y A_y$</td>
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<td>2.2</td>
</tr>
<tr>
<td>$S_0$</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

We note that the product $T_y A_y$ which determines the $\beta_y^*$ obtainable is over four times smaller for the quadrupole solution.

The maximum acceptance angle $\hat{\theta}$ is controlled by the disruption angles or beam size depending on whether the crossing is head-on or at a finite angle. In the head-on case the disruption angles are discussed in the next section and we take

$$\hat{\theta}_{x,y} = S_\theta \hat{\theta}_D(x,y),$$  \hspace{1cm} (67)

where $S_\theta$ is a safety factor taken to be three. In the finite angle case

$$\hat{\theta}_{x,y} = S_\theta \sqrt{\frac{\epsilon_n}{\beta^* \gamma}},$$  \hspace{1cm} (68)

where $S_\theta$, the safety factor, is now taken to be six.

5. \textbf{INTERACTION POINT}

5.1 \textbf{Luminosity}

When the two bunches collide, the luminosity obtained is

$$L = \frac{N^2 f H_x H_y}{4\pi \sigma_x \sigma_y \eta_L},$$  \hspace{1cm} (69)

where

$$\sigma_{x,y} = \left(\frac{\epsilon_{x,y} \beta_{x,y}^*}{\gamma}\right)^{1/2},$$  \hspace{1cm} (70)
and \( \eta_c \) is an efficiency factor to allow for effects of both a finite angle of crossing and a \( \beta^* \) not very much larger than the bunch length \( \sigma_z \).

\[
\eta_c = \frac{2}{\sigma_z \sqrt{\pi}} \int_0^\infty \frac{\exp \left\{ -\left( \frac{x}{\sigma_z} \right)^2 \left( 1 + \theta_d \frac{\theta_c}{\theta_d} \frac{1}{1 + (x/\beta_z)^2} \right) \right\}}{1 + (x/\beta_z)^2} \, dx,
\]

(71)

where \( \theta_d = \sigma_z/\sigma_x \) is the diagonal angle, \( \theta_c \) is the crossing angle, and \( \beta_z \) is the \( \beta_z^* \) at the final focus.

\( H_x \) and \( H_y \) in Eq. (69) are enhancement factors due to the pinch effect. I have assumed here that these enhancements can be factorized and that

\[
H_{x,y} = f(D_{x,y})
\]

(72)

where \( D_{x,y} \) are disruption parameters defined by

\[
D_{x,y} = \frac{\sigma_x}{f_{x,y}}
\]

(73)

and \( f_{x,y} \) are the effective focal length of the focusing of one bunch on the other, calculated for the center of Gaussian bunches.

Assuming a beam in which \( \sigma_x \geq \sigma_y \) then [11]

\[
D_y \approx \frac{r_e N \sigma_x}{\gamma \sigma_y^2} \cdot \frac{2}{1 + \frac{\sigma_x}{\sigma_y}}
\]

(74)

For round beams \( D_x = D_y \), but for flat beams with \( \sigma_x \gg \sigma_y \), \( D_x \approx 0 \). In the intermediate region we take [11]

\[
D_x \approx \frac{r_e N \sigma_x}{\gamma \sigma_y^2} \cdot \frac{2}{1 + \frac{\sigma_x}{\sigma_y}}
\]

(75)

The enhancements are given approximately [12] by

\[
H_{x,y} = 1 + 1.37 \left( \frac{1}{1 + D_{x,y}^{-5.5}} \right)^{1/2}
\]

(76)

For round beams the more conventional enhancement factor \( H = H_x H_y = (H_y)^2 \). This, calculated by this approximation, is plotted in Fig. 7 against \( D \) and compared with values given by other simulations [12].

![Fig. 7](image)

The luminosity enhancement \( H_D \) for round beams as a function of the disruption parameter \( D \). The smooth line shows the results of K. Yokoya’s calculation [13]; the crosses are Hollebeck’s; the dots are the approximation used here.
5.2 Disruption Angles

Without pinch, the maximum Disruption angle is given [13] by

\[ \hat{\theta}_{x,y} = \frac{2N\tau_e}{\gamma\sigma_x} \cdot k_{x,y}, \]  

(77)

where for

(a) \( \sigma_x = \sigma_y \quad k \approx 0.45 \)

(b) \( \sigma_x \gg \sigma_y \quad \begin{cases} k_x \approx 0.75 \\ k_y \approx 1.25 \end{cases} \)  

(78)

However, the situation is somewhat different in the three cases. For \( \theta_x \) and \( \theta_y \) in round beams a well-defined maximum angle occurs for particles at a finite impact parameter near \( \sigma \). But for \( \theta_y \) in flat beams the deflecting field rises to a plateau and the maximum angle occurs only for particles in the extreme tail of the distribution. As a result, the mean value is much less in this case.

With pinch, the round case has been studied by Minten and Yokoya [13] and the disruption is enhanced by a factor \( H_\theta \)

\[ H_\theta \approx \frac{1}{\left( \frac{1}{1.2 + 50D^2} + \left(0.06 + \frac{D}{3.38}\right)^{1/2} \right)} . \]  

(79)

Figure 8 shows this function together with Minten and Yokoya's simulation.

![Graph](image)

Fig. 8. The enhancement of disruption angles \( H_\theta \) for round beams. The line is Yokoya's calculation; the crosses are Hollebeek and Minten’s; and the dots the approximation used.

For flat beams the enhancement of maximum deflection in the vertical (y) direction should not occur. This is because the field for a current sheet is not a function of its thickness. However, Yokoya has demonstrated that with a Gaussian bunch, a strong suppression of the average vertical disruption angle takes place for large \( D \) due to the oscillation of a particle in the field instead of a unidirectional deflection. In principle the deflection of the extreme tail of the distribution is still not changed and my program does not include this Yokoya [13] suppression.

In this discussion I have not included quantum fluctuations in the disruption process. There is a finite probability that an electron radiates a hard photon and is then, because it has a low momentum, disrupted by a much larger angle:
\[ \theta_D(\text{quantum}) = \theta_D \left( \frac{E_e}{E_e - E_\gamma} \right) \]  

The factor \( E_e/(E_e - E_\gamma) \) can be large and the resulting disruption world be a serious problem. In round beams there seems little that can be done about it and larger quads and the resulting weaker focus would have to be employed. But with finite crossing angles one can employ a bending magnet to sweep the low energy disrupted electrons away from the quadrupole (Fig. 9).

![](image)

**Fig. 9.** The use of a sweeping magnet to return disrupted particles to the axis. Such correction will work independent of the beamstrahlung energy loss and resulting enhancement of the disruption angle.

The field length required to return electrons that had the maximum disruption angle \( \theta_D \) is:

\[ l_{\text{sweep}} = 2 \frac{\theta_D (E/e)}{Bc} \]  

where \( E/e \) is the beam energy in electron volts, \( B \) is the correction field and \( c \) the velocity of light.

### 5.3 Beamstrahlung

The beamstrahlung calculations are taken from the work of R. Noble [14]. The fractional loss of energy of one bunch passing through the other is given by

\[ \delta = \frac{F_1 r_e^2 N^2 \gamma}{\sigma_z (\sigma_y')^2} \left[ \frac{4}{\left(1 + \frac{\sigma_z'}{\sigma_y'}\right)^2} \right] H_T \]  

where \( F_1 \approx .22, r_e \approx 2.82 \times 10^{-15} \text{ m} \). In this form I have replaced the enhancement factor \( H_D \) that could account for the pinch effect by replacing the unpinched spot sizes (\( \sigma_z \) and \( \sigma_y \)) by effective ‘pinched’ values (\( \sigma_z' \) and \( \sigma_y' \))

\[ \sigma_z' = \frac{\sigma_z}{H_z} \]  

\[ \sigma_y' = \frac{\sigma_y}{H_y} \]
In the symmetric case $H_x H_y = H_D$. For a flat beam, $\sigma_z \gg \sigma_y$:

$$\delta \approx \frac{F_1 r_e^2 N^2 \gamma}{\sigma_z} \frac{4}{(\sigma_y^2)^2} H_T ,$$  \hspace{1cm} (84)

and is not a function of $\sigma_y$. Note also that in this flat beam case $H_x$ is usually near to unity (there is little disruption in the wide direction), and thus there is no pinch enhancement of the beamstrahlung.

The parameter $H_T$ is a correction for quantum effects [14]:

$$H_T \approx \left( \frac{1}{1 + 1.33 \Upsilon^{2/3}} \right)^2 ,$$ \hspace{1cm} (85)

where

$$\Upsilon = \frac{F_2 r_e \chi e \gamma N}{\sigma_x \sigma_y} \left[ \frac{2}{1 + \frac{\sigma_e^2}{\sigma_y^2}} \right] ,$$ \hspace{1cm} (86a)

where

$$F_2 \approx .43 , \quad r_e \approx 2.82 \times 10^{-15} , \quad \chi e \approx 3.86 \times 10^{-13} \text{ m} .$$ \hspace{1cm} (86b)

Note again that I have expressed $\Upsilon$ as a function of the effective spot dimensions $\sigma_x^2$ and $\sigma_y^2$. And we also note again that for $\sigma_x^2 \gg \sigma_y^2$, $\Upsilon$ is a function only of $\sigma_x^2$ and that this is not significantly enhanced by pinch. This is again a reflection of the fact that the fields in a flat beam are a function of the width of that beam, but not of its vertical thickness.

The approximation used in Eq. (85) is compared with Noble's plot in Fig. 10.

![Fig. 10. The beamstrahlung factor $H_T$ as a function of $\Upsilon$ as shown by R. Noble (line) and the function used here (dots).](image)

6. **ROUND VERSUS FLAT BEAMS**

A general choice concerns whether we allow the beams to be asymmetrical, i.e., flat. Initially it appears more natural to have round beams, and if we calculate the luminosity for given power in the two cases, we appear to see an advantage.
For round beams ($R = 1$) and fixed beamstrahlung $\delta$, using Eqs. (69), (70), (82), (83):

\[
\frac{L}{\rho} \approx \frac{f(\delta, \gamma, \sigma_y)}{(\varepsilon \beta^*)^{1/2}} H_x H_y ,
\]

which for a reasonable disruption parameter $D \approx 10$ gives

\[
\frac{L}{\rho} \approx 6.0 \frac{f(\delta, \gamma, \sigma_y)}{(\varepsilon \beta^*)^{1/2}} .
\]

For flat beams, $R \gg 1$, we find:

\[
\frac{L}{\rho} \approx 1.22 \frac{f(\delta, \gamma, \sigma_y)}{(\varepsilon \beta^*)^{1/2}} H_y .
\]

The factor of $1/2$ comes from the term $2/[1 + (\sigma_z^2/\sigma_y^2)]$ in Eq. (82). This term goes to one for round beams but two for flat beams. The absence of $H_x$ reflects that for a flat beam negligible disruption can be obtained in the horizontal direction. For $D_y \approx 10$, then $H_y \approx 6.0$ and

\[
\frac{L}{\rho} \approx 1.22 \frac{f(\delta, \gamma, \sigma_y)}{(\varepsilon \beta^*)^{1/2}} ,
\]

and we see that for the same emittance and final $\beta^*$ we have lost a factor of five in luminosity for given power.

However, it turns out that there are a number of rather strong advantages in the asymmetric case that can overcome this initial disadvantage.

1) Damping rings are naturally asymmetric. Without mixing the vertical emittance would damp to zero. It is quite reasonable to assume mixing of only about 1%, thus giving a much smaller vertical emittance.

2) In an RF structure the round irises could be replaced by ellipses or slots with greatly reduced transverse wake fields in one direction, thus allowing the transport of an asymmetrical beam without blowing up its small vertical emittance.

3) The chromatic correction section prior to the final focus will involve dipole magnets that will, through synchrotron radiation, blow up the beam emittance. But this blow up will occur in only one direction. A very small vertical emittance need not put additional constraints on the design.

4) The final focus, if it uses conventional quadrupoles is intrinsically asymmetrical. With a quadrupole it is easy to focus in one direction if we do not worry about the other. Much weaker focusing is possible if symmetry is required.

5) At the final intersection point for fixed $\delta$ with round beams we have [from Eq. (87)]

\[
\frac{L}{\rho} \propto \frac{1}{(\varepsilon \beta^*)^{1/2}} .
\]

But we also find, again assuming fixed $\delta$,

\[
N \propto (\varepsilon \beta^*)^{1/2} ,
\]
so high luminosity can only be obtained for small numbers of particles per bunch, which require for reasonable efficiency low accelerating wavelength and serious wake field effects.

With flat beams, Eq. (91) becomes

\[ \frac{L}{P} \propto \frac{1}{(\epsilon_{ny} \beta_y^*)^{1/2}} \]  

(93)

But Eq. (92) is now:

\[ N \propto (\epsilon_{nx} \beta_x^*)^{1/2} \]  

(94)

The two equations are now decoupled and we are free to keep \( N \), and thus the wavelength, up by keeping \( (\epsilon_{nx} \beta_x^*) \gg (\epsilon_{ny} \beta_y^*) \).

6) The final advantage in using a flat beam is that it allows a finite angle crossing at the intersection point. With zero angle crossing the quadrupole apertures have to be made large enough to accept the disrupted particles from the oncoming beam. In practice this angle is far larger than that taken up by the initial beam. With finite angle crossing we arrange that the disrupted beam passes outside the opposite final quadrupole. Thus the quadrupole aperture can be set by the incoming beam size. As a result of the smaller aperture requirement, the field gradient can be larger and the focusing strength greater.

In the following section the choice of parameters for a flat beam case will be discussed in detail. The luminosity obtained is \( 10^{33} \). A similar procedure was followed for a round beam case, but the final luminosity achieved was only of the order of \( 10^{33} \), a full order of magnitude less than for a comparable flat beam example. An approximate breakdown of the contributions to this difference is given below:

<table>
<thead>
<tr>
<th>Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) from ( L/P ) calculation for fixed ( \delta )</td>
</tr>
<tr>
<td>(2) from loss of horizontal enhancement ( H_z )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gains</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) from asymmetric damping ring</td>
</tr>
<tr>
<td>(2) from use of quadrupole focusing</td>
</tr>
<tr>
<td>(3) from finite angle crossing</td>
</tr>
<tr>
<td>(4) from use of larger ( N )</td>
</tr>
<tr>
<td>(5) from use of higher group velocity structure</td>
</tr>
</tbody>
</table>

\[ \text{Net Gain} \approx 12 \]

7. PARAMETER CHOICES

7.1 Introduction

In the above sections we have discussed each of the collider components separately. We have noted, however, that in many cases the requirements of one component conflict with those of another. I will discuss these conflicts one-by-one, although the interwoven nature of the problem generates difficulty in selecting the order. In each case, I will attempt to suggest reasonable choices and thus obtain an example parameter list.

I will leave discussion of the wavelength to the next section. Here I will attempt to make choices that will be reasonably independent of wavelength.
The energy of the collider studied will be

\[ E_{c.o.m} = 0.5 + 0.5 \text{ TeV} \]  

(95a)

7.2 Accelerating Gradient

A high gradient will reduce the overall length of the accelerator and may be expected to reduce a linear component of its cost. However, a higher accelerating gradient will imply a higher stored energy and higher costs associated with the RF power supply. The best gradient to minimize costs will then depend on the relative linear and stored energy related costs. An upper bound will exist on the acceleration gradient set by breakdown, excessive heating or beam deflections due to uncontrolled field emission in the structure.

Figure 11 illustrates a) the estimated limits [15] on accelerating gradient, and b) estimated lines of constant cost for both linear and stored energy costs. In both cases the dependence is shown as a function of the accelerating gradient and wavelength. The assumptions were:

- Linear cost per meter \( C_l \approx 40 \text{ K$}/\text{m} \)
- RF source cost per Joule \( C_j \approx 2.4 \text{ K$}/\text{J} \) (Sec. 8.5)
- group velocity \( \beta_g \approx 0.08 c \) (Sec. 7.3)
- fill time/attenuation time \( \tau \approx 0.25 \)
- average accelerating gradient/max \( \eta_\alpha \approx 0.8 \)

With these assumptions the linear cost

\[ $l \approx 5 \times 10^{10} \frac{\xi_a (\text{MeV/m})}{\xi_a} \]  

(95b)

and the RF energy cost

\[ $\text{RF} = C_j \frac{\xi_a^2}{s_4} \left( \frac{E}{\xi_a} \right) \frac{1}{\eta_\alpha} \]  

(96)

which with the above assumptions gives

\[ $\text{RF} \approx 7.4 \times 10^5 \lambda (\text{cm})^2 \xi_a (\text{MeV/m}) \]  

(97)

The minimum cost will then be for an accelerating gradient

\[ \xi_a (\text{min. cost}) \approx 260 \text{ MeV/m} \lambda (\text{cm}) \]  

(98)

This relation is also illustrated in Fig. 11. At this gradient, the accelerator and power source cost would be:

\[ $l + $\text{RF} \approx 0.38 \lambda (\text{cm}) (\text{B$}) \]  

(99)

The numerical constant in Eqs. (98) and (99) should not be taken too seriously, but are probably accurate enough to indicate that for any reasonable choice of wavelength (i.e., \( \lambda \geq 1 \text{ cm} \)), the optimum accelerating gradient is well below the estimated maximum gradient. Costs will not be lowered by higher acceleration gradients unless one first finds ways to lower the power source costs.

High accelerating gradients can be imperative if there is a limitation in the length at a particular site. At SLAC, for instance, the longest linear collider possible is about 7 km. If a center-of-mass energy
Fig. 11. Lines of constant cost for 1) RF power, and 2) length of accelerator, as a function of accelerating gradient and wavelength. The dotted line indicates accelerating gradients chosen to minimize overall cost. Breakdown and surface melting limits on accelerating gradient are also given.

of 1 TeV is required and allowances are made for phase advance, filling factors, etc., then a reasonable minimum gradient will be

\[
\varepsilon_a = 186 \text{ MeV/m}
\]  

(100)

From Eq. (98) one sees that this choice is at the estimated value for minimum cost if the wavelength were fixed at

\[
\lambda \approx 14 \text{ mm}
\]  

(101)

and we will, in fact, be considering wavelengths of this order of magnitude. Thus, for our examples it will not be unreasonable to use the assumption of Eq. (100).

7.3 RF Structure Group Velocity

In Eq. (99) we see that the stored energy and cost of a collider is related to the wavelength; but a shorter wavelength in general implies a smaller iris hole, and a smaller iris hole will cause larger wakefields that give all kinds of problems. For short bunches these wakefields are dependent primarily on the iris radius ‘a’ and only weakly on the wavelength. We can thus assume that the wakefield problems imply a bound only on ‘a’ and not on ‘\lambda’.

For a given value of ‘a’ the RF energy required per meter is given by Eqs. (21)-(27).

\[
w_{\text{RF}} = \frac{\varepsilon_a^2 a^2}{s_{\text{at}} \eta_p}
\]  

(102)
where the dependence on the group velocity $\beta_g$ is contained in the normalized and corrected elasstance $s_{st}$ which is plotted against the group velocity in Fig. 2b.

The dependence shown is, of course, dependent on the particular choice of accelerating structure considered (in this case a SLAC-like iris loaded cylindrical structure with $2\pi/3$ phase advance per cell).

The elasstance is seen to rise (and thus the required RF energy to fall) monotonically with increasing group velocity. But if a higher group velocity is chosen, the peak electron field within the cavity ($E_{pk}$) rises (see Fig. 2d). (The RF instantaneous power $P_{RF}$ also rises, but not seriously). From Fig. 11 we might conclude that the higher fields in the cavity are not a problem, but some reasonable compromise must still be made. For this example I will select

$$\beta_g = .08$$  \hspace{2cm} (103)

which gives

$$\frac{E_{pk}}{E_s} \approx 2.6$$  \hspace{2cm} (104)

$$s_{st} \approx 21 \times 10^9 \text{ VmC}^{-1}$$  \hspace{2cm} (105)

### 7.4 Fill Time

From Eq. (27) we see that the RF energy required depends on the parameter $\tau$:

$$w_{RF} \propto \frac{1}{\eta_\rho} = \frac{\tau^2}{(1-\exp\{-\tau\})^2},$$  \hspace{2cm} (106)

$$\tau = \frac{T}{T_0},$$

where $T$ is the fill time and $T_0$ the attenuation time. For $\tau \ll 1$ then approximately

$$w_{RF} \propto (1+\tau),$$  \hspace{2cm} (107)

$$P_{RF} \propto \frac{1+\tau}{\tau}.$$  \hspace{2cm} (108)

A compromise must be reached between the stored energy $w_{RF}$ that falls with $\tau$ and the peak power $P_{RF}$ that rises (see Fig. 12). For this example I take

$$\tau = .25$$  \hspace{2cm} (109)

yielding

$$\eta_\rho = .783$$  \hspace{2cm} (110)

### 7.5 Damping Ring Impedance $Z/n$

From Eqs. (2) and (3) we found that the equilibrium emittance of a damping ring will always be lower if $Q$, the tune, can be raised. But from Eqs. (10) and (12) we also found that a high tune implied a small $\alpha$ and correspondingly smaller impedance requirement $Z/n$. 
Fig. 12. Average and peak power requirements as a function of the fill time parameter $\tau$. $\tau = \text{fill time/attenuation time.}$

As a rough constraint on the allowable tune, I assume

$$\frac{\epsilon_x}{\kappa} \geq 0.5 \, \Omega$$

(111)

7.6 Emittance Ratio $\epsilon_x/\epsilon_y$

In the absence of intrabeam scattering, the vertical emittance in a damping ring with no mixing would go to zero. It is clearly desirable to use this simple fact. The limit will be set by how low a mixing can be obtained. For all flat beam cases, I have chosen 1% as a reasonable aim for this mixing, and thus

$$\frac{\epsilon_x}{\epsilon_y} = 100$$

(112)

One should note that we do not gain the full factor of 100. The lower vertical emittance increases the intrabeam scattering and increases the $\epsilon_x$. However, a gain of at least $\sqrt{100}$ is obtainable since if $\epsilon_x$ is increased by this and thus intrabeam scattering will remain the same.

7.7 Final Focus Pole Tip Field

We will see from our examples that the required quadrupole apertures are very small (of the order of .2 mm diameter). Under these circumstances it is not reasonable to use superconducting coils. Pulsed magnets could be built to these dimensions but it would be hard to avoid mechanical motions (the quads need to be steady to a few Å). For these reasons, I am assuming that conventional iron quads are employed and limit the pole tip fields to

$$B = 1.4 \, \text{Tesla}$$

(113)
7.8 Crossing Angle

With finite angle crossing we wish the oncoming disrupted beam to pass well clear of the final quadrupole. If I assume negligible beam at six times the calculated maximum disruption angle, then the full crossing angle $\theta_c$ must be

$$\theta_c \geq 6 \theta_{Dz} + \theta_{Qz} \quad ,$$

(114)

where $\theta_Q$ is the angle subtended by the outside of the final quadrupole. However, a quadrupole can be left open on its sides (see Fig. 13) and thus, providing the vertical disrupted size $\theta_{Dy}$ is small, $\theta_{Qz}$ can be zero. Nevertheless, some allowance for the quadrupole is needed and for these calculations I have assumed

$$\theta_c = 12 \theta_{Dz} \quad .$$

(115)

---

Fig. 13. Cross section at the start of the first final focus quadrupole showing incoming and disrupted beams.

A luminosity loss will occur if this angle is small compared to the angle of the diagonal of the bunch, i.e., we require

$$\theta_c < \theta_{\text{diag}} = \frac{\sigma_x}{\sigma_z} \quad .$$

(116)

7.9 Particles per Bunch $N$

Having fixed the wavelength, iris hole diameter and accelerating gradient we can now choose the number of particles per bunch and thus the loading ($\eta$) of the cavity, defined by

$$\eta = N e s \propto \frac{N}{\lambda^2} \quad ,$$

(117)
where \( s \) is the elastance [see Eq. (25)]. \( \eta \) represents the fraction of energy stored in the cavity that is transferred to the bunch. Common sense would indicate that a higher \( \eta \) will give a higher luminosity, but it is more complicated.

The luminosity [from Eqs. (69) and (70)], for fixed \( \epsilon_x/\epsilon_y \) and \( \beta_x/\beta_y \) is:

\[
\mathcal{L} \propto \frac{N^2}{\epsilon \beta^*} .
\]

But from Eq. (3) the emittance, if limited by intrabeam scattering, is

\[
\epsilon \propto N^{1/2} .
\]

From Eqs. (52) and (55) the uncorrectable momentum spread

\[
\sigma_p \geq 2\sigma_p \propto N .
\]

Using Eq. (66) we have for the final focus

\[
\beta^* \propto \sigma_p^2 \theta_{\text{beam}} \propto \left( \frac{\epsilon}{\beta^*} \right)^{1/2} .
\]

so

\[
\beta^* \propto \sigma_p^{6/3} \epsilon^{1/3} \propto N^{4/3} N^{1/6} \propto N^{3/2} .
\]

Combining Eqs. (118), (119) and (121c):

\[
\mathcal{L} \propto \frac{N^2}{N^{1/2} N^{3/2}} = \text{constant} ,
\]

i.e., when we work it through we find the luminosity is not dependent on \( N \) or \( \eta \)!

The above is only true if the final focus is indeed limited by momentum spread. If the momentum spread is too small, the tolerance requirements will become excessive and the dependence of Eq. (122) will fail. A not unreasonable lower bound on \( \sigma_p(\text{focus}) \) is taken at about one third of the SLC value; i.e., we assume Eq. (121c) valid only if

\[
\sigma_p(\text{focus}) \geq 0.15\% .
\]

This momentum spread can come either from wakefield effects [\( \sigma_p(\text{wake}) \)] or from the intrinsic longitudinal emittance of the beam [\( \sigma_p(\text{emittance}) \)]. If we fix these relative contributions, e.g., if

\[
\frac{\sigma_p(\text{emittance})}{\sigma_p(\text{wake})} = 0.7 ,
\]

then

\[
\sigma_p(\text{wake}) \geq \frac{\sigma_p(\text{focus})}{\sqrt{1 + 0.7^2}} = \frac{0.15\%}{\sqrt{1 + 0.7^2}}
\]

\[
\approx 0.12\% .
\]

Given the other assumptions on iris diameter and bunch length, the above requirement on the longitudinal wake can be interpreted as a bound on the loading parameter \( \eta \)

\[
\eta \geq 1.2\% .
\]
It could be tempting to choose a larger loading if it were not for another constraint. The momentum spread needed for Landau damping is also proportional to \( N \) [from Eqs. (36) and (33)]

\[
\sigma_p(\text{Landau}) \propto N \left( \frac{\sigma_z}{\lambda} \right) \beta_{\text{linac}}^2 ,
\]

and the distance to remove this momentum spread [from Eq. (39)]

\[
\ell_c \propto \frac{\sigma_p}{\sigma_z} .
\]

Thus

\[
\ell_c \propto N \beta_{\text{linac}}^2 \lambda^{-3} .
\]

Now from Eq. (31)

\[
\beta_{\text{linac}}^2 \propto a \propto \lambda ,
\]

so

\[
\sigma_p(\text{Landau}) \propto \frac{N}{\lambda^2} \cdot \frac{\sigma_z}{\lambda} ,
\]

and thus for fixed \( \sigma_z/\lambda \) (see Section 7.10)

\[
\ell_c \propto \frac{N}{\lambda^2} \propto \eta .
\]

So a high value of \( \eta \) implies a long distance needed to fix the Landau damping momentum spread. In our example we find if \( \eta = 1.2\% \), then \( \ell_c \approx 200 \; \text{m} \) which is already rather long. I therefore select,

\[
\boxed{\eta \approx 1.2\%}.
\]

### 7.10 Bunch Length \( \sigma_z \)

The bunch length is a very sensitive parameter and must satisfy many simultaneous conditions. It does not, however, for our energy machine, have much effect on the beamstrahlung.

At low energies, when \( T \ll 1 \) [see Eq. (86)], then the beamstrahlung parameter [Eq. (82)]

\[
\delta \propto \sigma_z^{-1} .
\]

At higher energies when the parameter \( T \gg 1 \), then the beamstrahlung parameter [from (82), (85) and (86)]

\[
\delta \propto \sigma_z^{1/3} .
\]

But in the energy region about \( 0.5 \; \text{TeV} \) we find that for \( \sigma_z \) between 5 \( \mu \) and 100 \( \mu \), the beamstrahlung is rather independent of \( \sigma_z \) (see Fig. 10).

\( \sigma_z \) does, however, effect other things. It should be kept small because

1. Luminosity is lost when \( \sigma_z \approx \beta_{\text{linac}}^* \), or larger.
(2) Luminosity is lost if \( (\sigma_x/\sigma_z) \approx \theta_{\text{crossing}} \), or larger.

(3) Transverse wakes \( \propto \sigma_z \).

(4) The disruption parameter \( D \propto \sigma_z \), and instabilities may occur if the disruption parameter \( D \) is much larger than ten.

However \( \sigma_z \) should be kept large because

(1) For fixed momentum spread a small \( \sigma_z \) implies a small longitudinal emittance \( \varepsilon_z \) which will increase the equilibrium emittance in the damping ring \( \varepsilon_y \) by Eq. (3). It should also not deviate too far from a convention value of the order of .02 m, or else the RF necessary to obtain the needed long bunch length becomes difficult.

(2) If \( \sigma_z \) is too small, the disruption parameter \( D \) could fall below two, and the disruption enhancement would be lost.

(3) If \( \sigma_z \) is large, it is harder to correct the longitudinal momentum spread in the linac.

It is this last constraint that seems to limit how small \( \sigma_z \) can be, so I will discuss it further. The first order momentum spread from the longitudinal wake, for short bunches, is approximately [Eqs. (48), (53), (54) and (117)]

\[
\sigma_p(\text{wake}) \propto \frac{N}{\sigma_z^2} \propto \frac{N}{\lambda^2} \propto \eta .
\]

(133)

The momentum spread required for Landau damping, from Eq. (130b),

\[
\sigma_p(\text{Landau}) \propto \eta \frac{\sigma_x}{\lambda} .
\]

(134)

The phase to maintain the spread required for Landau damping is thus

\[
tan \theta \propto \frac{\lambda}{\sigma_z} [\sigma_p(\text{wake}) - \sigma_p(\text{Landau})]
\]

\[
\propto \frac{\lambda}{\sigma_z} (\eta - \text{constant} \frac{\sigma_x}{\lambda})
\]

\[
\propto \eta \left( \frac{\lambda}{\sigma_z} \right) - \text{constant} .
\]

(135)

If we require that the accelerator length is not increased by more than 10\%, then

\[
\cos \theta \geq .9 ,
\]

(136)

which, with the other assumptions, gives

\[
\frac{\sigma_x}{\lambda} \approx 1.5 \times 10^{-3} .
\]

(137)

7.11 **Linac Focusing**

The transverse wake blow up of transverse emittance can be controlled by the introduction of a
longitudinal momentum spread \( \sigma_p(\text{Landau}) \) where [Eq. (36)]
\[
\sigma_p(\text{Landau}) \propto \frac{\partial W_t}{\partial z} \sigma_z N \beta^2 ,
\]
(138)

where \( \beta \) is the average focus strength in the linac. In order to keep \( \sigma_p \) small, it is desirable to have as small a \( \beta \) as possible. I assume we use quadrupoles with the least possible pole tip radius and place the quads between accelerator sections. I assume
\[
a(\text{quadrupole}) = 1.26 \text{ a (iris)} \quad (\text{as at SLAC})
\]
quadrupole fraction of \( \ell = 5\% \)
quadrupole pole tip field = 1.4 Tesla
phase advance per cell = 90° .

From the above and from Eq. (31)
\[
\beta \propto \sqrt{a} \propto \sqrt{\lambda} .
\]
(140)

From Eq. (33)
\[
\frac{\partial W_t}{\partial z} \propto \frac{1}{\lambda^4} ,
\]
(141)

from Eq. (137)
\[
\sigma_z \propto \lambda ,
\]
(142)

from Eq. (126) and (117)
\[
N \propto \lambda^2 .
\]
(143)

We have
\[
\sigma_p(\text{Landau}) \propto \frac{1}{\lambda^4} \lambda \lambda^2 (\sqrt{\lambda})^2 = \text{constant} ,
\]
(144)

and one finds that the momentum spread for Landau damping is indepedent of \( \lambda \). In our case
\[
\sigma_p \approx .8 \times 10^{-3} .
\]
(145)

7.12 Focus Asymmetry \( \beta_z^*/\beta_y^* \)

In Section 7.7 we specified the final focus maximum pole tip field, and using Eq. (66) we can determine the minimum \( \beta_y^* \) assuming that the quadrupole aperture is determined by the vertical beam size \( \theta_y \). It is important that the aperture is not determined by the horizontal beam size or else the \( \beta_y^* \) will be compromised and the luminosity obtainable for given beamstrahlung will be reduced [see Section 6 and Eq. (90)]. In order to assure this we must choose a sufficiently high ratio of \( \beta_z^*/\beta_y^* \).

We note that the ratio of beam divergence angles at the intersections will be
\[
\frac{\theta_z}{\theta_y} = \left( \frac{\varepsilon_z}{\varepsilon_y} \cdot \frac{\beta_y^*}{\beta_z^*} \right)^{1/2} .
\]
(146)

For the flat beam cases the ratio of required aperture in the final focus is greater than this because of the natural asymmetry of the quadrupole system
\[
\frac{a_z}{a_y} = \frac{A_z}{A_y} \cdot \frac{\theta_z}{\theta_y} \approx 1.8 \left( \frac{\varepsilon_z}{\varepsilon_y} \cdot \frac{\beta_y^*}{\beta_z^*} \right)^{1/2} .
\]
(147)
We require that

\[
\frac{a_x}{a_y} \leq 1 ,
\]  

and thus

\[
\frac{\beta^*_x}{\beta^*_y} \geq (1.8)^2 \frac{\varepsilon_x}{\varepsilon_y} .
\]

Since in Section 7.5 we selected \( \varepsilon_x/\varepsilon_y = 100 \) we obtain

\[
\frac{\beta^*_x}{\beta^*_y} \geq 324 .
\]

Higher values could be used and would reduce the beamstrahlung, if that were required, but 324 is already a large asymmetry and the use of an even larger value would probably introduce tolerance problems. Thus I will use:

\[
\frac{\beta^*_x}{\beta^*_y} = 324 .
\]

7.13 Wall Power

In the designs being considered, there is no strong constraint on the repetition rate except for the overall average power consumption. For these examples, I have assumed

\[
\text{Wall Power} = 100 \text{ MWatts} .
\]

There is no strong justification for this choice. It should depend on electrical power cost, potential running time per year and some reasonableness criterion. Double the power will double the luminosity and repetition rate, and ease the vibration requirements.

I will assume the RF power source efficiency.

\[
\text{RF power source efficiency} = 36% ,
\]

as estimated for a relativistic klystron (see Section 8.5).

8. CHOICE OF WAVELENGTH

8.1 Introduction

I have, using the assumptions of Section 7, generated parameter sets for different wavelengths

\[
\begin{align*}
\lambda &= 35.01 \text{ mm} \quad (8.56 \text{ GHz} = 3\times\text{SLAC}) \\
\lambda &= 26.26 \text{ mm} \quad (11.42 \text{ GHz} = 4\times\text{SLAC}) \\
\lambda &= 17.51 \text{ mm} \quad (14.14 \text{ GHz} = 6\times\text{SLAC}) \\
\lambda &= 11.67 \text{ mm} \quad (25.70 \text{ GHz} = 9\times\text{SLAC})
\end{align*}
\]

These parameter lists are given in full in Appendices I and II. Here I will examine different aspects of these parameters in turn, and note relative advantages and disadvantages.
8.2 Luminosity and Beamstrahlung

Figure 14 shows lines of possible combinations of luminosity and beamstrahlung for the four wavelengths. In each case the standard solution is given by the dot. Higher beamstrahlung is obtained if $\beta_0^2/\beta_y^2$ is chosen to be less than that given in Section 7.12, but no gain in luminosity is obtained—a futile exercise. Lower beamstrahlung can be obtained by lowering the number of particles per bunch (as indicated in the figure), but in these cases I have assumed that neither the focus or damping rings are modified and that no advantage is taken from the lower wakefields and impedance requirements. I am assuming that other limits now apply (see discussion in Section 7.9).

![Figure 14](image1)

Fig. 14. Luminosity versus beamstrahlung for different wavelength solutions.

Figure 15 shows the peak luminosity and luminosity at $\delta = .1$, as a function of the wavelength. At wavelengths above 20 mm there is little gain in maximum luminosity and a big loss in luminosity at fixed $\delta$. Below 20 mm the peak luminosity falls significantly, but the luminosity at low beamstrahlung rises. I would conclude from these considerations

$$10 \text{ mm} \leq \lambda \leq 20 \text{ mm}$$

(154)

![Figure 15](image2)

Fig. 15. Peak luminosity and luminosity at fixed beamstrahlung, as a function of the wavelength chosen.
8.3 Final Focus Criteria

In Section 7.10 in discussing the bunch length choice, a number of criteria were listed, but only one used. Three of these concerned the final focus and I now examine how well these are satisfied (see Table I).

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Wavelength (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>$\frac{\sigma}{\beta}^2 &lt; 1$</td>
<td>(1.08)</td>
</tr>
<tr>
<td>$\frac{\theta_{\text{cross}}}{\theta_{\text{diag}}} &lt; 1$</td>
<td>(1.18)</td>
</tr>
<tr>
<td>$3 &lt; D &lt; 10$</td>
<td>(23)</td>
</tr>
</tbody>
</table>

We see here that though all these criteria are well satisfied for the 17 mm and 12 mm cases, they are violated for 35 mm and only marginal for 26 mm. I thus conclude

$$\lambda \leq 20 \text{ mm}$$  \hspace{1cm} (155a)

To avoid the loss of a disruption enhancement when $D < 3$, we also need

$$\lambda \geq 12 \text{ mm}$$  \hspace{1cm} (155b)

Another criterion concerns the possible need to use a dipole field to sweep low momentum disrupted electrons away from the first quadrupole (see Section 5.2). The length required for this should certainly be less than the space available. With the assumptions made, see Table II.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Wavelength (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Length to first quad (m)</td>
<td>$\ell_1$</td>
</tr>
<tr>
<td>Length to sweep (m)</td>
<td>$\ell_{\text{sweep}}$</td>
</tr>
</tbody>
</table>

Once again, the requirement is violated for the two longer wavelength examples and we require

$$\lambda \leq 20 \text{ mm}$$  \hspace{1cm} (156)

8.4 Tolerances

Two kinds of tolerance have been defined in Section 3.3.

a) Alignment tolerances can be satisfied if beam position monitors have accuracy significantly below the tolerance and if feedback is employed to control the average orbit. The values of tolerance required are calculated [using Eq. (40)] and shown in Table III below.

The requirements are significantly more severe for the short wavelength examples than for the longer wavelength cases.
These alignment requirements can be relieved by the use of elliptical irises. In the 12 mm case the calculated tolerance is only 160 μ with a 2:1 elliptical iris—but the use of such asymmetric structures is another subject. But, larger wavelengths are still preferred, and if we require tolerances greater than 50 μ, we obtain:

\[ \lambda \geq 15 \text{ mm} \]

(157)

b) The second kind of tolerance concerns vibration. Any linac quadrupole motion that occurs between one pulse and the next cannot be corrected, even if it can be measured. From Eq. (47) the rms allowable random motion from one pulse to the next is also given in Table III, below.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Wavelength (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Beam size ( \sigma_y ) (μ)</td>
<td>.93</td>
</tr>
<tr>
<td>Number of quads ( N_q )</td>
<td>336</td>
</tr>
<tr>
<td>Alignment tolerance ( \langle \Delta \rho \rangle_a ) (μ)</td>
<td>122</td>
</tr>
<tr>
<td>Vibration tolerance ( \langle \Delta \rho \rangle_v ) (μ)</td>
<td>.02</td>
</tr>
<tr>
<td>( f ) (Hz)</td>
<td>55</td>
</tr>
<tr>
<td>( \langle \Delta \rho \rangle_{ground} ) (μ)</td>
<td>.002</td>
</tr>
<tr>
<td>( \langle \Delta \rho \rangle_{tolerance} / \langle \Delta \rho \rangle_{ground} )</td>
<td>10</td>
</tr>
</tbody>
</table>

We note again that this tolerance is more stringent for the short wavelength cases than for the long wavelength case. However, the repetition frequency \( f \) is higher for the short wavelength cases and thus serving is easier. If, for instance, we look at a typical ground vibration [16], we see that the amplitudes at high frequencies are much smaller than at lower frequencies. As a result the ratio of tolerance to ground vibration is better for the short wavelength examples, so a small wavelength is preferred.

It may, however, be noted that the ground vibration is in all cases less than the tolerance, so there is no real constraint on the wavelength.

8.5 **Damping Ring Criteria**

Some of the damping ring parameters for the different wavelength solutions are shown in Table IV.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Wavelength (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Horizontal emittance ( (10^{-3} \text{ m}) ) ( \varepsilon_x )</td>
<td>4.4</td>
</tr>
<tr>
<td>Long emittance ( \text{m} ) ( \varepsilon_x )</td>
<td>.044</td>
</tr>
<tr>
<td>Bunch length ( \text{cm} ) ( \sigma_x )</td>
<td>3.4</td>
</tr>
<tr>
<td>Ring radius ( \text{m} ) ( R )</td>
<td>12.3</td>
</tr>
<tr>
<td>Tune (Horizontal) ( Q_x )</td>
<td>18</td>
</tr>
<tr>
<td>Impedance ( \text{Ω} ) ( Z )</td>
<td>183</td>
</tr>
</tbody>
</table>
The lower wavelength solutions require damping rings with lower emittance, obtained because of the lower number of particles per bunch. As a consequence, however, the low wavelength cases require larger diameter, higher tune, and will be more costly and have tighter tolerances.

On the other hand, we note that the solutions with longer wavelength involve relatively large longitudinal emittance and correspondingly long bunches. This in turn will mean very low frequency RF systems that may be large, more costly, and possibly more of an impedance problem. This problem is compounded because the impedance requirement for the full ring (even though $Z/n$ is the same for all cases) is far more severe for the long wavelength cases.

On balance, the shorter wavelength solutions are probably more reasonable. If I require a bunch length less than 2 cm, I obtain

$$\lambda \leq 24 \text{ mm}$$  \hspace{1cm} (158)

8.6 RF Power Source Cost

If we assume that the linac is filled by an induction-linac-powered relativistic klystron then we are in a position to make a very rough first guess at the cost. Let us assume that the induction linac is of the type now operating at Livermore. It would then consist of some multiples of klystron units consisting of

- 1 DC power supply \hspace{1cm} (50 KS)
- 1 880 Joule, 1 $\mu$s, modulator \hspace{1cm} (80 KS)
- 1 Magnetic compressor \hspace{1cm} (175K $\ )
- 3 2 KA induction units \hspace{1cm} (500K $\ )
- Focusing magnets \hspace{1cm} (50K $\ )
- Bunching and extraction cavities \hspace{1cm} (100K $\ )

I do not wish to rule out the Two-Beam Accelerator concept in which the klystron beam is reaccelerated, and energy extracted, many times. In such a case the "klystrods" referred to here would be merely added together. No large cost differential would be expected.

Such a system might be expected to have an overall efficiency of 36% (modulator 90%, induction linac 90%, fraction of pulse flat 66%, klystron energy extraction 66%). The energy out would then be 320 Joules.

The costs listed above are those given by Dan Birx for the construction of single units; they do not include engineering, overhead or contingency costs.

If I assume a factor of 1.6 to cover these extra expenses, but allow a 50% cost reduction from mass production then I obtain a cost per output Joule of

$$\$/\text{Joule} = \frac{760 \text{ K$}}{320 \text{ } J} = 2.4 \text{ K$}/\text{Joule}$$  \hspace{1cm} (160)

The Livermore design, with minor modifications, could deliver an RF pulse length anywhere between 100 nsec to $\sim 14$ nsec, without significant cost differential (a 10% increase could be incurred for $t \leq 25$ nsec to provide a ferrite instead of metglast final pulse compression stage). A single unit could thus provide peak power between 3.2 GWatts and 21 GWatts without significant cost differential. It is the cost per stored energy that dominates.
Using Eq. (22) and allowing for extra length because of phase advance [Eq. (136)] and the length needed to correct the Landau momentum spread [Eq. (130c)], I now estimate the RF systems required as a function of wavelength in Table V.

**TABLE V.**

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Wavelength (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Total stored energy (kJ)</td>
<td>650</td>
</tr>
<tr>
<td>Pulse length (nsec)</td>
<td>70</td>
</tr>
<tr>
<td>Number of “klystrons” a)</td>
<td>2030</td>
</tr>
<tr>
<td>Estimated cost B$</td>
<td>1.56</td>
</tr>
<tr>
<td>meters per “klystron” a)</td>
<td>3.3</td>
</tr>
</tbody>
</table>

a) number of induction units is approximately three times this.

b) including 10% increase to cover possible costs associated with 14 nsec pulse length.

When compared to a possible linear cost for a 7 KM linac of the order of .3B$, it would appear that the RF costs for both 35 mm and 26 mm wavelengths are excessive (see Fig. 16).

An alternative way of judging what is reasonable or unreasonable is to consider the number of “klystrons” per meter.

For the 35 mm wavelength case we would need a complete unit every 3.3 m. Since each one is about 6 m long, they would have to be arranged side-by-side in a 6–m wide corridor parallel with the entire accelerator. This seems not reasonable.

![Fig. 16. Cost of RF power supply as a function of the wavelength. Also, this cost together with an assumed linear component. The dotted lines indicate uncertainty in cost estimation in a region of pulse lengths less than 15 nsec.](image-url)
For the wavelengths less than 17 mm the induction units could be parallel with the main accelerator and take up only a couple of meters of width. Thus from this, or from a requirement that the power source cost no more than the linear cost, we obtain

\[ \lambda \leq 17 \text{ mm} . \tag{161a} \]

There is, however, an argument against going below 12 mm since pulses of less than 14 nsec have not yet been achieved.

\[ \lambda \geq 17 \text{ mm} . \tag{161b} \]

8.7 Wavelength Conclusion

Reviewing the constraints on wavelength, we have:

- Eq. (154) \[ 10 \text{ mm} \leq \lambda \leq 20 \text{ mm} \]
- Eq. (155a) \[ \lambda \leq 20 \text{ mm} \]
- Eq. (155b) \[ 12 \text{ mm} \leq \lambda \]
- Eq. (156) \[ \lambda \leq 20 \text{ mm} \]
- Eq. (157) \[ 15 \text{ mm} \leq \lambda \]
- Eq. (158) \[ \lambda \leq 24 \text{ mm} \]
- Eq. (161a,b) \[ 17 \text{ mm} \leq \lambda \leq 17 \text{ mm} \]

From which we see that the only wavelength that satisfies all conditions is

\[ \lambda \approx 17 \text{ mm} . \]

This conclusion should not be interpreted as an exact statement. By adjusting the parameter choices and criteria of Section 7, one could clearly come up with solutions for other wavelengths. But if a wavelength significantly different is required, then some price in luminosity, beamstrahlung, cost, length or other parameter would have to be paid.

9. CONCLUSIONS

9.1 Warnings

This study has made many assumptions that are uncertain, and in some cases clearly unrealistic. It was not intended to yield a design of a real collider. In particular we note:

1. No emittance dilution has been included in the calculation. Finite misalignments, wakefields, synchrotron radiation and higher order aberrations will lower the effective emittances and lower the luminosity for fixed power.

2. The Landau damping calculation uses only the two-bunch approximation and is not exact.

3. The wakefield expressions used may not be correct for the short bunches that the study proposes to use.

4. Pulse-to-pulse variations in transverse fields in the accelerating structure may be a severe problem, and it has not been included.

Clearly much more study is required and this work should be taken only as a guide to what may be possible.
9.2 **Encouragement**

On the other hand, this study has left out many features that could make things much better. In particular:

(1) More than 100 MW could be used, thus giving both more luminosity and repetition rate.

(2) Asymmetric irises could be employed in the linac to reduce the vertical wakefields and, as a result, reduce the alignment tolerances.

(3) Higher order chromatic correction in the final focus could probably be employed. Alex Chou [17] has shown that when correction is only required in one direction, octupoles can improve the correction beyond that assumed here.

(4) Super disruption [18] is a concept that uses two closely spaced bunches, so that the first acts to focus particles of the second bunch and gives an increase in luminosity. In our case, two bunches would not be practical, but shaping of the bunches (the front should have a larger radius than the back) could probably help.

(5) Longitudinal shaping of the bunch would lower the uncorrectable third order momentum spread and help the final focus.

(6) Other focus schemes using plasmas or other high field magnets could lower the final focus $\beta^*$. 

(7) The use of RF focussing elements in the linac or final focus could eliminate the need for a Landau momentum spread correction section. This idea is being studied at CERN [19].

(8) Multiple bunches in the linac could dramatically increase the beam current and luminosity. The long term transverse wakefields make this impossible with a conventional cavity, but studies are underway on cavities that would damp the transverse modes and allow such operation.

10. **FINAL REMARKS**

This study, with many assumptions, has generated a self-consistent and semi-conventional parameter list for a .5 on .5 TeV $e^+e^-$ collider with a luminosity above $10^{33}$ cm$^{-2}$ sec$^{-1}$. It is true that many of the assumptions are optimistic (see Section 9.1), but it is also true that many ideas were not included that could make things much better (see Section 9.2). On balance, I believe the study is very encouraging.

Much work remains to be done, but I believe now that a collider with the proposed specification can be built in the not too distant future. The physics potentials of such a facility are well known. The relative ease of performing experiments with such a machine compared with the difficulties of working with such luminosities in a hadron collider have frequently been noted.

For these reasons, and because of the physics differences, electron positron colliders have always complimented hadron machines operating in a similar energy regime. The collider described here certainly approaches the regime of the SSC and would be an appropriate compliment to it. One hopes that the remaining uncertainties can be resolved and a proposal can soon be made for the construction of such a facility.
I would like to thank the many members of the groups at SLAC, CERN, KEK, LBL and Livermore who have contributed to these studies. In particular, I would thank C. Bane, K. Brown, D. Farkas, R. Ruth, and P. Wilson at SLAC for their many contributions and help in this work.

REFERENCES


4. J. Bisognano et al., "Feasibility Study of Storage Ring for a High Power XUV Free Electron Laser," LBL–19771 (1985). [Note that the factor four in Eq. (6) is missing in both this reference and Ref. 4.]


9. In Ref. 6, the dependence is given as $W \propto e^{1.7\lambda^2}$. However, from theoretical considerations there should be no $\lambda$ dependence for sufficiently short bunches. See SLAC Internal Report AAS–23 (1986).

10. K. Brown, private communication.

11. P. B. Wilson, "Future $e^+e^-$ Linear Colliders and Beam-Beam Effects," SLAC–PUB–3985 (1986); Proc. Stanford Linear Accelerator Conference, June 2–6, 1986. [Note that in this paper an enhancement of the beamstrahlung is included incorrectly in the flat beam case.]


17. Alex Chou, reported at this Workshop.


19. Wolfgang Schnell, reported at this Workshop.
APPENDIX I. Parameters Independent of Wavelength

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass energy</td>
<td>$E = 1.0$ (TeV)</td>
</tr>
<tr>
<td>Maximum accelerating gradient</td>
<td>$\xi_a = 186$ MeV/M</td>
</tr>
<tr>
<td>Overall length (excluding final focus)</td>
<td>$\ell = 6.8$ km</td>
</tr>
<tr>
<td>Bunch length/wavelength</td>
<td>$\sigma_x/\lambda = 1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Final spot width/height</td>
<td>$R = 180$</td>
</tr>
<tr>
<td>Vertical disruption enhancement</td>
<td>$H_D = 2.37$</td>
</tr>
<tr>
<td>Crossing angle/maximum disruption angle</td>
<td>$\theta_c/\theta_D = 12$</td>
</tr>
<tr>
<td>Final focus quadrupole pole tip fields</td>
<td>$B_q = 1.4$ Tesla</td>
</tr>
<tr>
<td>Momentum spread at final focus</td>
<td>$\sigma_p$(focus) = .15%</td>
</tr>
<tr>
<td>$\sigma_p$(from long emittance)/$\sigma_p$(from wakefields)</td>
<td>$F_{\sigma_p} = .7$</td>
</tr>
<tr>
<td>$\beta^<em>(\text{horizontal})/\beta^</em>(\text{vertical})$</td>
<td>$\beta^*_x/\beta_y = 324$</td>
</tr>
<tr>
<td>Vertical $\beta^*$ reduction from chromatic correction</td>
<td>27</td>
</tr>
<tr>
<td>Horizontal $\beta^*$ reduction from chromatic correction</td>
<td>.5</td>
</tr>
</tbody>
</table>

**Linac**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac quad pole tip fields</td>
<td>$B_{1q} = 1.4$ (Tesla)</td>
</tr>
<tr>
<td>Quad fraction of length</td>
<td>$F_{2q} = 5%$</td>
</tr>
<tr>
<td>Linac quad aperture/linac iris aperture</td>
<td>$R_{qa} = 1.26$</td>
</tr>
<tr>
<td>Phase advance per cell</td>
<td>$\phi_t = 40^\circ$</td>
</tr>
<tr>
<td>Momentum spread for Landau damping</td>
<td>$\sigma_p$(Landau) = $.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>Phase advance to maintain $\sigma_p$(Landau)</td>
<td>$\phi = 2\theta$</td>
</tr>
<tr>
<td>Length at end to correct $\sigma_p$(Landau)</td>
<td>$\ell_c = 210$ m</td>
</tr>
<tr>
<td>Linear momentum spread from wakes</td>
<td>$\sigma_p = .58%$</td>
</tr>
<tr>
<td>Second order momentum spread from wakes</td>
<td>$2\sigma_p = .01%$</td>
</tr>
<tr>
<td>Third order momentum spread from wakes</td>
<td>$3\sigma_p = .12%$</td>
</tr>
<tr>
<td>Second order momentum spread from acceleration</td>
<td>negligible</td>
</tr>
</tbody>
</table>

**RF System**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Structure group velocity</td>
<td>$v_p/c = \beta_q = .08$</td>
</tr>
<tr>
<td>Peak RF field/acceleration gradient</td>
<td>$\xi_{pk}/\xi_s = 2.6$</td>
</tr>
<tr>
<td>Normalized elastance</td>
<td>$s_{el} = 2.1 \times 10^{10}$ VmC$^{-1}$</td>
</tr>
<tr>
<td>Fill time/attenuation time</td>
<td>$\tau = .25$</td>
</tr>
<tr>
<td>Fill efficiency</td>
<td>$\eta_s = .78$</td>
</tr>
<tr>
<td>RF structure loading</td>
<td>$\eta = 1.2%$</td>
</tr>
<tr>
<td>RF source efficiency</td>
<td>$\eta_{RF} = 36%$</td>
</tr>
<tr>
<td>Wall power consumption,</td>
<td>$W_{wall} = 100$ MW</td>
</tr>
</tbody>
</table>

**Damping Ring**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping ring longitudinal impedance,</td>
<td>$Z_l/n = .5$ $\Omega$</td>
</tr>
<tr>
<td>Damping ring ratio of emittances</td>
<td>$\epsilon_x/\epsilon_y = 100$</td>
</tr>
<tr>
<td>Bending fields</td>
<td>$B_d = 2$ Tesla</td>
</tr>
<tr>
<td>Damping ring focus peak fields</td>
<td>$B_q = 1.4$ Tesla</td>
</tr>
<tr>
<td>Aperture</td>
<td>$a_{dr} = 12$ mm</td>
</tr>
<tr>
<td>Beta ratio: vertical/horizontal</td>
<td>$\beta_z/\beta_y = 4$</td>
</tr>
<tr>
<td>Partition functions</td>
<td>$J_z, J_y, J_x = 1, 1, 2$</td>
</tr>
</tbody>
</table>
## APPENDIX II. Parameters Dependent on Wavelength

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Wavelength (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Max Luminosity $10^{23}$ cm$^{-2}$ sec$^{-1}$</td>
<td>$L_{max}$</td>
</tr>
<tr>
<td>Beamstrahlung $E$ loss</td>
<td>$\delta$</td>
</tr>
<tr>
<td>Beamstrahlung quantum parameter</td>
<td>$\Upsilon$</td>
</tr>
<tr>
<td>Frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>Final spot size (vertical) (nm)</td>
<td>$\sigma_y$</td>
</tr>
<tr>
<td>Final spot size (horizontal) (\mu m)</td>
<td>$\sigma_z$</td>
</tr>
<tr>
<td>Particles per bunch ($10^{10}$)</td>
<td>$N$</td>
</tr>
<tr>
<td>Bunch length (mm)</td>
<td>$\sigma_x$</td>
</tr>
<tr>
<td>Vertical Disruption</td>
<td>$D_y$</td>
</tr>
</tbody>
</table>

### Final Focus

- Final focus (vertical) $\beta^*$ (mm) $\beta_y^*$ \(0.51\), 0.47, 0.43, 0.38
- Final focus (horizontal) $\beta^*$ (mm) $\beta_z^*$ \(17\), 15, 14, 12
- Maximum horizontal disruption angle (mrad) $\theta_{x,D}$ \(24\), 14, 6, 3
- Final convergent angle (horizontal) (mrad) $\theta_{f_\infty}$ \(0.016\), 0.015, 0.014, 0.012
- Final convergent angle (vertical) (mrad) $\theta_{f_V}$ \(0.030\), 0.027, 0.025, 0.022
- Bunch diagonal angle (mrad) $\theta_{\text{diag}}$ \(5.1\), 5.8, 7.3, 8.3
- Crossing angle (mrad) $\theta_c$ \(6\), 4, 2.2, 1.2
- First quad aperture (mm) $a_q$ \(0.15\), 0.13, 0.10, 0.08
- Length to first quad (m) $\ell^*$ \(0.47\), 0.43, 0.39, 0.35
- Length to sweep quantum disruption (m) $\ell_s$ \(0.84\), \(0.56\), \(0.30\), \(0.17\)

### Wakes

- Transverse wake potential V/pC$^{-1}$ m$^{-2}$ $W_t(2\sigma_z)$ \(1.5k\), \(3.7k\), \(12k\), \(43k\)
- Average $\beta$ in linac (m) $\beta_{\text{linac}}$ \(19\), 17, 14, 11
- Delta phase advance (radians) $\Delta \phi$ \(0.16\), 0.13, 0.22, 0.27
- Number of quads in linac $N_q$ \(340\), \(390\), \(480\), \(580\)
- Vertical alignment tolerance (\mu m) $\langle \Delta y \rangle$ \(122\), \(93\), \(66\), \(44\)
- Longitudinal wake (at $z = 0$) V/pC$^{-1}$ m$^{-2}$ $W_t(0)$ \(580\), \(1k\), \(2.3k\), \(5.2k\)

### Damping Ring

- Normalized emittance (vertical) \(10^{-8}\) m $\varepsilon_{x,y}$ \(4.4\), \(3.5\), \(2.5\), \(1.8\)
- Normalized emittance (horizontal) \(10^{-6}\) m $\varepsilon_{x,z}$ \(4.4\), \(3.5\), \(2.5\), \(1.8\)
- Longitudinal emittance m $\varepsilon_z$ \(0.044\), \(0.033\), \(0.022\), \(0.015\)
- Energy (GeV) $E_{dr}$ \(0.98\), \(1.0\), \(1.04\), \(1.09\)
- Ring radius (m) $R$ \(12.3\), \(14.6\), \(18.2\), \(23.3\)
- Tune (horizontal) $Q_y$ \(17.7\), \(20.7\), \(25.3\), \(31.8\)
- Tune (vertical) $Q_z$ \(4.4\), \(5.2\), \(6.3\), \(7.9\)
- Bunch length (cm) $\sigma_z$ \((3.4)\), \((2.4)\), \(1.5\), \(1.0\)
- Momentum spread \(10^{-3}\) $\sigma_p$ \(.68\), \(.69\), \(.70\), \(.72\)
- $E$ loss Volts/turn (MV) $U$ \(.17\), \(.22\), \(.29\), \(.40\)
- Damping time constant (msec) $\tau$ \(2.35\), \(2.28\), \(2.20\), \(2.11\)
- Impedance requirement (\Omega) $Z$ \((183)\), \(300\), \(600\), \(1200\)
APPENDIX II, continued

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Wavelength (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>RF System</td>
<td></td>
</tr>
<tr>
<td>Wavelength (mm)</td>
<td>(\lambda)</td>
</tr>
<tr>
<td>Elastance V pC^{-1} m^{-2}</td>
<td>(S_t)</td>
</tr>
<tr>
<td>(Q)</td>
<td>(Q)</td>
</tr>
<tr>
<td>Iris radius (mm)</td>
<td>(a)</td>
</tr>
<tr>
<td>Inside cavity radius (mm)</td>
<td>(b)</td>
</tr>
<tr>
<td>RF pulse length (nsec)</td>
<td>(t)</td>
</tr>
<tr>
<td>Length per feed (m)</td>
<td>(L)</td>
</tr>
<tr>
<td>Peak power per m (GW)</td>
<td>(W_{pk}/\ell)</td>
</tr>
<tr>
<td>Total peak power (TW)</td>
<td>(W_{pk})</td>
</tr>
<tr>
<td>Total RF energy (kJ)</td>
<td>(J)</td>
</tr>
</tbody>
</table>

Parenthesised values have some difficulty or objection.

* * *

Discussion

B. Montague, CERN

I have serious misgivings about maintaining a large emittance ratio down the linac in the face of coupling effects between transverse planes due to wakefields, misalignments, etc., or to asymmetric irises if used. The situation is different from that in storage rings.

Reply

Indeed, we all have our reservations. My hunch, however, is that to keep mixing below 1% should not be so difficult. PEP has operated in such a mode and a 3 km long linac is equivalent to only a few turns in PEP. It is true that a circular machine is different from a linac, but not so different when only three turns are considered.

G. Coignet, LAPP

In proton-proton machines four or six interaction regions can be accommodated. One criticism often made with linacs is that only one interaction region is foreseen. In the SLAC Study Group, have you discussed the possibility of sharing the luminosity or re-using the beams for more than one interaction region?
Reply

I cannot speak for a formal "SLAC Study Group" but certainly there has been plenty of
discussion. My personal view is that it would be better for three experiments each to have
full luminosity one third of the time than to have three with 1/3 luminosity all the time.
I would thus favour a system for moving experiments in and out of one region rather than
multiple regions.

B. Zotter, CERN

Longitudinal wakefields were discussed for their influence on tolerances, but not for
the energy loss which increases strongly for shorter bunches. Was this included and found
negligible?

Reply

No, it was not included, but YES it was calculated and found to be less than 1% with
our parameters.

E. Keil, CERN

When comparing emittance ratios between PEP and future damping rings one should
remember that the focusing in PEP is relatively weak.

Reply

Yes, of course, one has to do tracking of the linac with simulated nonlinearities and
positioning errors. This has not been done yet.
STATUS OF THE SLC*

J. T. Seeman and J. C. Sheppard
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

ABSTRACT
The construction project for the SLAC Linear Collider (SLC) was officially completed in April 1987, following a successful test in March of passing 46-GeV positron and electron beams through the collider hall on the same accelerator pulse. Since that time, commissioning of the SLC has concentrated on making the stability, intensity and transverse dimensions of both beams suitable to generate useful luminosity near the center of mass energy of 93 GeV.

1. INTRODUCTION

The SLC is the first linear collider and was designed to provide high luminosity electron-positron collisions for studying the production of the $Z^0$. A schematic layout of the SLC is shown in Fig. 1. The basic design parameters are shown in Table 1. The design luminosity is ambitious and will require several years to achieve. It is fortunate that interesting physics of the $Z^0$ can be obtained with a luminosity of $6 \times 10^{37} \text{cm}^{-2}\text{sec}^{-1}$ which is our initial goal for Fall 1987. The presently achieved conditions are also shown in Table 1. Steady progress is being made, and the expectations that we will meet our initial goal are high. The state of each subsystem of the SLC is reviewed here concentrating on areas of present study.

![OVERALL SLC LAYOUT](image)

Fig. 1. Schematic layout of the SLC.

2. COMMISSIONING OF THE SLC

Beam testing of components and SLC subsystems has been an ongoing enterprise since the fall of 1980 when the initial studies of the control system and injector began. In May 1986, commissioning of the full SLC began with the goal of tying the various subsystems together. By August 1986, damped electron beams were being extracted from the north damping ring for routine operation in the downstream portions of the machine. Two electron bunches on a single RF pulse were injected and stored in the north damping ring during October 1986. Positron bunches were first accelerated to the damping ring energy of 1.21 GeV in the following month, November. During December, electrons were first accelerated to an energy of 50 GeV at the end of the linac. Electrons were subsequently transported to the final focus.

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.
Table 1.
Basic parameters for the SLC.

<table>
<thead>
<tr>
<th></th>
<th>Design Goal</th>
<th>Initial Goal</th>
<th>Achieved</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>Beam energy at IP</td>
<td>50</td>
<td>46</td>
<td>46</td>
<td>GeV</td>
</tr>
<tr>
<td>Beam energy at end of linac</td>
<td>51</td>
<td>47</td>
<td>53</td>
<td>GeV</td>
</tr>
<tr>
<td>Electrons at entrance of arcs</td>
<td>$7 \times 10^{10}$</td>
<td>$10^{10}$</td>
<td>$3.5 \times 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>Positrons at Entrance of arcs</td>
<td>$7 \times 10^{10}$</td>
<td>$10^{10}$</td>
<td>$0.6 \times 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>180</td>
<td>60</td>
<td>5</td>
<td>Hz</td>
</tr>
<tr>
<td>Bunch length ($\sigma_x$ in linac)</td>
<td>1.5</td>
<td>1.5</td>
<td>$0.5 - 3^8$</td>
<td>mm</td>
</tr>
<tr>
<td>Normalized transverse emittance at end of linac (electrons)</td>
<td>$3 \times 10^{-5}$</td>
<td>$10 \times 10^{-5}$</td>
<td>$3 - 20 \times 10^{-5}$</td>
<td>rad-m</td>
</tr>
<tr>
<td>Spot radius at IP</td>
<td>1.6</td>
<td>2.8</td>
<td>—</td>
<td>$\mu$</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$6 \times 10^{30}$</td>
<td>$6 \times 10^{27}$</td>
<td>—</td>
<td>cm$^{-2}$ sec$^{-1}$</td>
</tr>
</tbody>
</table>

*Bunch length increases with current: at $1.2 \times 10^{10}$/bunch, the bunch length is 1.5 mm in the linac.*

region through the north arc during February 1987. Electrons were transmitted across the interaction point (IP) in March 1987. Also in March, damped positrons were extracted from the south damping ring; positrons and electrons were coaccelerated through the linac on the same RF pulse; and positrons were transmitted through the south arc. On March 27, 1987, electrons and positrons crossed at the IP signifying the completion of the construction phase of the SLC project.

Since the initial crossing at the IP, commissioning has continued. The present goal of the current commissioning effort is to tune the system so that useful luminosity can be achieved by the fall of 1987. The initial luminosity goal has been set to be $6 \times 10^{27}$ cm$^{-2}$s$^{-1}$. This goal is met by colliding $10^{10}$ electrons on $10^{10}$ positrons at 120 pps with an IP spot radius of 4 microns.

3. **INJECTOR**

The SLC injector$^1$ consists of an electron source and 100 meters of linac. The source is required to produce a pair of electron bunches which are accelerated through the initial portion of the linac for injection into the north damping ring. A single positron bunch is injected at 200 MeV and accelerated along with the electron bunches to the damping ring energy. Positrons are transported into the south damping ring. Control of the energies and energy spread of the three bunches are required for efficient injection into the damping rings. Intensity stabilization is important in the control of energy jitter of beams extracted from the damping rings. In addition, proper adjustment and stabilization of the temporal spacing of the bunches is necessary so that colliding beams always cross at the same location in the interaction hall.

As of June 1987, the electron source is fully operational. Pairs of electron bunches, spaced by 61.6 ns, can be accelerated and stabilized in energy for injection into the north damping ring.
At bunch currents greater than about $7.5 \times 10^{10}$ intensity jitter becomes a problem. At present, the source is operated to produce electron bunch intensities between about $5 \times 10^9$ and $3 \times 10^{10}$ particles per pulse according to the demands of the downstream users. Operation at $1 \times 10^{10}$ electrons per pulse is not a problem.

Positron transmission through the injector region depends upon the initial positron launch conditions. An increased positron bunchlength enlarges the energy spread which results in poor transmission and injection into the south ring. Best conditions achieved so far resulted in 60% transmission through the injector into the ring. Transmission efficiencies of 40% are typically achieved.

Whereas double electron bunch operation has been tested, only single bunches are routinely accelerated through the injector region. Two-bunch operation is awaiting the installation of a two-bunch extraction kicker in the north damping ring. Similarly, the low repetition rate of the SLC (10 pps in the linac) has not permitted testing of the full three-bunch acceleration in the injector. Testing of three bunch operation is scheduled for the fall of 1987 and is not expected to be a problem.

4. **POSITRON SOURCE**

The SLC positron source\(^2\) consists of a W-Re target, flux concentrator, 200 MeV of acceleration, and a 2000 m transport line. At the two-thirds point in the linac, 30 GeV electrons are deflected onto the target. Positrons in the resultant shower are accelerated to 200 MeV in a s-band, high gradient capture section followed by three standard SLAC sections. The 200 MeV positrons are transported to the beginning of the linac for subsequent acceleration to 1.21 GeV and injection into the south damping ring.

Initial plans called for a rotating, water cooled target. Testing of the device resulted in a vacuum failure of the rotating seal; the failure caused damage to the high gradient section. At present, a fixed target has been installed and the high gradient section is operated at 20 MeV per meter instead of the design goal of 50 MeV/meter. The fixed target is limited in power dissipation to the equivalent of $2 \times 10^{10}$ incident electrons per pulse at a repetition rate of 120 pps. Solenoids installed around the capture section have developed turn-to-turn shorts resulting in a reduction of the fields in the capture region.

The failure of the high gradient section and reduced solenoidal field decreases the electron to positron efficiency. The restriction of the maximum intensity on target, further limits positron production. Plans call for replacement of the solenoids and high gradient section in the fall of 1987. This will result in greater positron yields. Development of a rotating target to absorb greater electron fluxes is not anticipated until sometime in 1988.

With the reduced conditions, a yield of one positron injected into the linac from the south damping ring for every two electrons incident on target has been achieved. The maximum number of positrons stored in the south ring has been approximately $1 \times 10^{10}$ particles in a single pulse. In order to accomplish this yield, careful tuning of the positron bunchlength was required. This tuning was done by varying the RF phase in the capture section, tuning the subsequent downstream RF and transport line magnets, while observing the bunchlength using a streak camera. Fortuitously, the yield peaks where the bunchlength is minimized. The smallest achieved bunchlengths are approximately 1.5 times longer than can be expected to fit inside the damping ring energy aperture, after acceleration through the injector. This increase is attributed to a longer than expected bunchlength of electrons extracted from the north damping rings.
Reduction of the incident electron bunchlength, installation of a new high gradient section and capture region solenoids, as well as improved positron orbit control through the injector region are expected to bring the yield of damped positrons up to nearly one per electron incident on target by the fall of 1987. This improvement, will permit operation of $1 \times 10^{10}$ positrons per pulse in the collider hall for the same number of electrons on target.

5. DAMPING RINGS

Two damping rings\(^3\) have been built to reduce the transverse emittance of the positron and electron bunches to a value of $\gamma \epsilon = 3 \times 10^{-5}$ m-rad required for micron sized spots at the IP. Table 1 lists the design parameters of the SLC rings. Construction and development on the rings began in 1982. The north damping ring was completed in the spring of 1986. Routine operation of the electron ring (the north damping ring) for single bunch operation in conjunction with the SLC linac began in August 1986. A two bunch injection kicker\(^4\) was installed in the north ring in the fall of 1986 and a pair of electron bunches of about $2.5 \times 10^{10}$ particles each were stored in the north during October 1986. The rebuilt south damping ring was commissioned with electrons in the winter of 1986–1987. This ring was reversed in polarity to accept positrons; positrons were first injected into and extracted from the south ring in March 1987.

A two bunch extraction kicker is being prepared for installation in the north ring for the fall of 1987. Extraction kicker pulse jitter is expected to be within tolerance for operation at $1 \times 10^{10}$ electrons per pulse but may not be acceptable for higher bunch currents.

Bunch lengthening has been observed in both damping rings. Figure 2 shows the equilibrium bunchlength in the north damping ring as a function of beam current. The design parameters predict an rms equilibrium bunchlength of 5.9 mm. As seen in Figure 2, the design size is achieved at the lowest currents and increases with current. A straight line fit to the data is shown in the figure. Figure 3 illustrates the equilibrium energy spread in the ring as a function of beam current. This figure indicates a threshold of turbulent bunchlengthening at a current of about $1.5 \times 10^{10}$ particles per bunch. Similar results have been observed in the south damping ring. Model calculations using calculated impedances of bellows, BPMs, vacuum chamber transitions and irregularities predict the observed bunchlengthening with reasonable agreement.\(^5\)

![Figure 2](image_url)

**Fig. 2.** Equilibrium bunchlength in the damping rings as a function of beam current.
Fig. 3. Equilibrium energy spread in the damping rings as a function of beam current.

The bunch lengthening reduces the maximum usable beam current to about $2 \times 10^{10}$ particles per pulse. Even though it is possible to extract higher currents from the ring, it is not possible to compress the large bunchlengths in the transport line leading from the rings to the linac (RTL) because of energy aperture restriction in the RTLs. Furthermore, the minimum achievable bunchlength is limited by the equilibrium energy spread which increases above the turbulence threshold. An increased longitudinal beam size results in increased sensitivity to transverse wakefields in the linac. In addition, the increased scavenger bunchlength results in increased positron bunchlengths which are subsequently difficult to inject into the south damping ring because of an enlarged energy spread.

Several short term solutions are being considered for the fall of 1987. These include shielding the ring bellows, enlarging the RTL energy aperture, and increasing the available RF voltage in the ring. Some precompression in the rings is possible by launching a longitudinal quadrupole oscillation in the ring shortly before extraction and extracting the beam when a minimum in the beam size occurs. These fixes and procedures are expected to increase the maximum useful beam current to nearly $5 \times 10^{10}$ particles per bunch. For operation at $1 \times 10^{10}$ particles per pulse, the present system is adequate.

6. LINAC

The two mile SLAC linac has been upgraded to accelerate tightly focused beams of positrons and electrons on the same RF pulse without significant emittance increases. Over 200 new 67 MW klystrons have been installed in the linac, and beam energies of 53 GeV have been measured. Routine commissioning operates at 47 GeV per beam. $3.5 \times 10^{10}$ electrons and $0.6 \times 10^{10}$ positrons per bunch have been accelerated without loss.

Beam trajectories are corrected using dipole magnets and beam position monitors located every 12 meters (closer in the first 300 meters). Electron trajectories are routinely corrected to errors of 125 $\mu$ rms. When both beams are corrected simultaneously, typical trajectory errors are 300 $\mu$ rms for each beam. These trajectory errors have been steadily decreasing as the misaligned quadrupoles and errant electronic modules have been discovered and fixed.

The transverse shapes of the beams at the end of the linac depend on the quadrupole lattice, the energy-acceleration profile of the linac, entrance conditions from the RTLs, and transverse wakefields. The beam dimensions have been shown to remain constant as long as the upstream conditions do not change. The transverse beam emittances have been measured at high energy as a function of beam current, and a summary is shown in Table 2. Above about $8.0 \times 10^{10}$ electrons per pulse the bunch length increases due to the damping ring which increases the beam's energy spectrum dramatically in the linac. This causes sharply increased transverse wakefields and chromatic phase dilution effects to
Table 2.

Measured linac invariant emittances at 43–47 GeV. The units are in radian-meters ×10⁻⁶.

<table>
<thead>
<tr>
<th>$I \times 10^{10}$</th>
<th>Horizontal</th>
<th>Vertical</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>7 ± 1</td>
<td>2 ± 1</td>
<td>2/87</td>
</tr>
<tr>
<td>0.4</td>
<td>8 ± 1</td>
<td>3 ± 1</td>
<td>8/87</td>
</tr>
<tr>
<td>0.8</td>
<td>12 ± 4</td>
<td>1.1 ± 0.3</td>
<td>2/87</td>
</tr>
<tr>
<td>1.0</td>
<td>25 ± 5</td>
<td>2 ± 1</td>
<td>2/87</td>
</tr>
<tr>
<td>1.5</td>
<td>20 ± 5</td>
<td>4 ± 1</td>
<td>2/87</td>
</tr>
</tbody>
</table>

Fig. 4. Digitized beam shape monitor at the end of the linac used for maintaining linac conditions. The left images are used to monitor the vertical phase space of the electrons, the right images the horizontal. This monitor uses less than one percent of the linac pulses at 120 Hz.

appear. Improvements to the damping rings should reduce this effect. Thus, the apparent emittance increase above $10^{10}$ particles will improve.

An online monitor of the beam shapes at the end of the linac has been built. Four off-axis profile monitors and four low repetition rate pulsed dipoles sample the beam at one hertz. The resulting images of the beam shapes are digitized and stored. The images are used by the operators to verify that linac conditions have not changed. The screens were installed so that pairs of monitors were 90 degrees in betatron phase space apart allowing a good check of the phase ellipse orientation of both planes of both beams. An example of this display is shown in Fig. 4.

Many checks of the transverse and longitudinal wakefields⁸,⁹ in the linac have been made. The measured effects agree with the predictions to within a factor of two. One of the tests is particularly enlightening displaying the fact that the head of the bunch transversely drives the tail of the bunch. The beam is made to oscillate vertically using a dipole near the front of the linac. Thus, vertical wakefield
effects should increase the vertical size of the beam. To separate the head from the tail, the bunch was accelerated off the crest of the RF waveform so that the head of the bunch had more energy after acceleration than the tail. The head and the tail were then separated at the end of the linac by bending the beam into the beginning of the arc where there is horizontal dispersion. The beam was viewed by a profile monitor. The image on the screen shows energy horizontally and betatron motion vertically. The experimental setup is shown in Fig. 5. The results are shown in Fig. 6. As the dipole magnet was varied up and down, the head of the beam did not change position very much but the tail, driven by wakefields, moved dramatically and with the same sign as the dipole. Furthermore, it is clear that the particles in each longitudinal 'slice' of the bunch are driven in the same way and no internal growth of emittance in each slice is present. This fits theory very nicely.

![Diagram](image)

**Fig. 5.** Experimental setup for wakefield test in Fig. 6.

The launch of both positrons and electrons into the linac from the damping rings and into the arcs from the linac must be controlled with feedback systems. Presently the position and angle of electrons into and out of the linac are controlled once per minute by so-called slow feedback processes. The energy is also controlled once per minute. The processes for positrons are now just starting to be commissioned. A fast feedback on the energy of the electrons operating on a pulse basis has been shown to work well and is now being incorporated in the online control system. Fast pulse-by-pulse feedback on the positron energy and the wakefield induced beam tails is under development. It is expected in the fall.

7. **ARCS**

The north arc (electrons) has been under continual study since December 1986. The south arc (positrons) has been studied only briefly in March during the two beam collision test.

The goals for the arcs are to transport the SLC beams to the final focus without loss and without increasing the beams' emittances and to provide suitable betatron and dispersion functions at the end which are correctable by finite adjustments in the final focus. Electrons have been transmitted to the
Fig. 6. Experiment demonstrating that the bunch head drives the tail due to transverse wakefields.

The goal to provide correctable betatron and dispersion functions has not been met. Part of the problem of the beam mismatch is due to changing conditions in the linac and to magnet alignment problems in the linac-to-arc transition region. However, substantial errors arise from problems in the arcs. Mechanical hysteresis, binding, shaft slipping, and ball and socket alignment problems of the magnet movers make trajectory correction uncertain and irreproducible. Solutions for most of these problems are in hand, and corrections are being made. Some of the beam position monitor cables have intermittent connections which cause non-apparent 3 mm offsets in the readouts. The combination of discrete rolls of the achromats in the arcs (planned) and errors in the phase advance per cell (unplanned) causes horizontal-vertical coupling which mixes the phase space of the beam and can produce betatron amplification. An example of this is shown in Fig. 8 where a vertical mover in achromat N04 was changed to produce a vertical betatron oscillation. After several achromats, a horizontal oscillation appears and grows quite large by the end of the arc. Horizontal to vertical coupling is also observed. The solution
to this problem is to correct the phase advance per cell locally for each achromat. Phase correction is complicated by the sextupole term in the arc magnets and the movement procedure of the magnets but has been successfully applied to several achromats.

Fig. 7. Electron trajectory in the north arc correct by an automatic procedure using the magnet movers.

Fig. 8. Betatron coupling in the north arc caused by uncorrected phase advances per achromat.

8. **FINAL FOCUS**

In February 1987, the installation of the magnets, controls and instruments needed to transport both beams to the collision point was completed. Only a few components required to take the beams to their respective dumps and several collimators remain to be installed. In March, a program was undertaken to accelerate both positrons and electrons and pass them through the collider hall on the
same linac cycle. This goal was reached on March 27, 1987, at 4:45 p.m. when $4 \times 10^9$ electrons and $4 \times 10^8$ positrons passed through each other. A photograph of the two beams as seen on a position monitor at the interaction point is shown in Fig. 9. Both beams had energies of 46 GeV. The beam sizes were too large to make an interesting luminosity, but the event marked the end of the SLC construction.

![Image](image)

**Fig. 9.** Signals on the beam position monitor at the interaction point showing electrons (left) and positrons (right) colliding on the same linac cycle.

The areas of work underway are the reduction of beam induced noise in the beam position monitors, beam trajectory and transmission correction and betatron and dispersion matching of the beam from the north arc. A typical beam trajectory in the later north arc and the final focus is shown in Fig. 10. Studies soon to start include size, angle and chromatic shape corrections of the electrons at the collision point. At present the smallest spot sizes measured are 100 microns horizontally and 30 vertically. A moving wire scanner was used to determine the beam size. These large beam sizes are believed to be caused by mismatched dispersion and betatron functions exiting the north arc.

The present instruments at the intersection point include a screen profile monitor (40 micron resolution), an x-y wire scanner (20 and 7 micron wires), and a position monitor (50 micron resolution). After the MKII is installed, there will be an x-y wire scanner at the IP with seven micron wires, a vertex beam position monitor with about 100 micron resolution, beamsstralung monitors for both beams and equipment for measuring beam-beam deflections. Instruments located at low betatron functions outside the immediate collision region to measure the beam shape are under investigation.

9. **SLC FUTURE PLANS**

The general plan for commissioning the SLC as of June 1987 is to concentrate on electron studies in the north arc and final focus to produce an acceptable beam (size and background) for collisions and, as time allows, to pursue increased positron production, positron intensity in the south damping ring
and two-beam trajectory correction in the linac. Studies to provide stable beams through feedback are included as needed by the program.

If all the best parameters so far achieved at the SLC (not measured at the same time) are used to calculate a present possible luminosity, a luminosity of $2 \times 10^{25}$ cm$^{-2}$ sec$^{-1}$ is calculated. The details of this calculation are shown in Table 3. Three hundred times that luminosity is needed to produce fifteen $Z^0$ per day, the signal point for installing the MKII detector. The parameters needed to achieve $6 \times 10^{27}$ cm$^{-2}$ sec$^{-1}$ are also shown in Table 1. The main advance must be in the beam cross section. The milestones for achieving this luminosity are 1) to produce a 4 micron beam spot, 2) make $10^{10}$ particles ($e^+, e^-$) stable in the linac, 3) align both beams in the interaction region, 4) get high current beams to the collision point, 5) increase the repetition rate to 120 Hz, and 6) reduce beam halo and backgrounds. The expected rate of progress suggests that the detector will be installed in early fall.

Table 3.

<table>
<thead>
<tr>
<th>Luminosity projections, $L = \frac{N^+ N^- f}{4\pi \sigma_x^* \sigma_y^*}$</th>
<th>$N^+ \times 10^{10}$</th>
<th>$N^- \times 10^{10}$</th>
<th>$f$ (Hz)</th>
<th>$\sigma_x^*$ ($\mu$m)</th>
<th>$\sigma_y^*$ ($\mu$m)</th>
<th>$L$ cm$^{-2}$ sec$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible June 21, 1987:</td>
<td>1</td>
<td>1</td>
<td>60</td>
<td>100</td>
<td>30</td>
<td>$2 \times 10^{25}$</td>
</tr>
<tr>
<td>Expected Fall 1987:</td>
<td>1</td>
<td>1</td>
<td>120</td>
<td>4</td>
<td>4</td>
<td>$6 \times 10^{27}$</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

The authors acknowledge the discussions with many people which have entered into this report on the status of the SLC. We thank K. Bane of the Damping Ring Group for providing Figure 3. The Operations Group has been particularly helpful in the commissioning effort of the SLC.

* * *

REFERENCES


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Discussion

U. Amaldi, CERN

You have by now a lot of experience in getting bunches having $\epsilon_n \sim 2 \times 10^{-5}$ m through a long accelerator. Could you comment on how you see the performance of the same operations 10 years from now, at linear colliders with $\epsilon_n \sim 2 \times 10^{-6}$ m, $\epsilon_n' \sim 2 \times 10^{-7}$ m, $\epsilon_n \sim 2 \times 10^{-8}$ m.

Reply

Our main observations have been made using two dimensional phosphor profile monitors which have a 30-50 micron resolution. With emittances several orders of magnitude below $3 \times 10^{-5}$ m, new instruments need to be made to work at that size. Also, work will be needed to improve beam position monitor absolute and relative accuracies. Two-dimensional profile monitors are better than one-dimensional monitors (wire scanner) as the pulse-by-pulse shape changes and non-gaussian tails make one-dimensional measurements less useful. Furthermore, second-order effects of the beam shape have not yet been addressed and may provide new tolerances.
WORKING GROUP 1

SEMI-CONVENTIONAL HIGH-FREQUENCY LINACS
SUMMARY OF WORKING GROUP 1
ON "SEMI-CONVENTIONAL" HIGH-FREQUENCY LINACS

W. Schnell,
CERN, Geneva, Switzerland

A.M. Sessler,
LBL, Berkeley, California, USA

Participants in Working Group
M. Allen, B. Aune, M. Barletta, J. Bayless, V. Bobylev, D. Boussard,
T. Garvey, G. Geschonke, H. Henke, D. Hülsmann, R.A. Jameson, D. Keefe,
E. Laziev, P. Lapostolle, F. Leboutet, P. McIntyre, A. Mosnier, J. Nation,
W. Neumann, C. Pagani, R. Palmer, R. Ruth, U. Schryber, J. Seeman,
J. Sheppard, T. Shidara, D. Sutter, P. Tallerico, M.Q. Tran, F. Willeke,
C. Willmott, J. Wurtele, S. Yu

1. INTRODUCTION

Radio-frequency linear accelerators consist of two main parts: the accelerating structure and the source of rf power. The first topic includes all questions of type of structure, choice of frequency, wake fields, alignment tolerances, focusing and the choice of basic collider parameters. The second topic includes different types of dc to rf power converters and two-beam schemes. Our discussions proceeded along these main lines.

There was complete agreement that a superconducting main accelerating structure would be the ideal solution if it could be given an accelerating gradient at least approaching 100 MeV/m at acceptable refrigeration power. Basic development work on rf superconductivity (including the new high-temperature materials) should be much encouraged, therefore. However, given the very limited gradients obtained with present-day technology and proven materials the discussion then turned to normal-conducting (Cu) main structures exclusively. Superconducting cavities are, however, interesting candidates for drive linacs in two-beam schemes.

2. ACCELERATING STRUCTURES

There appeared to be a complete consensus that travelling-wave structures are the best choice for the main linac. The reasons are not fundamental but the practical advantages over standing-wave structures make travelling waves the method of choice at the high frequencies and short fill times required in an rf linear collider.
The well-known disc-loaded guide is still a good choice of structure at the
high frequencies considered here as it offers a good compromise — probably the
best obtainable — between the conflicting requirements of high shunt impedance, high shunt impedance over Q, low ratio of peak-to-axial fields and acceptable wake fields requiring the largest possible aperture. Disc-loaded structures for up to 35 GHz have been made and tested. Fabrication may be by electroforming or by brazing techniques. Assembly from radial, comb-like, segments spanning the full length of a section has also been proposed.

At any chosen frequency the beam-aperture (which is also the coupling aperture) should be increased over scaled dimensions from existing linacs, although this means a sacrifice in shunt impedance and peak-to-accelerating field ratio. The main reason is the predominant role of the beam-induced accelerating wake fields discussed below. Another reason is the need of a high group velocity required to arrive at a reasonable section length in spite of a short fill time.

Interesting variants of the disc-loaded guide may have asymmetric apertures (even slits, thus forming a "muffin-tin structure") for creating anisotropic wake fields or for rf focusing or side-slit propagating deflecting modes. This will be discussed below.

3. **THE CHOICE OF FREQUENCY**

Normal-conducting accelerating structures have to be pulsed and cannot conserve stored energy from one pulse to the next. Therefore an upper limit to the rf-to-beam efficiency of energy transmission is the fraction \( \eta \) of stored energy extracted by a beam pulse. This fraction is given by

\[
\eta = \frac{eNur'}{E_0} \left( \frac{E_{\text{acc.}}}{E_0} \right)
\]

where the term in brackets (the ratio of actual accelerating field \( E_{\text{acc.}} \) over the field \( E_0 \) at vanishing beam loading) will always be made close to unity. The pulse population \( N \) (the bunch population in single-bunch operation) is limited by beam-beam interaction in the final focus and is in the 0.5 to \( 1 \times 10^{10} \) range in most designs. The shunt impedance per unit length over Q, \( r' \), is proportional to frequency \( \omega \) making \( \eta \) proportional to \( \omega^2/E_{\text{acc.}} \).

Thus, inescapably, reaching a high accelerating gradient at good efficiency implies going to the highest frequency possible.
The choice of frequency is, however, conditioned by other considerations, Table 1 giving an overview. The most serious limitation to an increase of frequency comes from wake fields.

Table 1
Considerations in the choice of frequency

1. Acceleration gradient $\sim f^{7/8}$ (high frequency preferred)
2. Peak power $\sim f^{1/2}$ (high frequency preferred)
3. Average power $\sim f^2$ (high frequency preferred)
4. Efficiency $\sim f^2$ (high frequency preferred)
5. Structure fabrication complexity (low frequency preferred)
6. Wake-field effects $W_L \sim f^2$ $W_T \sim f^3$ (low frequency preferred)

4. WAKE FIELDS

Each bunch induces longitudinal and transverse-deflecting wake fields as it passes through the accelerating structure. The wakes left behind by downstream particles act on the upstream part of the same bunch. Longitudinal wakes lead to energy loss and energy spread. Dipole wakes may amplify accidental transverse oscillations (due to misalignment of accelerating structures or quadrupoles) so as to cause severe emittance blow-up or even beam loss.

For given structure geometry longitudinal wake potentials scale with $\omega^2$, transverse ones with $\omega^3$; however it is more logical to scale at fixed aperture, since the wakes depend almost entirely on aperture and other parameters change only slowly with frequency at fixed aperture.

Up to at least 30 GHz - generally considered an upper practical limit for the choice of frequency - the effects of transverse wakes can be cancelled by the introduction of a large spread in transverse wave number ("Landau damping"). This spread is most naturally obtained via the natural chromaticity of the focusing lattice by creating or tolerating an energy spread. A large spread might also be obtained directly, without requiring a concomitant energy spread, by rf focusing. In any case, however, a large spread in transverse wave numbers within the bunch aggravates the problem of alignment tolerances, discussed below.
5. ALIGNMENT TOLERANCES

The focusing elements along the linac have to be kept aligned within very tight tolerances in order to conserve the minute values of normalized transverse emittance (from a few times $10^{-6}$ m down to a few times $10^{-8}$ m) required in a linear collider. An automatic control system, sampling orbits during a few beam pulses and correcting subsequent ones, is required in any case. Pulse-to-pulse jitter is not felt to be a fundamental problem in view of the rapid decrease of amplitude with frequency in typical spectra of ground vibration.

If the spread of transverse wave numbers within the bunch is small an orbit deviation of many times the transverse beam radius can be allowed before eventual measurement and correction. If, however, the fractional spread of wave numbers is large, an initially coherent oscillation rapidly smears out into irrecoverable emittance blow-up. To avoid this, a tolerance smaller than the beam radius - of the order of a micrometre - has to be kept and it has yet to be demonstrated that this is possible in practice. This is, in fact, the situation around 30 GHz accelerating frequency where the damping of transverse wake fields requires transverse spreads of several per cent at least.

6. COLLIDER PARAMETERS

The considerations concerning the choice of frequency, wake fields and tolerances have led to two typical choices of parameters, given in Table 2.

<table>
<thead>
<tr>
<th>Energy per linac</th>
<th>500</th>
<th>1000</th>
<th>GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>$\omega/2\pi$</td>
<td>17</td>
<td>29</td>
</tr>
<tr>
<td>Alignment tolerance (approx.)</td>
<td>40</td>
<td>1</td>
<td>(\mu)m</td>
</tr>
<tr>
<td>Energy extraction</td>
<td>$\eta$</td>
<td>1.2</td>
<td>8</td>
</tr>
<tr>
<td>Bunch population</td>
<td>N</td>
<td>$8\times10^9$</td>
<td>$3.4\times10^9$</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>$f_{\text{rep}}$</td>
<td>200</td>
<td>5000</td>
</tr>
<tr>
<td>Beam power</td>
<td>$P_b$</td>
<td>0.13</td>
<td>5</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>$\epsilon_{\text{xy}}$</td>
<td>$2.5\times10^{-6}/2.5\times10^{-8}$</td>
<td>$3\times10^{-6}$</td>
</tr>
<tr>
<td>Amplitude function at collision point</td>
<td>$\beta^*$</td>
<td>20/0.04</td>
<td>3</td>
</tr>
<tr>
<td>Beam size at collision point</td>
<td>$\sigma_{x,y}^*$</td>
<td>190/1</td>
<td>65</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z$</td>
<td>26</td>
<td>300...500</td>
</tr>
<tr>
<td>Energy spread (after correction)</td>
<td>$\Delta E/E^*$</td>
<td>0.15</td>
<td>0.5...2</td>
</tr>
<tr>
<td>Luminosity</td>
<td></td>
<td>$1.3\times10^{33}$</td>
<td>$1.0\times10^{33}$</td>
</tr>
</tbody>
</table>
The first choice (pertaining to a possible SLAC collider for which 11.4 GHz frequency is also being seriously considered) puts the main emphasis on feasible linac alignment tolerances and a small final energy spread, so as to facilitate the design of the final focus system. This design features a 100/1 horizontal-to-transverse emittance ratio, a very flat beam at the final focus and a short bunch. On the other hand, the low energy extraction and concomitant low beam power lead to very small values of the vertical emittance, of the vertical value of $\beta^*$ and, especially, of the height of the final beam spot.

The second choice (for CLIC at CERN) emphasizes high rf-to-beam efficiency and beam power at the expense of very tight transverse tolerances along the linac.

It will be noted that the divergence of opinion about the choice of frequency has shrunk to about a factor of two. The choice is, however, influenced by one's preference for a particular power source, individual dc to rf converters being favoured by a low frequency, two-beam schemes by a high one.

7. MULTIBUNCHING

Other things being equal the luminosity could be increased by a substantial factor if multiple bunches per beam pulse could be employed. It appears, however, that regenerative beam break-up due to wake fields makes this very difficult. To overcome this problem a proposal was made to equip the accelerating structure with longitudinal slits in the outer wall, so as to let transverse deflecting modes be propagated away. Transverse Q factors will have to be depressed to values of a few tens at most, but this does not seem impossible. The longitudinal slits might be created by assembling an accelerating section from precision machined comb-like segments.

8. FOCUSING

The problems of transverse focusing and concomitant diagnostics were discussed. Permanent magnet quadrupoles form a convenient solution but pose problems if - as is likely - an energy range of more than two-to-one has to be covered without major reconstruction.

Radio-Frequency Quadrupole (RFQ) focusing, by means of asymmetric apertures being placed alternately vertically and horizontally at suitable period lengths, would obviate the need for precision quadrupoles and give a large energy range automatically. The RFQs might provide their own diagnostics in the form of beam-induced higher modes. The main feature of rf focusing is a very large spread of transverse wave numbers within the bunch. This might be seen as an advantage (for damping the wake fields) or a disadvantage (for tolerances) depending on the parameters chosen.
9. DC TO RF POWER CONVERTERS

Traditionally linear accelerators are powered by a large number of dc to rf power converters distributed along the linac. In order to extend this scheme to the higher frequency, shorter pulse and much higher total peak power of a linear collider a large variety of solutions has been proposed, including: Klystrons, Sheet Beam Klystrons, "Klystrinos" (small klystrons merged with the accelerating structure), Lasertrons, Microlasertrons, Ribbon Lasertrons, Free Electron Lasers, Cyclotron Auto Resonance Masers etc.

A Gyroklystron for 10 GHz and 40 MW, with a pulse length of 2 μs, is under development at Maryland University. It is expected that this tube will have a gain of 60 dB and be more than 45% efficient. It is expected to achieve 1% rf phase stability. Extension to 100-300 MW should be possible in the next generation (which will not differ significantly from the tube presently under development).

Radio-frequency pulse compression must be added to convert excess pulse length into increased peak power (SLAC). Note, however, that pulse compression requires very long lengths of low-loss waveguide. Thus 1 μs requires ~1,000 ft per compression unit. Pulse compressions are needed for regular klystrons and for gyrotrons.

A FEL has given well over 1 GW pulse power at 35 GHz, and with a pulse width (determined by the drive beam) of 15 ns. The efficiency of conversion from beam power to rf power was 40%. Thus the FEL has already been demonstrated (in contrast with the other schemes considered here) to produce copious amounts of power.

Lasertrons, albeit at frequencies below 10 GHz, are under development at KEK, LAL, Orsay and SLAC. The lasertron demands a very good vacuum (so as to maintain the photo cathode) and, hence, necessitates "windows" for the rf and careful vacuum techniques. Whether or not modulators are required, so as to be able to hold the accelerating voltage, is still to be determined. Since a major aspect of the lasertron concept is to do away with the modulators (so as to save on cost), it is important to settle this point. Above 10 GHz a sheet-beam-lasertron is required (so as to break the typical scaling law of all tube-like devices and get large power from the lasertron). Development work on this concept is under way in Texas.

A SLAC/LLNL/LBL collaboration aims at employing the beam from a 1.5 MeV induction unit for klystron-type power generation in the 10 GHz range. This might be viewed as a transition to the Relativistic Klystron Two-Beam scheme described below. A common problem with individual dc to rf converters is the very large number of converters required to power a typical collider.
10. **TWO-BEAM ACCELERATORS**

Instead of the multitude of pulsed dc generators, cathodes and electron guns, a continuous drive beam running along the main linac (or at least a good fraction of it) may be employed. The drive beam supplies energy to the main linac at regular intervals via transfer structures. The drive beam energy is restored, at the same or different intervals, by accelerating structures forming a "drive linac". Free electron lasers (FEL) and direct rf decelerating sections have been proposed as transfer structures, induction units and superconducting rf accelerating cavities as drive linacs.

In the original Two Beam Accelerator (Fig. 1) of LBL/LLNL the drive linac is formed by induction units and the transfer structure by FEL wigglers, the microwave radiation being collected in an overmoded smooth waveguide. Pulsed power at the gigawatt level has indeed been extracted from an FEL unit and a five-cell high gradient structure has been powered to 180 MV/m. Difficulties are being encountered with phase control, microwave extraction from the waveguide and the necessity of letting the collector waveguide traverse the gaps of the induction unit.

These difficulties might be avoided by bunching the low-energy drive beam and extracting energy by means of the longitudinal fields of resonant cavities, this scheme being called the Relativistic Klystron (Fig. 2). Longitudinal and transverse beam dynamics and transfer cavity design are being studied at LLNL/LBL.

Superconducting cavities at low UHF frequency (Fig. 3), drive beam energies in the gigavolt range and travelling wave sections as transfer structures are the main features of the Two-Stage rf scheme studied at CERN. The superconducting drive cavities hold the promise of high efficiency, even energy recuperation from the high gradient structure. The ultra-relativistic drive beam avoids all problems of phase control and the complications of longitudinal dynamics, provided the tightly bunched high energy drive beam can be efficiently generated. The travelling-wave transfer structure is under study at CERN; Fig. 4 shows a scale model.

11. **CONCLUSIONS**

During the last few years impressive progress has been made in understanding the details of radio-frequency linear colliders. The consensus of opinion about basic design parameters has sharpened to about the span covered by Table 2. The most fundamental outstanding questions concern the choice of rf power source from a large variety of proposals and the general problem of transverse alignment tolerances throughout the linac and in the final focus.
The Two Beam Accelerator (TBA) consists of a high power microwave FEL and a high gradient linac.

Fig. 1 Two-beam accelerator consisting of induction units as drive linac and FEL undulators as transfer structure.

Schematic of a relativistic klystron

Fig. 2 Relativistic klystron consisting of induction units as drive linac and decelerating cavities as transfer structure.
SCHEMATIC VIEW OF S.C. CAVITY AND CRYOSTAT MODULE

Fig. 3 Four-cell, 350 MHz, superconducting cavity (the LEP 2 prototype) suitable for an RF drive linac.

Fig. 4 Scale model of a travelling wave transfer cavity developed at CERN.
Discussion

H. Hora, Sydney

Since there was the question about wiggler-free FELs, I would like to mention the scheme of inverting our experiment [1] where up to 80% efficiency can be achieved from pumping the laser amplifier by the kinetic energy of electrons or clusters, radially injected into the laser pulse [2].


K.-J. Kim, LBL

Are copper linacs thought to be better than superconducting linacs at the present time?

Reply

Currently, superconducting linacs do not have enough gradient, and thus are not practical. The room temperature superconductor might be promising for high gradient in the future, but nobody knows yet.
BEAM DYNAMICS ISSUES FOR LINEAR COLLIDERS

Ronald. D. Ruth
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

ABSTRACT

In this paper we discuss various beam dynamics issues for linear colliders. The emphasis is to explore beam dynamics effects which lead to an effective dilution of the emittance of the beam and thus to a loss of luminosity. These considerations lead to various tolerances which are evaluated for a particular parameter set.

1. INTRODUCTION

In this paper we study the beam dynamics issues relevant to the preservation of the effective emittance or luminosity of a linear collider. It is convenient to divide the accelerator into several discrete sections. First we have a damping ring for the production of the transverse and longitudinal emittance at the appropriate intensity. The bunch then must be prepared for injection into the main linac with at least two bunch rotations and a pre-acceleration at some sub-harmonic of the linac frequency. Next comes acceleration by the main linac, and finally the final focus to focus the beams to a small spot for collision. In this paper the focus is entirely on the main linac. All of the other sub-systems have similar beam dynamics problems but these will not be discussed here.

In the first section the equations of motion are introduced along with the smooth approximation. In Section 3 we discuss the chromatic effects on the central trajectory. We examine the effect of coherent betatron oscillations in the absence of wakefields and also look at the effects of misaligned quadrupoles and trajectory errors. Transverse wakefields and beam break-up are discussed in Section 4 where the two particle model is used to derive a criterion for ‘Landau damping’ the instability. In Section 5 we turn pulse to pulse changes or jitter. This does not change the emittance of the beam, strictly speaking, but rather has the effect of causing the beams to miss each other at the interaction point. Various possible sources of jitter are considered. Finally in the last section we apply the results to a specific example.

2. THE EQUATIONS OF MOTION

The equations of motion for the transverse displacement of a particle in a constant magnetic field are given by

\[
\frac{d^2 z}{dt^2} + \frac{p_0 K(s)x}{p} = \frac{e \Delta B}{pc}
\]  \hspace{1cm} (2.1)

where \(K(s)\) is the focusing function, \(\Delta B\) is the bending field on the design orbit including all errors and corrections, \(p_0\) is the design momentum, and \(p\) is the momentum of the particle. In (2.1) the variation of the momentum due to acceleration has been neglected. This can be taken into account by adiabatic

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damping and will be included when relevant. It is convenient to define

$$\delta \equiv \frac{p - p_0}{p}$$  \hspace{1cm} (2.2)$$

which is a measure of the deviation of the momentum from the design momentum. With this change Eq. (2.1) becomes

$$x'' + K(s)(1 - \delta)x = \frac{(\delta - 1)}{\rho(s)},$$  \hspace{1cm} (2.3)$$

where $\rho(s)$ is the actual instantaneous bending on the design orbit for a particle of the design momentum including all errors and corrections.

The solution of Eq. (2.3) contains all the information necessary to evaluate the effects of errors and their corrections on the effective emittance of the beam in the absence of transverse wakefields.

To motivate the analysis and to make a connection with the standard approach consider the case when $\delta = 0$. In this case the solution of Eq. (2.3) is usually split into two parts, a solution of the inhomogeneous equation plus a solution of the homogeneous equation as follows:

$$x = x_\beta(s) + x_0(s)$$  \hspace{1cm} (2.4)$$

where $x_\beta$ and $x_0$ satisfy

$$x''_0 + K(s)x_0 = -\frac{1}{\rho(s)}$$

$$x''_\beta + K(s)x_\beta = 0.$$  \hspace{1cm} (2.5)$$

In a storage ring $x_0$ is the closed orbit and is uniquely defined by the requirement that it be periodic. The betatron oscillation, $x_\beta$, is centered on the closed orbit. The rms emittance $\epsilon$ of the beam of particles is related to the betatron amplitude by

$$\langle x_\beta \rangle^2_{\text{rms}} = \sigma_\beta^2 = \beta(s)\epsilon$$  \hspace{1cm} (2.6)$$

where $\beta(s)$, the Courant-Snyder amplitude function, is a periodic function of $s$ since the particle encounters the magnetic lattice periodically as it circulates in the storage ring.

In the case of a linac one can once again split the solution of Eq. (2.3) into the two parts shown in Eq. (2.5). In this case the solution of the inhomogeneous equation is uniquely specified by the initial position and slope rather than the requirement of periodicity. For this reason we refer to this as the central trajectory. However, if the beam is extracted from a damping ring then the initial conditions for the central trajectory are determined from the value of the closed orbit in the damping ring at the extraction point.

For the solution to the homogeneous equation it is sometimes useful to introduce a beta function for the linear accelerator in analogy to the beta function for a circular accelerator. However, in this case the beta function is determined by the initial conditions rather than the requirement of periodicity. This leads to questions of matching and for an ill-defined source can lead to some ambiguity. But in the case of a linear accelerator with a damping ring injector, the beta function in the linear accelerator is uniquely defined by the periodic lattice parameters ($\beta$ and $\beta'$) of the damping ring at the extraction point. More precisely, the beta function is uniquely defined by the magnetic elements in the damping ring and linear accelerator independent of the beam being transported.
In the approximation of linear magnetic focusing and $\delta = 0$, there is in principle no emittance dilution; however, if there are mismatches in the linear optics which are outside the range of correction elements, this can lead to an effective increase in the eventual spot size at the final focus. In addition, if the magnetic elements vary in position or field from pulse to pulse then this causes the central trajectory to vary from pulse to pulse and thus cause an effective increase in the emittance. The effects of this *jitter* will be treated in Section 5.

For the case of nonzero $\delta$ it is useful to deviate slightly from the standard practice of defining a dispersion function $D(s)$. In this case we simply split the motion as before except that $x_0$ and $x_0$ satisfy

$$x_0'' + K(s)(1 - \delta)x_0 = \frac{(\delta - 1)}{\rho(s)}$$

$$x_0' + K(s)(1 - \delta)x_0 = 0.$$  \hspace{1cm} (2.7)

Thus, the central trajectory has a chromatic dependence (as does the betatron oscillation about that orbit). In the next section we examine the effective emittance dilution from these chromatic effects.

3. CHROMATIC EFFECTS

The chromatic effect on the betatron oscillations, the homogeneous equation, is rather small in the linac. For this reason we treat only the equation for the central trajectory in this section. To study the chromatic effects on the central trajectory it is useful to smooth the focusing system while keeping the discrete nature of the bending errors and corrections. Thus, Eq. (2.7) is replaced by

$$x_0'' + k^2(1 - \delta)^2x_0 = \frac{(\delta - 1)}{\rho(s)}$$ \hspace{1cm} (3.1)

where $k$ is the betatron wave number and is related to the average beta function by

$$k = \frac{1}{\beta}.$$ \hspace{1cm} (3.2)

3.1 THE CHROMATIC EFFECT OF A COHERENT BETATRON OSCILLATION

The solution of Eq. (3.1) leads to a chromatic central trajectory. Particles of different momentum travel on different orbits down the linac. As we shall see most of the chromatic dilution of the emittance comes from the variation of the betatron phase advance with momentum rather than from the spectrometer effect of the bending fields on the design orbit. To see this consider the effect of one single misplaced quadrupole (or some other localized bending field). For this single kick the bending radius is given by

$$\frac{1}{\rho(s)} = \delta(s - s_i),$$ \hspace{1cm} (3.3)

where $\delta(s)$ is the Dirac delta function. If we assume an unperturbed trajectory upstream of the kick, then the solution of Eq. (3.1) is given by

$$x_i = \Theta(s - s_i)\frac{\theta_i}{k(1 - \delta)}\sin[k(1 - \delta)(s - s_i)] .$$ \hspace{1cm} (3.4)

where $\Theta(s)$ is the step function.
To understand the basic mechanism of the dilution of emittance due to the chromatic central trajectory, it is useful to study this simplified model somewhat. To do this consider three test slices of the beam in momentum at \( \delta = 0, -\sigma_t, \sigma_t \). In the absence of chromatic effects the central trajectory is simply a coherent betatron oscillation. In the presence of energy spread the different slices in momentum slowly get out of phase since the trajectories oscillate at slightly different frequencies. Consider the three slices mentioned above at a distance down the linac given by

\[
s = s_t + \frac{\pi}{2k\sigma_t} .
\]  

(3.5)

In this case the slices at \( \pm \sigma_t \) have moved \( \mp \pi/2 \) in phase, and thus if the initial orbit size is larger than the beam size, the beam emittance is greatly diluted.

Before going any further it is possible specify a tolerance condition on an uncorrected betatron oscillation of the central trajectory. If the chromatic variation of the phase advance of the beam is greater than or the order of unity, then the peak of an uncorrected betatron oscillation, \( \bar{z}_0 \), must be locally smaller than the beam size to avoid emittance dilution. Generally,

\[
\text{If } \delta \int_0^L \frac{ds}{\beta(s)} \gg 1 ,
\]

then \( \bar{z}_0 \ll \sigma_\beta . \)

(3.6)

In the case of a small chromatic effect we can estimate the tolerance to first order in \( \delta \) by using Eq. (3.4). The chromatic part of the orbit is then given by

\[
x_t(\delta) - x_t(0) = \Theta(s - s_t) \bar{\delta} k(s - s_t) \cos k(s - s_t) .
\]

(3.7)

At the end of the linac this effect must be small compared to the beam size to avoid dilution of the effective emittance. This leads to the tolerance for an uncorrected betatron oscillation for weak chromatic effects:

\[
\text{If } \delta \int_0^L \frac{ds}{\beta(s)} \ll 1 ,
\]

then \( \bar{z}_0 \ll \frac{2\sigma_\beta(L)}{\delta \psi N_q} . \)

(3.8)

where \( \psi \) is the phase advance per cell, \( N_q \) is the number of quadrupoles in the linac, and \( \sigma_\beta(L) \) is the beam size at the end of the linac. In this case the chromatic tolerance has been weakened. In addition, since by assumption the effect is small and therefore linear in \( \delta \), it can be measured and possibly corrected.

### 3.2 The Chromatic Effect of a Corrected Orbit

Now we would like to calculate the effect of a set of random misalignments of quadrupoles which, however, have been corrected so that the beam orbit is within some tolerance. It is important to emphasize that these are fixed misalignment errors corrected by fixed correctors. The case of pulse to pulse alignment jitter, which cannot be corrected by fixed corrector settings, will be discussed in Section 5.
A distinguishing characteristic of the corrected orbit is that it does not grow as we proceed down the linac because correctors are used to suppress the growth. This is not true of an uncorrected random alignment error which yields an ever growing orbit. The key difference here is that the errors and correctors are correlated.

To model this effect, consider first the following problem. Consider a model linac (no acceleration) in which quadrupoles have a beam position monitor (BPM) in them and a corrector superimposed. In one quadrupole, let the BPM be misplaced relative to the quad center, and let all the quads be aligned perfectly. Steer the beam to zero the measured orbit. The perceived orbit is then a straight line; however, the actual orbit has a bump in it at the location of the misplaced BPM.

To achieve this apparently zero orbit, it was necessary to use 3 correctors, one at the bad BPM and the two adjacent to it. A particle with the nominal beam energy has a zero orbit for the rest of the linac; however, an off momentum particle has an orbit given to first order in $\delta$ by

$$x_\delta \equiv x(\delta) - x(0) = (\Delta x) \psi \delta \sin(ks(1 - \delta) - \psi/2), \quad ks > \psi$$  \hspace{1cm} (3.9)

where $\Delta x$ is the BPM placement error and $\psi$ is the phase advance for one cell.

Thus, off-momentum particles follow a non-zero trajectory which can lead to emittance dilution. To estimate the effect for a linac, consider a random sequence of misplaced BPM's and their associated orbit bumps and chromatic residuals. This leads to an orbit which because of the correlations does not grow with $s$. However, the chromatic effects do not cancel and so yield a net chromatic beam size. The orbit for an off momentum particle is given by

$$x_\delta = \sum_{i=1}^{N_e} (\Delta x)_i \psi \delta \sin(k(s - s_i)(1 - \delta) - \psi/2) \Theta(s - s_i - \psi/k)$$  \hspace{1cm} (3.10)

where $N_e$ is the number of quadrupoles in the lattice. The square of the beam size is given by

$$x_\delta^2 = \sum_{i,j}^{N} \Delta x_i \Delta x_j \psi^2 \delta^2 S_i S_j \Theta(s - s_i - \psi/2) \Theta(s - s_j - \psi/k)$$  \hspace{1cm} (3.11)

where $S_i$ stands for

$$\sin(k(s - s_i)(1 - \delta) - \psi/2).$$  \hspace{1cm} (3.12)

Now consider an ensemble average over an uncorrelated sequence of $\Delta x_i$'s. In this case only terms with $i = j$ in the sum contribute; which yields

$$\langle x_\delta^2 \rangle = \sum_{i=1}^{N_e} (\Delta x_i)^2 \psi^2 \delta^2 \sin^2(k(s - s_i)(1 - \delta) - \psi/2) \Theta(s - s_i - \psi/2)$$  \hspace{1cm} (3.13)

Replacing the sum with an integral, we obtain

$$\langle x_\delta \rangle_{\text{rms}} = (\Delta x)_{\text{rms}} \psi \delta \sqrt{\frac{N}{2}}.$$  \hspace{1cm} (3.14)

For the particular model chosen $(\Delta x)_{\text{rms}}$ is the rms BPM misalignment; however, it could have been either the quadrupole placement error or the rms error in the position measurement.
To specify a tolerance, we require that this effect be small compared to the beam size at the end of the linac, $\sigma_\beta(L)$. This yields a tolerance on $\Delta x_{rms}$ given by

$$\Delta x_{rms} < \frac{\sigma_\beta(L)}{\psi_0} \sqrt{\frac{2}{N}}$$  \hspace{1cm} (3.15)

Comparing with Eq. (3.8) the effect of a sequence of random corrected errors leads to a smaller dilution of the emittance than an uncorrected betatron oscillation and thus to much weaker orbit tolerances. Equation (3.15) is modified only slightly if adiabatic damping and taper of the beta function with energy is included. These effects are included in Section 5.

4. THE TRANSVERSE WAKEFIELD AND BEAM BREAK-UP$^1$

4.1 THE TRANSVERSE WAKE

Consider two particles travelling down a linac structure. If the leading particle is offset transversely, it induces a deflecting field behind it. This deflecting force is characterized by the transverse wakefield, the value of which depends upon the longitudinal distance behind the first particle. The typical shape is shown in Ref. 1 and consists of an initial rise from zero followed by oscillations. The kick felt by the trailing particle is given by

$$\frac{d^2x_2}{ds^2} = \frac{eW(x_2)x_1Q}{E}$$  \hspace{1cm} (4.1)

where $Q$ is the charge of particle 1, $x_1$ is the offset of particle 1, $x_2$ is the longitudinal separation of the two particles, and $E$ is the energy.

To scale the effect for different wavelengths, note that if we scale all dimensions

$$W = W^0 \left( \frac{\lambda_0}{\lambda} \right)^3.$$  \hspace{1cm} (4.2)

However, due to the shape of the longitudinal wake, the wakefield also depends sensitively on the separation of the two particles or more precisely on the length of the bunch being studied. Frequently, over a limited range, this dependence is approximated by a linear variation in the longitudinal separation or bunch length.

This decrease in the transverse wake for small distances can be exploited. If we scale to shorter wavelengths, the increase in transverse wakefield can be partially offset by a decrease in the bunch length (beyond simple scaling).

Another method for decreasing the transverse wake consists of opening the iris holes in the linac structure. The wakefield at short distance behind the bending particle is dominated by the closest piece of metal. The short wake is independent of the distance to the outer wall of the cavity. That is, if $a$ is the iris size in the linac, then

$$W(z << \lambda) = W^0(z << \lambda) \left( \frac{a}{a_0} \right)^3$$  \hspace{1cm} (4.3)

One must balance the transverse benefit of increasing the iris size with the increased rf power necessary to drive the structure.
4.2 Transverse Beam Break-up

To see the effects of the transverse wake, let us consider a two-particle model. We place 1/2 of the charge in the bunch into each macro-particle and separate the particles by a distance \( \ell \) which should be set to about 2\( \sigma_s \) when comparing to actual bunch distributions. The distance between the particles is fixed since they both travel at \( c \), the speed of light; therefore, the wakefield at the trailing particle is fixed. The equations of motion for the two particles in the presence of the external focusing system are

\[
x''_1 + k^2 x_1 = 0 \tag{4.4}
\]

\[
x''_2 + (k + \Delta k)x_2 = \frac{e^2 N W(\ell)x_1}{2E} \tag{4.5}
\]

where \( N \) is the total number of particles in the 2 macro particles, and \( W(\ell) \) is the wakefield at the second particle.

Notice that the external focusing has once again been smoothed as in Eq. 2.1, and the second particle feels a different focusing force characterized by the parameter \( \Delta k \). This might be due to a difference in energy from the front to the back of the bunch; in this case, Eq. 2.1 yields

\[
\Delta k = -\delta k \tag{4.6}
\]

More precisely, for a general lattice we need to evaluate an average chromaticity \( \xi \) defined by

\[
\frac{\Delta k}{k} = \xi \frac{\Delta E}{E} = \xi \delta \tag{4.7}
\]

For typical lattices \( \xi \) is close to -1, and thus the smooth approximation is not too bad.

It is also possible to vary the focusing function along the bunch by the use of RF focusing. This decouples the focusing field from the energy spread but couples it to position within the bunch.

Now let us consider the solution of Eq. (4.5) in which both particles have the same initial offset, \( \hat{x} \). For small \( \Delta k/k \), the solution for the difference between the transverse positions is given by

\[
x_2(s) - x_1(s) = \hat{x} \left( 2 - \frac{e^2 N W}{2Ek \Delta k} \right) \sin \left( \frac{\Delta ks}{2} \right) e^{i(k + \frac{\Delta k}{2})s} \tag{4.8}
\]

To study Eq. (4.8) it is useful to consider 3 different cases:

Case 1. \( \Delta k = 0 \)

In this case the difference grows linearly

\[
x_2(s) - x_1(s) = -i \frac{e^2 N W \hat{x} s}{4Ek} e^{iks} \tag{4.9}
\]

This yields an amplification factor given by

\[
\frac{x_2 - x_1}{\hat{x}} = \frac{e^2 N W s}{4Ek} \tag{4.10}
\]

The linear growth is simply due to a linear oscillation driven on resonance. In an actual beam, the growth of the tail of the beam is much faster and has been calculated in Ref. 2.
Case 2. $\Delta k \neq 0 \quad \Delta k$ very small.

In this case the linear growth is turned over leading to a maximum amplification factor of

$$\frac{x_2 - x_1}{h} = \left(2 - \frac{e^2 NW}{2Ek\Delta k}\right) \simeq -\frac{e^2 NW}{2Ek\Delta k}$$  \hspace{1cm} (4.11)

the growth stops at $s = \pi/\Delta k$ and there is a beating at the maximum amplitude.

Case 3. "Landau Damping"

In this case, if we examine Eq. (4.11), we see that the amplification can be set to zero provided that

$$\frac{e^2 NW}{4Ek\Delta k} = 1.$$  \hspace{1cm} (4.12)

This yields no growth at all; in fact simulations of actual beam distributions show genuine damping of the oscillation. This effect is loosely referred to as Landau damping; however, it is really only a cousin to Landau damping. Landau damping refers to the lack of growth of coherent oscillations when there is some uncorrelated spread in the oscillation frequencies of the particles in the bunch. In this case, we see the lack of growth of a particular mode of oscillation. Since the bunches in a linac are quite short, it is likely that offsets occur to both the head and tail simultaneously. If, however, the head and tail were offset on opposite sides of the axis, this exact cancellation would not take place, although the amplitude is limited by a factor similar to that in Eq. (4.11).

The lack of growth is simply due to a cancellation of forces. The wakefield force is exactly cancelled by the additional focusing force for a trailing particle of slightly lower momentum. It is useful to rewrite the condition for the case of momentum spread:

$$\frac{e^2 NW\beta^2}{8E\delta_\beta} = 1,$$  \hspace{1cm} (4.13)

In this case $\delta_\beta$ is the half spread in energy required for Landau damping and the average beta function $\beta$ has been used rather than the wave number $k$.

5. PULSE TO PULSE CHANGES: JITTER

In a linear collider the effective spot size can be enhanced by pulse to pulse changes in the central trajectory. It is obvious that these must be kept small compared to the beam size at the final focus or else the beams would never collide. In fact, it is the local beam size which sets the scale for this problem since the final focus de-magnifies the jitter of the spot as well as the spot itself. The time scale for jitter is set by the repetition rate. Slow changes which can be sampled well can be corrected by feedback, a technique which is used extensively at the SLC at SLAC. All those effects which happen too fast to be cured by feedback are lumped into the category of jitter.
5.1 INJECTION JITTER

Let us consider the position jitter as we enter the main linac. Consider an abrupt change of position $\Delta x_0$. Then to keep the head of the bunch colliding we require that

$$\Delta x_0 << \sigma_0(0).$$

(5.1)

where $\sigma_0(0)$ is the beam size at the beginning of the linac. If we are using Landau damping to suppress the growth of the tail, then this is the final story. Otherwise the tail effect may be amplified with the amplification factor in Eq. (4.11). If we trace upstream to the source of the jitter in the injector, then it must come from the time variation of some bending field leading to some variation in bending angle $\Delta x'_0$. In order for this to be a small effect it must be small compared to local divergence of the beam, that is

$$\Delta x'_0 << \frac{\sigma_0}{\beta}.$$  

(5.2)

Of course, if there are several sources of jitter, then these must be added together with the appropriate phases. The effect of large numbers of elements is considered in the next section.

5.2 QUADRUPOLE ALIGNMENT JITTER

If we consider the changes due to the motion of one quadrupole, then we arrive at the same conclusions as in the previous section since the betatron oscillation just propagates down the linac. Therefore, in the absence of Landau damping the tail is amplified according to Eq. (4.11). If we use Landau damping for the tail, then the growth of the tail is controlled; however, we still must control the head of the bunch.

For a general sequence of misalignments we must superimpose the betatron oscillation of each misalignment to obtain

$$x(s) = \sum_i q_id_i\beta_i \sin k(s-s_i) \Theta(s-s_i)$$

(5.3)

where $q_i$ is the inverse focal length of the $i^{th}$ quadrupole and $d_i$ is the change in the position of the quadrupole on the present pulse. In this equation we have smoothed the focusing and ignored acceleration. To include acceleration we must include the adiabatic damping of the betatron oscillations and also include the profile of quadrupole strengths and beta functions. For a general lattice the orbit due to a sequence of misalignments is

$$x(s) = \sum_i q_id_i[\hat{\beta}(s)\beta(s_i)]^{1/2} \left[ \frac{\gamma(s_i)}{\gamma(s)} \right]^{1/2} \sin[\psi(s,s_i)] \Theta(s-s_i)$$

(5.4)

where

$$\psi(s,s_i) = \int_{s_i}^{s} \frac{1}{\beta(s')} ds'.$$

(5.5)

To be specific let us consider a lattice in which

$$\beta(s) = \beta_0 \left[ \frac{\gamma(s)}{\gamma_0} \right]^{1/2}$$

$$q(s) = q_0 \left[ \frac{\gamma_0}{\gamma(s)} \right]^{1/2}.$$  

(5.6)
This scaling can be realized by scaling the length of the cell and the length of all quadrupoles as

\[ \ell_{\text{cell}} \propto \gamma^{1/2} \]  

which yields a phase advance per cell which is constant. This scaling of the beta function and integrated focusing strengths was selected because it yields a Landau damping criterion which is independent of energy. The orbit in this case is given by

\[ x(s) = \sum_i q_i d_i \beta_0 \left( \frac{\gamma(s_i)}{\gamma(s)} \right)^{1/4} \sin(\psi(s, s_i)) \Theta(s - s_i) \]  

(5.8)

Let us now consider a random sequence of uncorrelated movements \( d_i \). To estimate the effect we perform an ensemble average as in Section 2 to obtain

\[ \langle x^2(s) \rangle = \sum_i q_i^2 (d^2) \beta_0^2 \left( \frac{\gamma(s_i)}{\gamma(s)} \right)^{1/2} \sin^2(\psi(s, s_i)) \Theta(s - s_i) . \]  

(5.9)

For a large number of magnets we can replace the sum by an integral to obtain

\[ x(L)_{\text{rms}} = q_0 \beta_0 d_{\text{rms}} \sqrt{\frac{N}{3}} . \]  

(5.10)

The displacement at the end of the linac must be small compared to the beam size there. This yields a tolerance on random magnet-to-magnet jitter given by

\[ d_{\text{rms}} \ll \frac{\sigma_p(L)}{q_0 \beta_0} \sqrt{\frac{3}{N}} . \]  

(5.11)

The tolerance above is probably a very pessimistic one. Ground motion is far from being uncorrelated from magnet to magnet. A more realistic calculation would start from the noise spectrum due to ground motion and filter that with the response function of the magnet supports.

### 5.3 Jitter of Transverse Kicks in Acceleration Sections

It is well known that due to various errors an acceleration section in a linac typically gives the beam a small transverse kick. These kicks may be due to coupler asymmetry, fixed misalignments or symmetry errors in construction. In addition, it has recently been pointed out that field emission currents may also cause large enough deflecting fields to cause a problem. If the kicks, from whatever source, are constant in time, the orbit can simply be corrected by dipole magnets to the required tolerance. However, if the kick varies from pulse to pulse, this can cause the beams to miss in the same way that a moving quadrupole can.

As an example consider an acceleration section which is rotated end to end by a small angle \( \alpha \). Then the transverse momentum kick is related to the longitudinal by

\[ \Delta p_\perp = \alpha \Delta p , \]  

(5.12)

where \( \Delta p \) is the momentum gain in the section. In an actual accelerator \( \alpha \) will vary from section to section but remain fixed in time provided there is little alignment jitter. In this case, the transverse jitter is almost entirely due to the jitter in the energy gain of the acceleration section, that is

\[ \delta(\Delta p_\perp) \equiv \delta p_\perp = \alpha \delta(\Delta p) . \]  

(5.13)

Note that due to unfortunate poor planning, \( \delta \) in this section refers to the jitter of a quantity rather than a relative momentum deviation.
To calculate the effect for a random sequence of transverse kicks we can follow the previous section with only slight modifications. As in Eq. (5.4) the orbit change due to the change in transverse kicks throughout the linac is

$$x(s) = \sum_{i}^{N_x} \left( \frac{\delta p_{L,i}}{p_i} \right) \frac{\beta(s) \beta(s_i)}{1/2} \left[ \frac{\gamma(s_i)}{\gamma(s)} \right]^{1/2} \sin[\psi(s, s_i)] \Theta(s - s_i). \tag{5.14}$$

where $N_x$ is the number of acceleration sections in the linac. If we scale the lattice as in the previous section, the orbit in this case is given by

$$x(s) = \sum_{i}^{N_x} \left[ \frac{\gamma_0}{\gamma_f} \right]^{1/2} \beta_0 \left( \frac{\delta p_{L,i}}{p_0} \right) \left[ \frac{\gamma(s)}{\gamma(s_i)} \right]^{1/4} \sin[\psi(s, s_i)] \Theta(s - s_i). \tag{5.15}$$

If we now consider an uncorrelated random sequence and ensemble average as in the previous section, we find

$$x(L)_{rms} = \left( \frac{\delta p_{L}}{p_0} \right)_{rms} \frac{\gamma_0}{\gamma_f} \sqrt{N_x}, \tag{5.16}$$

It is useful to write this in terms of $\Delta p$, the momentum change per section, which yields

$$x(L)_{rms} \approx \left( \frac{\delta p_{L}}{p_0} \right)_{rms} \beta_f \frac{\gamma_0}{\gamma_f} \sqrt{N_x}, \tag{5.17}$$

for $\gamma_f \gg \gamma_0$. This orbit change must be small compared to the beam size at the end of the linac which yields a tolerance on the jitter of transverse kicks in acceleration sections given by

$$\left( \frac{\delta p_{L}}{p_0} \right)_{rms} \ll \frac{\sigma_{\beta}(L)}{\beta_f} \sqrt{N_x}. \tag{5.18}$$

6. A NUMERICAL EXAMPLE

In this section we evaluate the various tolerances for the example shown in Table 1. This example is taken from Ref. 4 which appears in these proceedings and is a self consistent parameter set. Rather than simply plugging in numbers, we will briefly discuss each tolerance and evaluate it in the case given in Table 1. In those cases in which the beam size sets the tolerance, it is quoted for the vertical direction; the corresponding tolerance for the horizontal direction is a factor of 10 larger due to the larger emittance.

6.1 LANDAU DAMPING

This section is taken out of turn because we would like to specify the energy spread before the next section on chromatic effects. The condition for Landau damping is given Eq. (4.13). For the parameters shown in Table 1, the correlated half energy spread is

$$\delta_L = 8 \times 10^{-4}. \tag{6.1}$$

The beam also has an uncorrelated part due to residual beam loading energy spread and a residual longitudinal emittance from the damping ring. The longitudinal energy spread left from the initial longitudinal emittance is damped to this level in the first 1/10 of the linac. The spread due to the longitudinal wake is also about the same size as the correlated spread above. Therefore, in the subsequent sections we assume a $\delta$ given by that for Landau damping.
TABLE 1. Self-Consistent Parameters from Ref. 4

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<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
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<tbody>
<tr>
<td>Center-of-mass energy</td>
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<td>Max Luminosity $10^{33}$ cm$^{-2}$ sec$^{-1}$</td>
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</tr>
<tr>
<td>Normalized emittance (horizontal) $10^{-6}$ m</td>
<td>$\varepsilon_{nz}$</td>
<td>2.5</td>
</tr>
<tr>
<td>Normalized emittance (vertical) $10^{-8}$ m</td>
<td>$\varepsilon_{ny}$</td>
<td>2.5</td>
</tr>
</tbody>
</table>

6.2 CHROMATIC EFFECTS

First we need to evaluate the chromatic phase advance. This is given by

$$\delta \psi_T = \delta \int_0^L \frac{ds}{\beta(s)},$$  \hspace{1cm} (6.2)

which for the variation of the beta function in Eq. (5.6) yields

$$\delta \psi_T \simeq \frac{2 \delta L}{\beta_f},$$  \hspace{1cm} (6.3)

where $\beta_f$ is the beta function at the end of the linac. In the case shown in Table 1 the chromatic phase advance is small enough to use Eq. (3.8). This yields the tolerance on an uncorrected betatron oscillation given by

$$\delta_0 \ll 2.6 \sigma_\beta = 1.5 \mu m.$$  \hspace{1cm} (6.4)

To estimate the tolerance on quadrupole misalignment or errors in position measurement we turn to Eq. (3.15) to find

$$\Delta x_{\text{rms}} \ll 45 \sigma_\beta = 27 \mu m.$$  \hspace{1cm} (6.5)

With careful measurement at the end of the linac, we may be able to control the coherent oscillation effects by controlling the launch at the beginning of the linac.
6.3 Injection Jitter

From Eq. (5.1) the jitter in position must be much less than the spot size

$$\Delta x_0 \ll 2\mu .$$ (6.6)

To make much more precise statements on injection jitter we really need to know more details about the injection system. However, if we look upstream to a possible source of jitter, we find the kicker magnet in the damping ring as an important candidate. To ameliorate the problem there, it is desirable that the kick angle be as small as possible. The jitter of the kick angle is dominated by power supply jitter which gives a fixed fraction of the total angular kick. The kick angle should be reduced until the angular jitter is small compared to the beam divergence at the kicker. It is still possible to extract the beam in this case. If the jitter is $10^{-3}$ of the kick and we set this to be 1/10 of the beam divergence, then we can kick the beam by $100\sigma_\rho$ if we look $\pi/2$ downstream in betatron phase.

6.4 Quadrupole Alignment Jitter

To calculate the tolerance on quadrupole jitter we use Eq. (5.11). In a thin lens cell with a $\pi/2$ phase advance, the product of $q_0\beta_0$ is given by

$$q_0\beta_0 = 2\sqrt{2} ,$$ (6.7)

where $\beta_0$ here is the average of $\beta_{\text{max}}$ and $\beta_{\text{min}}$ in the cell. This yields a tolerance for the example in Table 1 of

$$d_{\text{rms}} \ll 0.03\sigma_\rho(L) = 0.02\mu m .$$ (6.8)

Although this is quite small recall that this motion must occur at high frequency and in an uncorrelated fashion from magnet to magnet.

6.5 Jitter of Transverse Kicks in Acceleration Sections

We evaluate the jitter in transverse momentum kick relative to the momentum gain in a typical section using Eq. (5.18). This yields

$$\frac{(\delta p_\perp)_{\text{rms}}}{\Delta p} \ll 3 \times 10^{-6} .$$ (6.9)

This same tolerance evaluated for the SLC at SLAC is

$$\frac{(\delta p_\perp)_{\text{rms}}}{\Delta p} \ll 6 \times 10^{-5} .$$ (6.10)

This sets tight tolerances on section alignment and asymmetries induced by asymmetric couplers or construction errors.
7. CONCLUSION and ACKNOWLEDGEMENTS

Various beam dynamics issues have been treated here to introduce the reader to the various
tolerance requirements for the main linac in a linear collider. This treatment has not been exhaustive,
but highlights the main effects. One important effect which has not been discussed is the tolerance on
alignment of the acceleration sections. For typical parameters this tolerance is usually much weaker
than those presented here. The transverse kicks on the tail of the bunch are Landau damped.

In addition, nothing has been said of tolerances or beam dynamics issues in other sub-systems. In
the damping ring the requirement of small vertical emittance puts tight tolerances on the vertical orbit.
However, PEP at SLAC, the VUV ring at BNL, and others have achieved these emittance ratios so this
seems plausible. In the bunch compressors emittance dilution due to chromatic effects must be avoided.
In the final focus there will be tight tolerances on orbits through sextupoles to avoid coupling and also
tight tolerances on the jitter of the final quadrupoles.

Finally, I would like to thank Karl Bane, Alex Chao, Phil Morton, Bob Palmer and John Seeman
for useful discussions.

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CHOICE OF PARAMETERS FOR LINEAR COLLIDERS IN MULTI-BUNCH MODE

J. Claus
(Brookhaven National Laboratory)

Abstract

The energy efficiency of a linear collider in multi-bunch mode is calculated for the case that the bunches in each of the two interacting beams are identical in all interaction points, a configuration which can be realized by taking advantage of the beam-beam effect between beams of opposite electric charge. The maximization of the efficiency is discussed, the maximum appears to increase nearly linearly with beam brightness and accelerating gradient, and about quadratically with the length of the IR. The optimum operating frequency for the linacs increases also, while the pulse repetition rate and the beam current needed for fixed luminosity, decrease. The increasing brightness and the decreasing current needed for higher efficiency lead to smaller transverse spotsizes in the crossing points; this imposes tighter tolerances on the relative transverse coordinates of the two beam-axes. Pillbox or similar resonators, excited in the TM01 mode, may be preferable to quadrupoles for transverse focusing, at the high frequencies and gradients that seem desirable, particularly in the final focus.

1. INTRODUCTION

Multibunch operation of linear colliders has been discussed before [1,2,3]. It occurs if each of the two interacting particle beam pulses is composed of several bunches, rather than of a single one, as is more usually considered. It offers some freedom in the choice of the operating frequency of the two linacs, which can be exploited to minimize the rf energy required for a specified luminosity and length of interaction region. This subject was treated in [2] under the assumption that the beam-beam interaction in the IR could be neglected, which is clearly not realistic. This work was extended, now keeping account of the beam-beam effect, for the case that the bunches in each beam are all identical to each other in all interaction points. It is found, as expected from SLAC's disruption and R.B. Palmer's Superdisruption studies [4], that the beam-beam effect is beneficial. It appears again, that the efficiency (luminosity per unit rf power) can be maximized by proper choice of the operating frequency. Both the efficiency and the optimum frequency increase with increasing beam brightness and increasing accelerating gradient, while the beam current and pulse repetition rate required for fixed luminosity, decrease. The relation between efficiency and brightness is very nearly proportional, as is that between efficiency and gradient, it is therefore important to push both. It is even more important to choose the pulse length, i.e. the length of the IR, as long as is acceptable to the experimenters because the relation between efficiency and it is nearly quadratic. These calculations will have to be revised if a substantial fraction of the spent rf energy is recovered, particularly if the efficiency is low.

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2. INTERACTION AREA

2.1 Beam self fields and transverse focusing

Studies of the beam-beam effect in storage rings, and of the so-called beam disruption in the crossing point of the SLC, show that the net transverse force felt by the individual particles from the self fields of highly relativistic beams is non-negligible in the regions where the particle distributions of the two opposing beams overlap and very small elsewhere. In the simple case of two bunched beams which move with equal velocities in opposite directions along a common axis, the regions where bunches can overlap are stationary in space. In passing through an opposing bunch each particle is exposed to its fields for a time interval $\Delta t = l_b/(2\beta c)$, with $l_b$ the length of the bunch and $\beta c$ the particle velocity, thus the effective longitudinal extent of the bunch field is $l_{\text{eff}} = 0.5l_b$. The location where the first particle of a bunch first encounters an opposing bunch is half a bunchlength downstream of where its last one does so. The self field of the opposing bunch has electric and magnetic components, described by:

$$E_r(r) = \Lambda r / (4\pi e_0 \rho^2), \quad B_\theta(r) = \mu_0 \beta c \Lambda r / (2\pi \rho^2)$$  \hspace{1cm} (2.1.1)

if the charge density distribution is transversely uniform and the bunch is long compared to its diameter. Here $\Lambda$ is the linear charge density $[C/m]$ in the bunch and $\rho$ the beam radius. A particle of charge $e$ and velocity $v_1 = \beta_1 c$ experiences in that field a force:

$$F_r = e(E_r + \beta_1 c \cdot B_\theta) = \frac{e \Lambda r}{2\pi e_0 \rho^2} \left(1 - \beta_1^2 \beta\right) = \frac{\mu_0 e c^2 \Lambda r}{2\pi \rho^2} \left(1 - \beta_1^2 \beta\right)$$  \hspace{1cm} (2.1.2)

If $\beta_1 = \beta = \beta$, i.e., if particle and bunch have about equal velocities in the same direction, $F_r = 0$, if their velocities have opposite directions $\beta_1 = -\beta$, $\beta = 1$ and

$$F_r \equiv \frac{2\mu_0 e c^2 \Lambda r}{2\pi \rho^2}$$  \hspace{1cm} (2.1.3)

with $t$ the instantaneous current in the bunch. The force is focusing, since it is proportional to $r$; it is truly focusing if the charges of particle and bunch have opposite signs, making $F_r$ negative, as occurs when, e.g., electron bunches interact with positron bunches. $F_r$ changes $r' = \frac{dz}{dt}$, where $z$ represents displacement along the axis, at a rate:

$$\frac{dz}{dt} = \frac{1}{mc^2\gamma^2} F_r = \pm \frac{\mu_0 e c^2}{\gamma^2 \rho^2} \frac{1 - r}{2\pi \rho^2}$$  \hspace{1cm} (2.1.4)

where the $+$ sign applies if the interacting bunches have equal, and the $-$ sign if they have opposite polarities; $\gamma$ is the Lorentz factor. If the change in the test particle's $r$ remains disregardably small while it travels through the opposing bunch, that bunch acts as a thin lens with an inverse focal length $q$ given by:
\[
q \equiv \pm 2 \frac{\mu_0 c}{E_0} \frac{1}{2\pi p^2} \int dz = \pm \frac{\mu_0 c}{E_0} \frac{1}{2\pi p^2} i\lambda
\]  

(2.1.5)

where \(i\) is the beam current averaged over a r.f. period and \(\lambda\) the r.f. wavelength (= distance between successive bunch centers). \(i\lambda\) is a measure for the charge in the bunch, as is \(i\int dz\). The integration interval in this integral is the effective axial length of the bunch field, thus half a bunchlength \(l_0\), as mentioned before. Therefore: \(2i\int dz = i\lambda\). The lens is centered on the beam axis, and the lens action reflects the opposing beams towards each other (beams of opposite polarities) or away from each other (equal polarities) if they do not travel along the same axis.

In real bunches the current distribution is never uniform, as assumed, though generally bell shaped. This makes \(F_r\) non-linear in \(r\), however, \(F_r(r)\) remains an odd function of \(r\) if \(f(r)\) is even, as is likely. The implied circular cylindrical symmetry can not be taken for granted either. Any quadrupole focusing along the route from source to interaction area will tend to introduce a cartesian symmetry. We will disregard these considerations in this discussion.

It is convenient to express \(q\) in terms of the beam brightness \(B\), defined as \(B = i/e^2\), where \(e\) is the invariant emittance of the beam, and the local amplitude function \(\beta\):

\[
q = \pm \frac{\mu_0 c}{E_0} \frac{(B\beta)^{1/2}}{2\pi \beta} \lambda
\]  

(2.1.6)

since \(p^2 = eB/\gamma\). To prevent possible confusion due to conflicting uses of \(\beta\), this symbol will no longer be used to represent \(v/c\), but only for Twiss and Frank’s amplitude function. For \(v/c\) we shall write:

\[
v/c = (1-\gamma^2)^{1/2} \approx 1 - 1/(2\gamma^2) \approx 1 \text{ for } \gamma >> 1 .
\]

2.2. Trains of bunches

The interaction between trains of bunches is complex because the interaction between any particular bunchpair, e.g., the \(k^{th}\) one from the left and the \(i^{th}\) one from the right, is determined by the, generally different, histories of each. However, if the two beams have opposite polarities, it appears possible to make all bunches of each beam, identical to each other in all crossing points. In that case each beam forms a periodic focusing system for the opposing one. If that beam is properly matched to the focusing system, its bunches will all have the same radius in all of the crossing points, presenting equally spaced focusing lenses of equal strengths to the counter streaming ones. Achieving this requires only that each beam enter the interaction region with the proper initial conditions (and that the bunches of each beam carry equal charges). Applying standard linear optics one finds for the value of \(\beta\) in the midplanes of the lenses and for the phase advance per cell \(\Delta \Psi\) of such a periodic system with lens strength \(q\) and a distance \(l\) between successive lens centers in the thin lens approximation:

\[
\beta = \frac{l}{\sqrt{lq(1 - 1/4 lq)}} , \quad \sin(1/2 \Delta \Psi) = 1/2\sqrt{lq}
\]  

(2.2.1)

Substitution of \(l = 1/2 \lambda\) and of expression (2.1.6) for \(q\) yields a pair of coupled equations for the matched \(\beta\)’s of the two beams:
\[ \beta_1 = \frac{\lambda \beta_2}{\sqrt{\lambda a_2 (2 \beta_2 - 1/4 \lambda a_2)}} , \quad \beta_2 = \frac{\lambda \beta_1}{\sqrt{\lambda a_1 (2 \beta_1 - 1/4 \lambda a_1)}} \] (2.2.2)

where the subscripts 1 and 2 refer to the two beams, and where

\[ a_j = q_j \beta_j = \frac{\mu_o c}{2 \pi E_0} (j \beta_j)^{1/2} \lambda , \quad j = 1, 2 \] (2.2.3)

Separation yields:

\[ x_i^{3/2} - 1/4 \ a_i \sqrt{\lambda a_i} \ x_i + 1/4 \ \lambda a_i \ x_i^{1/2} - \left( \frac{\lambda^2 a_i}{\sqrt{\lambda a_i}} \right) = 0 \] (2.2.4)

where \( x_i \) stands for:

\[ x_i = 2 \beta_i - 1/4 \ \lambda a_i \]

and where \( i = 1, j = 2, \) or \( i = 2, j = 1. \) Equations (2.2.4) have at least one real root for \( x_i, \) which has for both beams the simple form:

\[ x = \lambda x / a \] (2.2.5)

if \( a_i = a_j = a; \) this applies, e.g., when the two beams have equal brightnesses and currents, and yields for \( \beta: \)

\[ \beta = 1/2 \ \lambda (1/a + 1/4 \ a) \] (2.2.6)

I have found no convenient analytic solution for \( x_{1,2} \) if \( a_1 \neq a_2, \) but numerical experimentation suggests that the two beams can be matched to each other even so; I surmise that that is still true if they have two transverse axes of symmetry, instead of being circular cylindrical.

2.3 Luminosity

The luminosity produced by the interactions between two trains of identical bunches that move in opposite directions along a common axis can now be estimated. We calculate first the time integrated luminosity (TIL, \( \mathcal{L} = \int \mathcal{L} dt \)) from two interacting bunches. The TIL from the two trains, each \( N \) bunches long, is \( N^2 \) times that from a single bunch pair, since each bunch in each train interacts with all of the bunches in the other. If the process is repeated at a rate \( f \) per unit time the time average luminosity becomes: \( \mathcal{L} = fN^2 \mathcal{L}. \)

The TIL from a single bunch pair may be described by:

\[ \mathcal{L} = \frac{n_b^2}{4 \pi \sigma^2} = \frac{\nu_b^2}{4 \pi \beta} = \frac{\gamma (c \lambda / c)^2 \mathcal{B} i}{4 \pi \beta} \] (2.3.1)

where \( n_b \) is the number of particles per bunch and \( s \) the rms bunch radius under the assumption that the transverse distribution is Gaussian. Substitution of (2.2.6) and (2.2.3) yields an expression for the integrated luminosity from a single pulse, which, for the case of equal brightnesses and currents, may be written in the form:
\[ L = (L_B + \lambda)^2 \gamma \left( \frac{c}{\varepsilon} \right)^2 \frac{\mu_0 c}{4\pi E_0} \frac{1}{1 + \left( \frac{\mu_0 c}{4\pi E_0} \right)^2} \]  

(2.3.2)

Here is \( L_B = (N-1)\lambda \) the distance between the centers of the first and the last bunch in a beam pulse, thus the length of the inter-action region if both beams have the same number of bunches \( N \). This substitution is only approximately valid because the expression for the luminosity assumes a Gaussian distribution in each bunch, while the expression for \( \beta \) assumes a transversely uniform one. I will disregard the difference as being of little consequence for the present purpose.

3. LINAC AND BEAM CURRENT

In a previous paper [2] an expression was derived for the energy that the power source must supply to a linac for the acceleration of a beam pulse with specified characteristics. There is also an expression for the maximum beam current. These formulae are valid for linacs that are composed of resonant cells that are coupled individually to the rf power source. They may be said to be supplied in parallel. Such linacs deviate from the conventional ones, which may be regarded as disk loaded wave guides or, alternatively, as strings of resonant cells in which the rf power flows from one cell to the next one, supplying them in series. Linacs of the proposed type may have some advantages at the very short wavelengths that seem desirable for reasons of energy efficiency and their principal characteristics are easily calculated. We repeat the relevant expressions for the convenience of the reader:

\[ E_s = \frac{\gamma E_0}{U_s F_{tr}} \rightarrows Q_{ro} \tau_B (1+x)^2 [1+\alpha \cdot \ln(1+x)] \]  

(3.1)

where:

\[ x = \frac{U_s}{2i R_o} (1+R_o/R) = \frac{2\pi Z_c}{\alpha R_o} (1+R_o/R) \]  

(3.1.1)

\[ a = \nu/\tau_B \]  

(3.1.2)

\[ i = \frac{1}{4\pi F_{tr}} \frac{\bar{a}}{Z_c} \]  

(3.1.3)

\[ U_s = g \lambda E \]  

(3.1.4)

\[ Z_c = \frac{R}{Q} \left[ 1 - \left( \frac{1}{2Q} \right)^2 (1 + \frac{R}{R_o})^{1/2} \right] \]  

(3.1.5)
and where:

- \( E_s \): rf energy delivered by the source,
- \( i \): beam current
- \( \tau_B \): length of the beam pulse in time, \( (\tau_B \cdot c = L_B) \)
- \( E \): amplitude of the accelerating field
- \( U_g \): gap voltage
- \( g \): gap length in terms of rf wavelengths \( \lambda \)
- \( F_{tr} \): transit time factor
- \( R_o \): source impedance per cell
- \( R \): shunt resistance per cell
- \( Q \): Q factor per unloaded cell
- \( \tau \): time constant per cell \( (\omega \tau = 2Q/(1+R/R_o)) \)

- \( Z_c \): geometric factor, depends upon the relative distributions of the electric and magnetic fields in the cell, thus on the shape of the cell, but is largely independent of its resonant frequency, thus of its size \( (Z_c \approx \sqrt{L/C}) \).
- \( \alpha \): energy gain per bunch per cell as a fraction of the energy stored per cell.

4. **EFFICIENCY**

Division of (2.3.1), which describes the time integrated luminosity per pulse by (3.1), which gives rf energy delivered by the rf source as needed by that pulse, yields the TIL per unit rf energy and at the same time the luminosity (averaged over time) per unit (average) rf power. It may be written in the form:

\[
\eta_L = \frac{L}{P_{rf}} = \frac{\int dt}{E_{rf}} = \frac{8}{\mu_o(\omega c)^2 L_B} \left( \frac{x}{1+x} \right)^2 \frac{y(1+y)^2}{[1+b \cdot y \cdot \ln(1+x)](1+a \cdot y^3)}
\]  (4.1)

where:

\[
x = \frac{2\pi Z_c}{\alpha R_o} (1 + R/R_o)
\]  (4.1.1)

\[
y = \lambda/L_B
\]  (4.1.2)

\[
a = \left( \frac{\mu_o c^2}{4\pi E_0} \right) \frac{\alpha gEBL_B^3}{4\pi F_{tr}Z_c}
\]  (4.1.3)
and where the parameters $y$, $a$, and $b$ have been introduced for reasons of convenience. Inspection shows that $\eta_L$ is proportional with $a/L_B$, and that it can be maximized by proper choice of $x$ and $y$.

The opportunities for the maximization of $a/L_B$ are somewhat limited. The field $\boldsymbol{E}$ in the cavities is restricted to no more than a few GV/m, depending on frequency and pulse length, by surface effects at the cavity walls (field emission and photo emission, due to synchrotron light, of electrons, thermal effects due to dissipation).

The beam brightness $B$ is restricted by the source, and can be reduced seriously by transverse wakefields and by non-linearities in the transverse motion. As a measure of the density in four dimensional transverse phase space it is expected to depend less on the beam current than the emittance does. The value of $g/F_U$, determined by the design of the linac, leaves little choice: $\pi/4.5 \leq g/F_U \leq \pi/4$ for phase advances per cell between $(2/3)\pi$ and $\pi$, and decreases quickly for smaller phase advances.

The cavity loading factor $\alpha$ is limited to perhaps $\alpha \leq 0.05$ (SLAC number) by considerations of beam stability (wake fields) and momentum spread (constraint imposed by the users), a limit that may well depend on bunch length $\lambda$, becoming smaller for shorter bunches.

The length of the interaction region $L_B$ should be chosen as long as is still acceptable to the users, who should be aware that its choice affects the efficiency quadratically: double the source length gives four times the luminosity for the same money if the efficiency is low, as is likely.

The efficiency can be maximized for given values of $a/L_B$ by proper choice of the source impedance $R_0$ and the wavelength $\lambda$, in view of (4.1.1) and (4.1.2). Since analytic expressions for the maximized efficiency and the values for $R_0$ and $\lambda$ at the maximum appeared to be inconvenient we calculated a number of examples numerically. Our results are shown in Figs. (1-7). The beam brightness $B$ was chosen as independent parameter in all cases because we are least certain about what its value might be. That is also the reason for the large interval of variation chosen. It contains the brightness that is expected for the SLAC linear collider ($B = 3 \times 10^{10}$ A/(rad-m)$^2$). Although continuous curves are shown, only the points associated with $B$'s which yield $\lambda = L_B/(\eta_B - 1)$, with $n_b$ the number of bunches per pulse, are valid, because the interaction region is an integer number of wavelengths long.

Figures (1-3) represent results obtained for the parameter set $E = 1$ GV/m, $L_B = 1$ cm, $\alpha = 0.05$. Most of them are bounded on the left side by the consideration that $\lambda \leq L_B$; this condition is violated if $B$ is chosen too small. The crucial curve in these graphs is the one for $1/\eta_L$ (Fig. 1), which describes the RF power required per unit luminosity. It behaves approximately as $1/\eta_L = 2.0 \times 10^{-20} B^{-0.78}$, and shows, e.g., that a facility with a luminosity of $L = 10^{35}$ cm$^2$sec$^{-1} = 10^{39}$ m$^3$sec$^{-1}$, would require a RF power of 50 GW if the beam brightnesses are $B = 10^{11}$ A/(rad-m)$^2$, while only 27 MW would be needed if $B = 10^{15}$ A/(rad-m)$^2$ could be achieved.

The curve labeled $1/\Phi_L dt$ (m$^{-2}$sec$^{-1}$) gives the TIL per pulse, it is useful for calculating, e.g., the pulse repetition rate $f$ via the relation $f = L/\Phi_L dt$. It is evident that $f$ decreases with increasing $\gamma$ and increasing $B$. A luminosity of $10^{33}$ cm$^{-2}$sec$^{-1}$ at a final energy of 5.11 TeV ($\gamma = 10^7$ in the case of an $e^+e^-$ collider) in each
beam, would demand $f = 10^{39}/(10^7 \cdot 4 \cdot 10^{26}) = 250$ kHz at $B = 10^{11}$ A/(rad-m)$^2$, while $f = 20$ kHz would be adequate at $B = 10^{15}$ A/(rad-m)$^2$. We note that SLAC’s SLC is expected to operate at $B = 2.5 \cdot 10^{10}$ A/(rad-m)$^2$ and $f = 180$ Hz.

$P_s$ (MW) represents the rf power during the pulse.

$\tau_s$ (psec) is the pulse length of the rf source, as seen from a single cell, while $\tau_B$ (psec) is the length of the beam pulse, $\tau_B = L_B/c$; $\tau_s - \tau_B$ is the filling time for that cell. At least one power source must be active as long as the pulse is still in the linac, thus the rf energy delivered per pulse is at least $E_s = P_s E_f/(E_f - E)$, where $E_f$ is the final energy in eV.

$\lambda \leq L_B$ (cm) is the wavelength of the rf.

Figure 2 gives the behaviour of the beam current $I_B$, averaged over the pulse, and that of its invariant emittance $\varepsilon$. Also shown are the beam radius $\sigma_v \gamma$ in the crossing points and the value of $\beta$ that must be produced by the final focusing system in order to establish the matched condition on which this discussion is based.

Figure 3 gives the betatron phase advance $\Delta \psi$ between two successive crossing points and $\eta_{rf}$, a parameter that indicates what fraction of the incident rf energy ends up in the beam (the remainder, $1 - \eta_{rf}$, is either reflected back towards the power source or dissipated). Note that this figure is linear in the $\Delta \psi$ and $\eta_{rf}$ axes.

Figure 4 shows the behaviour of $1/\eta_L$ as a function of $\lambda$ for fixed $B$, $L_B$, $\alpha$ and $E$. $\lambda$ is chosen and the source impedance is adjusted for a minimum in $1/\eta_L$. It may be seen that deviations of $\lambda$ within a factor of two from the optimum value causes deterioration of $1/\eta_L$ by factors larger than three. It is thus important that $\lambda$ be chosen correctly, if at all possible. However, the shape of this curve may depend on the choice of the parameters $B$, $L_B$, $\alpha$ and $E$, and the sensitivity to deviations of $\lambda$ from its optimum may be different. The parameters for the curve shown are:

$$B = 10^{16} \text{A/(rad-m)}^2, \quad L_B = 1 \text{cm}, \quad \alpha = 0.05, \quad E = 1 \text{GV/m}.$$

Figures (5--7) show how $1/\eta_L$, $1/\eta_0 L dt$, $P_s$, $\tau_s$ and $\lambda$ respond to changes in the choice of parameters. They only illustrate what can be seen from (4.1): reductions in $\alpha$, $E$ and $L_B$ all lead to increases in the power needed for a specified luminosity. In particular: a reduction of $L_B$, the length of the interaction region from 1cm to 1mm is only possible (in this mode of operation) if a brightness of at least $1 \cdot 10^{13}$ A/(rad-m)$^2$ is available; for that brightness $1/\eta_L = 2.7 \cdot 10^{-28}$ Wm$^{-2}$sec, while it is $1/\eta_L = 1.1 \cdot 10^{-30}$ Wm$^{-2}$sec for the same brightness and $L_B = 1$ cm, a factor 25 better. Note that the optimum wavelength increases a little, from $\lambda = 0.72$ mm for $L_B = 1$ cm to $\lambda = 1$ mm for $L_B = 1$ mm.

5. TRANSVERSE MOTION

The previous discussion is based on the assumption that the two participating beams move in opposite directions along a common axis. In practice, each beam starts from a source and is guided towards the interaction region by a transverse focusing system which is incorporated in each linac and in each beam transport system. Steering elements are provided to place and direct the beam as desired at particular
locations, e.g., in the interaction area. There, the distance between the two beams must be small compared to
the smallest beam radius, e.g., 0.1 \( \rho \), and their axes may not deviate from parallelism by more than a small
fraction of the half angular spread in each beam, e.g., 0.1 \( \rho' \). The coordinates of the beam axes will vary
with time in response to, e.g., temporal displacements of the source and of the focusing elements. Servo
systems, that redirect the beams in response to measured deviations from target values, can be introduced to
minimize the magnitude of this random motion of the beam axes, but cannot eliminate it because of noise,
timedelays and limited bandwidths in the loops, and the position and direction of each beam axis will still
change from pulse to pulse. The magnitude of this residual motion must be kept within acceptable bounds.
Figure 2 shows that, at \( \gamma = 10^7 \), the beam has a diameter of a half \( \mu \)m or so in the crossing points, even at
the lowest brightness and also that it decreases with brightness as \( B^{-0.5} \), implying the need of a relative
position control of better than 25nm to 25pm.

We discuss the focusing conditions in linacs and interaction region separately because they are so very
different. The linacs represent systems that stretch over several km's each, and the diameter of the beam is
not of much consequence, provided that it fits everywhere inside the available effective aperture. They are
the sources that supply the interaction region with beams and must meet the requirement that the deviations
of the coordinates of each beam axis remain small compared to the beam emittance in \( xx'y'y' \)-space at the
interfaces with the interaction region. If this region can be kept relatively small in extent, it may be possible
to decouple it from the outside world as a unit. The final focusing systems, which convert the incident
beams to the ones wanted in the interaction region, would be part of that unit.

5.1. Linac cells as focusing elements \( \kappa' \)

The transverse motion is usually controlled by means of quadrupoles. The high fields and short
wavelengths that characterize the linacs under discussion suggest the use of similar structures as focusing
elements. In the TM01 mode there exists in each linac cell a toroidal transverse magnetic field, that is
independent of the axial position \( z \) and that behaves transversely approximately as

\[
B_\theta (r) = -i \frac{k}{\omega} E J_1(kr) \quad (5.1.1)
\]

\[
\partial B_y/\partial r = i \frac{k^2}{2\omega} E \left[ J_1(2kr) - J_2(2kr) \right] = i \pi \frac{\xi}{c\lambda} E J_1(2kr) \approx
\]

\[
= i \pi \frac{\xi}{c\lambda} E, \text{ provided that } kr = 2\pi/\xi \ll 1
\]

in the case of a cylindrical pillbox resonator and as

\[
B_x(y) = -i \frac{k}{\omega} E \cos(kx) \sin(ky), \quad B_y(x) = i \frac{k}{\omega} E \sin(kx) \cos(ky) \quad (5.1.3)
\]

\[
\partial B_y/\partial y = -i \frac{k^2}{\omega} E \cos(kx) \cos(ky), \quad \partial B_x/\partial x = i \frac{k^2}{\omega} E \cos(kx) \cos(ky)
\]

\[
= -i \pi \frac{\xi}{c\lambda} E, \quad \pi \frac{\xi}{c\lambda} E
\]

\[\text{Note added in proof: Section 5.1 on focusing properties of linac cells is based on an over simplified model. The author has recently become aware of a calculation by D. Neuffer, FNAL, (private communication) which shows that the fields in the vicinity of the beam passage holes in the resonator cells act to essentially cancel the focusing effect described. This leaves such devices without practical merit for this purpose.}\]
provided that \( kx = \pi \sqrt{2} x/\lambda, \ll 1, ky = \pi \sqrt{2} y/\lambda, \ll 1 \), in the case of a pillbox resonator of square cross-section. In these expressions \( E \) is, as before, the electric field on the axis, harmonic time dependence with frequency \( \omega/2\pi \), free space wavelength \( \lambda \), and operation at the resonant frequency is understood, \( i = \sqrt{-1} \). \( E \) and \( B_{0x,y} \) differ in phase by \( \pi/2 \) rad, thus the principal difference between accelerating cells and focusing cells is the phase with which they are run relative to the beam bunches. The average focusing gradient can be related to the instantaneous ones given, by transit time factors \( F_{tr}^{2}\pi \leq F_{tr} < 1 \), which account for the changes in the cell fields that occur during the time spent by a bunch in a cavity of finite length, and for the field distortions that exist in the vicinity of the holes for beam passage in the cavity side walls. Doing so we obtain for the focusing gradient \( B' = \partial B/\partial r \), where \( r \) stands for \( r = (x^2+y^2)^{1/2} \):

\[
B' = \frac{\pi}{c \lambda} E F_{tr}
\]

(5.1.5)

Approximating \( F_{tr} \) with \( F_{tr} = \sin(\pi g)/(\pi g) \), with \( g \) defined as before, one finds with \( E = 10^9 \text{V/m}, \lambda = 0.1 \text{mm}, g = 0.5 \): \( B' = 6.7 \times 10^4 \text{T/m} \), equivalent to the gradient in a quadrupole with a poletip field of 1T and a throat circle radius of 16\( \mu \text{m} \). One advantage of a linac section as focusing element is, that it focuses (or defocuses, depending on the phase with which it is driven) equally in both transverse directions, while a quadrupole focuses in one, but defocuses in the other. This makes the linac section more effective than combinations of quadrupoles with the same gradient for some application, e.g., the final focus.

5.2. Choice of parameters

A discussion of some of the effects of misalignments of focusing elements in a linac is given in appendix A. It appears that the tolerances on the alignment decrease with increasing beam brightness, and that they are maximized by using all of the available aperture everywhere. That aperture is a fraction of the wavelength, 0.25\( \lambda \)-0.2\( \lambda \) or so, depending on the structure; the (2.5\( \sigma \)) diameter of the beam can only be a fraction of that, perhaps 1/3, thus the effective beam radius \( \rho \) can be no more than a few percent of the wavelength: \( \rho \leq 0.04 \lambda \). One may see from Figs. 1 and 2, that the behaviour of \( \lambda \) and of \( \varepsilon \) as functions of \( B \) may be crudely approximated by:

\[
\lambda = 26.02 B^{-0.34}, \varepsilon = 638.7 B^{-0.67}
\]

(5.2.1)

for \( L_B = 1 \text{cm}, \lambda = 0.05, E = 1 \text{GV/m} \). It follows, that the \( \beta \) wanted at the exit of the linac is practically independent of \( B \) and proportional to \( \gamma \):

\[
\beta = \gamma \rho^2/\varepsilon = 0.0004\gamma, \text{ if } \rho = 0.02\lambda
\]

(5.2.2)

so that \( \beta = 4000 \text{m at } \gamma = 10^7 \). This \( \beta \) must be matched to the \( \beta_{mn} \) in the interaction region, 1/4\( \lambda \) upstream of the first crossing point, which behaves approximately as:

\[
\beta_{mn} = 6.681 B^{-0.33}
\]

(5.2.3)

as shown by Fig. 3. The final foci must therefore have transfer functions with linear (de)magnification factors of \( (\beta/\beta_{mn})^{1/2} = 24 \beta^{1/6} \), e.g., about 940 at \( B = 10^{10} \text{A/(rad-m)}^2 \) and about 8400 at \( B = 10^{14} \text{A/(rad-m)}^2 \). This is achieved if they have transfer matrices of the form
\[ |M|_{\text{linac} \rightarrow \text{IR}} = \begin{bmatrix} (\beta_{mn}/\beta)^{1/2} & 0 \\ 0 & (\beta/\beta_{mn})^{1/2} \end{bmatrix} = \begin{bmatrix} 1/(24B^{1/6}) & 0 \\ 0 & 24B^{1/6} \end{bmatrix} \] (5.2.4)

\[ |M|_{\text{linac} \rightarrow \text{IR}} = \begin{bmatrix} 0 & (\beta_{mn}/\beta)^{1/2} \\ (\beta/\beta_{mn})^{1/2} & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0.0027\gamma B^{-0.33} \\ -1/(0.0027B^{-0.33}) & 0 \end{bmatrix} \] (5.2.5)

Numerically we obtain for \( \gamma = 10^7 \) and \( B = 10^{10} \, \text{A/(rad-m)}^2 \):

\[ |M|_{\text{linac} \rightarrow \text{IR}} = \begin{bmatrix} 1/967 & 0 \\ 0 & 967 \end{bmatrix} \] or \[ |M|_{\text{linac} \rightarrow \text{IR}} = \begin{bmatrix} 0 & 3.30 \\ -1/3.30 & 0 \end{bmatrix} \]

and for \( \gamma = 10^7 \) and \( B = 10^{16} \, \text{A/(rad-m)}^2 \):

\[ |M|_{\text{linac} \rightarrow \text{IR}} = \begin{bmatrix} 1/8600 & 0 \\ 0 & 8600 \end{bmatrix} \] or \[ |M|_{\text{linac} \rightarrow \text{IR}} = \begin{bmatrix} 0 & 0.33 \\ -1/0.33 & 0 \end{bmatrix} \]

The anti diagonal matrix can be realized with a single triplet of thick quadrupoles and also with a linac section. The magnitude of the \( m_{14} \) element is restricted by the available focusing gradient, which limits the achievable demagnification. Nearly arbitrarily large demagnification factors can be obtained from more complex systems. They might have a diagonal transfer matrix and their lengths would increase with decreasing available gradient. This would affect their sensitivity for misalignments unfavourably; it follows that high gradients are desirable.

REFERENCES


Fig. 1  $E_U, \frac{1}{\gamma}, k, \bar{e}$, $\lambda$, $\rho$, $\tau_1$ and $\tau_2$ as functions of $B$ for optimized values of $\lambda$ and $R_N$.

$E = 10^8 \text{V/m}$, $l_m = 1 \text{cm}$, $\alpha = 0.05$

Fig. 2 $e$, $\sigma \sqrt{\gamma}$, $I_B$ and $\beta_{mn}$ as functions of $B$ for optimized values of $\lambda$ and $R_N$.

$E = 10^8 \text{V/m}$, $l_m = 1 \text{cm}$, $\alpha = 0.05$
Fig. 3 $\Delta \psi$ and $\eta_{rt}$ as functions of $B$ for optimized values of $\lambda$ and $R_0$.

$E = 10^5 \text{V/m}$, $l_B = 1\text{cm}$, $\alpha = 0.05$

Fig. 4 $1/\eta_L = f(\lambda)$ for $B = 10^{10} \text{A/(rad-m)$^2$, R_0$ optimized.}$

$E = 10^5 \text{V/m}$, $l_B = 1\text{cm}$, $\alpha = 0.05$
Fig. 5 $1/\eta_L = \frac{1}{\lambda} \lambda dt$, $\lambda$, $P_\lambda$, $\tau_s$ and $\tau_B$ as functions of $B$ for optimized values of $\lambda$ and $R_\lambda$.

$E = 10^6 V/m$, $L_B = 1 cm$, $\beta = 0.05$

Fig. 6 $1/\eta_L = \frac{1}{\lambda} \lambda dt$, $\lambda$, $P_\lambda$, $\tau_s$ and $\tau_B$ as functions of $B$ for optimized values of $\lambda$ and $R_\lambda$.

$E = 10^6 V/m$, $L_B = 0.1 cm$, $\beta = 0.05$
Fig. 7 \( \frac{1}{\eta_L} \), \( \frac{1}{\lambda} \), \( \frac{1}{\lambda} \), \( P_x \), \( \tau_s \) and \( \tau_y \) as functions of \( \theta \) for optimized values of \( \lambda \) and \( R_y \).

\[ E = 10^6 \text{V/m}, \quad L_y = 1 \text{cm}, \quad \alpha = 0.01 \]
Appendix A

MISALIGNMENTS IN LINAC

We consider some of the consequences of misalignments of the quadrupoles of a linac. We treat the quadrupoles as thin lenses, and assume that there is no coupling between the two orthogonal components ("horizontal" and "vertical" or "x" and "y") of the transverse motion. The quadrupoles are disposed and excited to form a periodic focusing system, however, the constants of that system may change gradually, i.e., adiabatically, along the length of the linac. The half cell length \( l \), the inverse focal length \( q \) of the quadrupoles, the betatron phase advance per cell \( \Delta \psi \) and the amplitude functions \( \beta_f \) and \( \beta_d \) in the focusing and defocusing quadrupoles of a conventional FODO lattice are related according to:

\[
\sin(\Delta \psi/2) = sn = lq/2
\]

\[
\beta_f = \frac{l}{sn} \left( \frac{1 + sn}{1 - sn} \right)^{1/2}, \quad \beta_d = \frac{l}{sn} \left( \frac{1 - sn}{1 + sn} \right)^{1/2}
\]

(A.1)

The displacement of a quadrupole with inverse focal length \( q \) over a distance \( x \) from its reference position is equivalent to the introduction of a dipole moment \( qx \) and causes an additional deflection \( x' = qx \) in the trajectories of all particles. It is convenient to describe this deflection in a phase space in which displacements and deflections are treated equally and independent of energy: \( \xi = x'(\gamma \beta)^{1/2}, \xi' = x'(\gamma \beta)^{1/2}, \)

with \( \beta \) the local amplitude function; in this system coordinate pairs \((\xi, \xi')\) for any particle fall on a circle with radius \( \varepsilon^{1/2} \), with \( \varepsilon \) the invariant emittance of the particle, if the motion is linear. Using the previous expressions, we obtain for \( \xi' \) in terms of the emittance radius:

\[
\left( \frac{\xi'}{\varepsilon} \right)_f = 2 \frac{\Delta x}{\rho} \left( \frac{1 + sn}{1 - sn} \right)^{1/2}, \quad \left( \frac{\xi'}{\varepsilon} \right)_d = 2 \frac{\Delta x}{\rho}
\]

(A.2)

where \( \rho = (\xi_f \xi_d)^{1/2} \) is the (local) half beam width, with \( \varepsilon \) the emittance, and where subscripts \( f \) and \( d \) refer to focusing and defocusing quads. The errors \( \xi' \) appear at the exit of the linac rotated by the their appropriate phase advances and contribute amounts \( \xi' \sin \psi \) and \( \xi' \cos \psi \) to the errors in position and direction at that point. The sum of all quadrupole misalignment errors is therefore: \( \Xi = \Sigma \xi_k \sin \psi_k, \Xi' = \Sigma \xi'_k \cos \psi_k \). The \( \xi'_k \) are random variables, because their origins, the \( x_k \), are so, \( \psi = k\Delta \psi/2 \), with \( k \) the number of half cells to the linac exit.

It may be seen, that for fixed \( x \), the contribution to the error decreases with increasing beam half width \( \rho \) and with decreasing phase advance \( \Delta \psi \). The maximum possible value for \( \rho \) is restricted to a small fraction of the operating wavelength of the linac by its physical structure, and is constant throughout its length. The available aperture is fully exploited if the beam width matches it everywhere. This can be done by keeping \( \beta/\gamma \) constant, thus, at constant \( \Delta \psi \), by making the half cell length \( l \) proportional to the average energy in that cell. \( l \) will increase along the length of the linac in consequence, and the energy gain per cell with it. It follows that the total energy gain increases exponentially with the number of cells, this can be used to determine the number of half cells \( n \) in the machine: \( n = C \ln(\gamma_{\text{fin}}/\gamma_{\text{in}}) \), where \( C \) is a constant of integration, determined by the required focusing strength, \( \gamma_{\text{fin}} \) is the final energy and \( \gamma_{\text{in}} \) the injection energy. The value of \( C \) may be calculated as follows. The energy gain in the \( k \)th half cell is:
\[ \Delta E_k = (\gamma_k - \gamma_{k-1}) E_o = \gamma_{k-1} E_o (\exp(1/c) - 1) = l_k F_{tr} \mathcal{E} \]

where \( F_{tr} \) represents the net accelerating gradient. For \( l_k \) one may write:

\[ l_k = \beta_{k-1} \sin \sqrt{[(1 - sn)/(1 + sn)]} = \gamma_{k-1} \rho^2 \sin \sqrt{[(1 - sn)/(1 + sn)]} \varepsilon, \]

if one assumes that the change in energy in a half cell may be disregarded in comparison with the average energy: \((\gamma_{k-1} - \gamma_k) \ll (\gamma_{k-1} + \gamma_k)\). This yields an expression for \( C \):

\[ C = \frac{1}{\ln \left( 1 + \frac{\rho^2}{\varepsilon} \frac{F_{tr}}{E_o} \sin \frac{1 - sn}{(1 + sn)^{1/2}} \right)} \]

\[ = \frac{\varepsilon}{\rho^2} \frac{E_o}{F_{tr}} \sin \left( \frac{1 + sn}{1 - sn} \right) \frac{1}{\sqrt{2}} \left\{ \frac{1}{\varepsilon} \frac{\rho^2}{\varepsilon} \frac{F_{tr}}{E_o} \sin \left( \frac{1 - sn}{1 + sn} \right) \right\} \ll 1 \]

The approximation appears to be acceptable for the cases under discussion here. With \( C \) available, the number of half cells, thus the number of quadrupoles, can be calculated and estimates of the error expectations due to quadrupole misalignments be made. Assuming that the errors \( x \) are uncorrelated and have equal rms values \( \Delta x_{\text{rms}} \), we obtain:

\[ \xi_{\text{rms}} = \left( \Sigma \left( \xi_k \sin k \right)^2 \right)^{1/2} \quad \xi'_{\text{rms}} = \left( \Sigma \left( \xi_k' \sin k \right)^2 \right)^{1/2} \]

(A.4)

This yields after some manipulation:

\[ \frac{\xi_{\text{rms}}}{\sqrt{\varepsilon}} = \frac{\xi'_{\text{rms}}}{\sqrt{\varepsilon}} = 2 \Delta x_{\text{rms}} \left( \frac{\varepsilon}{\rho^2} \frac{E_o}{F_{tr}} \sin \left( \frac{1 + sn}{1 - sn} \right) \right) \frac{1}{\sqrt{2}} \left\{ \frac{1}{\varepsilon} \frac{\rho^2}{\varepsilon} \frac{F_{tr}}{E_o} \sin \left( \frac{1 - sn}{1 + sn} \right) \right\} \]

(A.5)

This form can be minimized by choosing \( sn = (\sqrt{3} - 1)/2 = 0.3660 \), i.e., by choosing the phase advance per cell \( \Delta \psi = 43^\circ \); the minimum is not very critical however, choosing \( \Delta \psi = 99^\circ \) instead of \( 43^\circ \) increases \( \xi_{\text{rms}} \) with a factor 1.35. It is also evident that most of the damage is done at low energy, increasing the final energy by a factor 10 increases \( \xi_{\text{rms}} \) only with a factor 1.517. Substituting some numbers, we take \( \gamma_{\text{fin}}/\gamma_{\text{in}} = 10^4 \), \( sn = 0.3660 \), \( F_{tr} = 2/3 \), \( \mathcal{E} = 10^6 \text{V/m} \) and \( \rho = 0.02\lambda \) and obtain:

\[ \frac{\xi_{\text{rms}}}{\sqrt{\varepsilon}} = \frac{\xi'_{\text{rms}}}{\sqrt{\varepsilon}} = 1000 \frac{\Delta x_{\text{rms}}}{\lambda^2} \frac{1}{\sqrt{\varepsilon}} \]

(A.6)

The displacement of the beam axis as a fraction of the half beam width and its directional deviation as a fraction of the half angular spread are both equal to \( \xi/\varepsilon \). It may be seen from (5.2.1), that, crudely speaking, \( \varepsilon/\lambda^2 \) is constant; for the conditions shown: \( \varepsilon/\lambda^2 = 1 \). Using this we find

\[ \frac{\xi_{\text{rms}}}{\sqrt{\varepsilon}} = \frac{\xi'_{\text{rms}}}{\sqrt{\varepsilon}} = 1000 \frac{\Delta x_{\text{rms}}}{\lambda} = 39 \Delta x_{\text{rms}} \rho^{0.34} \]

(A.7)
where $B$ is the brightness of the beam, as defined earlier. For a jitter in the coordinates of the axis of $\xi_{\text{rms}}/\sqrt{\epsilon} \leq 0.1$, $\Delta \xi_{\text{rms}} \leq 0.0026 B^{-0.34}$ has to be realized, thus $\Delta \xi_{\text{rms}} \leq 1 \mu\text{m}$ at $B = 10^{10} \text{A/(rad-m)}^2$, and $\Delta \xi_{\text{rms}} = 9 \mu\text{m}$ at $B = 10^{14} \text{A/(rad-m)}^2$.

A linac could also be focused by linac sections as described in Section 5.2. A similar calculation for that case yields:

\[ s_n = \sin(\Delta \psi) = 0.5\sqrt{l_q} \quad (A.8) \]

\[ \beta = \frac{l}{2sn(1 - sn^2)^{1/2}} \quad (A.9) \]

\[ C = 1/\ln \left( 1 + 2sn(1 - sn^2)^{1/2} \right) = \frac{eE_0}{2\rho^2 F_r E} \frac{1}{sn(1 - sn^2)^{1/2}} \quad (A.10) \]

\[ n = \frac{eE_0}{2\rho^2 F_r E} \frac{1}{sn(1 - sn^2)^{1/2}} \ln \left( \frac{\gamma_{\text{fin}}}{\gamma_{\text{in}}} \right) \quad (A.11) \]

\[ \frac{\xi_{\text{rms}}}{\sqrt{\epsilon}} = \frac{\xi'_{\text{rms}}}{\sqrt{\epsilon}} = \frac{\Delta \xi_{\text{rms}}}{\rho} \left[ \frac{eE_0}{\rho^2 F_r E} \frac{sn}{(1 - sn^2)^{3/2}} \ln \left( \frac{\gamma_{\text{fin}}}{\gamma_{\text{in}}} \right) \right]^{1/2} \quad (A.12) \]

Now it seems best to choose $s_n$, thus the phase advance per cell small. It cannot be chosen arbitrarily small however, because $\beta$ must have a predetermined value: $\beta = \rho^2 \epsilon/\gamma$, we do not develop this subject any further here. Another matter is, that the choice of a fixed phase advance per cell combined with a variable cell length, was arbitrary: a fixed cell length and a variable phase advance seems equally possible and may be advantageous.
FINAL FOCUS

Consider a final focusing system with transfer matrix (for the x coordinate): \[ |M| = \begin{bmatrix} 0 & R \\ -1/R & 0 \end{bmatrix} \] relative to its axis. The system may consist of several lenses and drift spaces, but is regarded as a single, rigid device, that may be transversely misaligned relative to some external reference system. Its axis is straight, and the distance between entrance and exit planes, measured along that axis, is D. Let this system axis be misaligned by \( \xi_{en} \) and \( \xi'_{en} \), relative to the reference, in the entrance plane. Its coordinates \( (\xi, \xi')_{en} \) in the exit plane are then: \[ (\xi, \xi')_{ex} = \begin{bmatrix} 0 & 1 \\ -1/R & 1 \end{bmatrix} (\xi, \xi')_{en} \]. The coordinates \( (x, x')_{en} \) of a sample particle, relative to the reference at the system entrance, are transformed to \( (x, x')_{ex} \) at its exit according to:

\[
\begin{bmatrix} x \\ x'_{ex} \end{bmatrix} = \begin{bmatrix} 0 & R \\ -1/R & 0 \end{bmatrix} \begin{bmatrix} x \\ x'_{en} \end{bmatrix} + \begin{bmatrix} 1 \\ D-R \end{bmatrix} \begin{bmatrix} \xi \\ \xi'_{en} \end{bmatrix}
\]

It follows that the misalignment changes the coordinates of the beam axis by

\[
\begin{bmatrix} x_{a} \\ x'_{a_{ex}} \end{bmatrix} = \begin{bmatrix} 1 & D-R \\ -1/R & 1 \end{bmatrix} \begin{bmatrix} \xi \\ \xi'_{en} \end{bmatrix}
\]

at the exit of the system. It is evident that the axis moves as much as the system does in cases of system translation \( \xi' = 0 \), and that it is rotated in addition.

There are two, presumably identical, such final foci in a linear collider, one for each beam. Each of them affects its associated beam in the manner described above, although it has to be kept in mind, that transverse displacements are counted positive in opposite directions for beams that move in opposite directions. The changes in distance \( \delta x \) and angle \( \delta x' \) between the two beams in response to changes in the coordinates of the final foci are therefore:

\[
\frac{\delta x}{\delta x'} = \frac{x_{a_{l}} - x_{a_{r}}}{x_{a_{r}} - x_{a_{l}}_{ex}} = \begin{bmatrix} 1 & D-R \\ -1/R & 1 \end{bmatrix} \begin{bmatrix} \xi \\ \xi'_{en} \end{bmatrix}
\]

where subscripts \( l \) and \( r \) label the left hand and right hand sides of the crossing point. The misalignments \( (\xi, \xi')_{en} \) are likely to be uncorrelated random variables if the two final foci are physically separate units and the standard deviations of the differences in the coordinates of the beamaxes \( \delta x, \delta x', \delta y \) and \( \delta y' \) will be controlled by the standard deviations in the misalignments: \( \xi_{\sqrt{2}}, \xi'_{\sqrt{2}}, \eta_{\sqrt{2}} \) and \( \eta'_{\sqrt{2}} \). This changes if they can be integrated into a single physical unit. Expressing \( \xi_{l,r} \) and \( \xi'_{l,r} \) as translations and rotations \( \xi \) and \( \xi' \) of that combined unit we obtain:
\[
\xi_1 = \xi + D\xi' \\
\xi_2 = -\xi + D\xi' \\
\xi_1' = \xi_2' = \xi'
\]

In terms of these new variables the relative misalignment of the beam axes becomes:

\[
\begin{bmatrix}
\delta x \\
\delta x'
\end{bmatrix} =
\begin{bmatrix}
1 & D-R \\
-1/R & 1
\end{bmatrix}
\begin{bmatrix}
\delta \xi \\
\delta \xi'
\end{bmatrix}
\]

(B.5)

It may be seen, that the beam misalignment is primarily affected by rotations of the final focusing system, and that it is important to keep it short, i.e., \(D\) small, to minimize the sensitivity to such rotations.

A similar calculation for a final focus with a transfer matrix of the form \(M = \begin{bmatrix} -A & 0 \\ 0 & 1/A \end{bmatrix} \) yielded:

\[
\begin{bmatrix}
\delta x \\
\delta x'
\end{bmatrix} =
\begin{bmatrix}
\frac{x_a + x_a'}{x_{a_{ex}} + x_{a_{ex}}'} \\
0 + 1/A
\end{bmatrix}
\begin{bmatrix}
\xi_1 + \xi_2 \\
\xi_1' - \xi_2'
\end{bmatrix} =
\begin{bmatrix}
1 + A \\
0 + 1/A
\end{bmatrix}
\begin{bmatrix}
\delta \xi \\
\delta \xi'
\end{bmatrix}
\]

(B.6)

In cases of practical interest \(A \ll 1\), so that:

\[
\begin{bmatrix}
\delta x \\
\delta x'
\end{bmatrix} =
\begin{bmatrix}
1 \\
0 \\
1/A \\
0
\end{bmatrix}
\begin{bmatrix}
D \delta \xi \\
D \delta \xi'
\end{bmatrix}
\]

(B.7)

which emphasizes again the importance of keeping the length \(D\) and the angular misalignment \(\xi'\) small.
DISTORTION OF A SHORT RF PULSE
IN TRAVELLING-WAVE ACCELERATING STRUCTURES

G. Gaschenke
CERN, Geneva, Switzerland

ABSTRACT
Travelling-wave accelerating structures for high-energy linear
colliders necessitate very short RF pulses. The effect of
the structure's dispersion properties on the travelling RF
waves is analysed using Fourier analysis.

1. INTRODUCTION

For linear e⁺e⁻ colliders in the TeV range the use of travelling-wave radio-
frequency accelerating structures has been proposed [1-3]. Since high beam
power is required in these schemes in order to reach a luminosity of at least
10^{33} cm⁻²s⁻¹, a good efficiency of power transfer from the RF generating devices
to the beam is important.

In existing linacs the RF attenuation per section length has usually been
chosen so as to minimize the necessary peak power. In the high-energy regime,
however, a compromise has to be made between peak power and average efficiency.

Since the particles are injected once the structures are filled with RF
energy, the RF pulse length has to be at least one filling time \( \tau \). For high
average efficiency the power dissipation during the fill time has to be small.
In Ref. [3] an attenuation coefficient (for stored energy) per section length of
\( \alpha = 0.5 \) is suggested rather than the classical one of \( \alpha = 2.5 \). \( (\alpha = \omega \times \tau \times Q \) with
\( \omega = 2 \times \pi \times \text{frequency}, \tau = \text{structure filling time}, Q = \text{quality factor} \). This leads
to RF pulse lengths of only several hundred RF cycles if structure parameters
scaled from the SLAC design are taken. The relative width \( \Delta f/f \) of the passband
of accelerating waveguides ranges from a few per cent for SLAC-type disc-loaded
circular waveguides [4,5] to 30-40\% for crossbar and ladder-type structures [6].
These and the dispersion characteristics of the accelerating waveguide can lead to
a deformation of the wave travelling down the structure and hence a reduction of efficiency. These effects were studied numerically using Fourier analysis. All
examples have been calculated for constant impedance structures.

2. FORMALISM USED IN COMPUTER CODE

The wave train distortion has been studied by Fourier analysis. The frequency
spectrum of the RF pulse is calculated and each frequency component within
the structure bandwidth is delayed by a certain phase shift \( \phi \) according to the
dispersion characteristics of the structure before the pulse is reconstructed in
time domain.
2.1 Fourier analysis

The RF pulse is assumed to be a cos signal of N cycles at frequency \( \omega_0/2\pi \) extending from time \(-T/2\) to \(+T/2\).

\[
E(t) = \begin{cases} 
E_0 \cos \omega_0 t & \text{for } |t| < T/2 \\
0 & \text{elsewhere.}
\end{cases}
\]

The Fourier spectrum of such a signal is given by

\[
E(\omega) = \sqrt{2/\pi} \cdot E_0 \cdot \frac{\sin(\omega_0 - \omega)T/2}{\omega_0 - \omega}.
\]

2.2 Dispersion of the accelerating waveguide

The dispersion relation of the accelerating structure is approximated by a cos function as shown in Fig. 1.

![Dispersion of accelerating waveguide](image)

\[
\omega(k) = -\frac{B}{2} \cdot \cos \phi + \omega_m
\]

where

\[
\phi = kl \\
k = 2\pi/\lambda, \lambda = \text{wavelength in structure} \\
l = \text{cell length} \\
\omega_m = \text{mid-band frequency} \\
B = \text{bandwidth}
\]

The design phase shift per cell of the structure where the phase velocity \( v_p = \omega_0/k \) equals the speed of light \( c \) at the operating frequency \( \omega_0 \), can be chosen freely.

2.3 Reconstruction of RF pulse in waveguide

For the reconstruction in time domain of the propagating wave from its spectral components only the frequency components inside the structure's bandwidth are
taken and their phase shifts $\phi$ from cell to cell are derived from the dispersion relation as a function of frequency. The electric field in the centre of the $n$th cell is then given by

$$E(t,n) = \frac{E_0}{\sqrt{2\pi}} \cdot A(n) \cdot \int_{\omega_0 - B/2}^{\omega_0 + B/2} E(\omega) \cos(\omega t - n\phi(\omega)) d\omega$$

where

$$A(n) = e^{-\frac{\alpha n}{2N_s}}$$

$\alpha$ = attenuation constant for stored energy

$N_s$ = number of cells in waveguide section.

$E_0$ = input amplitude

The attenuation given by the factor $A$ is an approximation because it does not take into account the dependence of damping on frequency within the passband.

3. RESULTS OF NUMERIC COMPUTATIONS

3.1 Deformation of the travelling RF pulse

As the RF pulse described in 2.1 travels along the accelerating structure its time structure changes due to the limited bandwidth and dispersion of the structure. Figure 2 shows the shape of a pulse after having travelled through a

![Diagram](image-url)

Fig. 2 Time structure of an RF pulse of 330 cycles' length after different structure lengths
structure with a relative bandwidth referred to midband frequency of 6%. The RF pulse length is 330 cycles, which corresponds to an attenuation constant of $\alpha = 0.5$ and a structure $Q$ of 4147 at 29 GHz. The different graphs show various structure lengths from 0 to 100 cells; for the top curve the bandwidth of the signal was already clipped to 6%. The square-shaped input pulse is shown as a dotted line.

Figure 2a) shows the case of a structure with a $\pi/2$ phase shift per cell, Fig. 2b) that of $2\pi/3$. In Fig. 3a and 3b) the corresponding frequency spectra of the pulse within the passbands are shown.

![Fig. 3 Fourier spectrum within structure passband](image)

Figure 4 shows the variation of pulse width at design field between the rising and the falling edge with structure length for different bandwidths and

![Fig. 4 Width of an RF pulse of 330 cycles as a function of structure length](image)
structure design phase shifts. This width has been taken between the moment the pulse first reaches the design field and the moment it last falls below it. The arrows indicate the structure length one would have in order to match the filling time to the pulse length. A comparison of $\pi/2$ and $2\pi/3$ structures shows significantly wider pulses for $\pi/2$ structures.

3.2 Distribution of the accelerating fields along the structure

The accelerating fields relativistic particles see as they travel through the RF structure were computed by calculating the fields in successive cells at the times the particles cross their centres.

The results for different times during an RF pulse are shown in Figs. 5 and 6 for two different bandwidths of 12.8% and 4%. The section lengths have been so chosen that the filling time equals the duration of the RF pulse, which was taken to be 330 cycles. The particles and the pulse travel from left to right. Time is measured in units of RF periods.

In Figs. 5 and 6 the pulse length is 330 cycles, stretching from -165 to +165 cycles. The structure mode is $\pi/2$, $\alpha = 0.5$.

![Fig. 5](image1)

**Fig. 5** Accelerating field seen by a particle at different times after switch-on of the pulse. Bandwidth = 12.8%.

![Fig. 6](image2)

**Fig. 6.** As Fig. 5. Bandwidth = 4%.
3.3 Energy gain of particles

The total energy gain per section length is shown as a function of input phase for structures with different bandwidths and a design phase shift of $\pi/2$ in Fig. 7a) and of $2\pi/3$ in Fig. 7b). The dotted line gives the theoretical energy gain if the RF wave had the design amplitude in all cells (attenuation being taken into account). The particles are injected after the filling time $t$.

![Graphs showing energy gain for different cell counts and bandwidths](image)

**Fig. 7** Energy gain in one section for an amplitude of the input RF pulse of 1, so that the energy gain would be unity per cell with an ideal pulse and no attenuation. $a = 0.5$, pulse width 330 cycles.

Figure 7 shows that $2\pi/3$ structures not only give less energy gain but also introduce a phase shift as is also shown in a different analysis using Laplace transformation [7]. The reduction $\Delta E/E$ in energy gain due to these effects is given in the following table:

<table>
<thead>
<tr>
<th>Relative bandwidth</th>
<th>2%</th>
<th>4%</th>
<th>6%</th>
<th>8%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E/E$ for $\pi/2$ structure</td>
<td>3%</td>
<td>1.2%</td>
<td>0.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta E/E$ for $2\pi/3$ structure</td>
<td>7.1%</td>
<td>4.2%</td>
<td>3%</td>
<td>1.8%</td>
<td>1.2%</td>
</tr>
</tbody>
</table>
4. CONCLUSION

These results show that dispersion effects lead to a loss in energy gain of several per cent. This is particularly pronounced for structures with the conventional choice of \(2\pi/3\) phase shift per cell. The use of accelerating structures with bandwidths of \(= 5\%\) for \(\pi/2\)-mode and \(= 10\%\) for \(2\pi/3\)-mode reduces this loss considerably. Disk-loaded waveguides with large beam holes - although with reduced shunt impedance - or other structures such as crossbar, jungle gym, ladder etc. could be used for this purpose.

* * *

REFERENCES

STUDIES OF A FREQUENCY SCALED MODEL TRANSFER STRUCTURE FOR A TWO-STAGE LINEAR COLLIDER

T. Garvey, G. Geschonke, W. Schnell and I. Wilson
CERN, Geneva, Switzerland

ABSTRACT
Results are reported of bench-top measurements of the RF and electromagnetic properties of a travelling waveguide structure. These measurements are performed with the aim of assessing the suitability of this device for playing the role of a transfer structure in a two-stage RF linear collider.

1. INTRODUCTION

In the two-stage RF linear collider proposal of Schnell [1] it is envisaged that the extraction of energy from the low-energy (< 5 GeV), low-frequency drive beam will be by direct deceleration in an RF structure. This "transfer structure" would essentially consist of small sections of travelling waveguide linking alternate drive beam accelerating structures and would be coupled to the high energy (1 TeV) high frequency (29 GHz) linac by short runs of waveguide. Results are presented here of a dimensionally scaled-up model of a structure which may be suitable for this purpose. The results presented here were obtained with a 12-cell model and represent an extension of work previously carried out on a four-cell device. A preliminary account of this work is given in Ref. [2].

2. THE TRANSFER STRUCTURE

Although the structure will be required to be resonant at the same frequency as the main linac the model structure was machined for 2 GHz nominal operation. This obviated the need for machining and working with small structures and allowed us to operate within the frequency range of available sources and detectors. The device consists of a comb-like structure in rectangular waveguide rather like a linear magnetron (Fig. 1). The teeth of the comb however do not extend across the full height of the guide so allowing adjacent cells to couple through both electric and magnetic fields. As the device is desired to operate in the π/2 mode the cell spacing was set at λ/4 (where λ is the free space wavelength) resulting in an overall length of 450 mm. A complete geometrical description of the structure can be found in Ref. [2].
3. MEASUREMENTS

The properties of the transfer structure were investigated using two existing automated and computer-controlled test arrangements originally constructed for testing LEP components.

The first allowed low-power CW measurements to reveal the frequency response of the structure (terminated in electric walls) up to frequencies of 3 GHz. Having determined the resonant response of the device the distribution of longitudinal electric field on axis was obtained by the Muller-Slater perturbation technique [3,4]. The shunt impedance per unit length ($R'$) was calculated from the perturbation data for the $\pi/2$ mode and the cavity quality factor ($Q$) was calculated from the half power (3 dB) points. Identification of the normal modes of the structure was confirmed by measuring the relative RF phases of adjacent cells in standing-wave mode. Modal identification permitted construction of the dispersion relation of the structure.

The second arrangement consisted of a time domain co-axial wire measurement of the structure which gives information on the longitudinal wake potential [5,6]. A comparison between data obtained on the two test arrangements yields a value for the beam-loading enhancement factor of the structure.
4. RESULTS

4.1 CW measurements

The 12-cell structure would normally be expected to exhibit 11 eigen-modes corresponding to travelling-wave phase shifts of $\pi x/12$ ($m = 1, 2, 3, ..., 11$) from cell to cell. Transmission tests, however, revealed a much richer spectrum. Subsequent perturbation analysis of each resonance in turn indicated that the resonances could be grouped in pairs which exhibited identical field distributions along the faces of the combs, despite having distinctly different distributions on axis. These resonance pairs were believed to be due to the normal modes but with each pair corresponding to a situation in which the opposite combs, considered as coupled oscillators, resonated either in anti-phase or in phase with respect to each other. In contrast to the in-phase modes the anti-phase modes have non-zero magnetic fields on axis and these fields considerably complicate the signals obtained during perturbation runs with a metal bead (sensitive to contributions, of opposing sign, from electric and magnetic fields). In order to avoid the effects of magnetic fields the perturbation runs were repeated with a dielectric bead (sensitive only to electric fields) for the perturbing object. For the in-phase modes the field distribution of the $m^{th}$ mode has $m$ nulls while the anti-phase mode has $m-1$ nulls and all modes were duly identified from the observed distributions.

Another consequence of anti-phase modes is that the on-axis fields are purely transverse in contrast to the in-phase modes where the on-axis fields are always longitudinal. This situation was verified by performing perturbation measurements with disc- and needle-shaped objects which are sensitive to field polarity.

For some modes coupling to and from the cavity appeared weak and the resulting perturbation signals were not clean enough to unequivocally identify a mode. In this case the variation in phase between adjacent cells confirmed the identity of the resonance. The resulting dispersion diagram of the transfer structure is shown in Fig. 2.

Frequency tuning of the structure was carried out by altering the length of the teeth of the combs. The correct length was obtained empirically on the four-cell structure and interpolation of the data resulted in the 12-cell device having an in-phase $\pi/2$ mode resonant at 1.992 GHz.
In the usual theory of perturbation a metal bead of radius \( r \) located at a point in the cavity where the local electric field is \( E \) and the magnetic field is zero causes a frequency shift, \( \Delta f \), from the unperturbed resonant frequency, \( f \), where

\[
\frac{\Delta f}{f} = \frac{\pi r^3 \varepsilon_0 E^2}{W}
\]  

(1)

where \( \varepsilon_0 \) is the permittivity of free space and \( W \) is the average cavity stored energy.

This results in a phase shift between generator and cavity, \( \Delta \phi \), given by

\[
\tan \Delta \phi = 2Q \frac{\Delta f}{f}
\]

(2)

where \( Q \) is the resonator quality factor for the mode in question.

The automated equipment used to make the perturbation runs incorporates a computer program which performs a point-wise integration over the measured phase.
shifts [7]. This integral is then used to compute the standing-wave impedance of the resonator (suitably corrected for transit time effects).

The standing-wave shunt impedance of the π/2 mode was found to be 94 kΩ⁻¹ (±5%) and the measured Q was 2860. The latter was obtained by varying the excitation frequency until the 3 dB points were found.

4.2 Pulsed measurements

These measurements were made by sending a short (~110 ps FWHH) electromagnetic pulse down a coaxial wire threaded through the transfer structure so simulating the passage of a relativistic bunch. This is done for both the structure and for a reference line which is essentially a length of unloaded waveguide whose dimensions are equal to those of the structure in the absence of combs. Tapered waveguide is used to match into and out of the structure and to provide connections for the cable carrying the fast pulse. In principle the change in pulse deformation between the structure and the reference yields the value of the total longitudinal loss factor, k [5,6]. The transmitted current pulses are fed to a fast rising sampling scope, analog-to-digital converted and the data then stored in a desktop computer which contains a program for computing the loss factor [6].

Repeated measurements of the loss factor indicate that it has a value of < 0.055 V/pC. This corresponds to a loss factor per unit length, k', where

\[ k' < 0.122 \text{ V/pCm}. \]

Following the definition of the fundamental loss factor, k₀, we have [8],

\[ k_0' = \frac{\omega}{4} \frac{R'}{Q} \]  \( (3) \)

where \( \omega = 2\pi f \). This yields (using the perturbation data) a value of 0.1 V/pCm for the transfer structure which, when suitably corrected for a pulse of 110 ps FWHH, gives

\[ k_0' = 0.071 \text{ V/pCm}. \]

The longitudinal beam loading enhancement factor B is then given by

\[ B = \frac{k'}{k_0'} < 1.72. \]

5. DISCUSSION

An immediate consequence of the large transverse aperture of the structure is the wide bandwidth (= 20%) and corresponding high group velocity of the structure
(Fig. 2). As the fill time of the structure must equal the period of the low-frequency drive linac (2.86 ns) a high group velocity is required to prevent the structure being inconveniently short \[1\]. This large transverse aperture is also beneficial in terms of reducing the effects of transverse wakes.

The measured value of \(r'/Q\) is 32 \(\Omega^{-1}\) which scales to give 900 \(\Omega^{-1}\) for a travelling wave at 29 GHz. This value although small is not less than that required for the transfer structure. Interpolating between the data points of Fig. 2 one can easily estimate the group velocity of the forward wave structure using the relation

\[
\frac{V_g}{c} = \frac{1}{c} \frac{d\omega}{d\phi} = \frac{\pi}{2f} \left( \frac{A_f}{A_\phi} \right).
\]

(4)

For the structure under investigation we have \(V_g/c = 0.14\).

The value obtained for \(B\) can be taken to be a measure of the efficiency of energy transfer to the fundamental mode relative to all other possible longitudinal modes. The fact that this ratio is not too far from unity must be considered to be encouraging although one has to bear in mind the possible errors which typify coaxial wire measurements.

6. CONCLUSIONS

Preliminary measurements on the device discussed in this paper indicate that it may be a solution to the geometry required of a transfer structure for the linear collider proposal of Ref. [1]. Further studies are necessary however before proceeding with a more formal design. In particular, computational studies of the model would provide complementary information to that obtained by the measurements. Indeed three-dimensional codes are now available for computing such geometries and runs to calculate the normal mode frequencies of the structure are in excellent agreement (better than 3\%) with the values obtained experimentally [9].

ACKNOWLEDGEMENTS

We are indebted to H. Henke for providing the means to perform the coaxial wire tests and for his advice on the measurement techniques. He is the author of the computer code for the evaluation of the loss factor.

* * *

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REFERENCES


* N.B. The top figure of page 5 from this reference should have the dimension 150 mm replaced by 142 mm.
HIGH AVERAGE POWER LINEAR INDUCTION ACCELERATOR DEVELOPMENT

John R. Beyless and Richard J. Adler
Pulse Sciences, Inc.
5330 Derry Ave., Suite J, Agoura Hills, CA, USA 91301

ABSTRACT

There is increasing interest in linear induction accelerators (LIAs) for applications including free electron lasers, high power microwave generators and other types of radiation sources. Lawrence Livermore National Laboratory has developed LIA technology in combination with magnetic pulse compression techniques to achieve very impressive performance levels. In this paper we will briefly discuss the LIA concept and describe our development program. Our goals are to improve the reliability and reduce the cost of LIA systems. An accelerator is presently under construction to demonstrate these improvements at an energy of 1.6 MeV in 2 kA, 65 ns beam pulses at an average beam power of approximately 30 kW. The unique features of this system are a low cost accelerator design and an SCR-switched, magnetically compressed, pulse power system.

1. INTRODUCTION

The linear induction accelerator (LIA) concept, which is illustrated in Fig. 1, was first proposed in 1958. It has been extensively developed at Lawrence Livermore Laboratory (LLNL) and Pulse Sciences, Inc. (Ref. 1, 2, 3). This accelerator operates in many respects like an electrical transformer. A pulsed voltage, which is only a small fraction of the final beam voltage, is applied to a series of ferrite cores contained within accelerator cells. The electron beam, which is equivalent to the secondary of a transformer, passes through the cells where it is accelerated in the gaps between grounded electrodes to attain a final voltage that is the sum of the cell voltages. Thus, high beam voltage is achieved without requiring comparable voltages in the system. Furthermore, the use of a pulsed drive means that the cell voltage is present only a small fraction of the time (<0.1%). Thus, voltage breakdown issues are greatly reduced in comparison to other types of accelerators. Because LIAs readily operate at peak currents in the kilampere range, high electrical efficiency can be achieved. High average power is attained by repetitively pulsing the system. Because of these characteristics, the LIA is the only type of accelerator capable of providing the combination of high beam voltage and current, high average power, high efficiency, and low cost that is required for applications including free electron lasers, high power microwave generators and two-beam accelerators.

The major elements of a LIA system are the power supply, the pulsed power source and the LIA. Pulse lengths of less than 100 ns are necessary to achieve reasonable accelerating gradient, size and cost. For high average power systems, voltage pulses with this duration are generated using thyatron or SCR switches and a series of capacitors coupled through saturable inductors. These magnetic compression (MC) stages act to compress the pulses to
the final pulse length. A step-up transformer is employed to obtain the final charging voltage. Other devices such as spark gaps can be used as the primary switch; however, they are not appropriate for systems where life, repeatability, and reliability are critical. The combination of LIA and MC technology yields a concept which is inherently scalable to high beam energies and high average power levels with good efficiency. Furthermore, the concept is simple, and tolerances and tuning are not critical.

![Diagram](image)

Fig. 1. The LIA concept.

Over ten major LIA systems have been constructed in the U.S. and others have been developed in the USSR and the PRC. Many of these machines have been designed to demonstrate the feasibility of inertial confinement fusion, charged particle beam concepts and high power free electron lasers. These machines have operated at beam energies up to 50 MeV, peak beam currents in the range of amperes to 250 kA, pulse lengths from 20 ns to more than 1 μs, and pulse repetition rates exceeding 100 Hz. Accelerating gradients have typically been on the order of 1 MV/m. The early LIA systems used spark gap switches; however, recent designs have incorporated magnetic pulse compression. The use of magnetic pulse compressors, which facilitates the use of long life switch elements, is the key factor that now makes LIA systems attractive for high average power applications (Ref. 4).

2. **LIA DEVELOPMENT AT PULSE SCIENCES**

Our goals in extending LIA/MC technology are, in order of priority, to achieve: (1) high reliability corresponding to more than 6000 hrs/year of operating time; (2) low installed system cost; (3) low operating and maintenance costs and (4) power line to electron beam conversion efficiencies of greater than 50%. We have focused on the energy range of
1-10 MeV as required for many applications. An accelerator system design has been developed to meet these goals. In order to demonstrate this design, we are currently building a 1.6 MeV prototype LIA/NC system which will operate at an average beam power of up to 30 kW. Major portions of this prototype system are currently operational and we expect to begin operation of the complete system in July 1987.

2.1 Accelerator System Parameters

A LIA consists of a series of acceleration cells as shown in Fig. 1. One cell design can be used for a wide range of beam energies; cells are simply connected in series to give the desired output beam energy. We have chosen to build LIAs in modules which contain a number of cells. An accelerator module of <1 MeV gives us the flexibility to address a variety of applications in a multi-module system.

The energy per cell and the pulse length are based on the unique properties of the MAG I type of magnetic compressor developed by LLNL (Ref. 4). This device takes an input of 25 kV in 5 μs pulses and delivers ~800 J in 75 ns, 150 kV pulses with greater than 80% electrical efficiency. To be conservative we chose 140 kV/cell as our operating voltage, and 6 cells per module for a total output of 840 kV/module.

The pulse current is chosen by balancing considerations of core loss, beam stability, focusing, accelerator length, cost, and relevant applications. Operation at pulse lengths less than 100 ns dictates the use of ferrite core material in order to minimize losses. Suitable material is available commercially. An assembly of cores with an overall outer diameter of 50 cm and an inner diameter of 10 cm is used to construct the accelerator cells. At a selected beam current of 2 kA the resultant accelerator efficiency (pulsed electrical power input to electron beam power output) is greater than 80%. A solenoidal magnetic guide field of about 1 kG serves to maintain a beam diameter of 2 cm. This guide field is pulsed in order to minimize the power required to generate it. A block diagram of the prototype system is shown in Fig. 2 and the partially completed system is shown in Fig. 3. Each of the major system elements is discussed below.

![Block diagram of the prototype LIA system](image)
2.2 Electron Beam Injector

The injector, which is shown in Fig. 4, is designed as a modified accelerator section and operates at 840 kV. This total voltage is applied across the central gap between the Pierce corrected electron source and the drift tube anode. An M-type dispenser cathode is used since this type of cathode is capable of supplying $>25 \text{ A/cm}^2$ with long life. A conservative pulsed vacuum field stress level of $E < 100 \text{ kV/cm}$ is maintained at all points in the diode region. Independently controlled pulsed magnetic field coils are provided to facilitate optimum beam focusing. As will be discussed more in the next section, the entire injector, including cores, is placed in two oil-filled tanks with vacuum pumping in the connecting tube. This assembly is 57 inches long. The beam is compressed by the converging magnetic field in the injector, and exits with a diameter of approximately 3 cm.
2.3 Accelerator Modules

A diagram of a single 840 kV module is shown in Fig. 5. At the present time, we are fabricating the injector and one accelerating module. A 5 MeV machine, for example, would consist of 5 accelerating modules plus the injector and would be about 8 m long.

![Diagram of 840 kV linear induction accelerator module]

**Fig. 5.** 840 kV linear induction accelerator module.

The module is made from two separable pieces: the tank in which the cores for 6 cells are mounted, and the removable beam line. The tank is filled with transformer oil and voltage pulses are delivered to the module by six, 50 Ω, 200 kV DC high voltage cables. The cables are connected to a bus bar, which runs the length of the module. Conducting rods provide the connection between the bus and the beam line electrodes. The overall length of a module is 40 inches.

The beam line itself includes all the stainless electrodes, drift tubes, magnetic field coils, vacuum insulators, etc. required to transport the beam. It is held together with insulated bolts. Circulating oil is brought in through fittings on the beam line to provide cooling. At the planned operating frequencies of ~100 Hz, the waste heat per module is estimated to be ~2000 Watts; we expect to be able to run at up to 600 Hz with this design without excessive ferrite core heating. This type of construction has considerable advantages in cost and ease of maintenance over conventional cylindrical cell designs.
2.4 Power System

There are two key components in the power system: the SCR modulator and the MAG I magnetic compressor. We regard the use of SCRs in this application as a major advance since thyatrons are subject to unscheduled failure, and replacement was expected to be a major cost over the accelerator life. An SCR modulator of the type we have demonstrated also eliminates the need for a separate power supply and charging inductor.

A simplified schematic of the SCR modulator is shown in Fig. 6. The power train starts at the input power line with 3 phase, 208 V power. In our prototype modulator, a 3-phase SCR bridge (SCR1) charges the capacitors $C_1$ to ±160 V. The pulse capacitors $C_2$ are resonantly charged to ~550 Volts after the SCR2 pulse. SCR2 is the primary switch. The pulse generated when it is triggered is stepped up to 26 kV by the transformer and the two magnetic compression stages shorten the pulse to approximately 4 μs. The output of this modulator is then delivered to the MAG I.

![SCR modulator circuit diagram](image_url)

Fig. 6. SCR modulator circuit

Figure 7 illustrates the MAG I circuit. This unit has been modified slightly from the original LLNL design to deliver 70 kV, 65 ns, 200 J pulses. A 2:1 ferrite pulse transformer will be used to step the MAG I output up to the 140 kV LIA module drive voltage. No compensation is provided in the present design to offset the effects of the variation in LIA core magnetization current with time. Thus, we expect the beam current and voltage to vary about ±10% during the pulse "flat-top" period of 30-40 ns. Improved pulse voltage and/or current flatness can be achieved as required by using compensating circuit elements, tapering the output impedance of the MAG I or by controlling the injector current such as to offset the magnetization current variation.

Based on our preliminary results at 200 J/pulse, we expect the efficiency of the SCR modulator to be greater than 80% and that the overall efficiency of the power system will be greater than 70%. The overall efficiency for the prototype system is expected to be greater than 55%. At higher power levels, the wall plug to electron beam efficiency should exceed 60%.
3. CONCLUSIONS

Linear induction accelerators operating in the energy range of 1-10 MeV are attractive for a variety of scientific and commercial applications which require high beam current and/or average beam power levels in the range of 50-500 kW. LIA systems driven by all-solid state power sources are attractive for these applications since they can provide high reliability, high efficiency, low capital and operating costs, and a high degree of flexibility. Furthermore, such machines are simple in construction and do not have severe tuning, tolerance or high voltage insulation requirements.

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REFERENCES

POSSIBLE PARAMETERS OF PULSERS FOR LINEAR INDUCTION LINACS

V.I. Bobylev
Institute of Theoretical and Experimental Physics, Moscow, USSR

Induction linacs allow ion beams of high intensities to be achieved comparatively easily. The output energy is limited (at the same pulse duration) practically only by the quantity of accelerator modules, i.e. sequences of 1:1 transformers [1]. Modern technology requires ion beams with energies up to 50 and more MeV and currents of several kA with pulse lengths varying from 10-20 to 100-200 ns. Such energies demand the use of enormous quantities of powerful pulse generators operating practically in parallel to the accelerated beam. The accelerator LIU-5/5000 (USSR, ITEP), for example, uses 56 thyrotron generators, [2]. To achieve reliable operation of the accelerator and stable parameters of ion beam pulses it is necessary to use almost absolutely reliable pulse generators with strict time synchronisation. As a consequence power sources, pulse generators, circuits of magnetic compression and transmission lines occupy approximately 80% of the whole accelerator facility. Generators with thyrotrons and/or spark dischargers but without magnetic compression have some negative features:

1. Necessarily lowered pulse steepness, due to the inductance of the capacitor plates.

2. Rather long (from 20-30 to 100 ns) anode current rise times slowing down the pulse front and, as a consequence, under use of the cores' possibilities.

3. Unstable delay of thyrotron start relative to the firing pulses as a function of operating conditions. This disadvantage makes it practically impossible to start normal operation of the linac from the "first pulse".

Elimination of these negative features is possible nowadays by two promising technical methods. The first and more used is the pulse-length compression or power "transformation" [2-4]. This method allows a reduction in the requirements for peak amplitudes of currents triggered by thyrotrons, and to increase their duration to values longer than times of delay and propagation of gas discharge. But magnetic compression can solve only a part of these problems and leads to additional expense: every magnetic compression section with a compression factor of 3-5 requires ferromagnetic materials and capacitors of volumes approximately equal to those of the induction system of the linac. So, to achieve pulse lengths of 50-100 ns from thyrotrons usually operating with pulses of 5-10 μs it is necessary to use ferromagnetic materials and capacitors exceeding the quantities of those used in the linac. In addition, magnetic generators are rather sensitive to instabilities of feed voltage and even the values of the load. The latter may result in difficulties during alignment of the linac.
The second method is the use of inductive storage of the energy. It is known that inductive storage allows the use of energy "densities" approximately a thousand times more than in capacitors [5]. The simplest circuit of a generator with inductive storage consists of a tube or a gas-discharged tube with two-way control of current and an inductive storage device in series. Stored energy is thus transmitted into the load beginning at the moment of blocking the tube. Tubes capable of controlling currents of more than 1 kA with a peak forward anode voltage of more than 50 kV are now available [6]. There is some information [7] on the possibility of gas-discharge devices with two-way control of current. If such tubes are used to supply power to separate accelerator sections the total inductance is

\[
L = \frac{2 \Delta W}{hI^2}
\]

where \(\Delta W\) is the beam energy increase at the section in joules, \(I\) the peak current of the tube and \(h\) the efficiency of the section. If partial discharge of the storage is required \(L\) should be increased. The inductance voltage after the moment of blocking the tube is

\[
U_L = U_{r1} \left(1 + \frac{R_1}{R_{r1}} \right),
\]

where \(U_L\) is the peak voltage at the load and inductance, \(U_{r1}\) the voltage at the active part of the inductive storage before the moment of blocking the tube, \(R_{r1}\) the active resistance of the inductive storage and \(R_1\) the load [8]. The usefulness of generators with inductive storage should be noted, in particular in connection with the recent developments in high-temperature superconductivity. The use of superconductive storage will allow us to improve the parameters of generators and to increase output voltages with constant feeding voltages.

Comparable parameters of generators of both types are given in Table 1. In the cases where it will be necessary to study the discussed parameter in detail there is an interrogation mark in the corresponding column. The signs "+" and "-" ascribe to the parameter a positive or negative feature. It is clear that the generator with inductive storage possesses some serious advantages. Taking into account not only the advantages enumerated in the table, but also the qualitative ones mentioned in the text, it is possible to state that generators with inductive storage may find wide use in induction linacs for high energy beams.
Comparison of the advantages and disadvantages of magnetic generators and inductive storage

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Magnetic generators</th>
<th>Inductive storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Waveform of the pulse</td>
<td>Necessity for correction (?)</td>
<td>Rectangular (with partial dischage) (+)</td>
</tr>
<tr>
<td>2</td>
<td>Reliability</td>
<td>High (+)</td>
<td>Unknown (?)</td>
</tr>
<tr>
<td>3</td>
<td>Availability</td>
<td>Available (+)</td>
<td>Unknown (?)</td>
</tr>
<tr>
<td>4</td>
<td>Weight</td>
<td>Large (-)</td>
<td>Small (+)</td>
</tr>
<tr>
<td>5</td>
<td>Dimensions</td>
<td>Large (-)</td>
<td>Small (+)</td>
</tr>
<tr>
<td>6</td>
<td>Possibility to increase pulse</td>
<td>No (-)</td>
<td>Yes (+)</td>
</tr>
<tr>
<td></td>
<td>repetition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Values of feeding voltages</td>
<td>High (-)</td>
<td>Low (+)</td>
</tr>
<tr>
<td>8</td>
<td>Necessity for further studies</td>
<td>(?)</td>
<td>Yes (-)</td>
</tr>
</tbody>
</table>

* * *

REFERENCES


Cost Optimization of Induction Linac Drivers for Linear Colliders

William A. Barletta
University of California, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.

ABSTRACT

Recent developments in high reliability components for linear induction accelerators (LIA) make possible the use of these devices as economical power drives for very high gradient linear colliders. A particularly attractive realization of this "two-beam accelerator" approach is to configure the LIA as a monolithic relativistic klystron operating at 10 to 12 GHz with induction cells providing periodic reacceleration of the high current beam. Based upon a recent engineering design of a state-of-the-art, 10- to 20-MeV LIA at Lawrence Livermore National Laboratory, this paper presents an algorithm for scaling the cost of the relativistic klystron to the parameter regime of interest for the next generation high energy physics machines. The algorithm allows optimization of the collider luminosity with respect to cost by varying the characteristics (pulse length, drive current, repetition rate, etc.) of the klystron. It also allows us to explore cost sensitivities as a guide to research strategies for developing advanced accelerator technologies.

1. INTRODUCTION

The desire of high energy physicists to investigate phenomena at TeV energies has lead accelerator designers to consider new classes of machines that can achieve accelerating gradients >100 MeV/m in structures suitable for high repetition rate operation. The approach should be highly reliable and highly energy efficient if the costs of machine operation are to remain within currently acceptable bounds. In general, the accelerating gradient can be increased and the energy required per meter of accelerator structure reduced by scaling\(^1\) the (effective) rf-structure of the accelerator to high frequencies (\(\geq 210\) GHz.). The practical limits of this approach for conventional rf-cavities are set by the electron-induced breakdown limit and the surface heating limit, with little gain in gradient being achievable for frequencies exceeding 30 GHz. Considering that the cost of the rf-structure is likely to increase once it is miniaturized beyond a scale size of about 2 cm, we can select 10 to 30 GHz as the best frequency range for an advanced linear collider.

At the low end of this range we can employ many conventional klystrons to power the collider. More novel approaches, however, may offer the same performance at substantially lower cost. The two-beam accelerator (TBA) is a concept for using the high peak current beam produced with a linear induction accelerator (LIA) to excite an rf-generating structure at high frequency; the high peak power rf is then fed via a transfer structure to the miniaturized rf-cavities of the accelerator of the high energy beam. One variant of the TBA\(^2\) employs a free-electron laser amplifier to transform the kinetic energy of the high current beam to high peak power microwaves. Another variant\(^3\), more suitable to the frequency range from 10 to 15 GHz, converts the LIA into a monolithic relativistic klystron that runs the length of the high frequency rf-accelerator.

\(\text{\^1 Work performed jointly under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48 and for the Department of Defense; SDIO/BMD-ATC MIPR } \#\text{W31-RPD-53-A127.}\)
This paper describes a cost model developed to compare the relativistic klystron approach to powering a 12-GHz rf-accelerator with one powered by multiple klystrons. The considerations presented, however, are more general and can be used to estimate LIA costs over a wide range of operating parameters consistent with the constraints of beam dynamics and properties of materials. The scaling variables for the LIA include beam voltage (V), beam current (I), pulse length (T_p), repetition rate (f), and gradient (G) in the induction modules. The cost model is based upon the engineering design of a multistage, high repetition rate, induction linac (ETA II) now under construction at Lawrence Livermore National Laboratory (LLNL).

2. BASIS OF COST MODEL

The basis of any cost optimization study must be an accurate model of the scaling of accelerator cost with operating characteristics. The cost of LIAs is often assumed^1 to scale linearly with the number of volt-seconds in the accelerator cores; another frequently heard scaling is that LIAs cost $1 per volt. Although the cost algorithm developed below substantiates the rough linearity of cost with machine voltage, these and other rules of thumb can be grossly misleading. In particular, the cost per volt (C) can vary by nearly an order of magnitude depending upon the actual operating specifications of the accelerator.

2.1. General Considerations

The cost analysis begins with the division of the LIA into its primary subsystems: an induction-driven injector, the accelerator cells, beam transport, and ancillary systems.

\[ C_{\text{accel}} = C_{\text{inj}} + C_{\text{cell}} + C_{\text{tran}} + C_{\text{sys}} \]  

(1)

The injector and accelerator cells consist of nonresonant, axisymmetric gap structures that enclose toroidal cores of ferrimagnetic material. A drive voltage impressed across the gap by the power drive changes the flux in the core, inducing an axial electric field that accelerates the electrons. In general, the electron injector and accelerator cells have similar power drive networks (Fig. 1): a dc-power supply charges a set of intermediate storage capacitors via a command resonant charging circuit. These intermediate stores are discharged through the primary commutators—thyatrons (or SCRs)—into low impedance magnetic pulse compressors (MAG).^4 Each compressor can power a number of accelerator cells connected in parallel. Although the high current beam (~1kA) forms the primary load for the pulse compressors, a parallel compensation network maintains a constant accelerating voltage throughout the beam pulse. The fundamental limits to the operating characteristics of the LIA are set by beam transport physics, material properties, and primary commutator recovery times.^5

The injector scaling assumes a gridless, constant permeance design with space charge limited emission, i.e., the injector voltage (V_{inj}) is given by

\[ V_{\text{inj}} = k (I_{\text{beam}})^{2/3} \]  

(2)

where V_{inj} is in MeV, I_{beam} is in kA, and k = 0.75 (1.45) for high current (brightness) beams. The scaled designs employ a thermionic (dispenser) cathode. The primary cost components include the injector induction structure, focusing, MAG drives, intermediate stores and power supplies, alignment fixtures, and vacuum.

Ancillary systems include vacuum and gas handling systems, low and extremely low conductivity water (LCW), electrical fluids such as insulating fluids and compensation loads, alignment fixtures, miscellaneous fixtures and structures, and instrumentation and controls. Based
Figure 1. Schematic of baseline design of induction linac
on review of a detailed installation schedule, we find that the cost of installation, support engineering, and its associated supplies and expenses is each a nearly constant percentage of the hardware cost (~10%). The actual percentage will depend upon the labor rate at the accelerator site. Separate support facilities are not included, i.e., the hardware cost assumes an existing technical infrastructure in the vicinity of the accelerator site.

2.2. Accelerator Cell and Drive Design

The basis for scaling the design of the accelerator cells and drives is the prototype of the ETA II cell, illustrated in Fig. 2, the MAG-1D6 pulse compressor, and its associated thyatron-switched intermediate stores. The most important cell characteristics are the gap width (w), the inner radius of the cell (ri), the radius of the beam pipe (b), and the volt-seconds of core material. The cores consist of toroids of ferrite (TDK PE-11), which has minimal core losses for short saturation times (<1 μs). The gap size and shape is selected to minimize the Q of the cell and the coupling (Z) of the beam to transverse (beam breakup) modes of the cell. The baseline design has a gap width (w) of 0.635 cm for a conservatively chosen gap field stress (Eg) of 175 kV/cm. The insulator, which separates the vacuum from the insulating fluid (FC-75), is set at an angle such that all TM cavity modes will pass through the insulator without reflection to be absorbed by the ferrite. The slight reentrant design of the gap shields the insulator from stray beam electrons. The difference between the pipe size and inner cell radius (~2 cm) is accounted for by the size of steering magnets and focusing magnets (about 1 to 3 kG) and spacers to allow insulating fluid to flow along the inner boundaries of the ferrite.

The choice of inner radius (7.5 cm) for the baseline design was set to keep the beam breakup (BBU) growth below 10 in an accelerator for a mono-energetic, 3-kA beam transported with quadrupoles through ~10^3 gaps (accelerating cavities). With such a focusing system, the beam breakup growth (S) will scale as

![Figure 2. Cross section of a typical low-gamma 10-cell module of the new 150-kV accelerator cell](image)
\[ S \propto I_{\text{beam}} \left( w/b^2 \right) (\ln N_g) \Im P_1(\omega) / B E_g , \]  

(3)

where \( N_g \) is the number of gaps and \( B \) is the (effective) field strength of the magnetic transport. Typically, we can replace \( b \) in Eq. (3) with \( r_1 \) for the purpose of scaling costs. The quantity \( \Im P_1(\omega) \) is that part of the cavity response function that produces growth of TM_{10} beam breakup modes. To suppress BBU we minimize \( | \Im P_1(\omega) | \) by arranging that the beam induced fields in the cavity are purely outgoing. That is, we shape the gap so as to approximate a perfectly matched radial line. In that case, \( | \Im P_1(\omega) | \) is a slowly varying value of \( w/b \) and is roughly linear over the range \( 0.1 < w/b < 1; \)

\[ | \Im P_1(\omega) | = 0.71 - 0.33 \frac{w}{b} . \]  

(4)

Typically, in LIAs built to date, \( b \) is several centimeters, and \( w/b \approx 0.3 \). In contrast, the relativistic klystron variant of the TBA will require a pipe size \( < 1 \text{ cm} \) (beyond cutoff), in which case \( w/b > 1 \). Two factors suppress the BBU in this case: For the accelerator cells, \( w/b = 3 \), at which value \( | \Im P_1(\omega) | \) is of order \( 10^{-2} \). However, the BBU growth due to the beam interaction with the klystron cavity is rapid. Almost as rapid is the growth of transverse motion due to the resistive wall instability.\(^8\) Fortunately, the large spread in the beam's betatron frequency due to the large energy spread induced by the klystron action and/or by laser-guided transport\(^7\) allows shrinking the pipe size below cut-off \( (r_1 = 2.5 \text{ cm}) \) as is required for the operation of the klystron.

The outer radius of the cell is determined by the accelerating voltage \( (V_{\text{acc}}) \) and the cell length \((z)\) via the magnetic induction equation,

\[ V_{\text{acc}} T_p = A \left( \Delta B \right) , \]  

(5)

where \( A \) is the cross-sectional area of the ferrite, \( \Delta B \) is the total flux swing \((0.6 \text{ Wb/m}^2)\), and \( T_p \) is the pulse duration. Writing the cell length \((z)\) in terms of the effective gradient \((G)\) and the packing fraction for the ferrites \((p)\) we can recast Eq. (5) as

\[ r_0 = r_1 + \left( G T_p / p \right) / \Delta B . \]  

(6)

Typically, the packing fraction is 0.8. The effective gradient \((G)\) for the baseline design is 0.75 MeV/m.

For ease in designing the beam transport system, it is necessary that the waveform of the accelerating voltage vary by no more than 1% over time. In that case the length of the cell and the properties of the ferromagnetic material are subject to an additional constraint. The region between the high voltage drive blade and the back wall of the induction cavity should be designed to be a constant impedance transmission line loaded with a high \( \mu \) material to slow the wave speed. Even if the transverse dimension of the cavity is sufficiently large to avoid a saturation wave forming in the core, the transit time in the longitudinal direction must equal or exceed the pulse length. That is,

\[ z \geq T_p \left( \mu \epsilon \right)^{1/2} . \]  

(7)

Moreover, the requirement that the transmission line have a constant impedance dictates that the core must be composed of a material like ferrite rather than wound metallic glass tapes. For high fidelity ferrites

\[ (\mu \epsilon)^{1/2} = 100 ; \]  

(8)
hence, Eq. (5) can be written as

\[ c(r_o-r_l) / (\mu \varepsilon)^{1/2} \geq (V/\Delta B) \]  

(9)

If the core geometry is such that the value of the magnetic field in the core varies inversely with radius, then, to avoid saturation anywhere in the core, Eq. (9) should be modified to

\[ c(r_o-r_l) / (\mu \varepsilon)^{1/2} \geq [\ln (r_o/r_l)] (V/\Delta B) \]  

(10)

For both compactness and convenience in installation and maintenance, the accelerator cells are packaged in blocks of ten. Each block of cells is attached to a strongback structure, which is the primary means of assuring accelerator alignment to better than 0.5 mm. If the beam transport is provided by a laser-ionized channel or if the energy spread in the beam is large, as in the case of the relativistic klystron, the structural demands on the strongback are eased considerably, because the cell blocks are shorter and lighter.

The constraint to minimize operating costs of high luminosity linear colliders requires us to keep core magnetization (hysteresis) losses small. The same design consideration allows us to minimize beam energy variations during the pulse (\(\Delta E/E < 1\%\)). In practical terms, the magnetization current should not exceed 20% of the beam current, i.e.,

\[ I_m = (1/L) \int V_{acc} \, dt \leq 0.2 \, I_{beam} \]  

(11)

where the core inductance (L) is given by

\[ L = (\mu/2\pi) \ln (r_o/r_l) \]  

(12)

Then, the core loss (joules per volt) is

\[ \Re = (\pi/\mu) \, G \, T_p^2 \, (\ln r_o/r_l)^{-1} \]  

(13)

For the baseline design of the core \(T_p = 75\) ns and \(\Re = 16\) J/MV; reducing \(T_p\) to 50 ns would reduce \(\Re\) to \(< 9\) J/MV. For relativistic klystrons designed to power large linear colliders (\(-4\) GV of induction cells per TeV of high energy linac), the incentives to lower \(T_p\) are clear.

The accelerator cells are driven by Freon-cooled MAG-1Ds (Fig. 3) that consist of metallic glass, nonlinear inductors that operate from the unsaturated to fully saturated state in the pulse compression process. For linear colliders operating at repetition rates between 100 to 1000 Hz, the MAG-1D pulse compressors are capable of continuous operation\(^5\) and have been tested for hundreds of millions of pulses without change in operating characteristics. The cost model assumes that the thyratron switches used in the intermediate stores are ceramic envelope tubes (by English Electric Valve Corp.) capable of continuous 1-kHz operation. For collider operation at 100 to 200 Hz, glass envelope tubes (from multiple manufacturers) could be used with a cost savings of about a factor of three.

3. COST SCALING RELATIONS

3.1 Scaling Principles

By breaking down each subsystem into a set of components and their internal constituents (if necessary), we can arrive at a descriptive level at which scaling relations can be assigned on the basis of basic physical characteristics. For example, the cost of the accelerator cell housing is
Figure 3. Cutaway view of MAG-1D
determined by the quantity of metal and, more significantly, by the length of machining, finishing and welding time involved in the cell manufacture. This time scales linearly with the surface area to be machined, finished, welded, and inspected. The baseline cost estimate includes no reduction for the use of production engineering techniques, such as large scale metal casting and robot welding. Such techniques might reduce the cost of the accelerator cell housings by more than 30%. A complete set of components, internals, and scaling determinants of the accelerator subsystem are listed in Table 1.

In similar fashion, we can assign scaling determinants to the components included among the ancillary systems. These characteristics, listed in Table 2, require some qualifying comments: As the cell size decreases, the vacuum system will become conductance limited rather than pumping speed limited. Consequently, the system cost will then scale with machine length rather than with the pumping volume. Over the range of accelerator sizes of interest for linear colliders, the cost of the instrumentation and control system is assumed to be a "buy-in" fixed cost plus a percentage of the accelerator cell costs.

<table>
<thead>
<tr>
<th>Component</th>
<th>Internals</th>
<th>Scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Supplies</td>
<td>DC supplies, CRCs</td>
<td>Average Power</td>
</tr>
<tr>
<td>Intermediate stores</td>
<td>Capacitors, Thyratrons</td>
<td>Pulse energy, Average current, pulse energy</td>
</tr>
<tr>
<td>Magnetic compressors</td>
<td>MAG-1D</td>
<td>Pulse energy</td>
</tr>
<tr>
<td>Accelerator cells</td>
<td>Ferrites, Cell housing, gap</td>
<td>Volume ($V_{acc}$, T, G), Surface area ($r_i$, $r_o$, G), Total voltage</td>
</tr>
<tr>
<td>Strongback</td>
<td></td>
<td>Cell weight and length</td>
</tr>
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Table 1.
Scaling principles for accelerator cell components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCW and ELCW</td>
<td>Pulse energy, average power</td>
</tr>
<tr>
<td>Vacuum</td>
<td>Pumping volume</td>
</tr>
<tr>
<td>Insulating fluids</td>
<td>Average power</td>
</tr>
<tr>
<td>Fixtures and Alignment</td>
<td>Length</td>
</tr>
<tr>
<td>Instrumentation and Controls</td>
<td>System complexity</td>
</tr>
<tr>
<td>Beam dump</td>
<td>Average power into dump</td>
</tr>
</tbody>
</table>

Table 2.
Cost scaling determinants for ancillary systems.
The injector subsystem consists of a collection of components similar to those of the accelerating cells. In addition, the injector includes some separate ancillaries such as vacuum, focusing, and alignment fixtures. The subsystem is characterized by an anode-cathode voltage \( V_{\text{INP}} \), which is related to the beam current by Eq. (2). The scaling of the cost of the injector follows from the same physical considerations as for the accelerator cells.

The most complex scaling applies to the beam transport system as several alternative focusing schemes are possible:

a) continuous solenoid,

b) solenoids in the first 20 MeV followed by a quadrupole lattice, and

c) laser guiding.

The guiding principle in the specification of the transport system is that the BBU growth parameter \( S \) in Eq. (3) is kept constant. Equation (3), however, assumes a mono-energetic beam with uniform betatron frequency \( \nu_0 \). Consequently, scaling the transport schemes is complicated by the degree of energy spread, \( \Delta E/E \), of the electron beam. For the relativistic klystron, \( \Delta E/E \leq 1\% \) for the first 15 to 40 MeV of induction modules; following the klystron cavity interaction, \( \Delta E/E \) increases to about 50\%. With such a large energy spread, the betatron frequency spread for the beam will be sufficiently large that the phase mixing of the beam is more rapid than the maximum possible BBU growth rate. That is, the transverse mode for a 3-kA beam will actually damp even for \( r_0 \) as small as 2.5 cm if the solenoidal field is kept constant throughout the accelerator at 3 kG, the value for the baseline linac design. Therefore, the cost of powering the continuous solenoidal transport can be scaled in proportion to the total field volume and the square of the beam current. The cost of the magnet windings is proportional to the accelerator length, the current, and the inner radius \( r_i \).

For induction linacs designed for other applications, BBU constraints may be relaxed, or they may be combined with other constraints on the transport system such as the reduction of corkscrewing of the beam. In such alternate cases the optimum transport strategy may require the variation of \( B \) with the beam energy. Then the scaling relation should be recast in terms of an appropriate average value of the magnetic field.

The use of a quadrupole lattice between the accelerating cells will reduce the average gradient in the induction linac by as much as 50\%. This consideration alone makes the use of solenoids in the first 20 MeV followed by a quadrupole lattice (scheme b above) relatively uninteresting for the driver of a linear collider.

Laser guiding\(^7\) (scheme c above) introduces a number of design elements foreign to all linacs save one—the Advanced Test Accelerator (ATA). This technique, used daily to transport high current beams through the ATA, may reduce the cost of the transport in the induction linac by an order of magnitude. The transport components in this approach are a very low angular jitter, near-diffraction-limited, repetition-rated KrF laser (\( \approx 1 \) J per pulse in \( \approx 20 \) ns), a gas handling system to maintain a partial pressure of \( \approx 10^{-4} \) Torr of benzene, and magnetic transition sections to match the electron beam onto (and off of) the laser-ionized gas channel. For repetition rates \( \approx 250 \) Hz, suitable KrF lasers are available commercially. Diffraction will eventually reduce the laser fluence below the level needed (\( \approx 0.2 \) J/cm\(^2\) ) to ionize a suitably large fraction of the benzene; therefore, a new laser beam must be reintroduced into the linac every \( \approx 125 \) m. The beamline must have periodic chicanes with differential pumping and matching magnets to accommodate introduction of the laser pulse. For this scheme, cost will scale in proportion to the length of the linac.

In addition to the focusing components discussed above, all schemes with magnetic transport must include steering magnets at periodic intervals, the length of which is determined by alignment requirements. All transport schemes require a matching section between the injector output and the main accelerator transport.
3.2. Scaling Equations

Variables to be used in the scaling equations include the total accelerating voltage (V) in MV, the total volt-seconds of core (W = V Tp), the gap stress (Er) in kV/cm, the single pulse energy (E = V IbeamTp) in joules, the average power (P = f E) in MW, the effective gradient (G) in MV/m, and the inner radius (r1) in cm. In the scaling equations italicized quantities refer to injector voltage, power, pulse energy, etc. Costs are specified in constant FY87 thousands of dollars.

3.2.1 Injector Subsystem

The scaling equation for the injector is divided into five separate components:

\[ C_{\text{inj}} = \left[ \frac{724}{0.17} W \right]_{\text{cells}} + \left[ \frac{475}{450} E \right]_{\text{mag}} \]
\[ + \left[ \frac{450}{2.25} P \right]_{\text{lsp}} + \left[ \frac{165}{3} V \right]_{\text{vac}} - \left[ 60 \right]_{\text{align}}. \]  

(14)

As each arm of the linear collider is driven by a separate induction linac, this injector cost must be doubled in the estimate of total hardware cost. For most variants of the two-beam accelerator approach this cost is a small fraction of the total.

3.2.2 Beam Transport Subsystems

For solenoidal transport, the cost has three separate components:

\[ C_{\text{sol}} = \left[ \frac{57 + 81}{1/3000} \left( \frac{r1}{7.5} \right) \left( \frac{1}{3000} \right) \right]_{\text{focus}} \]
\[ + \left[ \frac{42}{1.5} \left( \frac{r1}{7.5} \right) \left( \frac{0.75}{G} \right) \right]_{\text{steer}} + \left[ 78 \right]_{\text{match}}. \]  

(15)

For the alternative laser guiding scheme the scaling equation is

\[ C_{\text{laser}} = 7.5 V G^{-1}, \]  

(16)

which includes laser, gas handling, and matching magnet costs for \( f \leq 250 \text{ Hz}. \)

3.2.3. Accelerator Cell Subsystems

The cell block cost is

\[ C_{\text{block}} = 234 \left( \frac{V}{1.5} \right) \left( \frac{r0}{20} \right)^2 \left( \frac{0.75}{G} \right) \left( \frac{175}{E_r} \right), \]  

(17)

where \( r_0 \) is related to \( r_1 \) by Eq. (6). The ferrite cost is given by

\[ C_{\text{ferrite}} = 44 \left( \frac{W}{0.225} \right) \left[ \frac{r_0 + r_1}{27.5} \right]. \]  

(18)

where we have used the relation between the area and volume of the ferrite, \( \text{Vol} = \pi A (r_0 + r_1). \) The cost of intermediate stores and power supplies scales as

\[ C_{\text{lsp}} = 698 \left( \frac{P}{3.2} \right) + 5 (E / 630). \]  

(19)

The scaling for the magnetic pulse compressors is

\[ C_{\text{mag}} = 241 (E / 630). \]  

(20)
For power systems delivering pulses at repetition rates =100 Hz the magnetic modulators and intermediate stores can be reengineered to reduce costs by nearly a factor of two. The cost of the strongback alignment structure is

\[ C_{\text{strong}} = 450 \left( \frac{V}{12.5} \right) \left( \frac{r_0}{20} \right)^2 \left( \frac{0.75}{G} \right) K \]  

(21)

where the constant K depends on the focusing scheme; namely,

\[ K = 1.0 \text{ for quadrupoles,} \]
\[ = 0.6 \text{ for solenoids,} \]
\[ = 0.5 \text{ for laser guiding.} \]  

(22)

3.2.4. Ancillary Subsystems

The cost for low and extremely low conductivity water will scale as

\[ C_{\text{lcw}} = 90 \left( \frac{P}{13.1} \right) \]  

(23)

for \( f > 100 \text{ Hz.} \) For \( f < 100 \text{ Hz} \) we should use the value of \( C_{\text{lcw}} \) at \( f = 100 \text{ Hz.} \) The vacuum system is scaled as if it were pumping-speed limited (valid for \( r_1 \geq 2.5 \text{ cm.} \))

\[ C_{\text{vac}} = 660 \left( \frac{V}{12.5} \right) \left( \frac{r_1}{7.5} \right)^2 \left( \frac{0.75}{G} \right) K \]  

(24)

where K is given by Eq. (22). The cost of electrical fluids is proportional to average beam power;

\[ C_{\text{fluid}} = 542 \left( \frac{P}{13.1} \right) \]  

(25)

The scaling of dump costs is similar to that for reactors, i.e., $1 per watt of beam power into the dump (\( P_d \)). For the relativistic klystron, we assume that the average beam voltage at the dump (\( V_d \)) is 35 MeV, hence, \( P_d = V_d T_p I_{\text{beam}} f \).

The collider, therefore, has two dumps of cost,

\[ C_{\text{dump}} = 1000 P_d \]  

(26)

The cost of fixtures is proportional to the length of the induction linac;

\[ C_{\text{fixture}} = 20 \left( \frac{V}{12.5} \right) \left( \frac{0.75}{G} \right) \]  

(27)

The cost of the instruments and controls scales as a fixed value plus a percentage of the cost of the hardware to be monitored and controlled;

\[ C_{I&C} = 3000 + 0.04 (C_{\text{inj}} + C_{\text{cell}} + C_{\text{focus}}) \]  

(28)

Summing the cost equations ((14) through (21), and (23) through (28)) yields the total hardware cost for the induction linac driver.

3.2.5 Installation and Engineering Support

The installation costs for the base design were estimated on a component by component basis; for estimating purposes the installation costs can be taken as a fixed percentage of the total hardware costs adjusted to the fully-loaded labor rate (R) in $K/\text{man-month.}
Similarly, a cost for engineering management and support is estimated as a percentage of the hardware costs, i.e.,

\[ C_{\text{engin}} = 0.125 \cdot C_{\text{hardware}} \]  \hfill (30)

Supplies and equipment used for engineering and installation increases the total cost by 10%:

\[ C_{\text{sep}} = 0.1 \cdot C_{\text{hardware}} \]  \hfill (31)

Adding these installation costs to the hardware cost yields a total cost that includes \(-10\%\) contingency distributed (unevenly) among the various cost centers.

4. APPLICATION OF THE SCALING ALGORITHM

4.1. Driver Cost for a Linear Collider

The scaling algorithm developed in the preceding section can be applied to estimate the hardware costs of the induction linac driver for a high luminosity, 400 GeV-on-400 GeV linear collider described in Ref. 3. The induction driver is configured as a relativistic klystron producing 1.4 GW/m of \(-11.4\) GHz rf power. The results, given in Table 3, use the baseline values for those component characteristics not specified. The total hardware cost, \$483M, translates to \(10^{-4} \$/$rf$-watt\), which is much smaller than the cost of rf power delivered by conventional klystrons \((10^{-2} \$/$rf$-watt)\), and which compares quite favorably with earlier estimates\(^2\) of the requirements to make high gradient colliders practical. Moreover, if the anticipated savings from using standard production engineering techniques can be realized, the hardware costs can be reduced by 25%.

4.2. Cost Sensitivities and Optimization

Having obtained encouraging results from this initial estimate, we can proceed to use the scaling relations to study the sensitivity of driver cost to its design characteristics. The rationale for sensitivity studies is to suggest how we might optimize the specification of the driver for the linear collider. One way to proceed is vary the induction driver specifications so as to maximize the collider luminosity per unit capital cost. An alternative would be to formulate a measure that accounts for both capital and operating cost, and then maximize the luminosity per unit measure.

Three examples of the cost sensitivities indicate the directions offered by the first approach. Figures 4, 5, and 6 show the variation of driver cost per volt with pulse length, gradient, and repetition rate, respectively. For constant gradient designs the costs are seen to rise quadratically with pulse length. At constant pulse length the costs rise quadratically with gradient. Lowering the reference design value from 60 ns to 50 ns would reduce driver costs by greater than 22%, assuming that the voltage rise time can be shortened in proportion to the pulse length. This assumption is valid for \(30 \leq T_p \leq 80\) ns. For the driver to provide the same power per unit length to the rf-structure, the induction linac voltage (and gradient) would have to rise by 12%. The number of rf feed lines would have to increase. As these feed lines are inexpensive, we should expect this optimization approach to realize a net savings of \(-5\%\) \((-\$25M)\) over the estimate of Table 3. A different tack might be to increase the current to compensate for the shorter pulse length. In that case, the savings should exceed \$50M.
Table 3. Induction linac cost for relativistic klystron driver of linear collider.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Component</th>
<th>Cost ($K)</th>
<th>Totals ($K)</th>
<th>Production engineered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector</td>
<td>injector (2)</td>
<td>1,363</td>
<td>1,363</td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>laser guide</td>
<td>19,688</td>
<td>19,688</td>
<td></td>
</tr>
<tr>
<td>Accelerator</td>
<td>cell blocks</td>
<td>230,344</td>
<td>161,241</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ferrites</td>
<td>26,133</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAG-1D</td>
<td>131,211</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>i.s. and p.s.</td>
<td>11,776</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>strongback</td>
<td>26,578</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ancillary</td>
<td>Vacuum</td>
<td>9240</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fixture and Align</td>
<td>4,200</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LCW</td>
<td>303</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elec. fluids</td>
<td>1,825</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>I &amp; C</td>
<td>19,820</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dump (2)</td>
<td>81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total components</td>
<td></td>
<td>482,561</td>
<td>379,351</td>
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<td>Install</td>
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<td>43,430</td>
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<td></td>
</tr>
<tr>
<td>Engineering support</td>
<td></td>
<td>60,320</td>
<td>47,419</td>
<td></td>
</tr>
<tr>
<td>S &amp; E</td>
<td></td>
<td>48,256</td>
<td>37,935</td>
<td></td>
</tr>
<tr>
<td>TOTAL (as of 12/24/86)</td>
<td></td>
<td>634,567</td>
<td>498,846</td>
<td></td>
</tr>
</tbody>
</table>

**Accelerator Specifications**

- Voltage (MV): 3500
- Grad (MV/m): 1
- Current (A): 1750
- Radius-inner (cm): 2.5
- Pulse (ns): 60
- Radius-outer (cm): 15.00
- Frequency (Hz): 120
- Packing: 0.8

![Figure 4. Induction driver cost vs pulse length](image-url)
Figure 5. Driver cost vs gradient

Figure 6. Driver cost vs repetition frequency

Figure 7. Relative costs vs gap stress
The electrical power requirements for the reference collider design (at 120 Hz) are 60 MW. If the allowed power consumption is 120 MW, the luminosity of the collider can be doubled at a less than 1% increase in the capital cost by designing the driver to operate at 240 Hz.

Finally, a plot of relative cost vs $E_g$ (Fig. 7) shows the impact in advancing pulsed-power technology so that the electrical stress in the accelerating gap can be increased from the baseline value of 175 kV/cm. Doubling the allowed stress would reduced the driver cost by ≈10%.

5. CONCLUSIONS

The costs of induction linacs can be estimated over a wide range of operating specifications relevant to driving large linear colliders. The estimates, based on scaling the costs of the ETA II now under construction at LLNL, show that the relativistic klystron has the potential to produce rf-power at <10^{-5} $/rf-watt. This value is both strongly cost-competitive with conventional means of powering rf-structures at frequencies about 10 to 20 GHz and is sufficiently low to make practical high gradient linear colliders with TeV center-of-mass energies. Initial cost sensitivity studies indicate that the driver characteristics can be optimized to reduce costs at least an additional 20%.

REFERENCES


CONVENTIONAL POWER SOURCES FOR COLLIDERS

M. A. ALLEN

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

ABSTRACT

At SLAC we are developing high peak-power klystrons to explore the limits of use of conventional power sources in future linear colliders. In an experimental tube we have achieved 150 MW at 1 μsec pulse width at 2856 MHz. In production tubes for SLAC Linear Collider (SLC) we routinely achieve 67 MW at 3.5 μsec pulse width and 180 pps. Over 200 of the klystrons are in routine operation in SLC. An experimental klystron at 8.568 GHz is presently under construction with a design objective of 30 MW at 1 μsec. A program is starting on the relativistic klystron whose performance will be analyzed in the exploration of the limits of klystrons at very short pulse widths.

1. Introduction

A colliding linear accelerator is being considered for the Stanford Linear Accelerator Center (SLAC). It is likely that a proposal will be written in 1990 for construction of a 0.5 - 1 TeV c.m. collider. This Large Linear Collider (LLC) will consist of several critical items, one of which is the type of power source. Early conceptual designs suggest linacs of 3 km in length and for 0.5 TeV this requires gradients of 166 MeV/m. From total power considerations, higher frequencies than the SLAC frequency (2.856 GHz) are preferred and designs have been suggested at frequencies of four times SLAC frequency and higher. Peak power requirements then are in excess of 500 MW/meter. No conventional power sources exist which can supply this power in units which could energize one meter or more of the proposed accelerators. The SLAC Linear Collider (SLC) presently being commissioned is successfully employing over 200 klystrons to accelerate a stable beam meeting SLC specifications to over 50 GeV. [1] These klystrons produce over 65 MW each in 3.5 μsec pulses and use RF pulse compression to reach about 200 MW peak power over 1 μsec. Also in an experimental tube 150 MW has been achieved in 1 μsec pulse widths. Thus klystrons are a potential candidate for LLC power sources. A scaling of existing klystrons suggests that 100 MW peak power at 10 GHz is possible with a pulse width of 2 μsec. To explore this power range a research and development program is underway at SLAC. The first stage of that program is a 30 MW peak power klystron at X-Band. If it turns out that 100 MW tube is feasible, it might be possible to compress the 2μsec RF pulse to produce a peak power in excess of 500 MW. This pulse compression requires the development of low-loss delay lines which are cumbersome, expensive and suffer mode coupling problems of a very formidable nature. Thus another approach is

* Work supported by the Department of Energy, contract DE – AC03 – 76SF00515.
needed. One way would be to compress the energy pulse before the RF is generated. The performance of the klystron type interaction at very short pulse widths has not been explored but there are reasons to believe that much higher peak power is attainable as the pulse width decreases. Single bunch linear colliders at X-Band require peak powers of 500 MW/meter but only for about 50 ns per pulse. If pulses of adequate quality (fast-rise time, good flat top) can be produced, the scaling laws for long pulse (> 1μsec) will not apply. Previous breakdown studies suggest that high electric fields can be maintained for nanosecond pulses. If these pulses can be maintained, then the response time of the klystrons to short pulses becomes important and requires study.

2. Short Pulse Production

In modulators for microsecond pulse tubes, compression is done by using pulse forming networks consisting of delay lines formed from an array of capacitors and chokes. Recently, at the Lawrence Livermore Laboratories new ferro-magnetic metallic glass materials have been used to produce pulse compression. [2] This is a high-efficiency method which produces fast rise-time pulses in the tens of nanosecond range. These have been applied successfully in induction linear accelerators to produce MV/kA beams. This technique makes feasible the production of short-pulse beams for klystron interactions. These beams would be in excess of 1 MV and if properly bunched and made to interact with extraction cavities, very high peak RF power would be produced. This describes relativistic klystron amplifiers (RKA).

3. Relativistic Klystrons

There exists in Lawrence Livermore National Laboratory (LLNL) an ongoing program in induction linear accelerators producing and accelerating high voltage (> 1 MeV) and high current (> 1 kA) short pulse (<100 ns) electron beams. Some of this work is also being done in collaboration with Lawrence Berkeley Laboratories (LBL). At SLAC there is an ongoing program of development of high peak power klystrons at up to the 10 GHz range of frequencies. Since the three laboratories are interested in RF power sources for high gradient linacs, a collaborative program has been started between the laboratories. This program is discussed in the Workshop by Simon Yu. [3] A variety of high voltage, high current beams produced by induction acceleration and bunched by velocity modulation or other means and using RF extraction cavities are being explored to produce the necessary gigawatts of RF power for LLC.

The program has three main approaches. They are:

a. The production of a 1 MV, 1 kA short pulse beam by magnetic compression in a conventional klystron amplifier and extraction from this 1 GW beam of at least 50% of the power at RF frequency. This would give in excess of 500 MW peak power from a single unit.

b. In a small induction linear accelerator the production, bunching and acceleration of a 10 GW beam. This beam could be nominally 5 MeV and 2 kA. This beam would drift through a series of RF extraction cavities with each of them extracting 1 GW of RF power. This module would energize 10 meters of LLC in a single unit.
c. In true two-beam accelerator [4] an induction linear accelerator would accelerate nominally 20 kA of beam up to 50 MeV for a 1 TW beam and by using a series of RF extraction cavities 1 GW would be extracted from each cavity. This would energize 1 km of LLC in a single unit.

The feasibilities of all three approaches are being studied and experiments are being planned utilizing induction accelerators in operation at LLNL.

4. Conclusion

Prospects for using some derivative of a relativistic klystron in large linear colliders look promising and are being explored.

This report to the Workshop is a brief summary of work in progress. There are a large number of people contributing to this SLAC/LLNL/LBL collaboration and their work will be reported in the appropriate manner in the future.

5. References


Discussion

J. Nation, Cornell University

Will you please comment on the choice of the klystron for the TeV power source in the context of extensive alternative source development. There are extensive investigations of the phase stability at the 100's of MW level, in TWT amplifiers, Cerenkov devices, magnetrons and gyroklystrons, in progress in several laboratories.

Reply

In my talk I described the relativistic klystron work at SLAC/LLNL/LBL. Other laboratories are developing other power sources. If they prove suitable for TeV linear colliders we will propose them for our collider. In particular the gyroklystron has great promise and the work at the University of Maryland is of great interest.
HIGH POWER GYROTRONS AS MICROWAVE SOURCES FOR PARTICLE ACCELERATORS

M.Q. Tran
Centre de Recherches en Physique des Plasmas, Association Euratom - Confédération Suisse, Ecole Polytechnique Fédérale de Lausanne, 21, Av. des Bains, CH-1007 Lausanne/Switzerland

ABSTRACT
A reasonable extrapolation from the existing radio frequency linac towards the TeV collider would require microwave sources in the frequency range of 10-30 GHz with peak power around 300 MW. A promising microwave source meeting these specifications is a gyroklystron amplifier. A review of existing experiments on high peak power gyrotron oscillators and amplifiers will be presented in this paper. Their potentialities as microwave sources for the future accelerators will also be discussed.

1. INTRODUCTION

The development of high power microwave sources has been greatly stimulated by applications in controlled thermonuclear fusion (CTF) research and, potentially, in accelerators for high energy physics (HEP). Requirements of the sources are quite different for both applications. For heating and non-inductive current drive in CTF, continuous wave (CW) oscillators and amplifiers with power per unit of the order of 1-5 megawatts are needed in the frequency range of 8-10 GHz and of 60-600 GHz. Accelerators for HEP demand more challenging performances on peak power (hundreds of megawatts) but only for at most 1-2 μs (using pulse compression techniques) and at a repetition rate of 1000-500 Hz. Thus the average power is considerably reduced compared to the previous case. Another important mandatory feature is the ability to control precisely the phase of the radio frequency (RF) wave since hundreds or thousands of tubes distributed along the accelerator will be needed.

The very high power required (hundreds of MW) leads naturally to the use of very high voltage beam (Vb ~ 500 kV with a relativistic factor γ = 2). Many instabilities can generate microwave such as stimulated Cerenkov radiation of electron beams, cyclotron maser instability (for a discussion of the physics of the various mechanisms, see for example Ref. 1). Using high energy electron beam, powers in the hundred megawatt range were reported\(^2\). Among these devices, gyrotrons were the most studied ones both theoretically and experimentally.

The paper will include first a brief review of the electron cyclotron maser instability. The various relevant experiments will then be discussed. Although gyrotrons, using weakly relativistic electron beams (Vb < 100 keV, γ ≲ 1.2), have now achieved high power (P ~ 650 kW) at very high frequency (f = 150-250 GHz)\(^3\), these will not be discussed since the requirements useful for accelerators are quite different. The last part will be devoted to a general discussion on the potentialities of gyro devices for accelerators.
2. THE PHYSICS OF ELECTRON CYCLOTRON RESONANT MASER INSTABILITY

In a gyrotron, the microwaves are generated through the interaction of a relativistic electron beam guided by a static magnetic field $B_0$ with the electromagnetic (EM) wave. The EM wave frequency is close to the relativistic cyclotron frequency $\Omega_R = eB_0/m_e\gamma$ or its harmonic $n \Omega_R$, $e$, $m_e$, and $\gamma$ are respectively the electron charge, rest mass and relativistic factor. The source of free energy is the rotational energy of the electrons around the field line $B_0$. A net energy output occurs due to the bunching of the electron in the momentum plane $(p_x, p_y)$ (Fig. 1): this process is known as phase bunching. We have assumed that the $B_0$ field line in the z direction, $p$ is the momentum and all the electrons are supposed to have the same perpendicular momentum $p_\perp = (p_x^2 + p_y^2)^{1/2}$. The phase bunching is due to the variation of $\Omega_R$ with the particle $\gamma$. Electrons losing (resp. gaining) energy through the interaction with the EM wave will have a larger (resp. smaller) relativistic cyclotron frequency $\Omega_R$. If the wave frequency $\omega$ is slightly less than $\Omega_R$, the electrons will bunch in the region of the $(p_x, p_y)$ plane where energy is transferred from the electron beam to the EM wave. This effect leads to the so-called electron cyclotron resonant maser (ECRM) instability of EM waves in presence of a relativistic electron beam immersed in a static field $B_0$.

As in other electron tubes, the interaction between the electron beam and the RF occurs in an appropriate resonant structure. Within the bandwidth of the ECM instability, the RF frequency is determined by $\Omega_R$ (i.e. the magnetic field). Overmoded cavity which resonates the desired frequency $\omega$, can then be used. Cylindrical resonators operating in the TE$_{mn}$ modes are generally considered although TM$_{mn}$ modes have also been excited$^{1,3}$.

![Diagram](image)

Fig. 1  
(a) Particle distribution in the $(p_x,p_y)$ plane at the beginning of the interaction. The electrons are uniformly distributed on a circle of radius $p_{\perp 0} = (p_x^2 + p_y^2)^{1/2}$.

(b) Due to the interaction with the EM wave, the relativistic factor $\gamma$ of different electrons changes. They are no longer uniformly distributed on the circle but are "bunched" in the positive $p_x$ half-plane where a net transfer of energy from the e-beam to the wave occurs.
3. HIGH PEAK POWER GYROTRONS

High peak power gyrotrons energized by pulse line have been developed for more than ten years (cf. Table 1). In 1975, Granatstein et al. reported an output power of 1 GW at 8 GHz using a beam of 3.3 MeV and 80 kA. In the Soviet Union, experiments using high power relativistic electron beams \( (V_b \sim 400 \text{ keV}-1200 \text{ kV}, I_b = 1-10 \text{ keV}) \) have yielded powers in many tens of megawatts in frequencies between 10 GHz to 107 GHz. The group in the Lebedev Institute has achieved power of 60 MW at 10 GHz\(^{6,7} \) and up to 40 MW at 40 GHz\(^{8,9} \). In all these experiments the beam voltage was 400 kV with a current of 1-2 kA. In one experiment\(^{5} \), the electron beam was neutralized by a low density plasma (plasma density \( n = 2 \times 10^{11} \text{ cm}^{-3} \)) to overcome the limiting current in vacuum: the maximum current reached in presence of plasma was nearly twice the one without plasma whereas the output power increased by an order of magnitude.

In the frequency range around 35 GHz, the experiment of the Naval Research Laboratory\(^{10,11} \) yields two important results. Firstly, 100 MW at 35 GHz in the \( \text{TE}_{62} \) mode ("whispering gallery" mode) was reported. Secondly, stepwise tunability between 28 and 49 GHz was achieved by tuning the magnetic field: the cavity mode was \( \text{TM}_{m2} \), with the azimuthal index \( m \) varying between 4 and 10.

In the previous experiments, the cavity operated in the TE mode. Bratman et al.\(^{1,3} \) have reported that the electron beam can also occur with the TM mode of a cavity. The efficiency is however low, around a few percents.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Power</th>
<th>Mode</th>
<th>Efficiency</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 GHz</td>
<td>3 GW</td>
<td></td>
<td>30%</td>
<td>[5]</td>
</tr>
<tr>
<td>8 GHz</td>
<td>1 GW</td>
<td>( \text{TE}_{0,1} )</td>
<td>15%</td>
<td>[6]</td>
</tr>
<tr>
<td>10 GHz</td>
<td>60 MW</td>
<td>( \text{TE}_{1,3} )</td>
<td>20%</td>
<td>[7]</td>
</tr>
<tr>
<td>10 GHz</td>
<td>25 MW</td>
<td>( \text{TE}_{1,3} )</td>
<td>8%</td>
<td>[10,11]</td>
</tr>
<tr>
<td>35 GHz</td>
<td>100 MW</td>
<td>( \text{TE}_{6,2} )</td>
<td>8%</td>
<td>[10,11]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \text{TE}_{m2} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( 4 \leq m \leq 10 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 GHz</td>
<td>40-25 MW</td>
<td>( \text{TE}_{1,3} )</td>
<td>6%</td>
<td>[8,9]</td>
</tr>
<tr>
<td>79 GHz</td>
<td>20-30 MW</td>
<td>( \text{TM}_{1,n} )</td>
<td>&lt;3%</td>
<td></td>
</tr>
<tr>
<td>88 GHz</td>
<td>20-30 MW</td>
<td>( 3 \leq n \leq 10 )</td>
<td>1%</td>
<td>[1,3]</td>
</tr>
<tr>
<td>107 GHz</td>
<td>20-30 MW</td>
<td>( 3 \leq n \leq 10 )</td>
<td>1%</td>
<td>[1,3]</td>
</tr>
</tbody>
</table>
4. AMPLIFIER EXPERIMENTS

In an RF linac, a very large number of microwave sources will be required. In their parametric studies of high frequency linacs, Granatstein and Mondelli\(^{12}\) computed that at 10 GHz the number of feeds is around 7500. Assuming that four feeds could be powered by one gyrotroon, the total number of tubes is still very high! Phase relationship between the RF output of these thousand tubes must be maintained within a jitter of less than 1°.

High peak power amplifier experiments are relatively scarce. A group of Kharkov\(^{13}\) has described a relativistic amplifier delivering 3 MW with a gain of 14 dB at 9.45 GHz. The amplification is due to the ECRM instability and to parametric effects.

The Maryland group led by Granatstein is now assembling a 10 GHz gyrokystron amplifier designed to deliver up to 30 MW\(^{12,14}\). The experiment is designed as a first step towards high peak power amplifiers suitable for TeV linacs. The amplifier (Fig. 2) has three bunching cavities followed by the energy extracting one operating in the TE\(_{01}\) mode. The computed gain is 56.2 dB. Theoretical predictions of the phase stability when various external parameters such as magnetic field \(B_0\), beam voltage \(V_b\) indicate that these quantities should be kept constant with variations of less than .05% for \(B_0\) and .1% for \(V_b\). These requirements are within the state of the art specially in high voltage modulators. An experiment performed at lower frequency (4.5 GHz) and lower power (50 kW) has confirmed that a combined voltage ripple of less than 1% and a current ripple of less than 0.3% leads to phase jitters of 0.75°\(^{15}\). Thus both theoretical predictions and experimental evidences indicate that gyrokystron amplifiers could, in principle, meet the very strongest requirments on phase control.

![Schematic of the gyrokystron amplifier](from Ref. 14).
The Maryland gyrokystron designed specifications are comparable to the relativistic klystron under development\cite{16,17} at the Stanford Linear Accelerator Center (SLAC) (cf. Table 2). A detailed analysis of the gyrokystron parameters\cite{17} reveals that this type of tube could be scaled to higher power (~ 300 MW), mainly because the low electric field in the space between the electron gun and the electrodes (91 kV/min.) allow to increase the beam voltage and thus the tube power.

Table 2
Characteristics of the Maryland gyrokystron and the SLAC klystron.
(The specifications of the SLAC klystron are listed in Ref. 17.)

<table>
<thead>
<tr>
<th></th>
<th>Gyrokystron</th>
<th>Klystron</th>
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</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>10 GHz</td>
<td>8.568 GHz</td>
</tr>
<tr>
<td>Power</td>
<td>36-48 MW</td>
<td>30 MW</td>
</tr>
<tr>
<td>Gain</td>
<td>&gt; 60 dB</td>
<td>50 dB</td>
</tr>
<tr>
<td>Efficiency</td>
<td>45-40%</td>
<td>60%</td>
</tr>
</tbody>
</table>

5. DISCUSSION

High efficiency microwave generation from relativistic electron beam has been shown by many experiments (Fig. 3). These oscillator studies have yielded valuable information on the important issue of the mode stability. At high power (P > 300 MW) and/or high frequency (f > 10 GHz) an overmoded cavity will be required. A 300 MW-10 GHz gyrokystron would likely use $\text{TE}_{02}$ or $\text{TE}_{03}$ cavities\cite{16}. This requirement is due to the need of keeping the voltage drop $\Delta V$ across the electron beam and the beam depression $\text{V}_0$ at reasonable value. For higher frequency (f ~ 30 GHz) the heat load due to ohmic dissipation becomes an important factor. For a given cavity mode, the power loss per area $P_W$ scales as $P_W \propto \omega^{5/2} \sigma^{-1/2}(\omega)QP$ where $\sigma$ is the conductivity, $Q$ the output power, $\Omega$ the quality factor. Note that the conductivity $\sigma$ is anomalous at high frequency\cite{18}; at 35 GHz $\sigma$ is about 13% lower than the DC value. With this scaling law, the peak value $P_W$ at 300 MW and 35 GHz would be around 2.40 MW/cm$^2$, using the value of 100 kW/cm$^2$ at 300 MW and 10 GHz given in Ref. 14. Even at a duty cycle of $10^{-3}$, this value gives an average wall loss of 2.4 kW/cm$^2$ which is excessive. Moreover since both $\Delta V$ and $\text{V}_0$ are inversely proportional to the average electron beam radius, these quantities will also increase proportionally with the frequency if the cavity mode is kept fixed. These two considerations lead to the use of a high order mode cavity, such as $\text{TE}_{03}$, $\text{TE}_{13}$ [Ref. 6-9] or $\text{TE}_{02}$ [Ref. 10-11]. The main problem in such a configuration is the suppression of unwanted mode in the amplifier cavities and drift space. Some possible solutions are discussed in Ref. 14. The new high temperature superconductors, if they could be
Fig. 3 Performances of high peak power gyrotrons. The asterisks (*) represents oscillators, the (AG) the gyrokystron amplifier of the University of Maryland, and the full circle (○) the amplifier described in Ref. 13. For comparison we have included the SLAC relativistic klytron (mK).

used at RF frequency and in the presence of an important RF magnetic field, could free the designer from the limitations of the thermal loading of the cavity [for a discussion of RF properties of superconductors, see Ref. 19]. The question of unacceptably large V₀ and ∆V will then be the major criterion in the design of the RF circuit.

The problem of operating hundreds or thousands of high power tubes are common to linacs fed from separated sources, as opposed to the two-beam accelerator approach. This would mean a very precise control of the high voltage applied to the gun so that no voltage difference larger than 0.1% would exist between them. Reliability will also be an important issue. The characteristics of the high peak power gyrotron amplifier are too different from the gyrotron oscillator for CTF to allow any conclusion to be drawn from this field. On the other hand, a large number of klystrons have been produced and put into operation. Gyrodevices use basically the same technology and it could be expected that a similar degree of reliability can be achieved.

The 36 MW-10 GHz gyrokystron development at the University of Maryland represents an important step in the development of high power sources for HEP accelerators. The state-of-the-art klystron delivers 150 MW at f = 2.87 GHz[17], and the one under development at SLAC is designed to achieve comparable power at slightly reduced frequency. Although the peak power of 36 MW is already a thousand fold larger than the one obtained with an existing gyrokystron amplifier, a useful tube would still need another factor of 5-10 in power. Considering the steady progress made in the development of gyrotrons for CTF during the last decade, and drawing on the expertise available, one can be confident that, if needed, gyroamplifiers could be built to meet the requirements of RF linacs.
ACKNOWLEDGEMENTS

It is a pleasure to acknowledge enlightening discussions with Prof. V.L. Granatstein who has given us many details of his experiment. We would also like to thank Prof. G. Coignet who has brought to our attention Ref. 19 on the application of the high temperature superconductor in RF cavities.

* * * *

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Discussion

U. Amaldi, CERN

What would be the cost of a gyrotron of 300 MW peak power?

Reply

The cost of the existing bare tube is relatively modest (order of a few hundred thousand Swiss Francs). However, to this amount one must add the cost of ancillary systems such as magnets, power supplies for the magnets and the high voltage production. Eventually mass production of these items could lead to a substantial cost reduction.
PHASE CONTROL OF THE MICROWAVE RADIATION IN FREE ELECTRON LASER TWO-BEAM ACCELERATOR

Y. Goren and A.M. Sessler
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

Abstract
A phase control system for the F.E.L. portion of Two-Beam Accelerator is proposed. The control keeps the phase error within acceptable bounds. The control mechanism is analyzed, both analytically in a "resonant particle" approximation and numerically in a multi-particle simulation code. Sensitivity of phase errors to the F.E.L. parameters has been noticed.

1. INTRODUCTION

The two-beam accelerator (T.B.A.) which utilizes the free electron laser (F.E.L.) has been proposed for future high gradient linear colliders.\textsuperscript{1} To operate the T.B.A. a tight electro-magnetic phase control in its F.E.L. portion is needed.\textsuperscript{2,3} Phase deviation results from accumulating errors in the F.E.L. section. Error sources are continuous current loss, wiggler field inaccuracy, or spatial fluctuation of the accelerating voltages across the induction units. Of particular concern is phase deviation resulting from shot-to-shot jitter in current, magnetic wigglers, and accelerating voltages. In this paper we propose a solution to the phase error caused by shot-to-shot jitter, via a "phase injection" mechanism. In this mechanism a number of correction stations will be spaced along the F.E.L. drift tube. At each station the microwave power flow will be replaced with microwave radiation of the same intensity, but with the phase expected from an ideal run (Fig. 1). In Section 2 we represent an analytical solution in the resonant particle approximation. A multi-particle numerical analysis is given in Section 3. In this section the results for phase error evolution from 1000 particles 1-D F.E.L. code will be presented and compared with the analytical results.

Fig. 1 Conceptual configuration of the phase injection system.
2. **PHASE INJECTION IN THE RESONANT PARTICLE APPROXIMATION**

To make the analysis easily understandable we shall treat the phase control mechanism only in the case of a current jitter. The same procedure applies in the other cases of fluctuations in the physical parameters. We shall use the resonant particle approximation with the standard K.M.S. notations. The equations of motion are:

\[
\frac{d\phi}{d\varphi} = k_w - \frac{\omega_w}{2\gamma c} \left( 1 + \frac{a_w^2}{\gamma c} - 2a_w a_s \cos \psi \right) + \frac{d\phi}{d\varphi},
\]

where continuous acceleration, \( \Delta' \), is assumed. The quantity \( \Delta' \) is related to the microwave power extracted \( \alpha \) through energy conservation:

\[
\Delta' = \alpha \cdot \frac{2\omega w a_s^2}{w_p^2}.
\]

With periodic replacement of the microwave radiation with radiation of the expected phase (phase injection) Eq. (4) should be changed into:

\[
\frac{d\phi}{d\varphi} = \frac{1}{2} \frac{w_p a_w}{w_c a_s} \frac{\cos \psi}{\gamma} + \sum_{M=1}^{N} (\Delta_M') \delta(Z-M\cdot L),
\]

where \( \Delta_M' \) is the phase deviation at the \( M \)-th port and we assume in this analysis that all connected stations are equally spaced with a distance \( L \) between successive parts. The equilibrium condition (ideal run) is given by:

\[
a_{s_0} = \frac{1}{2} \frac{w_p a_w}{\alpha \cdot w_c} \frac{\sin \psi_0}{\gamma_0},
\]

\[
\phi_0 = \frac{d\phi_0}{d\varphi} = \frac{1}{2} \frac{w_p a_w}{w_c a_{s_0}} \frac{\cos \psi_0}{\gamma_0},
\]

\[
k_w = \frac{\omega_w}{2\gamma c} \left( 1 + \frac{a_w^2}{\gamma c} - 2a_w a_{s_0} \cos \psi_0 \right) + \frac{d\phi_0}{d\varphi} = 0,
\]

\[
\Delta' = \frac{w p a \cdot a s_0}{c} \frac{\sin \psi_0}{\gamma_0}.
\]
We now study phase errors by assuming a small change from equilibrium originating from a small deviation \( \xi = - \frac{\Delta I}{I_0} \) in the injected current. Expanding all dynamical variables in \( \xi \), we may write:

\[
\begin{align*}
\psi &= \psi_0 + \xi \psi_1 + \xi^2 \psi_2 + \ldots, \\
\gamma &= \gamma_0 + \xi \gamma_1 + \xi^2 \gamma_2 + \ldots, \\
a_s &= a_{s0} + \xi a_1 + \xi^2 a_2 + \ldots, \\
\phi &= \phi_0 + \xi \phi_1 + \xi^2 \phi_2 + \ldots.
\end{align*}
\]  

To first order in \( \xi \), we obtain four linear equations:

\[
\begin{align*}
\frac{d\psi_1}{dz} &= -\frac{w}{2c\gamma_0} \left\{ -2\delta_1 U_0 + 2a_w a_{s0} \sin \psi_0 \psi_1 - 2a_w \cos \psi_0 a_1 \right\} + \frac{d\phi_1}{dz}, \\
\frac{d\gamma_1}{dz} &= -\frac{a_w}{c\gamma_0} \left\{ \psi_1 \sin \psi_0 + \psi_1 a_{s0} \cos \psi_0 \right\}, \\
\frac{da_1}{dz} &= \frac{1}{2} \frac{w a_{s0}}{w^2 c \gamma_0} \left\{ -\sin \psi_0 + \psi_1 \sin \psi_0 + \psi_1 \cos \psi_0 \right\} - a_{s0}, \\
\frac{d\phi_1}{dz} &= \frac{1}{2} \frac{w^2 a_w}{w^2 c \gamma_0 a_{s0}} \left\{ -\cos \psi_0 - \frac{a_1}{a_{s0}} \cos \psi_0 - \psi_1 \sin \psi_0 \right\} + \sum_{M=1}^{N} \Delta \phi_M(1) \delta(2-M \cdot L),
\end{align*}
\]

where we use the notations:

\[
U_0 = 1 + \frac{a_w^2}{w} - 2a_w a_{s0} \cos \psi_0,
\]

\[
\delta_1 = \frac{\gamma_1}{\gamma_0},
\]

and have assumed the following expansion for the phase deviation:

\[
\Delta \phi_M = \xi \Delta \phi_M(1) + \xi^2 \Delta \phi_M(2) + \ldots.
\]  

The phase injected term in Eq. (12) acts as a periodic driving force initiating spatial oscillations of the dynamical variable. We expand the perturbed variables (Eqs. (9)-(12)) in a discrete Fourier expansion of the form:

\[
\theta(Z) = \sum_{m=0}^{n-1} \theta_m \exp \left\{ i k_m Z \right\},
\]

where \( k_m = 2\pi m / L \),

\[
\theta_m = \frac{1}{L} \int_{0}^{L} e^{ik_m Z} \theta(Z) \, dZ.
\]

We obtain the four algebraic equations:

\[
\begin{align*}
ik \psi_1 &= 2\delta U_0 \frac{v}{2c \gamma_0} - \psi_1 \frac{\Delta'}{\gamma_0} + \frac{a_1}{a_0} \frac{\Delta'}{\gamma_0} \cot \psi_0 + ik \phi_1, \\
\delta_1 &= \frac{\Delta'}{\gamma_0} \left( \frac{a_1}{a_0} + \delta_1 - \psi_1 \cot \psi_0 \right), \\
a_1 &= a_0 (-1 - \delta_1 + \psi_1 \cot \psi_0), \\
\phi_1 &= -\phi_0 \left( 1 + \frac{a_1}{a_0} + \delta_1 + \psi_1 \cot \psi_0 \right) + \frac{\Delta \phi(1)}{L}.
\end{align*}
\]

where we drop the subscript "m" in the dynamical variables and the wave number \( k \), and we assume the same phase deviation, to first order in \( \xi \), in each section \( L \). The solution for the electromagnetic phase shift \( \phi_1 \) in terms of the equilibrium parameters is given from Eqs. (15)-(18):

\[
\begin{align*}
\begin{align}
\Phi_{1m} &= \left( 1 - \frac{\alpha}{q_{\text{am}}} \cdot \frac{\phi_0'}{q_{\psi m}} \cot \psi_0 \right) \left[ 1 - 1 - \frac{\Delta'}{\gamma_0 q_{\gamma m}} \right] + \frac{\phi_0'}{q_{\psi m}} \frac{\Delta'}{\gamma_0 q_{\gamma m}} \cot \psi_0 \left[ 1 - \frac{\alpha}{q_{\text{am}}} \right] \\
&= \frac{1}{q_{\text{am}}} \frac{\alpha}{q_{\text{am}}} \left( 1 - i P_{m} \cot \psi_0 \right) \left[ 1 - 1 - \frac{\Delta'}{\gamma_0 q_{\gamma m}} \right] - i \frac{\phi_0'}{q_{\psi m}} \tan \psi_0 \left[ 1 - \frac{\alpha}{q_{\text{am}}} \right] \\
&= P_{m} \frac{\alpha}{q_{\text{am}}} \cot \psi_0 \left[ 1 - i \frac{\Delta'}{\gamma_0 q_{\gamma m}} \right] \\
&= - \phi_0' \left( 1 + \frac{\alpha}{q_{\text{am}}} - \frac{\Delta'}{\gamma_0 q_{\gamma m}} \cdot \frac{\alpha}{q_{\text{am}}} \left[ 1 - i P_{m} \cot \psi_0 \right] + P_{m} \tan \psi_0 \frac{\alpha}{q_{\text{am}}} \right) + \frac{\Delta \phi(1)}{L}.
\end{align}
\end{align}
\]
where we use the following notations:

\[ i q_{\gamma m} = i k_m - \frac{\Delta'}{\gamma_0} \]

\[ i q_{\psi m} = i k_m + \frac{\Delta'}{\gamma_0} - i \frac{v}{c \gamma_0} \frac{U_0}{q_{\gamma m}} \frac{\Delta'}{\gamma_0} \cot \psi_0 \]

\[ i q_{\alpha m} = i k_m + \alpha + ia \frac{\Delta'}{\gamma_0} \frac{1 - i P_m \cot \psi_0)} + i a \cot \psi_0 \cdot P_m \]

and

\[ p_m = \frac{\Delta'}{q_{\psi m} \gamma_0} \left[ i \frac{v}{c \gamma_0} \frac{U_0}{q_{\gamma m}} + \cot \psi_0 \right] \]

For the zero oscillation mode, \( m = 0 \), the l.h.s. of Eq. (19) vanishes and we end up with an equation for the phase shift:

\[ \Delta \phi(1) = L \phi_0 \left\{ 1 + i \frac{\alpha}{q_{\psi 0}} \frac{\Delta'}{\gamma_0} \frac{\alpha}{q_{\psi 0}} [1 - i P_0 \cot \psi_0] + \right. \]

\[ \left. + P_0 \tan \psi_0 \frac{\alpha}{q_{\psi 0}} \right\} \]

(20)

In our parameter region (see Table 1) the wave numbers \( q_{\gamma 0}, q_{\psi 0}, q_{\alpha 0} \) and the parameter \( P_0 \) can be approximated by:

\[ q_{\gamma 0} = i \frac{\Delta'}{\gamma_0} \]

\[ q_{\psi 0} = i \frac{v}{c \gamma_0} U_0 \cot \psi_0 \]

\[ q_{\alpha 0} = 2i \alpha \]

\[ P_0 = -i \tan \psi_0 \]

(21)

The average phase deviation, to first order in \( \xi \), is given by substituting Eq. (21) in Eq. (20):

\[ \Delta \bar{\phi} = \xi \cdot \Delta \phi(1) + \frac{1}{2} \xi \cdot L \Delta \phi' \]

(22)

Hence the peak to peak phase oscillation is:

\[ \Delta \phi_{pp} = 2 \Delta \bar{\phi} = \xi \cdot L \Delta \phi' \]

(23)

In the next section we present numerical results from a many particle simulation code. We shall see that analytical approximation given in Eq. (23) is in a good agreement with the numerical results.
3. MANY PARTICLE SIMULATION

In this section a many particle simulation code is used to study the behaviour of the electromagnetic phase in the phase injection scheme. Detailed description of the code is found in Ref. 6. The simulation uses discrete replenishment of the beam energy in the F.E.L. section. The code simulates the microwave propagation for different initial conditions and according to our phase injection scheme it replaces, at each correction station, the electromagnetic phase with the phase calculated from the optimum run.

In Fig. 2 we present the evolution of the phase error with distance along the F.E.L. drift tube, for the case of initial current deviation $\gamma = 0.13\%$ and without phase correction. The parameters of the run are given in Table 1. In Fig. 3 a phase injection has been applied at correct stations 60 m apart. One can see from the figure that the phase is confined in this case to $\Delta\phi_{pp} \leq 8.8\%$. The analytical prediction for this set of parameters, given from Eq. (23), is $\Delta\phi_{pp} = 7.4\%$. Each phase correction initiate a synchrotron oscillations, which results from the phase shift between the bunch center of gravity and the center of the potential well. The power extraction, represented by the parameter $\alpha$ in Eq. (3), tends to suppress these oscillations. We can see from the figure that after 3 to 4 e folds (15 to 20 m) the oscillations disappear and the phase deviation increases linearly with $z$ up to the next correction station.

| Table 1 |
| Parameters of the F.E.L. portion in two-beam accelerators |
| Average beam energy (units of $mc^2$) | 40 |
| Beam current | 2.4 kA |
| Bunch length | 6 m |
| Wiggler wavelength | 27 cm |
| Peak wiggler field | 3.2 kG |
| Average beam power | 48 GW |
| Power production | 2.4 GW/n |

Fig. 2 Phase error vs. distance for 0.13% error in current $I_0 = 2.4$ kA.
Fig. 3 Phase error vs. distance with phase injection stations 60 m apart.

To improve on this scheme we must increase the distance between correction stations without increasing the phase error. For this purpose we reduce the current flow from $I_0 = 2.4$ kA (see Table 1) to $I_0 = 2.0$ kA and the wiggler to 2.5 kG. In this mode of operation we could confine the phase error to $\Delta \phi_{pp} \leq 9^\circ$ for 100 m between stations, and for the current deviation $\gamma = 0.13\%$. Figure 4 describes the phase vs. $Z$ for this case. Thus we see that phase error is rather sensitive to TBA parameters, and since phase control is a central issue in a TBA perhaps parameters should be chosen with careful attention to phase control.

Fig. 4 Phase error vs. distance for 0.13% in current $I_0 = 2$ kA, and phase injection stations 100 m apart.
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PHYSICS OF RELATIVISTIC KLYSTRONS*

S. S. Yu
Lawrence Livermore National Laboratory, University of California
Livermore, California, USA

ABSTRACT

There has been much activity on the development of relativistic klystrons since the beginning of 1987 by many people at Stanford Linear Accelerator Center (SLAC), Lawrence Berkeley Laboratory (LBL), and Lawrence Livermore National Laboratory (LLNL). The following paper is one worker's summary of the status of the work. While many of the ideas described have come from the work of other individuals, the author takes responsibility for possible errors and particular viewpoints expressed in this paper.

Considerations of cost and efficiency for large colliders have led to the choice of short rf wavelengths (1 to 3 cm).[1] Two consequences of the higher frequency, high-gradient accelerator on the power source are the increase of required peak power (to ~1 GW/m) and the reduction of pulse length (~50 nsec). This dual requirement makes high-current induction linacs a natural match as a power source. Present induction machines [2] typically produce electron pulses of the order of 50 nsec, and the peak power in these relativistic beams is well in excess of GWs. As a power source, induction machines together with recent developments in pulse power, have the desirable features of being reliable and efficient (>50%, wall plug to beam).

The relativistic klystron presents a straightforward mechanism to convert the high-peak power in the intense electron beam to rf power. When a high-current beam, bunched at the appropriate frequency, is made to traverse resonant cavities, ample rf power will be produced. Klystron tubes and induction linacs are both matured technology. The relativistic klystron is a natural integration of the two technologies.

The design of an rf accelerator structure is to a certain extent affected by the power source under consideration. The relative ease of attaining high-peak power and short pulse length in relativistic klystron concepts lead naturally to disk-loaded structures with high-group velocity. These structures have some advantages in reducing wall losses and, hence, in increasing efficiency. In addition the associated enlarged frises lead to reduction of wakefield effects in the high-gradient structure.

The parameters of the intense electron beam depend on the details of design. But generally we are considering beams of 1 to 2 kA. From the point of view of induction cell economics, one might, in fact, wish to go to higher currents (e.g., the Advanced Test

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Accelerator (ATA) at LLNL is capable of operating at \( \geq 10 \text{ kA} \). The reason for staying at the 1- to 2-kA level comes from the desire to match to conventional klystron cavities with reasonable (R/Q) and quality factor Q. High current also accentuates transport and beam-stability problems.

At present, beyond these general considerations a continuum of concepts is under study, ranging from the two-beam-accelerator (TBA) approach (1 or a few power-sources for each rf accelerator) [3] to much smaller devices where the role of the induction accelerator and associated pulse power is to provide an advance injector for a "conventional" klystron tube. [4] Each concept has its own merits as well as associated physics issues.

The TBA is a long device where a bunched beam is made to go through rf cavities and induction cells alternately. The energy lost to rf cavities is replenished by inductive reacceleration. The TBA approach is attractive primarily because of efficiency and cost considerations. A simple way of understanding the efficiency advantages is credited to W.K.H. Panofsky [5] who first proposed the relativistic klystron version of the TBA. The TBA may be viewed as an extension of the conventional klystron, where instead of wasting half of the beam energy on the collector plate, one uses the beam over and over again. The beam to rf efficiency is, therefore, close to 100%, in contrast to conventional klystrons, where one has to work quite hard to get the efficiency much above 50%. The cost trade-off between the TBA and a large number of smaller klystrons is that of replacing sets of induction cells with injectors of approximately twice the beam power.

While the long-term advantages of TBA are evident, experimental demonstration of its feasibility requires a much-longer-term investment than do the smaller devices. The major issues that require experimental demonstration can be categorized under bunched beam formation, rf power transfer, induction cell interaction, and high-current beam dynamics.

The formation of bunched beams from a direct-current (dc) beam is a required first step in any relativistic klystron experiment. We are not aware of any go/no-go issue here. The considerations are primarily that of engineering convenience. The devices under consideration are typically ones in which the dc beam is injected into cavities where rf modulation (either longitudinal or transverse) is induced. The beam then goes through magnetic bends and/or various focusing/defocusing elements where the rf modulations give rise to path-length differences, and hence bunching at corresponding frequencies. There are also considerations of chopping schemes that consist of apertures intercepting beams at some prescribed phase interval over the rf cycle. Such bunching and chopping experiments were in fact conducted at LLNL years ago at frequencies much lower than what is presently considered. [6]

The critical issue in rf power transfer is surface breakdown. There is no experimental data on breakdown characteristics of short pulses (~50 nsec) at these frequencies, and quantitative information here is essential both for klystron cavity operation as well as for high-gradient-structure design. Experimental data on mode
content and phase stability are also required. Conceptually, phase stability in a relativistic klystron TBA is much less of an issue than its free-electron laser (FEL) counterpart. This difference results from the fact that klystron cavities involve primarily standing wave while an FEL TBA involves waves that propagate with the beam.

While beam bunching and rf power transfer are issues common to all relativistic klystron concepts, induction cell interaction is an issue specific to TBAs. Here, the goal is to minimize rf power drain from induction cells and to minimize effects on beam-breakup (BBU) instability. The beam pipes are required by rf cutoff considerations to be very narrow \( r < 1 \text{ cm for } 11.4 \text{ GHz} \), and completely new induction cells need to be designed to work in this new regime.

Beam dynamics is perhaps the most critical issue in the TBA concept. The first issue has to do with whether one could keep the particles bunched over long distances, since there are space-charge debunching and finite emittance effects that tend to degrade the bunched beam. Our calculations indicate that one could keep the particles continuously bunched if rf output cavities are inductively detuned. The particles will then perform synchrotron oscillations in stable buckets. For typical TBA parameters, the region of stability is quite large.

The narrow pipe gives rise to very serious transverse instability problems. Both the resistive wall instability as well as the BBU instability are drastically enhanced with decreasing pipe radius. Fortunately, particles oscillating in synchrotron buckets have a large energy spread which may be enough to suppress the instabilities totally by Landau damping.

The synchrotron period as well as transverse instability growth depend strongly on energy. A 5- to 10-m TBA experiment at > 5 MeV can provide significant tests of beam bunching and beam stability. Such an experiment is being planned at LLNL.

As a first phase of this TBA experiment, we will attempt to extract as much of the beam energy as possible without reacceleration. If a series of output cavities are appropriately spaced, we may be able to reduce the average energy of the beam adiabatically, maintaining stable buckets during the energy extraction process. Such a pure decelerator would not be quite as efficient as a TBA proper but should have efficiencies much higher than conventional klystrons.

While the TBA concept has potential long-term advantages, the risk is also higher. It seems a very sensible approach, therefore, to start with smaller devices that will give end-products in themselves in a relatively short time and also provide incremental information towards future efficiency upgrades. The "upgraded klystron," as proposed by Matt Allen and others at SLAC, [4] is, therefore, a rather natural step in this direction. The idea here is to build "conventional" high-power klystrons with an input cavity, an output cavity, and three or four idler cavities, in much the same way as
existing S-band tubes. Induction machines are used to provide the front-end of the tube. Bunching by longitudinal velocity-modulation and drift is possible for beam energies ≤ 3 MeV.

While the tube technology is well known, some physics issues need to be addressed in the new regime. First, the rf pulse-length of the new device is of the order of 50 nsec, in contrast to existing tubes with pulse lengths of several μsec. The fill-time to reach peak rf power, which is generally a small fraction of the pulse length in μsec tubes, may no longer be a negligible effect in 50-nsec tubes. The fill-time in existing S-band tubes has been measured to be ~ 40 nsec. [4] This is consistent with the calculated Q-values, which are of the order of 100, and come primarily from beam loading. However, the beam-loaded Q increases drastically with beam energy and becomes much too large at 1.5 MeV. To bring the rise-time to a more reasonable length (≤ 10 nsec), external loading [7] must be added to the idler cavities to reduce the Q.

Another problem has to do with the BBU instability through the idler cavities. The high-Q idler cavities, which give high gain in the axisymmetric bunching, also lead to high gain in transverse deflections. Gain in transverse displacement through a five-cavity tube has been calculated to be ~10^5. Roger Miller [8] has proposed stagger-tuning the deflecting modes in the cavities to reduce BBL. Calculations indicate that 10 to 20X spread in the dipole frequencies in the cavities can reduce the growth to less than 100. BBU growth can be further reduced by phase-mixing effects, and also by employing additional schemes such as making the cavity spacing a multiple of the betatron wavelength. [9]

Complications associated with idler cavities can be bypassed if one starts with a strong input drive (~MW). There is no existing X-band drive at these power levels, but 5-MW C-band klystrons (5.7 GHz) are in use. Since the bunched beam from a strong rf drive (~500 to 700 kV) is rich in harmonics, one can get second and third harmonic current of several hundred amperes with relative ease. Hence, a strong C-band drive followed by an output cavity allows one to extract power of several hundred MW at the fundamental (5.7 GHz), the second harmonic (11.4 GHz), or the third harmonic (17.1 GHz). The frequency at which power is extracted is controlled by the resonant frequency of the output cavity. Driving at C-band has the additional advantage that one can accommodate a larger pipe diameter over most of the tube, easing the transport problem associated with narrow pipes. Both the high-gain and low-gain experiments are being planned at the Accelerator Research Center (ARC) at LLNL as a joint project with SLAC.

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* * *

Discussion

J. Nation, Cornell University

How does your beam brightness requirement compare with that achieved to date in ETA and ATA?

Reply

The beam brightness requirement is very weak, and is well within what is presently achieved. The reason is that the stable particle buckets for relativistic klystrons are very big (as compared, for example, to FEL buckets). Thus one can accommodate large spread in v, which in turn implies weak requirements on transverse emittance.

M. Cavenago, INFN, Pisa

How is the typical shape of the accelerating potential necessary for longitudinal phase stability achieved by the induction accelerator?

Reply

The phase stability is achieved not by the accelerating potential but by the rf cavities. The stable region of phase space is determined by the amount of inductive detuning in the klystron cavities. If there is no inductive detuning, there is no stable bucket. However, if the detuning angle is several tens of degrees the stable bucket is larger.
LASERTRON DEVELOPMENT AND TESTS OF HIGH GRADIENT ACCELERATING STRUCTURES IN JAPAN

T. Shidara
National Laboratory for High Energy Physics, KEK, Oho-machi, Tsukuba-gun, Ibaraki, 305, Japan

ABSTRACT
Experiments on a high power lasertron and high gradient accelerating structures are currently under way by the Japanese Linear Collider Study Group with the aim of applying these in future $e^+e^-$ linear colliders. With the lasertron, a maximum power of 79 kW at 2856 MHz has been obtained with an efficiency of 2.5%. An average accelerating gradient of 104.5 MV/m on beam axis was attained for a five cell structure operated at this same frequency in the $2\pi/3$ traveling wave mode.

1. INTRODUCTION

An $e^+e^-$ linear Collider in the TeV region is one of the various proposals for future accelerators beyond LEP energy. It requires high power microwave sources with a peak output power of about 1 GW and traveling wave accelerating structures operating at a field gradient of about 100 MV/m or more.

Such high peak power is much beyond the level which can be achieved with conventional technology. There are several candidates for this power source such as klystrons, gyrotrons and photocathode microwave sources, etc.1) Among these, we began studies on the lasertron2). Figure 1 shows a conceptual drawing of a lasertron. A microwave modulated beam is produced, by direct emission modulation of a photocathode with a microwave modulated optical beam. Compared with a klystron, it has the potential merit of producing higher peak power with higher efficiency in a more compact device.

Fig. 1 A conceptual drawing of the lasertron
We proved the lasertron principle by testing several small lasertrons at S-band frequency.\textsuperscript{2)} Extending these studies, a new R/D program has started to construct a MW and ten MW lasertron.\textsuperscript{3)} Details of 2 MW lasertron experiments will be described in section 2.

High gradient field accelerating structures have been already tested by SLAC\textsuperscript{4,5)} and Varian Associates Inc.\textsuperscript{6,7)} In the SLAC experiment, an accelerating structure was excited in a standing wave mode. The peak surface field was calculated to be 318 MV/m, around the beam hole in the disk. A single-cell cavity was used in the Varian experiment. A peak surface field of 239 MV/m was reached.

Although these standing wave mode experiments may give some measure of the high gradient field behavior, direct tests on a structure in a traveling wave mode is preferable for the final design of a future linear collider. Experimental results of an S-band structure operated in the 2π/3 traveling wave mode will be described in section 3.

2. \textbf{LASERTRON EXPERIMENT}

2.1 \textbf{EXPERIMENTAL SET-UP OF LASERTRON}

The lasertron consists of a laser system, a modulator power supply, a coaxial cable to supply charge to the photocathode, a cathode chamber, an output cavity and a beam collector as shown in Fig. 2.

![Fig. 2 Experimental arrangement of lasertron](image_url)

The laser system was developed by an outside company.\textsuperscript{8)} The configuration of this system is shown in Fig. 3. A cw mode-locked Nd : YAG oscillator produces a continuous train of 85 ps infrared optical pulses (Fig. 4-a) with 5.8 ns separation. A waveform shaper gives the necessary transmission waveform by a programmed waveform to an optical shutter (Pockels' cell). This made it possible to generate a long, flat-topped pulse train from several gain-saturated Nd : YAG amplifier stages. Following the SHG (Sub-Harmonic Generator) crystal, the infrared beam is frequency doubled into the green 532 nm 60 ps optical pulses (≈ 40 mJ). A mirror system increases the frequency by a factor of 16 to form a 2856 MHz optical pulse train (Fig. 4-b). A GaAs wafer with an active area of 20 mm in diameter was used for the photocathode. The quantum efficiency was ≈ 5 %.
Fig. 3 The configuration of the laser system for lasertron experiment. AMP, amplifier; DP, dielectric polarizer; EXP, expander or reducer; SHG, second-harmonic generator; DM, dichroic mirror; MP, multiplexer.

Fig. 4-a 178.5 MHz optical pulses of 1.06 μm with a width of 85 ps. Fig. 4-b 2856 MHz optical pulses of 532 nm with a width of 60 ps.

2.2 EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 5 shows a curve of beam current, I, as a function of beam voltage, V. Below 50 kV, the beam current exhibits the normal diode characteristics of a typical klystron (I=constant•V^{3/2}). On the other hand, above 50 kV, the beam current is proportional to beam voltage (I=constant•V). This linear dependence of the beam current is a characteristic property for bunched beam from the gun. Below 50 kV, there exists more than one bunch between the anode and cathode area, leading to normal diode characteristics.
When a 5 \mu s 150 kV pulse was applied to the lasertron, a peak power output of 79 kW with a peak current of 21 A was generated (Fig. 6). The conversion efficiency from beam power to microwave power (∼2.5 % in this case) is not as high as we expected for the lasertron. This might be due to the debunching effect of space charge forces. We are now working to get a good efficiency and high power output.

3. **HIGH GRADIENT FIELD EXPERIMENT**

3.1 **SET-UP OF HIGH GRADIENT FIELD EXPERIMENT**

The schematic diagram of the experimental set-up is shown in Fig. 7. The test accelerating structure was inserted in a resonant ring. The klystron output power (30 MW with a pulse width of 2 μs) is fed into the ring through a 6.04 dB coupler. This coupling was adjusted to obtain a maximum circulating power $P_c$ inside the ring (∼120 MW). The ring has a stub-tuner section and a phase shifter to suppress the reverse circulating power and to adjust the phase length. Two Bethe-hole type directional couplers are located just before and after the accelerating structure to monitor the circulating power. An analyzer magnet of 45° bending angle was put just behind the test section to measure the energy spectrum of the field emission current.
Fig. 7 A schematic set-up of high gradient field experiment

The accelerating structure consists of three regular cells and two coupler cells at each end (Fig. 8). The regular section is a conventional disk-loaded structure with a beam aperture of 16 mm diameter. Parameters of the accelerating structure are summarized in Table 1. The average accelerating field $E_{acc}$ is estimated by using

$$E_{acc} \text{ (MV/m)} = 9.42 \sqrt{P_c \text{ (MW)}}$$

(1)

where $P_c$ is the forward circulating power level in MW.

Fig. 8 Cross-sectional drawings of the accelerating structure
Table 1

<table>
<thead>
<tr>
<th>Parameters of the Accelerating Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Shift/Cell</td>
</tr>
<tr>
<td>Structure Length</td>
</tr>
<tr>
<td>Beam Hole Diameter (2a)</td>
</tr>
<tr>
<td>Cavity Diameter (2b)</td>
</tr>
<tr>
<td>Resonant Frequency (f)</td>
</tr>
<tr>
<td>Q</td>
</tr>
<tr>
<td>Shunt Impedance (r)</td>
</tr>
<tr>
<td>Attenuation</td>
</tr>
<tr>
<td>Group Velocity (Vg/c)</td>
</tr>
</tbody>
</table>

3.2 EXPERIMENTAL RESULT

After about 500 hours of integrated microwave conditioning (20 Hz, 2\(\mu\)s pulses), an accelerating field gradient of 104.5 MV/m (\(P_c = 123\) MW) was stably achieved without any baking of the structure. This level is limited only by the maximum available klystron power. At this gradient, the accelerating structure could be operated quite stably for 10 hours as shown in Fig. 9.

![Fig. 9 A picture of the microwave power in the ring built up to 123 MW (upper) and microwave power of the klystron (lower) (Image)](image)

The electron energy spectra of the field emission current are shown in Fig. 10. The maximum electron energy values agree with those values calculated with eq. (1) and the structure length of 17.5 cm. The scallops that appeared on the spectrum may be due to acceleration over the five-cell structure.
Fig. 10 Electron energy spectra at various accelerating gradients

Fig. 11 Fowler–Nordheim plot of the field emission current
The field emission currents $I_f$ on the beam axis were plotted in a modified Fowler-Nordheim diagram as shown in Fig. 11. The Fowler-Nordheim formula is expressed as follows:

$$\frac{I_f}{g^{2.5}} = C \exp \left| \frac{-1.34 \times 10^7 \phi^{1.5}}{\beta E_p} \right|$$

where $C$ is a constant, $\phi$ is the workfunction of the copper, $\beta$ is the microscopic field enhancement factor, and $E_p$ is the maximum field on the surface which is 2.1 times $E_{acc}$ by the SUPERFISH calculation.

The slope (1) shows that the field enhancement factor, $\beta$, in the conditioned region by microwaves reached finally $\beta=122$, which is very close to the value obtained at SLAC. On the other hand, the slope (2) with a larger value ($\beta=260$) indicates that a new domain was reached.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude for the encouragement and financial support received from director T. Nishikawa. He also wishes to express his thanks to Prof. Y. Kimura, organizer of the Linear Collider Study Group, for the guidance and continuous encouragement. He would also like to thank Prof. G. Horikoshi, leader of the lasertron study group, for his encouragement and valuable discussions.

This report is based on the work of the members of the Linear Collider Study Group: Y. Fukushima, H. Matsumoto, H. Mizuno, T. Shintake, K. Takata, S. Takeda, Y. Yamazaki and M. Yoshioka.

The author is much indebted to Profs. S. Anami, A. Asami, Drs. A. Ban, S. Sasaki and Mr. H. Nomma for their help in the present experiments.

* * *

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1) P.B. Wilson, SLAC-PUB-2884 (1982)
4) J.W. Wang et al., SLAC-PUB-3597 (1985)
5) J.W. Wang et al., SLAC-PUB-3940 (1986)
Discussion

N.K. Sherman, NRC, Ottawa

There are at least three reasons for the smearing of time response of photocathode: Single-bunch space charge, multi-bunches in flight simultaneously and response of the photocathode material.

1) How many bunches are in flight at once?
2) Is secondary emission the cause of the response of the photocathode?

Reply

1) In our lasertron experiment, the distance between the cathode and anode is 2 cm. So, there is only one bunch between them when we apply more than 50 kV.

2) No, I do not think so. I think the drift velocity of excited electrons inside the photocathode material is a problem. Since the skin depth of GaAs is of the order of 1 nm in green, the response time from the deepest part to the surface is estimated at about 1 ns. This is probably the cause of bad time response of the photocathode material.

M. Boussoukaya, LAL

1) Do you think that diffusion in the cesiated CdAs is partially responsible for a part of the pulse length?

2) What is the contribution of space charge to the "bad" photo-response time that you got?

Reply

1) Since the carrier density of our photocathode is very high, I think there is no problem at all for the charge supply. Actually, the beam current shape has almost the same shape with the laser pulse comb in the 1 μs region. It seems to me that the low drift velocity of an excited electron inside the GaAs is the main cause of the bad response time.

2) According to our simulation, space charge effect increases the pulse width of a bunch from 60 ps up to 200 ps when we apply 100 kV. This surely decreases the conversion efficiency from beam power to microwave power. But I do not think this space charge effect is the main cause of the "bad" photo-response time.
ACCELERATOR R & D AT LAL-ORSAY*

J. Le Duff
LAL, Orsay, France

ABSTRACT
An R & D programme was launched at LAL/Orsay at the end of 1985 as a contribution to the short term future. The programme mostly concentrates on conventional technologies for which improvements can still be made in terms of power efficiencies in the frame of very high energy linear colliders.

1. INTRODUCTION

LAL has recently been involved in the design and construction of LIL (LEP injector linacs). Consequently, new experience was gained in modern linac technologies which motivated the present research and development programme on future linear colliders.

This programme is based essentially on improvements and extensions of conventional technologies, and a start was made possible due to some major equipment being provided by SLAC and CERN. The main items of this R & D programme are:

- Beam dynamics simulation
- Generation of short-pulse, high-peak currents
- RF power source: LASERTRON
- High gradient warm structures

2. SIMULATION OF BEAM DYNAMICS IN THE LASERTRON [1-3]

A computer code, named RING, has been specially written to simulate the beam dynamics in the lasertron, but can also be used to design laser-triggered guns. The main features of this code are:

- Time is the independent variable
- Relativity is considered, but radiating fields are ignored
- Each bunch is split into disks (z coordinates) and each disk is made of rings (r coordinate). Both z and r are tracked for each particle and the velocity of is obtained from Busch's theorem (2^1/2 D code)
- Transient bunch behaviour is studied in the gun and drift regions
- Steady state is considered in the output cavity of the lasertron
- The code is relatively fast since high precision is obtained with only a few particles (for example 45 minutes c.p.u. for 100 electrons on a VAX II/785).

* Work supported by IN2P3 and DRET
More details on the physics of this code and examples of computer runs are given in a contribution from A. Dubrovin and J.P. Coulon to this Workshop. In particular the code has been used to design a prototype Lasertron at Orsay, with the characteristics and theoretical performance summarized in Table 1.

Table 1
Design parameters of the Orsay prototype Lasertron

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency</td>
<td>6 GHz</td>
</tr>
<tr>
<td>RF power</td>
<td>20 MW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>75%</td>
</tr>
<tr>
<td>Beam power</td>
<td>25 MW</td>
</tr>
<tr>
<td>Acc. voltage</td>
<td>400 kV</td>
</tr>
<tr>
<td>Average current</td>
<td>62 A</td>
</tr>
<tr>
<td>Charge/micro pulse</td>
<td>10 nC</td>
</tr>
<tr>
<td>Cathode area</td>
<td>1 cm²</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>2.8 KG</td>
</tr>
<tr>
<td>Optical frequency</td>
<td>UV</td>
</tr>
<tr>
<td>Micropulse length</td>
<td>35 ps</td>
</tr>
<tr>
<td>Micropulse energy</td>
<td>1 μJ</td>
</tr>
</tbody>
</table>

An interesting result from the simulation study is the optimum geometrical configuration of the gun region corresponding to a non-focusing geometry but giving a maximum uniformity of the accelerating field. The latter, for a short pulse, leads to a minimum distortion of the bunch with respect to the distance r to the axis, since all particles achieve almost the same velocity.

3. MICROPULSED PHOTOCATHODES STUDIES [4-6]

The Lasertron programme has led to specific experimental studies of high-current, pulsed photoemission, with the aim of achieving the best choice of photocathode. For instance, a good compromise between quantum efficiency and lifetime seems necessary. The first experimental apparatus consisted of:

- A picosecond Nd: YAG laser providing short bursts of a few 10 mJ in the IR, green and UV regions.
- A small ultra-high vacuum tank in which the distance between the cathode and anode could be adjusted and fitted with a 10 kV high voltage supply. The cathode support was especially designed to handle metallic needles and arrays of needles.
The first experimental results were obtained with single W needles and an array of Nb₃ Ti needles. These results are shown in Table 2, where $\Delta t$ is the micropulsed current width as measured with a 1 GHz bandwidth oscilloscope. Note that each laser macropulse (burst) is made of seven micropulses whose theoretical width is expected to be $35 \text{ ns}$. If the micropulse current shape follows the light pulse we should expect, in fact, much higher peak currents. In these experiments the high voltage is adjusted to be slightly below the field emission threshold. Hence the required laser pulse energy needed for electron extraction becomes smaller (photo-field emission).

<table>
<thead>
<tr>
<th>Photocathode</th>
<th>I peak [A]</th>
<th>$\Delta t$ [ns]</th>
<th>Laser burst energy [$\mu$J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single W needle</td>
<td>Green 2 UV .A</td>
<td>&lt; 1</td>
<td>40 10</td>
</tr>
<tr>
<td>Nb₃ Ti array (400 needles)</td>
<td>UV 10</td>
<td>&lt; 1</td>
<td>70</td>
</tr>
</tbody>
</table>

Since these first results were quite encouraging a more sophisticated ultra-high vacuum tank is being built to handle a much higher voltage (150 kV) such that photo-field emission can be tested in a more realistic HV environment. This tank (Fig. 1) should be ready before the end of 1987. In order to control the accelerating field at the needle, an intermediate anode is included in the gun region.

It is believed that just by changing the ceramic insulator, it should be possible to operate the same tank at up to 400 kV. In that case, with little modification, it will serve as a prototype Lasertron. In view of this future experiment the tank has been designed to allow easy access to the anode region. Finally, the experimental work is scheduled as follows:

a) High current photo-field emission tests. Extracted charges will be measured by using a wide band coaxial Faraday cup behind the anode.

b) Space charge effects. The micropulse current will be measured using a transient radiation monitor such that a picosecond streak camera can make the comparison with the incident laser pulse width.

c) RF efficiency. The previous monitors will be replaced with an extraction cavity. However, this experiment will only be possible after modification of the laser in order to get a long train of micro pulses with little amplitude modulation.
Fig. 1 High voltage, ultra-high vacuum tank for photocathode experiments.
4. HIGH GRADIENT TEST FACILITY

A high gradient test facility has been mounted in one of the old experimental halls of the Orsay Linac. It uses a 39 MW pulsed klystron (4.5 μs) of the LIL type (3 GHz), and a SLAC-PEP type gun (1 A, 1 ns). It will also use storage cavities for RF pulse compression. The aim is to test short, warm, accelerating structures at high gradients (up to 100 MV/m) with a beam passing through them. Equipment for beam analysis is included in the facility.

The short term schedule can be summarized as follows:

a) High gradient test of the LIL type structure. This structure was optimized to get the highest shunt impedance from an iris-loaded guide. The internal geometry is circular. A short structure (0.5 m long) corresponding to the last landing of the LIL quasi-constant gradient structure (iris diameter = 18 mm) has been built. The test will consist of determining the operational gradient limit of this type of structure.

b) Backward travelling wave structure. One can increase the shunt impedance by increasing the capacitance of the elementary accelerating cells. In an iris-loaded structure with electrical coupling from cell to cell this would lead to smaller group velocity hence to a longer filling time.

A magnetic coupling (holes in the irises) would permit both the shunt impedance and the group velocity to be handled independently. In that case the phase and the group velocity have opposite directions (backward wave).

Such a prototype structure, 1.2 m long, 4π/5 mode, is being built now as a LAL-CERN MeV collaboration and will later be installed at the LAL test facility.

CONCLUSION

The R & D programme related to future linear colliders is now well underway at LAL after almost 2 years of preparation. However, it is believed that some effort should be made in the future not to limit the experimental work to a single RF frequency (3 GHz) since the tendency is to use higher frequencies. On the other hand, it is clear that ideas can go much faster than the setting up of an experimental test facility. Hence effort should be concentrated on such a facility being adaptable in order to allow closer collaboration with other laboratories.
REFERENCES


LASERTRON COMPUTER SIMULATION AT ORSAY: "RING" CODE

A. Dubrovin and J.P Coulon
Laboratoire de l'Accelerateur Lineaire, Orsay, FRANCE.

ABSTRACT

A 2D½ code, "RING", has been written\(^1\) to simulate the electron dynamics in high peak current micropulsed RF sources, such as a lasertron. The simulations\(^2\) show the limitations of such devices in terms of maximum current generation from the photocathode, beam power and RF extraction efficiency. The starting conditions and comparisons between 3 and 6 GHz devices will be discussed.

1. INTRODUCTION

As this code was intended to work on a VAX 8600, we tried to obtain the best compromise between accuracy and rapidity of execution, therefore, we chose a 2D½ simulation \((r,z)\) for cylindrical symmetry, using time as the independent variable. The electrons are considered as points for the dynamics and as rings for the space charge forces (Green functions), the singularity of the fields being avoided by integrating the rings over a finite volume.

Approximate but faster space charge evaluations are available and external steady state fields (gun, cavity, magnetic focusing) are analytically computed or included from external codes such as "HERMANNSFELDT, SUPERFISH, POISSON \(\ldots\)". Self consistent iterations are made over them to determine the RF cavity gap voltage or shunt impedance.

Another program for lasertrons, "PARADE", is under development at L.A.L\(^3\), using mixed finite element evaluation of transient fields.

2. PROGRAM BEHAVIOUR

We observed less than 1% change in RF efficiency when using 10 electrons instead of 100. This provides us with a common simulation using three iterations over RF fields with about 5 minutes C.P.U time on a VAX 8600, and less than 1.5% difference in RF efficiency compared with the same case simulated with the MASK code (about 1 hour on a CRAY 1).

This good agreement is mainly due to the use of a very high D.C voltage (400 kV) and short pulses that minimize wakefields which can then be neglected. On the other hand, RING is able to show the charge extraction limit due to space charge effects in a single bunch (see Section 5).
3. EFFECTS OF FREQUENCY ON PARAMETERS: 3 AND 6 GHz DEVICES

We were interested to compare 3 and 6 GHz lasertrons knowing that the frequency of future linacs should be nearer 6 GHz than 3 GHz. Therefore, we designed and computed a 6 GHz prototype to give the same RF efficiency as the SLAC 3 GHz lasertron for a 30 ps laser impulsion length.

Figures 1 to 4 illustrate the geometries and the simulation results in both cases. All the points on these figures were optimised (by changing the shunt impedance) to obtain the best interaction between the beam and the RF cavity, the case of a given cavity is described in Fig. 4 by the broken lines. We see that the 6 GHz case needs twice as much magnetic focusing, gun and RF fields, and that laser impulsion length durations greater than 60 ps have to be avoided.

Figures 1-4: 3 and 6 GHz geometries and simulation results
4. GUN GEOMETRY OPTIMISATION

We first started with a Wehnelt gun as we wished to use low external magnetic fields (around 1.5 kG) and squeeze the bunch radially as much as possible. However, simulations showed that the curvature of the equipotentials strongly provokes a longitudinal spreading of the bunch and causes a loss of about 15% in RF efficiency (for the same beam power) compared with the flat case. The use of a Pierce gun minimized this effect, but the initial longitudinal delay cancelled the gain of a more uniform acceleration so that we obtained almost the same debunching as in the Wehnelt case. Finally, the magnetic fields required for the flat case are not tremendous (around 3 kG) and the retained beam densities require that these fields be twice as high at the RF gap than at the cathode (around 1.5 kG), where the Wehnelt electrostatic focusing no longer acts.

For all these reasons (in addition to the one explained at Section 5), the flat gun turns out to be the best for a lasertron.

5. CATHODE CHARGE EXTRACTION LIMITS

There are two main limits to charge extraction from the cathode.

First we have to consider whether all the electrons expected have sufficient time to leave the cathode before the laser illumination stops. The answer must take account of many parameters such as the electron speed in the given material, the laser active depth, the total cathode volume, local fields (needle emission) ... but these are not currently included in our code.

The other limit is due to space charge repulsion between the electrons already emitted and the ones which are just leaving the cathode. If the laser light intensity and cathode efficiency are very effective, it appears possible to reach the state where the emitted electrons, in spite of their removal from the cathode, are numerous enough to forbid a new emission. This effect is described by RING in loading the expected charge in many time steps from the beginning to the end of laser illumination, taking image charges into account. We observed, for a laser impulsion duration around period/10, an upper limit for the loaded charge which is about 65 nC for the SLAC 3 GHz lasertron, 20 nC for our flat 6 GHz lasertron and 6 nC for a 6 GHz lasertron using a Wehnelt gun, as in this case the average field on the cathode is lower (so making it impossible to obtain 25 MW with such a device). Note that using needle emission should strongly reduce this limitation since the local fields would be tremendous.

6. INITIAL CONDITIONS: LASER LIGHT SHAPE AND INITIAL SPEED

We made the code able to simulate any kind of laser pulse shape by translating it into emission delay times. The gain, when changing from a rectangular to a gaussian bunch shape, was only around 2% for our frequencies, since the electrons in the centre of gaussian bunches
are so close that the density quickly becomes uniform. We also examined the effects on charge extraction and RF efficiency of the initial speed of the electrons. This we thought would be justified in the case of a laser where $h$ is greater than the potential extraction barrier, the difference being around 1 eV, which is equivalent to $5.8 \times 10^5$ m/s speed. Different spatial distributions of this initial energy were simulated, but in all cases the effect was very low (around 0.3% on RF efficiency). This is due to the strong acceleration of the motion that rapidly raises the electron speed to two then three orders of magnitude greater than the initial one.

7. **ESTIMATION OF ORSAY LASERTRON PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency</td>
<td>6 GHz</td>
</tr>
<tr>
<td>RF power</td>
<td>25 MW</td>
</tr>
<tr>
<td>RF efficiency</td>
<td>75%</td>
</tr>
<tr>
<td>Cathode area</td>
<td>1.13 cm²</td>
</tr>
<tr>
<td>Charge/micropulse</td>
<td>15 nC</td>
</tr>
<tr>
<td>Average current</td>
<td>90 A</td>
</tr>
<tr>
<td>Acceleration D.C voltage</td>
<td>400 KV</td>
</tr>
<tr>
<td>Magnetic fields (maximum)</td>
<td>3 KG</td>
</tr>
<tr>
<td>Optical frequency</td>
<td>U.V.</td>
</tr>
<tr>
<td>Micropulse length</td>
<td>35 ps</td>
</tr>
<tr>
<td>Micropulse energy</td>
<td>1 µJ</td>
</tr>
</tbody>
</table>

8. **FUTURE IMPROVEMENTS TO THE "RING" CODE**

The simulation of needle emission is under development. Faster methods of space charge computation are under study so that multiple cavities and the estimation of space charge forces between periodic bunches can be taken into account with the smallest time expense.

**ACKNOWLEDGEMENTS**

We thank Professor J. Perez y Jorba and Doctor J. Le Duff for constant support.

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GIGATRON

Hana M. Bizek, Peter M. McIntyre, Deepak Raparia, Charles A. Swanson
Department of Physics, Texas A&M University, College Station, Texas, USA.

ABSTRACT
The gigatron is a new rf amplifier tube designed for linac collider applications. Three design features permit extension of the lasertron concept to very high frequencies. First, a ribbon beam geometry mitigates space charge depression and facilitates efficient output coupling. Second, a traveling wave output coupler is used to obtain optimum coupling to a wide beam. Third, a gated field-emitter array is employed for the cathode. A prototype device is currently being developed.

1. INTRODUCTION

The gigatron is a design for a compact, efficient microwave power amplifier tube. It employs the lasertron concept, in which a bunched electron beam is extracted from a modulated cathode and accelerated through a DC diode structure as shown in Fig. 1. The resulting beam is fully modulated at high energy without the requirements of a modulator and drift region that characterize all conventional amplifier tubes. RF energy is then extracted from the beam in an output coupler. Because there is no DC component to the beam current, very high efficiency can in principle be obtained.

A major motivation to develop the gigatron arises in current efforts to design a multi-TeV $e^+e^-$ linac collider for elementary particle physics. The performance of a linac collider improves substantially as the frequency of the linac structure is increased. Several current design concepts would operate at frequencies from 10 to 30 GHz. One key

![Fig. 1 Cross-sectional view of the gigatron](image-url)
challenge for future linac colliders is to develop a compact, efficient source for 2100 MW peak power, 20 GHz. Technologies that are being explored in this connection include the lasertron, the gyrokystron, the free-electron laser, and the relativistic klystron.

The gigatron has been designed to extend the advantages of previous lasertron designs to very high frequency and high peak power. Three developments make this possible. First, a ribbon beam geometry is adopted instead of the conventional round beam. Second, a traveling wave output coupler is used to obtain optimum coupling across a wide beam. Third, a gated field emitter array is employed for the cathode; this appears to offer a simpler and more reliable modulated cathode than the laser-modulated photoathode of previous designs.

A preliminary design has been prepared for a prototype gigatron. It is designed to produce 10 MW peak power at 20 GHz with an efficiency of ~70%. Major specifications are summarized in Table 1. The prototype design is readily extended to produce 2 100 MW/m peak power. The following text describes several novel features of the gigatron and presents the results of beam transport and rf field calculations for the prototype design.

2. RIBBON BEAM GEOMETRY

The ribbon beam geometry is used to eliminate several limitations of round-beam devices for high power operation at high frequency. High output power requires large beam current. Large beam current in a round beam entails substantial space charge depression and consequently a transit time spread in the diode region. The resulting phase spread limits high frequency performance. Large beam current also requires a transverse beam size that becomes comparable to wavelength at high frequency, so that output coupling becomes inefficient.

These problems are mitigated by adopting a ribbon beam geometry. Space charge depression for a given beam current is reduced by a factor equal to the transverse aspect ratio (w/l). High beam currents are readily achieved. The narrow (height) dimension can be kept small to facilitate efficient output coupling. Extension to higher power can be achieved simply by making the entire device wider. The wide dimension of the beam raises special problems for output coupling, which have been solved by the invention of the traveling wave coupler structure described in the following section.

The ribbon beam geometry is produced from a standard Pierce rectilinear diode. The diode voltage is 200 kVDC; the diode spacing is 1.8 cm; and the emission current density is 65 A/cm². The cathode is a (4 x 14) cm² ribbon.
3. TRAVELING WAVE COUPLER

The ribbon beam geometry makes it possible to couple strongly to a high current beam even at high frequency. There is however a problem in matching the phase of the rf field stored in the coupler with that of each beam bunch as it passes through the coupler slot. A coupler extracts energy from an electron by decelerating it across a gap $g$ (see Fig. 2). The coupler must store energy to produce a decelerating field $E$ sufficient to extract a significant fraction of the electron energy:

$$E \times g = eV.$$  \hspace{1cm} (1)

The decelerating field is oscillating at the desired frequency, $E = E_0 \cos(\omega t + \phi)$. Coupler structures are normally designed as standing wave resonators. In the gigatron, however, the beam is wide ($l \gg \lambda$). The phase $\phi$ in a standing wave structure would thus vary through several full cycles across the width of the beam. Some elements of the beam would be accelerated, while others would be decelerated, so that no net energy transfer would result.

The traveling wave coupler of Fig. 2 removes this difficulty. The coupler is a segment of waveguide which is slot-coupled to the beam. The ribbon beam is modulated such that the incident beam front makes an angle $\theta$ with respect to the beam direction. A simple model requiring uniform acceleration across the beam yields a relation between the beam angle $\theta$, electron velocity $\beta_e$, and the waveguide phase velocity $\beta_p$:

$$\beta_e = \beta_p \tan \theta.$$  \hspace{1cm} (2)

The beam will then drive this traveling wave at a constant phase across the entire beam width. The beam "surfs" with the traveling wave.

Figure 3 shows the electric fields in the slotted waveguide coupler as calculated using the computer code MAFIA.\textsuperscript{11} Radiation into the diode region is strongly attenuated and should not disrupt the ribbon bunch structure. Waveguide magnetic fields require
Further refinements to this simple model. Each beam component is bent sideways by an angle $\Psi$ due to the in phase magnetic field ($B = E/\delta_p c$) of the traveling wave:

$$\Psi = \phi \left( \frac{\delta E \Delta l}{\sqrt{m_e m_v \Delta v}} - \frac{\gamma E_0 \cos \phi}{E_0'} \right) = 24^\circ. \quad (3)$$

This effect can be partially compensated by a static vertical dipole magnetic field across the coupler beam exit. The magnetic effects are being studied numerically.

The coupler must return sufficient beam energy back into its input to generate the required decelerating field. This can be accomplished by 1) shorting the waveguide at each end and slot coupling output power at one end (only one traveling wave component will be driven by the tilted beam); 2) linking two traveling wave couplers end-to-end in a resonant loop; or 3) configuring the waveguide in a circular ring driven by a helical beam. The required $Q$ is

$$Q = \omega \left[ \frac{\text{Stored Energy}}{\text{Output Power}} \right] = \frac{\omega [2\pi E^2 \Delta l / 2b]}{P_0} = 1250. \quad (4)$$

The unloaded $Q$ for the TE$_{16}$ mode is:

$$Q = \frac{b}{\delta} \left[ 1 + \frac{b}{a} \left( \frac{2\pi}{\omega} \right)^2 \right]^{-1} = 3000 \quad (5)$$

where $\delta = 0.53 \mu m$ is the skin depth of copper at 18 GHz.

4. THE GATED FIELD-EMITTER CATHODE

Present lasertron designs utilize either a photocathode$^3$ or a field-emitter brush$^4$ which is excited by a modulated laser beam. Several problems attend these approaches. First, Cs-doped GaAs deteriorates in frequency response above $1 \text{ GHz}$ because the charge mobility is inadequate to clear the depletion depth during an rf cycle. Second, the laser and particularly the photocathode represent significant uncertainties for reliable continuous operation in an accelerator system. The gated field-emitter array appears to offer an attractive alternative.

C.A. Spindt et al.$^9$ have developed microfabrication techniques by which they can prepare planar arrays of gated field-emitting points as shown in Fig. 4. Electrons are field-emitted from an array of metal point cathodes. Each point is situated within a metal gate structure. Application of a modest gate-cathode voltage ($V_g = 30 V$) results in full modulation of emission current. Currents of $>100 A/cm^2$ have been routinely achieved. There is no evidence of in-service deterioration during extended life tests. A different approach has been developed by H. Gray at the Naval Research Laboratory.$^{12}$ He uses directional etching techniques to produce atomically sharp needle and knife-edge arrays directly on silicon.
Several modifications will be required for the gigatron application. First, the gate layer, which currently is deposited as a uniform sheet with holes for each tip, must instead be fabricated as a pattern of ring electrodes surrounding each tip and connected by lines. In this way the gate capacitance could be reduced from 1500 pF/cm² to \( \leq 100 \text{ pF/cm}^2 \). While the cathode would still represent a very capacitive load (\( X_c \approx 1 \Omega \text{ mm} \)), it could be adequately modulated using GaAs MMIC amplifier chips bonded along the edge of the cathode structure.

Second, the gate layer must be configured as a suitable point-to-parallel optical lens. The electrons leave each cathode tip in a wide-angle cone. The effective electron transverse temperature is \( T_{\perp} \approx 30 \text{ eV} \). The gate field geometry is being modeled in an effort to transform this cone into a nearly uniform, parallel beam before acceleration in the diode. Figure 4b shows the modified cathode design.

![Diagram of gated field-emitter cathode](image)

**Fig. 4** Gated field-emitter cathode  
(a) thin-film field-emission cathode array;  
(b) modified array for gigatron application.

5. **Performance Calculations for the Prototype Design**

We have calculated beam transport through the gigatron. Calculations were performed using the MASK computer code.\(^{13}\) Figure 5 shows the trajectories of two successive ribbons through the coupler structure. Trajectories are shown on five points across each ribbon. Both transverse position and energy are shown for each trajectory. Slot width and height, coupler peak field, rf phase and beam phase width were varied to optimize rf efficiency while transporting residual beam to the collector. For the optimized parameters rf conversion efficiency of 70% is obtained. No beam is intercepted before entering the collector structure.
6. CONCLUSION

In conclusion, a preliminary design for the gigatron has been studied. It appears to offer a number of attractive features for high frequency, high power amplifier applications. Further work will focus on the development and evaluation of the individual systems - the gated cathode, the traveling wave coupler, and the ribbon diode.

It should be noted that the gigatron could also be configured either as a circular device, using a thin cylindrical beam, or as two flat ribbons. The choice of geometry would be determined by the application for the device. For a stand-alone amplifier, a cylindrical geometry might be simpler to build. For a linac collider, rf power must be distributed along kilometers of linac length. The ribbon geometry offers the intriguing possibility of integrating the entire rf drive structure into the same envelope with the linac structure itself to make a single, essentially continuous structure as shown in Fig. 6. The power capability (~100 MW/m) of the prototype device is appropriate for such a configuration.
Fig. 6 Extruded gigatron structure along linac.

Table 1

Parameters of Prototype Ribbon Lasertron

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega/2\pi$</td>
<td>rf frequency, 18 GHz</td>
</tr>
<tr>
<td>$P_0$</td>
<td>rf peak power, 10 MW</td>
</tr>
<tr>
<td></td>
<td>efficiency, &gt;60%</td>
</tr>
<tr>
<td>$V$</td>
<td>beam voltage, 200 kVDC</td>
</tr>
<tr>
<td>$I$</td>
<td>peak beam current, 360 A</td>
</tr>
<tr>
<td>$\phi$</td>
<td>rf phase, 230°</td>
</tr>
<tr>
<td>$A\phi$</td>
<td>beam phase width, 60°</td>
</tr>
<tr>
<td>$a \cdot w$</td>
<td>cathode size, $1/4 \times .4$ cm²</td>
</tr>
<tr>
<td>$g \cdot h$</td>
<td>waveguide coupler (WR42), $1.1 \times .4$ cm²</td>
</tr>
<tr>
<td>$\beta_e$</td>
<td>electron velocity/c, .70</td>
</tr>
<tr>
<td>$\beta_p$</td>
<td>phase velocity/c, 1.37</td>
</tr>
<tr>
<td>$\theta$</td>
<td>ribbon tilt angle, 27°</td>
</tr>
<tr>
<td>$E_{O_e}$</td>
<td>peak rf field, 125 MV/m</td>
</tr>
<tr>
<td>X</td>
<td>cathode/anode spacing, 1.6 cm</td>
</tr>
</tbody>
</table>

ACKNOWLEDGEMENTS

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* * *

Discussion

M.Q. Tran, EPFL

Did you consider the stability of the ribbon beam?

Reply

Probably at the edge there are some fringe effects at the two ends of the beam. We
have not been able to calculate those end effects. Along the length of the beam it is
stable. We have studied the phase dispersion and that is taken into account; we have also
studied the magnetic effects since we are dealing with a travelling wave that we are exci-
ting. The magnetic and electric fields are in phase so there is a magnetic effect on the
beam as well. One of the things about a ribbon beam geometry in a compact structure like
this is that immediately after it runs through the cavity you don't have to worry about
stability.
THE MICROLASERTRON
AN EFFICIENT SWITCHED-POWER SOURCE OF MM WAVELENGTH RADIATION

R. B. PALMER

Stanford Linear Accelerator Center, Stanford, CA 94305
and
Brookhaven National Laboratory, Upton, Long Island, New York 11973

ABSTRACT
photocathode wire, or wires, within a simple resonant structure. The resulting pulsed electron
current between the wire and the structure wall drives the resonant field, and RF energy is extracted
in the mm to cm wavelength range. Various geometries are presented, including one consisting of
a simple array of parallel wires over a plane conductor. Results from a one-dimensional simulation
are presented.

INTRODUCTION
The radio frequency power that can be generated by a lasertron is bounded by the beam power,
i.e., by the average current times the applied anode voltage. If a suitable cathode can be found
then this average current is limited only by space charge considerations. In a simple diode the
maximum charge per area (qtc) that can be taken from the cathode is

$$q_{tc} = e \xi$$

where $\xi$ is the accelerating field. The transit time $\tau$ to cross a gap $g$ is

$$\tau = \left( \frac{2m}{e} \right)^{1/2} \left( \frac{g}{\xi} \right)^{1/2}$$

Since we cannot start another charge until the first has crossed the gap (if we did, then Eq. (1) would not be valid), the maximum average current per unit area is $q_{tc}/\tau$
and the maximum power output is

$$P_{max} = \frac{q_{tc}AV}{\tau} = \frac{e}{2m} \left( \frac{e}{2m} \right)^{1/2} \xi^{5/2} g^{1/2}$$

thus there is a strong motivation for using high accelerating fields $\xi$.

The maximum fields that can be sustained continuously in a vacuum are only of the order
of 100 KV/cm (10 MV/m). But for short pulses and small gaps very much higher fields can be
obtained. For instance, Warren et al. [3] have reported fields of 160 MV/m across a 1 mm gap for
5 nsec pulses, and Jüttner et al. [4] report 3,000 MV/m across 27 $\mu$m for 1 nsec pulses.

The pulse length required for a linac falls as the wavelength to the 3/2 power; so for short
wavelengths long pulses are not required. For instance, at a wavelength of 6 mm the natural fill
time of an accelerating cavity is only of the order of 5 nsec and thus fields of 100 MV/m could be
employed across a gap of the order of 1 mm, without breakdown.

Applying such a field to Eq. (1) implies a maximum power output of the order of a GW
per cm$^2$ of cathode (compared with approximately 10 MW/cm$^2$ for conventional fields and gaps).
This high power per unit area would, however, be offset by the small natural beam area in a
lasertron designed for short wavelengths. What is needed is a laseortron design for which the total
beam area does not fall with the wavelength. It is the solution to this problem that this paper
addresses.

* Work supported in part by the Department of Energy, contracts DE-AC03-76SF00515 (SLAC)
and DE-AC02-76C0016 (BNL).
Fig. 1 Switched power accelerator concept as proposed by W. Willis (Ref. 1)

The genesis of the idea is the proposal by Bill Willis [1] for a Switched Power Linac (see Fig. 1). In this idea a single burst of electron current is switched by a single pulse of laser light. That burst as it crosses a circumferential gap generates a pulse of electromagnetic radiation which is focussed by the cylindrical geometry and used to accelerate particles on the axis.

In the present proposal, the same concept is used, except that a train of light pulses is employed, and these are used to excite fields in a resonant cavity (see Fig. 2).

Unlike in the lasertron, however, the acceleration of the electron by a dc field, and their deceleration by an RF field, is accomplished in a single gap. It is this simplification that allows a multiple linear geometry in which the total photocathode area can remain large even as the wavelength becomes very small.

DESCRIPTION

The basic concept is represented (Fig. 2) by a long, vacuum-filled rectangular cavity with a wire passing down the center. The wire is held at a high potential relative to the enclosure. By illuminating a photocathode on one side of the wire, electron bursts are allowed to pass from the wire to one wall of the box. Repeated pulsing of the photocathode at the cavity resonant frequency results in the excitation of a transverse electric mode within the cavity. Energy can then be extracted by coupling the cavity to a waveguide.

Fig. 2 Microlasertron concept as discussed here
This simple concept may be compared to that of the lasertron [2] (Fig. 3) in which the pulsed photocathode is used to generate a bunched accelerated beam. The energy is then extracted as the beam is decelerated passing one or more ring cavities. Since the beam's kinetic energy will be lost when it hits the anode, high efficiency is only obtained if the beam is decelerated to as near rest as possible.

Fig. 3 The conventional lasertron concept

In the microlasertron, the acceleration and deceleration occur within the same gap. High efficiency is again obtained when the electrons are brought nearly to rest as they arrive at the anode. But the processes of acceleration and subsequent deceleration are controlled by the phase of the field rather than the position along the beam.

The grid indicated in Fig. 2 may not be practical in a short wavelength realization of the idea. One finds, however, that the grid can be omitted so long as a relatively deep slot is enclosed between conducting walls (see Fig. 4a). An extension of this idea has an array of parallel wires under a single slotted cover (see Fig. 4b). In this case we find that the slots do not need to be deep. A drive frequency is chosen so that the distance between wires is approximately one half wavelength and the light pulses entering alternate slots are arranged to be 180° out of phase. At all finite angles radiation from the slots cancel. Even in the direction parallel with the plane the fields do not sum because the loading from the wires causes the phase velocity in the cavity to be less than the speed of light. Fields leaking through the slots will also have a phase velocity less than the speed of light and will thus be evanescent waves, falling exponentially from the slotted wall.

Fig. 4 Realizations of the microlasertron: a) single cavity, b) multi cavity, c) grating cavity, d) modification to grating cavity to couple to outgoing wave
The above observation leads to a further extension of the idea (see Fig. 4c). Now the upper cover of the cavity has been removed, the photocathodes placed on the remaining surface and the pulsed light brought down at an angle between the wires. Again, because of the presence of the wires, the phase velocity along the surface is less than the speed of light, and the field excited will be evanescent, falling exponentially from the surface.

As in the single wire case, electromagnetic energy could be taken out of the multiwire cavities by coupling them to waveguides. It is possible, however, and perhaps more convenient, to arrange that they couple to plane parallel waves emanating from the surface. In case of Fig. 4c, this can be achieved by disturbing the periodicity of the wires (see Fig. 4d).

![Diagram of microlasertron geometry, including cavity end design](image)

Fig. 5 Microlasertron geometry, including cavity end design

In the above discussion we have not mentioned how the cavities would be ended at the end of the wire. To investigate this question a radio frequency model was made at a wavelength of 5 cm. It was found that if the cathode plane was terminated well before the wire ends (see Fig. 5) then the fields were effectively constrained to the area above this plane and no loss of power occurred along the wires beyond it.

The attraction of the microlasertron is its simplicity, and thus the possibility of scaling it down to produce very short wavelengths. It also appears from the following analysis that very high powers and efficiencies may be obtainable.

**ANALYSIS**

**EQUIVALENT CIRCUIT**

Under the conditions where

\[ g \text{ (gap)} \ll w \text{ (gap width)} \]
\[ v \text{ (electron velocity)} \ll c \text{ (vel. of light)} \]
\[ w \text{ (gap width)} \ll \lambda \text{ (wavelength)} \]

then the device of Fig. 2 may be thought of as a separate diode gap coupled to a resonant circuit (see Fig. 6).

For our purposes we can think of \( L_2 \) as an infinite inductance that allows a dc current \( i_{DC} \) to flow from the high voltage supply \( V_{stat} \). \( C_2 \) may be thought of as an infinite capacitor that isolates the dc from the resonant circuit.

In the following discussion we will consider an equivalent circuit which will allow us to make approximate calculations of performance. The analysis is strictly applicable only to the plane parallel examples of Figs. 2, 4c and 4d although similar results are probably obtainable for the cases of Figs. 4a and 6.
The current $i$ may be divided:

$$i = i_{res} + i_v$$

where $i_{res}$ is a resonant oscillatory current associated with the resonant circuit of $L_1$ and $(C_1 + C_3)$; and $i_v$ which is associated with motion of charges in the gap.

$$i_v = q \frac{v}{g}$$

where $q$ is the charge in the gap and $v$ the velocity of that charge across the gap.

With these definitions we have

$$i_{RF} = I_{RF} \sin(\omega t + \theta) + q \frac{v}{g} \quad .$$

(4)

The voltage $V$ across the gap will again have two components:

$$V = V_{RF} \cos(\omega t + \theta) + V_{stat} \quad .$$

(5)

$V_{RF}$ may, of course, vary if there is a net transfer of energy to the system. The energy transferred per cycle will be

$$\Delta E = \frac{(V_{RF})^2}{Z} = \int_0^{\lambda/\varepsilon} i_v(t) V_{RF} \cos(\omega t + \theta) \, dt$$

(6)

where $Z$ is the impedance of the resonant system. The phase $\theta$ may also be perturbed. The change in phase per cycle will be

$$\Delta \theta = \frac{2\pi}{Q} \tan \chi$$

(7)

where

$$\tan \chi = \frac{\frac{\lambda/\varepsilon}{0} \int_0^{\lambda/\varepsilon} i_v(t) \sin(\omega t) \, dt}{\frac{\lambda/\varepsilon}{0} \int_0^{\lambda/\varepsilon} i_v(t) \cos(\omega t) \, dt} \quad .$$

(8)
If driven at the resonant frequency $\omega_0$, then clearly $\chi$ must be equal to zero. But if the driven frequency is off the resonance, then we have

$$\omega - \omega_0 = \Delta \phi \cdot \frac{\omega}{2\pi} = \frac{\omega}{Q} \tan \chi \quad (9)$$

**EFFICIENCY**

The energy used from the dc source per cycle will be

$$\Delta E_{dc} = \int_0^{\lambda/e} i_s V_{stat} \, dt = q \, V_{stat} \quad ,$$

the difference between this and $\Delta E_{res}$, the energy going into the rf field, is lost as heat in the anode as electrons arrive with finite kinetic energy. Thus,

$$\Delta E_{dc} - \Delta E_{res} = \frac{q \, m}{2 \, e} \, v_f^2$$

where $v_f$ is the velocity with which the electrons hit the anode, $m$ is the electron mass and $e$ its charge. Thus the efficiency $\epsilon$ of transferring energy from the dc source to the resonant circuit is

$$1 - \epsilon = \left[ \frac{m e^2}{e} \cdot \frac{v_f^2}{2 \, c^2 \, V_{stat}} \right]$$

$$1 - \epsilon = \left[ 0.51 \, 10^6 \frac{v_f^2}{2 \, c^2 \, V_{stat}} \right] \text{(mks)} \quad (10)$$

To get $v_f$ we obtain first the acceleration of a charge in the gap which will be

$$\frac{dv}{dt} = \frac{e}{m} \left[ \mathcal{E}_s + \mathcal{E}_{RF} \cos (\omega t + \phi) \right] \quad (11a)$$

where $\mathcal{E}_s = V_{stat}/g$, $\mathcal{E}_{RF} = V_{RF}/g$ and $\phi$ is introduced as an arbitrary phase so that we can define $t = 0$ as the time when the charge is initially released from the cathode. Integrating Eq. (11a) we obtain the velocity of the electrons at time $t$:

$$v(t) = \frac{e}{m} \left[ \mathcal{E}_s \, t - \frac{\mathcal{E}_{RF}}{\omega} \sin (\omega t + \phi) + \frac{\mathcal{E}_{RF}}{\omega} \sin \phi \right] \quad (11b)$$

Integrating again we obtain the distance traveled:

$$x = \int_0^t v(t) \, dt = \frac{e}{m} \left[ \frac{\mathcal{E}_s t^2}{2} - \frac{\mathcal{E}_{RF}}{\omega^2} \cos (\omega t + \phi) + \frac{\mathcal{E}_{RF}}{\omega} \sin \phi \right]_0^t \quad (11c)$$

Setting $x = g$ in Eq. (11c) will give the transit time $\tau = t$ which when substituted into Eq. (11b) gives the final velocity $v_f$ and thus the energy loss and efficiency using Eq. (10).

**LOW RF FIELD CASE**

If $\mathcal{E}_{RF} \ll \mathcal{E}_{stat}$, then

$$g \approx \frac{g}{2m} \, \mathcal{E}_{stat} \, r_0^2$$
and
\[ \tau_0 \approx \left( \frac{2m}{e} \right)^{1/2} \left( \frac{g}{E_{stat}} \right)^{1/2}. \]

This may be compared with the cycle time \( \lambda/c \) and we define this ratio as:
\[ F_r = \frac{\tau_0}{\lambda} \approx \left( \frac{2mc^2}{e} \right)^{1/2} \left( \frac{1}{V_{stat}} \right)^{1/2} \left( \frac{g}{\lambda} \right)^{1/2}, \]
(12a)
\[ F_r = 1.01 \times 10^3 \left( \frac{1}{V_{stat}} \right)^{1/2} \frac{g}{\lambda} \text{ (mks)} \] (12b)

We will continue to use this definition of \( F_r \) even when \( E_{RF} \) is not less than \( E_{stat} \). \( F_r \) then becomes a useful scaling fact or rather than an actual ratio of transit time to cycle.

**SHORT TRANSIT TIME APPROXIMATION**

If we assume
\[ F_r \ll 1 \] (13)
then \( \omega t \ll 1 \) and Eq. (11c) reduces to
\[ g \approx \frac{e\tau^2}{2m} \left( E_a - E_{RF} \cos \phi \right) \] (14a)
and
\[ v_f \approx \frac{e}{m} \frac{\tau}{\lambda} \left( E_a - E_{RF} \cos \phi \right). \] (14b)

Maximum efficiency is realized if \( v_f \) is minimum, i.e., the least kinetic energy is dumped on the anode. This will occur for \( \phi = 0 \). Referring to Eq. (6) and noting that throughout the transit \( \omega t \approx \phi \), we see that this maximum efficiency condition also implies \( \chi = 0 \), i.e., that the structure is driven on resonance: \( \omega = \omega_0 \).

So for \( \phi = 0 \), and remembering that \( \tau = F_r \lambda/c \) we obtain
\[ 1 - \varepsilon \approx \frac{mc^2}{e} \left( \frac{g}{\lambda} \right)^2 \frac{1}{F_r^2 V_{stat}} \] (15a)
\[ 1 - \varepsilon \approx 1.02 \times 10^6 \left( \frac{g}{\lambda} \right)^2 \frac{1}{F_r^2 V_{stat}} \text{ (mks)}. \] (15b)

If, for example, we chose \( \lambda = 6 \text{ mm} \), \( g = .5 \text{ mm} \), \( \varepsilon = 50\% \) and \( F_r = .38 \), then we require
\[ V_{stat} \approx 50,000 \text{ V} \]
and
\[ E_a \approx 100 \text{ M V/m} \]

Now from the references quoted by Willis [1], we note that [3] for times less than 5 nsec, voltages as high as 160,000 V have been held over 1 mm—2 mm gaps (\( \xi = 160 \text{ MV/m} \)) and for times less than 1 nsec [4], 80,000 volts could be held across a 27 \( \mu \) gap (3000 MV/m). Thus, although the values of our example are high, they are by no means unreasonable for times less than 5 nsec.

The above example, however, assumed an efficiency of only 50\%. Higher efficiencies would seem to imply even higher fields. It also assumed a transit time rather long (.38) compared with the cycle time. This hardly satisfies Condition (13). Clearly, we should calculate the effect of finite transit times.
ONE-DIMENSIONAL SIMULATION

To study this problem for finite transit times, a small computer program was written that would emit and track the electrons as a function of time in the varying fields. Initially, we consider short pulses and ignore space charge effects.

WITH SHORT PULSES $\chi = 0$ (ON RESONANCE)

Keeping the driving phase $\chi = 0$, i.e., driving at a frequency equal to the cavity resonant frequency, we calculate the efficiency as a function of the ratio of $\mathcal{E}_{RF}/\mathcal{E}_{stat}$. The results are shown in Fig. 7a for the case where $F_r$ (defined by Eq. (12)) is 0.38 (e.g., for $V = 50,000 \nu$, $g = .5 \text{ mm}$). As expected, the efficiency 1) rises as the RF field rises and 2) is somewhat less than that expected for $F_r \to 0$ (dotted line). (Due to the finite transit time, the electrons do not feel the maximum deceleration field over their full transit.) What is surprising, however, is that the efficiency remains finite even when $\mathcal{E}_{RF}$ is greater than $\mathcal{E}_{stat}$.

\[
\begin{align*}
\text{Fig. 7 Efficiency vs. strength of RF field a) for phase advance } & \chi = 0 \text{ and} \\
\text{b) phase advance adjusted to give maximum efficiency}
\end{align*}
\]

If we examine the variation of electron velocity (and thus current) as a function of the RF phase for a case of low RF field (e.g., $\mathcal{E}_{RF}/\mathcal{E}_s = .5$, see Fig. 8a), then we see the velocity rising more or less linearly and hitting the anode at its maximum. This then is much as predicted by Eq. (14b).

For higher values of the RF field the situation becomes more complicated (Fig. 8b for $\mathcal{E}_{RF}/\mathcal{E}_{stat} = 1.5$). Now the particles are started at a phase when the RF field is helping the static field. The electrons are thus initially accelerated, then decelerated for awhile, and finally accelerated again to arrive at the anode at a phase which again corresponds to the $\mathcal{E}_{RF}$ helping the $\mathcal{E}_{stat}$.

SHORT PULSE DRIVEN OFF RESONANCE

As we noted above (Eq. (7)), it is not necessary to operate at $\chi = 0$. If we drive the photocathode at a frequency $\omega$ different from the resonant frequency $\omega_0$, then the stable phase $\chi$ is finite. If we adjust $\omega$ and thus $\chi$ to give maximum efficiency (i.e., minimum arrival electron velocity), then we obtain efficiencies as plotted on Fig. 7b.

Now we observe that efficiencies of a 100% are achieved as $\mathcal{E}_{RF} \approx 2\mathcal{E}_s$. We examine this case in Fig. 8c. The particles are again initially accelerated and then decelerated. The parameters, however, are such that the electrons come to rest just as they arrive at the anode. We note further that for this magic case the electrons are not only at rest as they touch the anode but that their acceleration is also zero. This situation should be contrasted with that obtained at an even higher RF field (e.g., $\mathcal{E}_{RF}/\mathcal{E}_s = 2.5$, Fig. 8d).
In this case the electrons are also at rest as they approach the anode, but they are at that point being decelerated. An electron that just missed the anode would move away from it and only arrive some time later and at a finite velocity. This is a less desirable operating point than the magic one of Fig. 8c.

Fig. 8 Motion of electrons in the gap as function of RF phase, with electric field and electron velocity also shown:

a) For $\frac{E_{RF}}{E_{stat}} = .5$ and $\chi = 0$.

b) For $\frac{E_{RF}}{E_{stat}} = 1.5$ and $\chi = 0$.

c) For $\frac{E_{RF}}{E_{stat}} = 2$ and $\chi$ adjusted for maximum efficiency. This represents the magic condition.

d) $\frac{E_{RF}}{E_{stat}} = 2.5$ and $\chi$ adjusted for maximum efficiency.
Fig. 9 Values of \( \mathcal{E}_{RF}/\mathcal{E}_{stat} \) and the phase advance \( \chi \) to give the magic condition for different transit time factors \( F_r \).

All of the above analysis was done for \( F_r = .38 \). We find a different magic point for each value of \( F_r \) and these are plotted on Fig. 9. Remember that \( F_r \) is the fractional cycle time taken for transit in the absence of an RF field. \( F_r \to 0 \) corresponds to very high fields and a small gap. In that case 100\% efficiency is obtained at \( \mathcal{E}_{RF}/\mathcal{E}_{stat} = 1 \) and no phase lag \( \chi \) is needed. For larger transit times a phase lag is required and larger RF fields are needed to obtain the magic condition. In our following studies we will assume

\[
F_r = .38
\]

FINITE PULSE LENGTHS

The above calculations have all been performed for electrons emitted at one phase, i.e., for light pulses on the photocathode of arbitrarily short duration. If pulses of finite extent are used then it is no longer possible to bring all the electrons to rest at the anode, and the efficiency varies as a function of the initial phase of each part of the bunch (see Fig. 10). We see that for the magic condition (Curve a) the variation is very rapid with the efficiency dropping to 50\% when the phase is wrong by only + 4° or - 10° from the magic value. At lower values of the RF field, although the maximum efficiency is less, the sensitivity to phase is weaker (Curves b and c). As a result a plot of efficiency vs \( \mathcal{E}_{RF} \) for finite pulse lengths (Fig. 11a) shows maximum efficiencies being obtained at progressively lower values of \( \mathcal{E}_{RF} \). Figure 12a shows the maximum efficiencies as a function of pulse duration (\( \Delta \phi \)) in degrees. For an example we will consider a pulse duration (\( \Delta \phi \)) of 18°, for which the efficiency would be \( \approx 90\% \).

Fig. 10 Efficiency vs. relative phase for:

a) The magic condition with \( \mathcal{E}_{RF}/\mathcal{E}_{stat} = 2.0 \);

b) \( \mathcal{E}_{RF}/\mathcal{E}_{stat} = 1.5 \);

c) \( \mathcal{E}_{RF}/\mathcal{E}_{stat} = 1.0 \).
Fig. 11 Efficiency vs. $\varepsilon_{RF}/\varepsilon_{stat}$ for a) different pulse lengths and b) different ratios $F_{sc}$ of charge $q$ to the space charge limit $q_{sc}$.

Fig. 12 Maximum efficiencies and corresponding phase advances $\chi$ as a function of a) pulse length and b) charge.

SPACE CHARGE EFFECTS

If a charge density $q$ in coulombs/m$^2$ exists just above the cathode surface then the induced electric field behind this charge $\varepsilon_{sc}$ is given by

$$\varepsilon_{sc} = \frac{q}{\varepsilon_0}$$

where $\varepsilon_0$ is the dielectric constant of free space in mks units ($8.855 \times 10^{-12}$).

The maximum charge that can be accelerated with a given static field $\varepsilon_{stat}$ is then

$$q_{sc} = \varepsilon_{stat} \varepsilon_0$$

and we define a scale invariant fraction $F_{sc}$

$$F_{sc} = \frac{q}{q_{sc}} = \frac{q}{\varepsilon_{stat} \varepsilon_0}.$$
Clearly, if \( F_{ec} \ll 1 \) the effect of space charge will be negligible. As \( F_{ec} \) increases the earlier charges will be accelerated more and the later charges less than in the small charge case. As a result it again becomes impossible to bring all charges to rest at the anode and the efficiency suffers.

Figure 11b shows the efficiency for different amounts of charge \( F_{ec} \) and different \( \xi_{RF} \). As with the long pulse case, maximum efficiency occurs at fields less than the magic value. Figure 12b shows maximum efficiencies as a function of the charge.

At first it would seem natural to pick a charge of the order of .4 times the space charge limit, for which the efficiency would still remain above 70% even with a pulse length of 18°. Such a large charge, however, would have two difficulties:

1. The current density in our example (\( V = 50 \text{ KV} \), \( g = .5 \text{ mm} \), \( \lambda = 6 \text{ mm} \)) would be 44 KA/cm² which may be excessive.

2. The instantaneous voltage drop of the wire would be large. In a closed device as illustrated in Fig. 4a or 4b, assuming equal gaps above and below the wire, then the fractional voltage drop would be \( q/(2 q_{ec}) \) or 20%. In the open structure case of Fig. 4c or 4d the capacity is only half and the voltage drop would be 40%.

Thus for an example we will chose a somewhat smaller value of \( q/q_{ec} \), such as 0.1, for which the resulting inefficiency is very small.

A POSSIBLE PARAMETER LIST

THE CAVITY

I will consider an open structure of the type illustrated in Fig. 4d, with 1 mm square wires and a total area of 10 cm by 10 cm. For a wavelength of \( \sim 6 \text{ mm} \) the wires would be placed about 2.5 mm apart. Thus there would be \( \sim 40 \) wires. The total photo cathode area is about 40 cm². I will consider a pulse length of 18° and \( q/q_{ec} = 0.1 \). I then obtain:

\[
\begin{align*}
V_{stat} & = 50 \text{ KV} \\
g & = .5 \text{ mm} \\
\xi_{stat} & = 100 \text{ MV/m} \\
\lambda & = 6 \text{ mm} \\
\lambda/c & = 16 \text{ p sec} \\
t_{pulse} & = .9 \text{ p sec (18°)} \\
q_{ec} & = 8.8 \times 10^{-4} \text{ c/m²} \\
F_{ec} & = .1 \\
q & = 8.8 \times 10^{-5} \text{ c/m²} \\
Q_{pulse} & = 3.5 \times 10^{-7} \text{ coulombs} \\
\xi_{RF} & = 150 \text{ MV/m} \\
\zeta & = 80\% \\
\phi & = -130° \\
\chi & = -38° \\
peak \ t_{photo \ cathode} & = 10 \text{ KA/cm²} \\
ave. \ t_{photo \ cathode} & = 500\text{A/cm²} \\
W_{output} & = .78 \times 10^{9} \text{ watts} \\
\end{align*}
\]

The time for the microlasertron to fill requires knowledge of both the stored energy in the structure and the average efficiency during the fill, neither of which we have. Rough estimates suggest:

\[ \tau_{las \ fill} \approx .8 \text{ nsec} \]
If this power source is to fill a semiconventional accelerating cavity then the pulse duration must be less than the natural fill time of that cavity. If we scale from SLAC’s $r_{\text{fill}} = 0.8 \mu\text{sec}$ at $\lambda = 10 \text{ cm}$ then for $\lambda = 6 \text{ mm}$:

$$r_{\text{acc fill}} = 12 \text{ nsec} \ .$$

Reference 3, however, suggests that breakdown could occur after about 5 nsec and thus the pulse length and energy per pulse would have to be reduced to:

$$r \approx 5 \text{ nsec}$$
$$n_{\text{cycles}} \approx 250$$
$$J_{\text{output}} \approx 3.9 \text{ Joules} \ .$$

This still represents a large total energy output for such an apparently simple device.

**LASER AND PHOTOCATHODE REQUIREMENTS**

The laser would be required to deliver 1 psec pulses approximately 18 psec apart for trains lasting of the order of 5 nsec. The optic frequency and power required would depend on the photo cathodes. If a conventional S 20 type of cathode could be employed and if $\epsilon_q = 10\%$ quantum efficiency is assumed at a wavelength of the order of 500 n meters ($V_\nu = 2.5$ volts) then the power required would be

$$J_{\text{opt}} = \frac{J_{RF} \cdot V_\nu}{\epsilon \cdot V_{\text{stat}}} \cdot \frac{1}{\epsilon_q}$$

$$= 2.4 \text{ mJ/ train of pulses} \quad (e.g. 3.9 \text{ Joules output})$$

Such a train of pulses could, for instance, be generated by multiplexing a single psec pulse generated by a mode locked dye laser. If the whole train were finally amplified by a $X_e F$ laser the overall efficiency might be expected [9] to be about $2\%$. In this case the power going to the laser would be negligible compared to that going to the electrical supply ($\sim 3\%$).

It is unlikely, however, that a conventional photocathode could carry the required current or survive long in the expected environment. A more rugged photocathode would be required and lower quantum efficiencies are to be expected. If the power to the laser is to remain less than half the total then a quantum efficiency of the order of $1\%$ is needed.

It has been reported [5] that a $C_{87}$ photocathode can give the required current densities and quantum efficiency if UV light is used, but its lifetime is not known. Very high current densities and quantum efficiencies [6] have also been reported from a brush-like photocathode but the time response and mechanism in this case is yet to be determined. Lanthanum hexaboride is another possible cathode. At low fields and UV light it has been observed to give a quantum efficiency [7] of $10^{-3}$ and may be expected to have higher efficiency at the field levels employed in our example.

Perhaps the most promising approach would be to use a metal photocathode and UV light. It is observed [8] that the quantum efficiency of most metals peaks at about 2500 Å and that this efficiency is given very approximately by the relation

$$\epsilon \approx 3 \times 10^{-3} (V_{\nu} - W_{\text{eff}})^3$$

where $V_{\nu} \approx 5 \text{ V}$ for 2500 Å and $W$ is the work function of the metal. Table I gives some examples. It is reasonable to assume that the quantum efficiency would be raised in a high field due to the Schottky reduction of the effective work function

$$W_{\text{eff}} = W - \left( \frac{e}{4\pi \epsilon_0 \epsilon} \right)^{1/2} \xi^{1/2} \ .$$

On this assumption values are given in Table I for expected quantum efficiencies for some values of surface fields.
Table I. Work functions $W$ in volts and quantum efficiencies for $\approx 2500$ Å light at different surface fields. The zero field values are measured and the others extrapolated.

<table>
<thead>
<tr>
<th>Metal</th>
<th>$W$ (Volts)</th>
<th>Percentage Quantum Efficiency for $\mathcal{E}$ (MV/m) =</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Na</td>
<td>2.1 – 2.5</td>
<td>6</td>
</tr>
<tr>
<td>Ce</td>
<td>2.8 – 4.2</td>
<td>2</td>
</tr>
<tr>
<td>Tw</td>
<td>3.4 – 3.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Zr</td>
<td>3.7 – 4.3</td>
<td>.3</td>
</tr>
<tr>
<td>Ta</td>
<td>4.0 – 4.2</td>
<td>.15</td>
</tr>
<tr>
<td>Cn</td>
<td>4.4</td>
<td>.08</td>
</tr>
</tbody>
</table>

If we take a Zirconium photocathode then with a field of 100 MV/m we can assume a quantum efficiency of 0.8%. The optical power then required for our example is 60 mJ/rain of pulses which is a significant fraction of the output power (1.5%).

A $KrF$ Excimer laser at a frequency of 2480 Å, however, could be used and such lasers have given [9] 15% intrinsic efficiency. If we assume an overall laser efficiency of 9% then the electrical power required for the laser is still only 17% of the output power.

**SCALING**

**BREAKDOWN**

To discuss the scaling of the microcathodtron, we need a theoretical model of the electrical breakdown. In Table II we give published values for the breakdown fields for different gaps and times ($\tau$). In all cases listed the electrodes were of copper or brass. For comparison we give also the transit time ($t$) for a copper ion and the ratio $n$ of the breakdown time to this transit.

We note that for a fixed voltage $V$ the ratio $n$ is relatively insensitive to the gap and thus the field. For lower voltages $n$ is higher, and for higher voltages $n$ seems to tend towards 1. This observation clearly suggests that the breakdown in these cases was a result of a cascade process involving the release, by electron impact, of ions at the anode, their movement back to the cathode and release there of more electrons. The number of ion transits required for breakdown would be dependent on the numbers of ions and electrons released by the impacts, and these would depend only on the voltage. This is as observed. For scaling purposes, therefore, we assume that the time for breakdown is a fixed multiple of the ion transit times at fixed voltage $V$.

Table II. Observed breakdown times for copper or brass electrodes and different gaps and voltages.

<table>
<thead>
<tr>
<th>$V$ (KV)</th>
<th>$g$ (mm)</th>
<th>$\mathcal{E}$ (MV/m)</th>
<th>$\tau$ (nsec)</th>
<th>$t$ (nsec)</th>
<th>$n$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1</td>
<td>40</td>
<td>24</td>
<td>5.7</td>
<td>4.2</td>
<td>3</td>
</tr>
<tr>
<td>80</td>
<td>2</td>
<td>40</td>
<td>22</td>
<td>8</td>
<td>2.8</td>
<td>3</td>
</tr>
<tr>
<td>80</td>
<td>1</td>
<td>80</td>
<td>11</td>
<td>4</td>
<td>2.8</td>
<td>3</td>
</tr>
<tr>
<td>80</td>
<td>.057</td>
<td>1400</td>
<td>.57</td>
<td>.23</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>160</td>
<td>2</td>
<td>80</td>
<td>5</td>
<td>5.6</td>
<td>.9</td>
<td>3</td>
</tr>
<tr>
<td>160</td>
<td>1</td>
<td>160</td>
<td>5</td>
<td>2.8</td>
<td>1.8</td>
<td>3</td>
</tr>
</tbody>
</table>
WAVELENGTH SCALING

It is reasonable to keep the relative geometry constant, i.e.,

\[ \frac{q}{\lambda} = \text{const} (.083) \]
\[ F_r = \frac{r_{oc}}{\lambda} = \text{const} (.38) \]
\[ \Delta \theta = \text{const} (18^\circ) \]
\[ \frac{q}{q_{sc}} = \text{const} (.1) \]

Then from Eq. (12b)

\[ V_{stat} \approx 10^6 \frac{q}{r_{oc}} = \text{const} (50 K V) \]

From the breakdown scaling of Sec. 6.1 we obtain the time before breakdown to be

\[ \tau_{\text{breakdown}} = n_{bd} \left( \frac{2M}{e} \frac{g}{V} \right)^{1/2} \propto \lambda \]

and the number of RF cycles before breakdown (\( n_{RF} \))

\[ n_{RF} = n_{bd} \frac{3 \times 10^5}{V^{1/2}} \left( \frac{g}{\lambda} \right) = \text{const} (\approx 400) \]

Since the gap \( g \) is proportional to \( \lambda \) the field, for fixed voltage

\[ E \propto \frac{1}{\lambda} \]

the space charge limit per unit area

\[ q_{sc} \propto \frac{1}{\lambda} \]

and the average current per unit area

\[ i_{ave} \propto q_{sc} \omega \propto \frac{1}{\lambda^2} \]

and thus the average power per unit of cathode area

\[ W \propto i \cdot V \propto \frac{1}{\lambda^2} \]

and the output energy in Joules

\[ J \propto W \tau \propto \frac{1}{\lambda} \]

Using these relations we obtain for a 10 cm \( \times \) 10 cm device as described in Sec. 5, but with different wavelengths.

<table>
<thead>
<tr>
<th>( \lambda )</th>
<th>( \mathcal{E} )</th>
<th>( i_{ave} )</th>
<th>( W_{out} )</th>
<th>( \tau_{\text{breakdown}} )</th>
<th>( J_{out} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 cm</td>
<td>20 MV/m</td>
<td>20 A/cm²</td>
<td>30 MW</td>
<td>36 n sec</td>
<td>.8 Joules</td>
</tr>
<tr>
<td>1 cm</td>
<td>70 MV/m</td>
<td>200 A/cm²</td>
<td>300 MW</td>
<td>10 n sec</td>
<td>2.3 Joules</td>
</tr>
<tr>
<td>3 mm</td>
<td>200 MV/m</td>
<td>2 KA/cm²</td>
<td>3 GW</td>
<td>3.6 n sec</td>
<td>8 Joules</td>
</tr>
</tbody>
</table>

The advantage in going to short wavelengths is remarkable. It will be limited, presumably, by cooling, photocathode, or nonscaling breakdown phenomena.
CONCLUSION

The above analysis has shown that a microlasertron might be a source of powerful mm radiation but there are many assumptions that need to be demonstrated:

1. Firstly we have assumed that a gradient of the order of 100 MV/m can be maintained over a .5 mm gap for 5 nsec. This is consistent with extrapolations from experimental results using metal electrodes but may not be possible if one of the electrodes has a low work function surface (photocathode). Experimental work is required.

2. We have assumed current densities of the order of 10 K amps/cm² for 1 psec pulses, and average currents of the order of 500 A/cm² for the order of 5 nsec. Both values are higher than observed with a conventional photocathode. Values of the required order have been observed from metal photocathodes, but with low quantum efficiency.

3. The analysis ignores the finite width of the diode gaps and also ignores the direct radiation from the electrons into the cavity. Full two-dimensional numerical calculation is required.

4. Details of switching the primary current have not been discussed. Laser activated solid state switches may be suitable, but much work remains to be done.

5. Details of RF windows, heat removal and a thousand other questions have not yet been addressed.

Despite these questions the potential of the proposed device seemed to justify its presentation now. Work on many of these problems is being pursued at various labs and future publication will hopefully answer some of the questions.

I would like to thank W. Willis whose original idea started this work and whose continued interest and suggestions have nurtured it. I also wish to thank J. Claus, U. Stumer, V. Radeka, T. Rao, and many others for their contributions.

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5. F. Villa (SLAC), private communication.


WORKING GROUP 2
TRANSFORMER ACCELERATION MECHANISMS
Summary of Working Group 2 on Transformer Mechanisms

T. Weiland
Deutsches Elektronen-Synchrotron DESY
Notkestr. 85, 2000 Hamburg 52, Germany

Participants in Working Group
J. Fisher, BNL A. Rao, BNL, W. Willis, CERN, V. Bharadwaj, FNAL, S. Peggs, LBL/SSC, L. Palumbo, Univ. Roma, Xiao Chengde, DESY, P. Schütz, DESY, P. Wilson, SLAC

1 Introduction

The principle of using transformer mechanisms originated from the observation that wake fields in existing accelerators can produce enormously strong decelerating wake potentials. Figure 1 shows a typical wake potential of a short gaussian bunch of particles caused by the interaction of its fields with the surrounding waveguide structure. However, the maximum accelerating potential behind the bunch can not exceed twice the maximum decelerating potential inside. Thus, such an accelerator is not very economical, taking into account that the charge in the following bunch must be much smaller than the one in the driving one.

The situation is significantly improved by using the mechanism of wake field transformation [1]. The ratio of accelerating wake to decelerating wake can be increased to almost any value by having the driving beam and the accelerated beam traversing the structure at different locations. The most simple transformer geometry (and also the only one that could properly be analyzed when first proposed in 1982) is the circular symmetric hollow beam transformer. Figure 2 shows the principle of this device. An electron ring of 10 cm diameter (say), 2 mm rms minor radius, an energy high enough to be relativistic and a total charge of 1 μC excites wake field while traversing the transformer through the slot near to the outer diameter. The generated wave packet first runs radially toward the outer boundary, is reversed there in its sign and subsequently travels toward the center. As the total volume containing the electromagnetic energy is thereby reduced, the field strength is increased. When the wave has reached the center, the accelerating field at this location can be 10 to 20 times higher than the decelerating field seen by the particles in the driving hollow bunch.

Just to give some idea of the strength of these fields, figure 3 shows all potentials in the above mentioned device producing an accelerating gradient of 188 MeV/m. In principle one may also improve the transformation ratio in a colinear standard cavity structure by making the driving beam longitudinally asymmetric. However, figures for the charges necessary to produce high gradients yield somewhat unphysical densities of up to two orders of magnitude higher than used in the hollow beam device [2].

An experiment with a hollow beam wake field transformer set up at DESY [3] has recently shown for the first time, that this mechanism works and also has pointed out what the major technical difficulties are due to. In a (not at all optimized) first “proof of principle” experiment a bunch of 1 cm rms length and 100 nC charge has been produced and accelerated to about 8 MeV. With a central witness beam a gradient of 8 MeV/m has been measured in a short wake field transformer using five subsequent hollow bunches in one pulse.

The generation of the hollow driving beam was (by many people) considered a very difficult task. One idea to replace the beam is to have high voltage storage devices at the outer location and to switch them sequentially to produce the collapsing wave structure [4]. Figure 4 shows the principal arrangement with high voltage wires which are triggered by a laser pulse. The circular current produces a collapsing pulse similar to the beam generated wave packet in the Wake Field Transformer.
Again, to give some idea of the requirements: the device itself is similar in size to the beam transformer, say twice as big. The peak currents necessary are of the order of 50,000 Amperes. The laser power for switching requires on the order of 1 Terawatt per longitudinal meter of transformer structure. Thus beam qualities are very similar to the beam driven device, with the major difference being that here the driver beam has to be produced at every cell, i.e. every 4mm.

![Diagram](image)

Figure 1: Wake potentials generated by a relativistic Gaussian bunch ($\sigma_m = 3\text{mm}, Q = 1\mu\text{C}$) in a disk loaded structure.

![Diagram](image)

Figure 2: Schematic view of a cylindrical wake field transformer. The driving ring current is produced by a relativistic electron ring. The outer cavities are shaped to improve reflection of the fields. The beam to be accelerated traverses the structure on axis.
Figure 3: Wake Potentials in a Cylindrical Wake Field Transformer

Driving beam: \( Q = 1 \mu\text{C}, \) \( \sigma_{\text{rms}} = 2 \text{ mm}, \) beam radius= 53 mm
accelerated beam: \( Q = 0.01 \mu\text{C}, \) \( \sigma_{\text{rms}} = 2 \text{ mm} \)

1... driving beam density
2... driving beam decelerating wake potential, \( W_{\text{min}} = 20\text{MeV/m} \)
3... accelerating wake potential for electrons on axis, \( W_{\text{max}} = 157\text{MeV/m} \)
4... accelerated beam density
5... decelerating wake potential of the accelerated beam, \( W_{\text{min}} = 7.3\text{MeV/m} \)
6... accelerating wake potential for positrons, \( W_{\text{max}} = 110\text{MeV/m} \)

Figure 4: The Switched Power Linac
An arrangement of charged wires provides stored energy which is released by a very short laser pulse (3ps) into a 50kA current pulse. This high current pulse generates a wave packet travelling toward the center producing a very high accelerating field on the symmetry axis of up to 300MeV/m.
2 Working Group Report

The working group spent about half of the available time with discussions and presentations in other groups, especially with the plasma accelerator group because they were interested in plasma wake field acceleration. Also, a strong interaction was necessary with the source group as one of the key problems in transformer technology is the generation of these high current, short pulse beams.

A very preliminary comparison of the two transformer concepts, the Switched Power Linac (SPL) and the Wake Field Transformer (WFT) was performed using existing figures for the geometries. The idea was to list all ingredients of both schemes and compare them to an ordinary disk loaded structure (DLS).

As was done in the experiment at DESY, both schemes could be run in a multi-pulse mode. A sequence of driver pulses at a proper distance would easily add up to a much higher gradient, or for a constant gradient, they would lead to greatly reduced requirements for the driver beams. This can be seen from figure 5 where the wake potential far behind the driving beam does not show any significant decrease in amplitude. For a copper transformer the typical decay time corresponds to about 100 pulses in a train of hollow bunches generated in a 500 MHz linac.

For the case of the SPL this cannot be assumed at the present state of knowledge. The major difficulty comes from the fact that with the SPL there is no simple termination of the radial line at the outermost radius. Thus reflection of pulses causes degradation. More detailed studies about this operation mode are necessary before making any relevant statements as to whether or not it is possible to build a multi pulse SPL.

For both schemes energy recovery means have been discussed. For the SPL no straightforward solution was found, but this was mainly due to the fact that not much thought had gone into that problem before.

Figure 5: Long Range Wake Potential on axis produced by a hollow driver bunch
As can be seen, there is no dramatic decay of wake potential behind the driving beam due to dispersion. The typical decay due to wall losses corresponds to about 20 times the time interval displayed here. Thus up to 100 ring pulses can be run subsequently through the transformer at proper distance producing an almost linear increase of the single pulse wake potential by a factor of 100.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>WFT</th>
<th>SPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disk radius</td>
<td>b/\text{mm}</td>
<td>45</td>
</tr>
<tr>
<td>Beam hole radius</td>
<td>a/\text{mm}</td>
<td>2</td>
</tr>
<tr>
<td>Gap between disks</td>
<td>g/\text{mm}</td>
<td>4</td>
</tr>
<tr>
<td>Disk thickness</td>
<td>t/\text{mm}</td>
<td>1</td>
</tr>
<tr>
<td>Geometric transformer ratio</td>
<td>R_g</td>
<td>10</td>
</tr>
<tr>
<td>Single bunch charge</td>
<td>Q/\mu\text{C}</td>
<td>12</td>
</tr>
<tr>
<td>Pulse width</td>
<td>\tau/\text{ps}</td>
<td>16</td>
</tr>
<tr>
<td>Decelerating gradient</td>
<td>G^-/(\text{MV/m})</td>
<td>20</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>G^+/(\text{MV/m})</td>
<td>200</td>
</tr>
<tr>
<td>Stored energy/pulse</td>
<td>W/J</td>
<td>200</td>
</tr>
<tr>
<td>Elastance</td>
<td>s/(V/\text{pC}/\text{m})</td>
<td>2000</td>
</tr>
<tr>
<td>Elastance of a DLS of same beam hole radius</td>
<td>s_{DL}/(V/\text{pC}/\text{m})</td>
<td>1600</td>
</tr>
<tr>
<td>Refractor power of the repetition frequency</td>
<td>P_{ref}/(\text{kW/m})</td>
<td>40</td>
</tr>
<tr>
<td>Superconducting drive linac</td>
<td>f/\text{kHz}</td>
<td>2</td>
</tr>
<tr>
<td>RF power from wall plug</td>
<td>P_{RF}/(\text{kW/m})</td>
<td>80</td>
</tr>
<tr>
<td>Laser power for switching</td>
<td>P_{Laser}/(\text{TW/m})</td>
<td>-</td>
</tr>
<tr>
<td>Laser efficiency</td>
<td>\eta_L</td>
<td>-</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>\eta_Q</td>
<td>-</td>
</tr>
<tr>
<td>Total driver efficiency from mains to accelerating field</td>
<td>\eta_{drive}</td>
<td>0.33</td>
</tr>
<tr>
<td>Total efficiency of a DLS</td>
<td>\eta_{DL}</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 1: Comparison of single pulse Switched Power Linac SPL with single Wake Field Transformer (WFT) and a disk loaded structure (DLS). Various parameters have been assumed, such as a superconducting drive linac with a gradient of 5\text{MeV/m}, common figures for the wall plug to rf conversion efficiency etc. Note that the mains-to-rf accelerating field efficiency is quite high in the WFT scheme.
However, for the WFT there is an easy way of extracting energy left behind the accelerated bunches and to store it back into the hollow beam drive linac. Under the assumption that the hollow beam driver is a superconducting 500MHz or 1GHz linac, one may have a train of energy transfer bunches following right behind the accelerated bunch. These energy transfer bunches will be accelerated by the remaining wake field pulses in the transformer. They will follow the high energy bunch and travel through the driver linac cavities. There, the high energy bunch will be accelerated by a small amount. The distance to the following train of energy transfer bunches can be chosen such that they arrive at the phase where the driver field is near the minimum. Thus they will be decelerated, i.e. energy will be recovered into the driver linac fundamental mode. No detailed study was performed on how much of that energy can be recovered. This is under study right now and there is hope to increase the overall efficiency by a significant amount.

3 Outlook

Although transformer technology was considered to be technically very difficult at the time it was first proposed in 1982, it has now been proven to work experimentally. A WFT multi-pulse operation with five pulses was studied successfully in the DESY experiment. Theoretical investigations with many more pulses are underway. They promise to significantly relax the beam quality requirements such as the azimuthal symmetry and the electron charge density.

Compared to quasi-conventional approaches needing extreme numbers of very high power sources, the technical feasibility of a WFT collider seems to be somewhat closer to reality. The basic ingredients are conventional driver linacs, either superconducting or normal copper structures, running at today's gradients. The transformer section itself is very simple in construction and needs much less fine machining than e.g. 30GHz cavities. Furthermore, there is no phasing necessary between the driver and the accelerated bunch as is needed in a rf linac.

The SPL is in a more theoretical stage and some experiment is urgently needed to show that these high voltage lines with field strengths up to 1GV/m can be realized in practice.

References


Discussion

U. Amaldi, CERN

I have three questions about the wake field accelerator:

(1) What is the total acceleration voltage for the hollow drive beam?

(2) Do you have a feeling for the wakefield effects in hollow bunches in the multibunch beam?

(3) What is the minimum emittance of the main bunches that can be accelerated, taking into account the possible azimuthal asymmetry of the hollow bunches?

Reply

(1) It is the final energy divided by the transformation ratio and the number of driving bunches. With our superconducting cavities you can have large driving beams that allow a transformation ratio of 15. With 10 bunches this gives you 6 GeV for a TeV collider.

(2) This problem is under study right now.

(3) It is of the same order as in a linac with 30 GHz and 4 mm beam hole diameter, but detailed studies have been delayed until the first experimental results were available and that happened just a few weeks ago.
The Wake Field Transformer Experiment at DESY


Deutsches Elektronen-Synchrotron DESY
Notkestr. 85, 2000 Hamburg 52, Germany

Abstract

The basic principle of Wake Field Transformation is to use imploding electromagnetic waves generated by high density electron bunches. One of the most simple structures for a Wake Field Transformer is the cylindrical pill-box excited by a hollow beam. The fundamental mechanism will be briefly reviewed. A Proof of Principle experiment has been set up at DESY by a group of scientists with collaborators from China, Japan and USA. The layout of the experiment is presented together with a status report and most recent results. Several bunches each of 50 to 100 nC charge have been produced and accelerated to an energy of 8 MeV and bunched down to a length of 1 cm. With a central witness beam a gradient of 8 MeV/m has been measured in a short Wake Field Transformer using six subsequent hollow bunches in one pulse.

Introduction

The principle of the wake field acceleration mechanism has been described in detail in other papers [1,2]. Thus, we recall only the basic points of interest: A high charge driving beam of 1 μC (say) and a central low charge driven beam of 0.01 μC both traverse a special kind of multi-cell cavity which we call a Wake Field Transformer. In this transformer the driving beam excites wake fields that lead to its deceleration. By proper shaping of the transformer geometry the driving beam excites a wave packet that is subsequently spatially focused. Thus, there is an increase in field strength proportional to the inverse square root of the volume containing the wake fields. A second pulse of particles entering the transformer focal line with proper delay traverses this concentrated wake field and experiences an acceleration which is much greater than the deceleration of the driving beam. The ratio of acceleration to deceleration we call its transformation ratio. Values for the transformation ratio of around 10 are expected in our experiment. Thus, one could accelerate a bunch of electrons to 1 TeV using the wake fields of a 100 GeV driving beam and according to our calculations the accelerating gradient will exceed 100 MeV per meter.

This scheme is considered to be a candidate for the next TeV electron-positron collider. It could be built within a total length of about 10 km if the predicted gradients can be reached.

An experiment with a hollow beam Wake Field Transformer has been set up at DESY. A laser driven electron gun produces a high current hollow beam of 10 cm diameter. The beam is bunched in a pre-buncher and accelerated in the following linac. This whole unit is in a solenoid guiding field. The final longitudinal compression is achieved in the high energy buncher. Finally, the beam is fed into the Wake Field Transformer. The energy of the central witness beam passing through this transformer on axis is analyzed in a spectrometer adjacent to the transformer.

*On leave from Tsinghua University, Beijing, People’s Republik of China
1 Experimental Set Up

In order to study the problems associated with the Wake Field Transformer concept we have assembled an experiment [3,4,5] using a complete linac for generation of the driving beam. We chose a cylindrically symmetric transformer since it should provide high transformation ratios and since it was the only one that could properly be analyzed when first proposed in the year 1982.

The driving hollow beam has a diameter of 10 cm. When extracted from the gun the charge should be 1 µC over a pulse length of 1 ns. Thus, we need 1 kA electron current. The design peak value of the pulsed cathode voltage is 150 kV. The beam is accelerated to about 8 MeV and compressed before entering the Wake Field Transformer. The overall layout of the experiment is shown in Fig. 1 and the major components will be described below.

Hollow Beam Gun. A laser driven gun was chosen for which the photon energy of the laser light is much lower than the work function of the cathode material. The infrared light beam (wave length 1.064 µm) produced by a Q-switched Nd:YAG laser (peak power > 100 MW) is focused onto a ring at the conical tantalum cathode and is absorbed inside a very thin layer. Thus, since the surface temperature increases, thermionic emission and thermionic supported photoelectric emission is possible. The emitted electrons are extracted by a pulsed high voltage and guided by a solenoid field (field strength ~ 0.2 T) through a slit in the anode. A more detailed description of the gun and the emission mechanism and some experimental results are given in a separate contribution to these proceedings [6].

Linear Accelerator. The linac consists of a prebuncher and a chain of four 3-cell cavities powered by a 1 MW klystron (500 MHz) which is pulsed at 25 Hz with 100 µs duration. The prebuncher consists of a single-cell cavity and a following driftspace. The zero current energy gain is 8 MeV and the measured shunt impedance of the accelerating cavities is 20 MΩ/m. Solenoid coils surround the cavities wherever possible. All cavities are mounted with a periodicity of λ/2. Additional phase shifters enable the phases to be controlled. The first phase shifter between the prebuncher cavity and the first accelerating cavity adjusts the injection phase. A second phase shifter between the first and the second cavity corrects for the delay in phase owing to the subrelativistic energy of the injected electrons. The third phase shifter at the fourth cavity allows us to generate a variable energy spread which is needed for the high energy bunching mechanism in the antisolenoid. As cavities are located in the magnetic field of the solenoid, multipactoring is much more severe than usual.

![Diagram of the Wake Field Transformer experiment at DESY.](image-url)

Figure 1: Overall layout of the Wake Field Transformer experiment at DESY.

Shown from left to right: The infrared light beam produced by a Q-switched Nd:YAG laser (peak power > 100 MW) is focused onto a ring shaped tantalum cathode. The emitted thermionic- and photoelectrons are extracted by a voltage of about 100 kV and guided by solenoid fields of 0.2 T into the linac. Firstly, the hollow beam is compressed longitudinally in a prebuncher. Then, four 3-cell cavities (500 MHz) accelerate it to 8 MeV. A pulsed klystron (peak power 1 MW) feeds the cavities. In the antisolenoid further longitudinal compression is achieved. Then the ring is radially compressed by increasing solenoid fields. Finally, the electron ring enters the actual Wake Field Transformer, consisting of 80 cylindrical cells arranged one after another. For monitoring and adjustment of the ring beam, several beam monitors have been set up.
Figure 2: Movable fluorescent screen for monitoring of the hollow beam at the entrance of the linac. A thin foil of bronze coated with zinc sulphide is pressed against the beam pipe. The hollow beam can pass. If required, the screen can be moved in by a pneumatic system. The projection can be observed by two CDC video cameras (which can be operated in a magnetic field). - A typical photograph of the hollow beam is shown on the right. The lower part is masked by the beam pipe.

Stable conditions for the prebuncher cavity cannot be achieved owing to the relatively low rf field strength. The field breaks down after approximately 20 μs. In order to avoid this instability situation, the rf-power for this cavity is generated separately in a second transmitter and switched off before break down starts. There is an adjustable delay between the prebuncher rf source and the main linac klystron. Thus we can run at a phase where the main linac cavities are at peak voltage, and the prebuncher cavity is still on the rising slope so that no multipactoring occurs.

Measurements of the Hollow Beam. Elements for monitoring the hollow beam are mounted in the drift space of the Prebuncher and at the end of the linac behind the last cavity (see Fig. 1). For the nonrelativistic hollow beam we use a movable fluorescent screen monitor and a gap monitor, for the relativistic beam a gap monitor and a Čerenkov light monitor.

Figure 3: Schematic layout of the gap monitor. The beam pipe is interrupted by an insulating tube and bridged by 64 10 Ω resistors. Around the circumference of the pipe, 16 pick-ups are fixed. The mean value of the beam current is obtained by a passive network from the signal heights of eight pick-ups. The other eight pick-ups are used for the measurement of the azimuthal distribution of the hollow electron bunches.
A projection of the hollow beam is produced by a fluorescent screen which can be moved into the beam pipe if required and observed by CDC video cameras. The layout of this device is shown in Fig. 2.

A gap monitor (Fig. 3) measures the wall current induced in the beam pipe. The tube is simply interrupted by an insulating ring and bridged by resistors. The voltage drop across the resistors is proportional to the wall current. For measuring the pulse length of shorter bunches a Čerenkov monitor has been designed. A part of the hollow beam excites Čerenkov radiation in a small quartz wedge. With a light collection system consisting of two mirrors and three lenses the light pulse is guided to the imaging slot of a streak camera. The corresponding peak current must be derived from the signal of the gap monitor mounted near by.

High Energy Buncher. The final longitudinal compression of the hollow beam is achieved in an antisolenoid. The field strength of the solenoid and of the antisolenoid are equal. The region where the field is radial must be very short. Therefore iron plates are inserted between the coils.

The total effect on the beam of the longitudinal field of the solenoid and the radial end fields is to cause the ring to rotate around its symmetry axis. As some of the particle energy is now in the circular motion, the longitudinal velocity decreases. The phase of the fourth cavity is adjusted such that the earlier particles are accelerated less than the later ones. Thus the ring can be bunched even at high energies, where classical bunching mechanisms fail.

At the end of the antisolenoid, the rotation is stopped by another inversion of the solenoid field.

Wake Field Transformer. The central part of the whole experiment is the Wake Field Transformer. A cross-sectional drawing is shown in Fig. 4. An electron ring of 10 cm diameter, 2 mm minor radius, at an energy high enough for it to be relativistic and of total charge 1 μC excites wake field while traversing the transformer through the slot near the outer diameter. The generated wave packet first runs radially towards the outer boundary, is reflected there with reversed sign and subsequently travels towards the center. As the total volume containing the electromagnetic energy is thereby reduced, the field strength is increased inverse proportionally to the square root to the volume containing the wake fields. Thus, when the wave has reached the centre, the accelerating field at this location can be 10 to 20 times higher than the decelerating field seen by the particles in the driving hollow bunch. Just to give some idea of the strength of these fields, Fig. 5 shows all wake potentials in the above mentioned device producing an accelerating gradient of 157 MeV/m.

![Figure 4](image-url)  
Figure 4: Cross section of one part of the Wake Field Transformer.

On the inner wall of the beam tube rebates are turned, on which wake fields are excited by the driving hollow beam. The wake fields are guided by the disks into the centre of the beam tube where they interact with the driven beam. The disks are held together by metal strips and form a stack lying normal to the axis of the tube. All parts are made from stainless steel.
Computer Simulations. The DESY Wake Field Transformer experiment has always been accompanied by theoretical studies and computer simulations. Two codes are used for the numerical studies: WAKTRACK[7], a fast tracking code including collective effects, is used as an operating tool in parallel with the experiment. It will also be used for investigations on the feasibility of a future TeV collider. More detailed investigations, especially in the low energy region (q ≤ 20), are carried out with TBCI-SF[8], a new particle-in-cell code. Both programs are described in more detail in another contributions to these proceedings[9].

2 Stage-1 Experiment

In order to investigate step by step the problems concerned with hollow beam dynamics we first omitted the high energy buncher and set up a stage-1 experiment to get a first proof of the Wake Field Transformation concept. The layout of this experiment is shown in Fig. 6.

We are using a transformer which is optimized for the hollow beam size bunched by the linac. The separation of the plates is 1 cm and the thickness 2 mm. The plates are held by four longitudinal sticks near the slot for the hollow beam. The test beam is produced by a field emission gun which uses the first transformer plate as anode. The cathode consists of a pointed tantalum needle. Since the beam was nonrelativistic only a short transformer could be used: Slow particles are not able to stay in phase with the wake field pulse running at the speed of light. The optimum transformer consists in this case of two cells. Two lead blocks provide shielding against electrons from the hollow beam and parasitic electrons. The energy of the electrons accelerated by the excited wake fields is measured by a decelerating grid method. Only particles with energy greater than the grid voltage penetrate to the zinc sulphide screen and can be detected by a photomultiplier. From the difference with the test gun voltage we can determine the energy rise in the transformer.
A Čerenkov light monitor measures the pulse width of the hollow beam and a gap monitor measures the charge of the subsequent bunches of a pulse. The surface of the first lead block is used as a fluorescent screen for monitoring the adjustment of the hollow beam relative to the slot.

3 Experimental Results of the Linear Accelerator

The study of the properties of the linear accelerator involved many measurements. We have chosen three typical ones for this report.

Azimuthal distribution of the hollow beam. The moments of the charge distribution within the hollow beam relative to the centre of the beam pipe can be measured by the gap monitor using the signal heights of the eight pick-ups mounted around the circumference of the monitor. The signals for two different currents are shown in Fig. 7. In order to get the correct azimuthal distribution of the hollow beam the different damping of the eight signals due to the different length of the lines and the cross talk between one signal and the others must be taken into account. The relative dipole moment of the hollow beam is less than 20 % in this example.

Figure 7: Azimuthal distribution of the hollow beam for two different currents.

Eight signals around the circumference of the gap monitor are delayed by delay lines, added by a passive resistor network and measured by one channel of an oscilloscope. Thus it is possible to measure the eight signals of one pulse simultaneously. On the left photograph a distribution is shown for a hollow beam current of 22 A and on the right photograph for 39 A.
Measuring subsequent bunches. The prebuncher cavity (ν = 500 MHz) compresses the gun pulse sequence of short bunches within a period length of 2 ns (see Fig. 8). The bunches can be monitored by a gap monitor positioned at the end of the drift space. At relatively high currents (I₀ ≈ 50 A) only a weak compression can be achieved due to longitudinal space charge effects. At low currents very short bunches are achieved, whose length approaches the resolution limit of this gap monitor (σ ≈ 50 ps).

![Figure 8: Two bunches of six generated by the prebuncher.](image)

Measurement of picosecond bunches. For measuring short bunches a Čerenkov light monitor has been built. Particles of the hollow beam excite Čerenkov light within a small quartz wedge. The light is detected by a streak camera. Fig. 9 shows a typical signal measured by the streak camera. This is compared with the corresponding response of the gap monitor mounted nearby. It can be seen that the time resolution of the gap monitor has been reached. But, the charge in one of the bunches can be calculated from the integrated signal and together with the length measured by the light monitor, the amplitude of the current can be determined indirectly.

![Figure 9: Comparison of the signal response by a gap monitor (left) and a Čerenkov monitor (right).](image)
4 First Experimental Proof of Wake Field Acceleration

In the stage-1 experimental set up as described above, we first tried to study the problems concerned with steering the hollow beam through the transformer. We were able to generate a current pulse of rms length 1cm and a peak current in excess of 500A. The corresponding gun current was 55A, the gun voltage 85kV. The hollow beam consists of a train of six subsequent electron bunches separated by the rf wavelength of the drive linac (60cm). Wake fields excited in the transformer travel continuously back and forth radially with a reversal in sign after each reflection at the outermost radial boundary. The travel time of a wake field pulse in the transformer used in this experiment was exactly one fourth of the period of the linac frequency. Thus subsequent ring pulses generate a wake field which adds constructively. For the field at the center there is no difference between six pulses and one pulse with six times the charge.

The beam radius could be adjusted by means of additional power supplies hooked onto the three last solenoids. The beam penetrated through the transformer without significant loss in intensity.

At the end of the linac the hollow beam bunches are much longer than the 2mm that we intend to achieve with the high energy bunching scheme. Thus, wake fields excited by these bunches are significantly weaker than they will be in the final set up as described in Section 1. Even with six bunches we could not expect a change in energy in a transformer placed at this location in the beam line to be high enough to be detectable with a central witness beam running all along the linac. This is because beam loading of the hollow beam and other effects create an energy jitter in the witness beam which is just of the same magnitude as the expected acceleration.

In order to be able to detect even small changes in energy we decided to install a separate witness beam gun with a well defined and low energy. The witness beam dc current was injected at an energy of 20kV into the transformer.

The low energy of the witness beam however has other severe disadvantages. Particles at 20keV are much too slow to stay in phase with the wake field pulse running at the speed of light. In a transformer which is a few times longer than the width of the wake field pulse, the net energy gain of witness particles would average out to zero. The only way to avoid this effect is to make the transformer as short as the pulse width. Following an optimization procedure of maximizing the energy gain as a function of transformer length we obtained an optimum for a length between 2 and 3cm. We optimized the period length, slot height, central beam hole radius and upper cavity depth for a bunch length of 1cm and obtained a two-cell structure, each cell being 1cm long and separated by a 2mm thick metallic disk.

We ran the linac for the above mentioned beam parameters and injecting the witness beam into the transformer. First we switched off the central beam in order to see the background due to secondary photons produced by the hollow drive beam particles. Fig.10 shows the background signal of the photomultiplier tube.

We then switched on the witness beam and slowly increased the stepping voltage on the grid (see Fig.6) behind the transformer. We expected a maximum acceleration of around 30keV, which we calculated under

![Figure 10: Photomultiplier signal of light produced by electrons traversing the final potential barrier.](image)

*Left:* Background signal due to secondary photons created by scattered electrons of the driving beam.

*Right:* Signal from particles accelerated in the wake field transformer.
the pessimistic assumption that the capture efficiency of the drive linac is only 50% and that the ring shape is Gaussian in the longitudinal direction. At a voltage of 70kV we were limited by the power supplies but could not yet see any significant decrease of the clear signal from the witness beam particles, see Fig. 10.

Thus we not only had a clear signal of the first particles accelerated by the mechanism of Wake Field Transformation but we also found an acceleration higher than expected at least more than 50keV. Thus the charge capture efficiency was better than assumed and/or the bunch shape was narrower than in a Gaussian distribution. This acceleration of 50keV over 2.4cm (which is the length of the transformer including two of the three disks) yields a gradient of 2 MeV/m for 20keV particles.

It is relatively straightforward to evaluate by means of computer simulation that relativistic particles would be accelerated by these fields at a rate of 8 MeV/m.

5 Summary

The first experimental proof of the new acceleration mechanism of Wake Field Transformation has been completed at DESY. The experiment did show that this scheme is technically feasible.

A number of effects concerned with the unusual beam dynamics of high density hollow bunched beams were studied. The charge densities achieved in this first (not at all optimized) experiment are around 1/10 of the original design values.

Means to improve this situation, such as increasing the laser power, increasing the gun voltage, increasing the width of illuminated cathode area, replacing the present buncher by a subharmonic one etc., are under investigation.

The stage-2 experiment will mainly be concerned with the longitudinal bunch compression in the antisolenoind region. In this compressor the bunches will also be significantly improved in their azimuthal symmetry since a local asymmetry at a specific angular position will be smeared out (due to the energy spread produced in the last linac cavity) over all the bunch circumference. This next step will presumably increase the peak intensities by a factor of five and the peak values of the wake fields even by a factor of ten.

In the case of a multi-pulse operation which is now being considered, the bunch charge experimentally achieved is in fact high enough for a scheme with 10-20 pulses or even too high in a scheme with more pulses.

Also, the multi-pulse operation relaxes many beam quality requirements. Whereas longitudinal wake fields add up coherently, in general this is not so for transverse deflecting wake fields since the two classes of modes do not have the same frequencies. Thus for such a multi pulse WFT with more than 20 bunches the existing experimental setup already fulfills the requirements for a real 1TeV Wake Field Transformer linear collider.

Acknowledgement

Over the years from 1982 to 1987 a large number of people have contributed to the design and construction of this experiment. We wish to express our deep thanks to our collaborators from KEK, S.Ohsawa and K.Yokoya who both spent a year working at DESY, Prof. S.L.Wang from the University of Beijing, K.Bane from SLAC and G.Rodenz from LANL.

Our thanks are also due to many colleagues at DESY who were members of the wake field group during the design phase and worked on the beam dynamics and the layout of the experiment: H.C.Dehe, M.Leneke, J.Rossbach and F.Willeke.

Special thanks are also due to M.v.Hartrott (now at BESSY, Berlin) who was with our group for a period of one year and who designed the analyzing apparatus which, as described above was successful.

A great portion of the success of the experiment was due to the intensive help by all the technical groups at DESY: The rf group headed by H.Musfeldt, the controls group headed by F.Peters, the power supply group headed by H.Narciss and W.Bothe, the injection group headed by A.Febel, the civil engineering group headed by K.Sinram and the vacuum group headed by J.Kouptaidis.

Finally, we would like to thank D.Barber for careful reading of the manuscript.

1The actual shape as observed is steeper than a Gaussian bunch and thus presumably creates stronger wake fields.
References


Discussion

A. Sessler, LBL

Did you have the opportunity to reduce the number of driving rings from 5 to 1?

Reply

No, not yet. The laser pulse is too long and we have not yet been able to make it shorter.

P. McIntyre, Texas A and M University

Do you have the capability in your Phase I experiment to measure off-axis fields in the wake-field structure?

Reply

Yes.
Hollow Beam Gun
for the Wake Field Transformer Experiment at DESY

W.Bialowons, H.-D.Bremer, F.-J.Decker, H.-Ch.Lewin,
P.Schütt, G.-A.Voss, Th.Weiland, Xiao Chengde *

Deutsches Elektronen-Synchrotron DESY
Notkestr. 85, 2000 Hamburg 52, Germany

Abstract
Most of the future accelerator concepts require new types of electron guns. A short pulse high current electron gun is needed for wake field accelerators. A group at DESY is investigating the possibility of accelerating particles with a high gradient in a Wake Field Transformer. This paper will focus on the hollow beam gun developed for this experiment. A laser driven gun was chosen which uses the general Richardson effect. The theory of this effect is described and compared with experimental results. At a cathode voltage of nearly 100 kV, the gun produces a hollow beam of 10 cm diameter with a space charge limited current of about 100 A over a pulse length of a few nanoseconds.

Introduction
The principle of the wake field acceleration mechanism [1,2] and the Wake Field Transformer experiment at DESY [3,4,5] has been described in detail in other papers. Thus, here we recall only the basics of interest for the electron gun. A relativistic hollow beam of high charge excites wake fields in the transformer. This wave packet is spatially focused in the centre. At the proper time and position a second pulse of particles follow the driving beam and will be accelerated by the increasing electrical field inside the excited wave packet.

The driving hollow beam has a diameter of 10 cm. When extracted from the gun the charge should be 1 μC over a pulse length of 1 ns. Thus, we need 1 kA electron current. The design peak value of the pulsed cathode voltage is 150 kV. On the one hand this peak value is necessary to reach a sufficiently high space charge limited current and on the other hand to obtain favourable initial conditions for the following linear accelerator.

A laser driven gun with a tantalum cathode was chosen. The photon energy of the laser light is much lower than the work function of the cathode material. For the opposite case we need an in situ activated photo cathode and an excellent ultra high vacuum (below 10^{-10} mbar) [6]. In order to avoid both of these difficulties we have decided upon a more complex process. In this case the emission mechanism is explained by the generalized Richardson effect. The light of a short pulse high power laser is absorbed inside a very thin layer of the cathode. Thus, since the surface temperature increases, thermionic emission and thermionic supported photoelectric emission is possible. The calculation of the surface temperature by solving the heat diffusion equation and the extracted electron current by using the generalized Richardson equation is compared with experimental results. The characteristics of the hollow beam gun were measured and are compared with calculations of the limit of emission by space charge effect in the gun.

*On leave from Tsinghua University, Beijing, People's Republic of China
1 Layout of the Gun

A cross-sectional drawing of the hollow beam gun is shown in Fig. 1. A Nd:YAG laser made by Quanta Ray is used as light source. It consists of a Q-switched oscillator with an unstable resonator and an amplifier. The laser rod yields infrared light (wavelength 1.064 μm) over a pulse length of 10 ns and a maximum energy of 900 mJ per pulse can be obtained. Due to the output mirror of the resonator the laser beam has a doughnut profile of 8 mm outer diameter with a 4 mm hole in the centre. This profile is well suited for forming a large and thin light ring.

The laser light enters the vacuum section of the gun through a common viewing port. The beam will be enlarged by a conical mirror and focused on a ring at the conical tantalum cathode by a lens. The conical mirror is a glass cylinder with a polished inverse cone at the top, making use of the total reflection at the glass vacuum surface. The cathode was manufactured out of a 0.3 mm thick tantalum plate. The reasons for choosing this material is the high vaporizing point of tantalum (~ 5700 K) and the relative ease of machining which is similar to stainless steel. The electrons are extracted from the metal via heating and photoeffect. These electrons are accelerated by the high voltage and follow the magnetic field lines. The entire gun is embedded in a solenoid field, which guides the electrons through a slot hole in anode. The field at the cathode is necessary to generate a nonrotating hollow beam inside a guiding field. It also allows us to use a conical cathode and thus to simplify the optics for the laser beam. In order to reach the design value of 150 kV for the pulsed cathode voltage the insulating ceramic of the gun is surrounded by an insulating gas for which SF₆ is used. Since the high power laser light must not penetrate the gas, because otherwise glass surfaces would be etched, it travels in air inside an insulating tube (see Fig. 1). The peak value of the pulsed high voltage is limited by the minimum cathode—anode distance of 1 cm and additionally reduced by switching on the solenoid field. During firing of the gun for some nanoseconds.

![Figure 1: Cross section of the laser driven hollow beam gun.](image)

The infrared light beam (wavelength 1.064 μm) produced by a Q-switched Nd:YAG laser (peak power > 100 MW) is focused on a ring at the conical tantalum cathode. The optical train consists of a viewing port, a focusing lens and a conical mirror. The conical mirror is a glass cylinder with a polished inverse cone at the top, making use of the total reflection at the glass vacuum surface. The emission mechanism is explained by the generalized Richardson effect (pure thermionic emission and thermionic supported multiphoton photoelectric effect). The emitted electrons are extracted by a pulsed high voltage (design peak value 150 kV) and guided by a solenoid field (field strength ~ 0.2 T) through a slot hole in the anode. In order to increase the breakdown voltage, the insulating ceramic is surrounded by SF₆ gas at atmospheric pressure. The optical train is separated from the gas by an insulating tube.
the voltage depends on the capacity close to the cathode. In order to achieve high currents we have provided a coaxial structure with a low impedance ($\varepsilon = 90\%$) compared to the load impedance. The advantage of a coaxial device is a constant cathode voltage over twice the traveling time in the tube.

2 Principle of Laser Generated Electron Emission

The characteristic of the laser driven hollow beam gun is that the work function of the used cathode material (Ta: $\phi_A = 4.12 \, eV$) is much higher than the photon energy of the laser light ($h\nu = 1.165 \, eV$). Thus common photoelectric emission is not possible. But in our arrangement the parameters of the Nd:YAG laser are sufficient for heating the cathode surface. If the illuminated area at the cathode is small enough, the temperature can exceed the melting point (Ta: 3269 K). Significant thermionic emission and thermionic supported photoelectric emission is possible.

2.1 Surface Temperature Calculations

Inside a metallic plate a light quantum will be absorbed by the photo effect. The energy transfers totally to an electron of the conduction band. If this electron does not leave the solid it collides with an ion after the drift time. A part of its energy transfers to the lattice. For conductors the drift time is in the order of 0.1 ps. That means the energy of a nanosecond light pulse will be nearly immediately transferred to the lattice and classical heat diffusion calculation can be used.

The temperature of a laser irradiated cathode can be calculated by solving the homogeneous heat diffusion equation with constant coefficients. We assume that the specific heat capacity $c_v$, the thermal conductivity $\gamma$ and the optical reflection $R$ of the metallic surface are independent of the temperature and we neglect the penetration of the light into the metallic plate. Employment of the Green's function method leads to the integral equation for the surface temperature [7]

$$ T_s(t) = T_0 + (1 - R) I_0 \frac{1}{\pi \gamma c_v \rho} \int_0^t h(t - \tau) \frac{1}{\tau} \, d\tau, \quad (1) $$

where $T_0$ is the initial temperature and $\rho$ the specific mass. The intensity of the laser light in terms of the temporal distribution is $I_0 h(t)$. This integral expression is valid for time differences for which the transversal heat diffusion can be neglected. For nanosecond laser pulses the condition is always achieved.

For a rectangular time dependence of the laser intensity Equation (1) yields the peak value of the surface temperature

$$ \hat{T}_s = T_0 + 2(1 - R) I_0 \frac{t_p}{\pi \gamma c_v \rho}, \quad (2) $$

where $t_p$ is the laser pulse length. Assuming an absorbed laser intensity of 50 MW/cm$^2$ and a pulse length of 3.5 ns from this relationship we obtain a maximum surface temperature difference $\Delta T_s = T_s - T_0 = 2987 \, K$ for a tantalum plate.

2.2 Generalized Richardson Equation

In a simple model the conduction electrons are moving without any interaction inside the metal and a potential step prevents them from leaving the solid. At the temperature zero point the electrons occupy every energy level up to the Fermi energy $E_F$, higher energies are not occupied. The difference between this energy and the border of the potential step is the work function $\phi_A$. At higher temperatures energy levels above the Fermi energy are also occupied. If the temperature is high enough some electrons are able to leave the solid. Additionally the electrons can absorb the photon energy $h\nu$ of penetrating light. The condition for electrons leaving the metal is for the thermionic emission and for the thermionic supported photoelectric emission

$$ \frac{m_0}{2} v_{\perp}^2 + n \, h\nu - E_F - \phi_A = n = 1, \ldots, N + 1, $$

where $m_0$ is the rest mass of an electron, $v_{\perp}$ the thermionic velocity of an electron normal to the surface of the cathode and $N$ the largest integer less than $\phi_A/h\nu$, and $n$ is the number of photons absorbed by
one electron. This condition together with the Pauli principle and Fermi statistics leads to the generalized Richardson equation for the current density

$$j = \sum_{n=0}^{N+1} j_n,$$

with

$$j_n = A T_s^2 a_n \Gamma^n \int_0^\infty \ln(1 + e^{k/x}) \, dx; \quad \kappa_n = -\frac{\varphi_A - \mu \hbar \omega}{k_B T_s},$$

where $A$ is the Richardson constant and $I = (1 - R) I_0 h(t)$ the absorbed laser intensity. $j_0$ represents the pure thermionic emission, for $n > 0, j_n$ represents the $n$-photon photoelectric emission and $a_n$ are the appropriate coefficients related to the matrix element of quantum $n$-photon process. At typical temperatures and for $n \leq N$ the exponential term of the integral is much less than one and the current density is approximately

$$j_n = A T_s^2 a_n \Gamma^n e^{k_n}, \quad n = 1, \ldots, N,$$

and for $n = 0$ the expression is the well known Richardson-Dushman equation. At sufficiently high temperatures the thermionic emission dominates the current density. If we use the parameters from Section 2.1 we can expect a pure thermionic current density of $180 \, \text{A/cm}^2$ at a cathode surface temperature of $3200 \, \text{K}$.

### 2.3 Characteristics of a Gun

An electron leaves the solid if its kinetic energy is high enough and if it has a velocity component normal to the surface of the metal. But a free electron causes an electric field at the surface, which decelerates the following particles. Already for very low current densities the emission will be totally stopped. We need an external electric field for extracting a sufficiently high current. A current is called space charge limited, if it compensates the external field at the active cathode surface. The dependence of the current on the applied voltage for different cathode surface temperatures (i.e. laser energies per pulse) will be called the characteristics of a gun. For sufficiently high emission at the total active cathode surface the dependence of the beam current $I$ on the applied voltage $U$ is represented by the Child-Langmuir law

$$I = p U^{3/2},$$

where $p$ is the pereance of a gun, which is a geometric factor. For an electron beam thick compared to the anode cathode distance $d$ the pereance of the gun is

$$p = 2.334 \frac{\mu A}{V^3} \frac{A}{d^3},$$

where $A$ is the emission surface at the cathode. For a thin hollow beam the pereance will be approximately enhanced by a factor $0.6 \sqrt{2d/A}$, where $\Delta$ is the wall thickness of the hollow beam. Assuming a thickness of 0.5 mm we will expect a space charge limited current of $85 \, \text{A}$ at a cathode voltage of $50 \, \text{kV}$ for an anode cathode distance of $1.5 \, \text{cm}$ and $440 \, \text{A}$ at $150 \, \text{kV}$.

At high voltage the current depends on the emission. The dependence of the beam current on the voltage can be derived from the Schottky effect and, for thermionic emission and thermionic supported photoelectric emission,

$$I = I_0 e^{e^v},$$

The crossing between these two regions will be approximately described by [7]

$$I = I_0 \left\{ 1 - \left[ 1 - \left( \frac{U}{U_0} \right)^{1.5} \right]^2 \right\}.$$

This expression is only valid for a hollow beam gun.
3 Experimental Results

To study the laser generated electron emission and the properties of the hollow beam gun several experiments were made. We have chosen three typical experiments for this report. First we describe a simple arrangement for measuring the surface temperature of laser illuminated metallic plates. Second we have measured the temporal current distribution of the gun in the emission limited region and compared it with theoretical predictions, and third we have measured and examined the characteristics of the hollow beam gun.

3.1 Surface Temperature Measurements

With a simple experiment we can test the surface temperature calculations [8]. A Nd:YAG laser irradiates metallic samples. The surface will be extremely heated, which can be seen from intense visible radiation (see Fig. 2).

![Figure 2: Heating of a metallic surface by a pulsed high power laser](image)

*This photograph shows the thermal radiation of a Nd:YAG laser irradiated tantalum surface. This surface is extremely heated (in the range of the vaporizing point), which can be seen from an intense blue shining radiation.*

A part of the radiation is guided through a monochromator at the cathode of a photomultiplier. Using this device we measured the dependence of the peak radiation intensity for a wavelength of $450 \text{ nm}$ on the laser energy per pulse. For this measurement we need not know the spectral transmission of the monochromator and the spectral sensitivity of the photomultiplier. Using the Planck formula for the radiation of a black body for $h \omega > k_B T$ and Equation (2) leads to the dependence of the radiation intensity per frequency interval on the laser energy per pulse

$$
\frac{dI}{d\omega} = \frac{h \omega^3}{(2\pi c)^2} e^{-\frac{h \omega}{k_B (T_h + \alpha E)}}.
$$

We have fitted the measured points for tantalum and tungsten with this theoretical dependence (see Fig. 3) and determined the constant $\alpha$ for both materials. A remarkable result is that the constant for tantalum is much higher than the constant for tungsten which means that for identical parameters the temperature at a tantalum surface is much higher than the temperature at a tungsten surface. This was one reason for choosing tantalum. Another result is that we can reach peak temperatures in the range between the melting and vaporizing point.
3.2 Longitudinal Current Distribution

In this and the following section we will discuss the dependence of the measured longitudinal current distribution on the laser pulse shape and the dependence of the peak current on the laser energy per pulse. In the drift space of the prebuncher we installed a gap monitor for the current measurement. A gap monitor measures the induced wall current of the beam pipe. Therefore the tube will be interrupted by an insulating ring and bridged by resistors. The voltage drop across the resistors is proportional to the wall current. A typical hollow beam current versus time measured by the gap monitor is shown in Fig. 4 for a cathode voltage of $60\,kV$ and a laser energy of $350\,mJ$ per pulse. At these parameter values the hollow beam gun is working in the emission limited region and it is possible to compare the measured pulse shape with theoretical calculations. The calculated surface temperature and current are shown in Fig. 5. The measured current pulse shape is nearly in agreement with the calculated pulse shape. The difference between the pulse shapes can be explained by linear theory for the calculation of the surface temperature (1). Particularly, the reflection $R$ depends strongly on the temperature. But from the comparison of the calculated pulse shape with the measured pulse shape it is not possible to decide whether a thermionic emission or a thermionic supported photoelectric emission is the major component of the laser driven current.

Figure 4: Measured longitudinal current distribution of the hollow beam for a cathode voltage of $60\,kV$ and a laser energy of $350\,mJ$ per pulse.

This photograph shows two subsequent pulses due to the long exposure time.
Figure 5: Calculated surface temperature at the cathode and longitudinal current distribution for a given laser pulse.

The surface temperature (dash-dotted line) is calculated by using Equation (1) for a given time dependence of the laser intensity (dashed line) and normalized to the maximum surface temperature (2). The upper solid curves show the thermionic current distribution for a maximum surface temperature of 2000 K on the left side and for 3000 K on the right side. The lower solid curves show the thermionic supported photoelectric current for both temperatures. For the calculation, tantalum with a work function $\phi_A = 4.12 eV$ was taken as cathode material and Nd:YAG laser light with a photon energy $h\omega = 1.165 eV$.

3.3 Characteristics of the Hollow Beam Gun

The characteristics of the hollow beam gun are shown in Fig. 6. The points represent the measured current from the cathode. The curves are fitted with theoretical values given by Equation (9). For laser energies up to 450 mJ per pulse the gun current is limited by the emission. Due to this reason these curves are fitted with theoretical values given by Equation (8) for higher cathode voltages. The perveance of the hollow beam gun is $p = 4.1 \mu A/V^{1.5}$ which is derived from the parameter values of the fitted curve for the maximum laser energy per pulse. For a hollow beam thickness of 0.5 mm the theoretical calculated perveance is $p_0 = 7.6 \mu A/V^{1.5}$. Thus the illuminated thickness on the cathode is much lower.

From the Child-Langmuir law (6) it can be seen that the maximum current can be enhanced by increasing the cathode voltage and the illuminated area. In the first case the current is proportional to $U^{1.5}$ and in the second case to $U^{0.5}$. Since the voltage is limited by vacuum breakdown, a higher value of emitted current is only possible if the pulse length of the cathode voltage is shortened. Increasing the illuminated area requires a higher laser intensity. The intensity is limited by the self-focusing effect in the glass body of the conical mirror. A higher voltage should be the right way to proceed and a factor of two seems possible.

The maximum current density for the different laser energies can be taken from the fitted curves. These values, without consideration of the Schottky effect, versus the calculated surface temperature are shown in Fig. 7. The solid curve is the theoretical thermionic current density and the dashed curve is the thermionic supported photoelectric current density respectively. From the comparison it follows that for lower temperatures the photoelectric emission is the major component of the laser driven current and for higher temperatures it is the thermionic emission.
Figure 6: Characteristics of the hollow beam gun for different energies per laser pulse.

The points represent experimental results. The curves (solid and dashed lines) are the fitted theoretical values given by Equation (8) and Equation (9) for laser energies of up to 450 mJ per pulse and higher cathode voltages. The dash-dotted line is the space charge limited current with a perveance $p = 4.1 \mu A/V^{1.5}$ derived from the measured values. The dotted curve is the theoretical space charge limited current of the gun for a hollow beam thickness $\Delta = 0.5\, \text{mm}$.

Figure 7: Measured current density of a tantalum cathode versus the calculated surface temperature.

The solid curve is the thermionic current density and the dashed curve the thermionic supported photoelectric current density for tantalum with a work function $\phi_A = 4.12\, \text{eV}$ and a Richardson constant $A = 55\, \text{A cm}^{-2}\, \text{K}^{-2}$ and Nd:YAG laser light with a photon energy $\hbar\nu = 1.165\, \text{eV}$.
Summary

A laser driven hollow beam gun was developed for the Wake Field Transformer experiment at DESY. The main property of the gun is that the work function of the cathode material is much higher than the photon energy of the used laser light. In this case the emission mechanism is explained by the generalized Richardson effect. Thermionic emission is the major component of the laser driven current. At a cathode voltage of nearly 100 kV, the gun produces a hollow beam of 10 cm diameter with a space charge limited current of about 100 A over a pulse length of a few nanoseconds. The voltage is limited by vacuum breakdown between cathode and anode. If the pulse length of the voltage would be shortened an increase of the peak value should be possible and therefore an enhancement of the space charge limited current by a factor of two to three should be obtained.

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Hollow Beam Measurements

W. Bialowons, H.-D. Bremer, F.-J. Decker, H.-Ch. Lewin, P. Schütz, G.-A. Voss, Th. Weiland, Xiao Chengde *

Deutsches Elektronen-Synchrotron DESY
Notkestr. 85. 2000 Hamburg 52, Germany

Abstract

High current tightly bunched beams are needed to drive wake field accelerators. Investigations of the beam qualities are necessary to understand all possible effects in detail and to control them. Here, the measurements of the hollow beam for the Wake Field Transformer Experiment at DESY are presented. Beside high peak current and short bunch length other parameters such as the azimuthal distribution and radial thickness of the hollow beam have to be observed. With fluorescent screens the transverse position and the radial thickness can be measured. Effects of the longitudinal and radial space charge forces have been observed. Gap monitors measuring the induced wall current on the beam pipe are used to determine the azimuthal and longitudinal distribution and the peak current. The long bunch (7ns) behind the gun as well as the bunching effect in the prebuncher section have been investigated. Shorter bunches at the end of the linac have been detected by a Čerenkov monitor. In a small quartz wedge Čerenkov radiation is excited and observed by a streak camera. With this arrangement also radial oscillations within the bunch have been detected.

Introduction

The principle mechanism of the particle acceleration by wake fields, especially by a wake field transformer, are described in [1,2]. The basic idea is that in a cylindrically symmetric transformer section a short (≈ 2 mm rms) hollow driving beam with high charge (≈ 1 µC) excites wake fields that lead to deceleration (≈ 20 MeV/m). Between the plates an electromagnetic wave packet is spatially concentrated to the centre. There, a following second beam bunch can be accelerated with a gradient of about 200 MeV/m. The field concentration due to the geometrical compression leads to a transformer ratio of about 10.

At DESY an experiment [3,4,5] has been set up to study the creation and behavior of a hollow beam and the technical possibility of wake field transformer acceleration. Figure 1 shows the overall layout and the location of the measuring equipment of the experiment. A laser driven gun produces a hollow beam with radius $R \approx 5$ cm and an energy of up to 100 keV. In the prebuncher section the beam is bunched due to the 500 MHz structure of the RF and then in the following four 3-cell cavities accelerated to about 7 MeV. To increase the electric field around the hollow beam and the excited wake fields in a transformer, the beam will be longitudinally and radially compressed by a special arrangement of the guiding solenoid field behind the end of the linac.

*On leave from Tsinghua University, Beijing, People’s Republik of China
Figure 1: Overall layout of the Wake Field Transformer experiment at DESY with location of the measuring equipment (from left to right): screen monitor and gap monitor in the driftspace and gap monitor and Čerenkov monitor at the end of the linac.

Diagnostic elements for the hollow beam, especially fluorescent screen monitors, gap monitors and a Čerenkov monitor are mounted in the drift space behind the prebuncher and at the end of the linac. With these devices the behavior and the parameters of the hollow beam have been measured. In the following sections special effects due to the creation, acceleration or guiding of the hollow beam will be mentioned together with the monitors with which they can be observed.

1 Fluorescent Screen Monitors

A projection of the hollow beam is produced by a fluorescent screen which can be observed by video cameras (see Fig. 2). A rough estimation of the azimuthal homogeneity of the ring can be made. The transverse

Figure 2: Movable fluorescent screen monitor and image of the hollow beam.

position (here: $x = (1.5 \pm 0.5) \text{ mm}$, $y = (3.0 \pm 0.5) \text{ mm}$) and the radial thickness of about 5 mm can be measured. The illuminated thickness at the gun cathode is about 0.5 mm. The reason for the measured thickness and an observed ring deformation will be described next.
Ring Thickness. In the gun the accelerating electric field is not parallel to the guiding magnetic field of the solenoids (see Fig. 3). This causes a gyration of the electrons on a helix around the field lines of the magnetic guiding field B. The radius of the helix is \( R_h = \frac{p}{eB} \), with the transverse momentum \( p_t \) and the elementary charge \( e \). A gun voltage of 80 keV leads to a momentum \( p = 300 \text{ keV}/c \) of the electrons. With \( p_t \approx p/4 \) and \( B = 0.18 \text{ T} \) is \( R_h \approx 1.4 \text{ mm} \). Other reasons for an excitation of even larger gyrations are the transverse fields in the cavities and the deformations of the guiding magnetic field at some unavoidable gaps in the solenoid structure.

With a very low beam current of \( I \approx 1 \text{ A} \) a thin ring of about 1 mm can be achieved. By changing the strength of the magnetic field or the height of the gun voltage the radius of the thin ring varies between \( R - R_h \) and \( R + R_h \). In Fig. 4 a part of the ring is shown for both these cases. The experimental value of \( R_h \) is about 1.3 mm. Due to the longitudinal space charge forces the length of the helix is different between particles at the head and at the tail of the bunch. Therefore at the screen the whole area between \( R - R_h \) and \( R + R_h \) is illuminated and a 3 mm thick ring is observed. In Fig. 2 the magnetic field at the gun has been decreased, so the whole ring can be seen by one camera and the thickness increases to about 5 mm.

Figure 4: Part of the hollow electron beam showing the gyration effect: Varying the B-field changes the helix length and thus arrival radius of the electrons on the screen. This photo was double exposed with the maximum and minimum in arrival radius.
Ring Deformation. In order to investigate the space charge effect at high current, low voltage gun, low magnetic field, a long flight length and a strong azimuthal inhomogeneity has been used (see Fig. 5). In the rest frame a hollow beam with a radius \( R \) and a charge per length \( Q/L \) leads to a radial electric field \( E_r = Q/(2\pi\epsilon_0 L r) \) for \( r < R \). With the guiding field \( B \), the electrons start to drift in the azimuthal direction \( \phi \) with the velocity \( v_\phi \) (see e.g., [6]): \( v_\phi = \frac{E_z}{B_z^2} \). With \( v_z = e/3 \) (30 keV), \( B_z = 0.1 \) T and \( I \approx 5 \) A (\( Q/L \approx 50 \) nC/m) is \( v_\phi = 0.0016 \cdot v_z \). For a length of 6.5 m up to the end of the linac the outer particles have drifted about 10 mm in \( \phi \)-direction. If there is an azimuthal gap in the beam the drift direction changes and the ring is deformed (see Fig. 5).

\[ B = 0.1 \text{T} \]
\[ E_{kin} = 30 \text{KeV} \]

Figure 5: Part of the Ring: Due to the \( \vec{E} \times \vec{B} \) drift of the electrons the shape of the ring has changed near a gap produced by a tag holding the inner part of the gun anode.

2 Gap Monitors

The beam induces a wall current on the beam pipe. The amplitude of this current and its azimuthal and longitudinal distribution can be measured with a gap monitor. The beam pipe is interrupted by a ceramic ring. The gap is bridged by 64 resistors, 10 \( \Omega \) each (see Fig. 6).

Azimuthal Distribution. If the beam is centered in the pipe the azimuthal distribution on the wall can be measured with the signal height of eight pick ups around the circumference of the pipe (see Fig. 7). In order to get the correct azimuthal distribution of the hollow beam from the wall current distribution the following corrections must be considered:

a) Different damping of the signals due to the different delay length of the cables,

b) Cross talk between one signal and the others at the monitor,

c) Difference between the hollow beam radius and the beam pipe radius.

For the points b) and c) we make first a multipole expansion of the electric field produced by a displaced filament beam:

\[ E_r = \frac{Q}{2\pi\epsilon_0 L b} \left( 1 + 2 \sum_{n=1}^{\infty} \left( \frac{a}{b} \right)^n \cos n\phi \right) \approx \sum_{n=0}^{\infty} E_n, \]

where \( a \) is the displacement and \( b \) the pipe radius. A displaced filament beam with \( a = R \) can be looked at as a maximal inhomogeneous hollow beam with radius \( R \). All relative moments \( E^n/E^0 \) (\( n \geq 1 \)) have
Figure 6: Cut through the gap monitor with a ring ceramic and a pick up cable, measuring the induced wall current of the hollow electron beam.

Figure 7: Eight pick up signals, each delayed by 20 ns show the azimuthal distribution of the wall current for two different currents of 22 A (left) and 39 A (right).
the same value of 200 GeV, but on the wall these moments have decreased by a factor of $(R \ h)^n$. This must be corrected (point c). Because there is no azimuthal resistance, but only azimuthal inductance at the gap monitor, long beam pulses deliver a more homogeneous distribution at the pick ups than shorter pulses. Calibration measurements and simulations have shown [8] that this effect can be parametrized by an effective larger pipe radius $b(\sigma)$. In our case $b(\sigma)$ was determined to $b(\sigma) = b_0(1 + 0.57\sqrt{\sigma/\sigma_0})$ with the real pipe radius $b_0 = 5.5$ cm, $\sigma_0 = 3$ ns and the rms-length $\sigma$ of the pulse. For correcting the measured $n$-th moment it must be multiplied by $(b(\sigma)/b_0)^n$. Figure 8 shows the distributions which were made up to the quadrupole moment for two different beam currents and a ring part, which was achieved by scraping the rest by a partly inserted screen monitor. The relative dipole and quadrupole moments of the complete beam with $I = 33$ A were about 20% each.

![Figure 8](image_url)

**Figure 8:** Corrected azimuthal hollow beam distribution for two currents and the measured distribution of a ring part over about two pick ups.

### Longitudinal Distribution.

To measure the longitudinal distribution of the hollow beam eight pick up signals are combined to be independent from the azimuthal distribution. Figure 9 shows the current distribution of the nonrelativistic hollow beam ($E_{kin} = 75$ keV) before and after the linac measured by two gap monitors. With low peak currents both monitors show nearly the same result. With higher currents the amplitude of the second pulse decreases while its length increases due to space charge forces. At the highest currents ($I \approx 60$ A) some particles were lost before they reached the second monitor. The dependency of the peak current from the gun voltage with different laser powers is reported in another paper [7]. 80 A at 90 kV were reached.

The prebuncher cavity ($\nu = 500$ MHz) compresses a period of 2 ns of the gun pulse to a short bunch (see Fig. 10). At high currents ($I_0 = 50$ A) only a weak compression can be achieved (space charge). At low currents very short bunches are achieved, which reaches the resolution limit of this gap monitor ($\sigma_{rms} < 100$ ps) [8]. By damping the oscillations with a higher resistance of the monitors the charge per bunch can be estimated by $Q \approx I \cdot \Delta t / (\Delta t = FWHM)$. The real bunch length is measured with a Čerenkov monitor. A comparison is shown in Fig. 11.
Figure 9: Gun pulse ($E_{\text{kin}} = 75$ keV) before and after the linac with different peak currents, produced by varying the laser lamp energy between 17 J and 39 J per pulse.

Figure 10: Two bunches compressed at different peak currents.
Figure 11: Comparison of signal response by a gap monitor (left) and a Čerenkov monitor (right).

Figure 12: Layout of the Čerenkov monitor for measuring the hollow beam bunch length with high resolution.
3 Čerenkov Monitor

For measuring short bunches ($\sigma_{rms} < 100$ ps) a Čerenkov monitor was built. Figure 12 shows the physical layout. A part of the hollow beam excites Čerenkov radiation in a small quartz wedge. With a light collection system consisting of two mirrors and three lenses the light pulse is guided to the imaging slot of a streak camera. This camera has a resolution of $\sigma_t = 5$ ps. In comparison with a gap monitor signal ($\sigma \approx 150$ ps, see Fig. 11) a bunch length of $\sigma_{cerv} \approx 40$ ps was measured. The peak current must be derived from the gap monitor signal and the bunch length $\sigma_{cerv}$ by: $I \approx \frac{I_{gap}}{\sigma_{cerv}} \sigma_{cerv}$.

The shortest light signals at low currents ($I_0 < 3$ A) were about $\sigma = 10$ ps (Fig. 13), while the longest ones with $\sigma \approx 80$ ps at high currents ($I_0 > 30$ A) show also an intensity structure. This structure can be explained by a radial structure of the bunch within the bunch length. So the electrons don’t hit the quartz wedge at the same point and even some electrons couldn’t be detected, because they were outside the observed region or were lost at the beam pipe. By adjusting the strength of the guiding solenoid field and the phases of the accelerating cavities properly a bunch with mostly only one pulse with $\sigma \approx 30$ ps can be achieved.

4 Summary and Future Plans

The measurements of the hollow beam have shown different effects. With the achieved hollow beam densities and lengths a first acceleration by wake field transformation was expected and is now achieved (see [93]). Also several beam dynamics were observed and must be studied in detail for guiding a hollow beam over long distances in future wake field accelerators.

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Computer Simulations for the DESY Wake Field Transformer Experiment

W.Bialowons, H.-D.Bremer, F.-J.Decker, H.-Ch.Lewin, P.Schütt, G.-A.Voss, Th.Weiland, Xiao Chengde *

Deutsches Elektronen-Synchrotron DESY
Notkestr. 85, 2000 Hamburg 52, Germany

Abstract

The Wake Field Transformation Experiment at DESY has always been accompanied by theoretical studies including numerical analysis of beam dynamics. In the last two years, these investigations have focused on the dynamics of the high current, hollow driving beam of the Wake Field Transformer. The computer code WAKTRACK, which has been used for this purpose, will be described and some example output will be shown. This code will be used for investigations on the feasibility of a future TeV collider. Additionally, more detailed investigations of the bunching and shaping process of the ring in the low energy region will be necessary. For this purpose TBCI-SF, a particle-in-cell code, has been developed. It will also be discussed here and its applications for the wake field transformation linac as well as for other subjects will be indicated.

Introduction

The principle of the Wake Field acceleration mechanism [1,2] and the Wake Field Transformer experiment at DESY [3,4,5] have been described in detail in other papers. Here we will focus on the computational methods which are used for the accompanying theoretical studies. Two simulation codes are discussed and some results are presented. More detailed descriptions of the programs and more results will be published elsewhere [6].

The dynamics of the hollow beam and of the central beam can be studied with WAKTRACK [7]. This tracking code includes the cavity fields as calculated by URMEL [8], arbitrary magnetic fields as calculated by PROFI [9] and wake fields as calculated by TBCI [10]. Using known characteristics of the trajectories and some approximations this code is very fast and can be used for optimization studies parallel to the experiment. It can generally be applied to high current linacs.

For more detailed investigations in the low energy region (γ ≤ 20), especially of the transverse dynamics, and for optimization of the ring forming process a particle-in-cell code has been developed. In this code Maxwell's equations and the Lorentz equation are solved simultaneously. The electromagnetic field is implemented on a two-dimensional-z-mesh whereas the particle trajectories are calculated three-dimensionally. Resonant cavity fields are precalculated with URMEL. Static fields can be superimposed as calculated by PROFI. The code is generally applicable to high current gun design, buncher dynamics, design of RF power sources, etc.

*On leave from Tsinghua University, Beijing, People's Republic of China
1 WAKTRACK

The computer code WAKTRACK is a tracking code: the particle trajectories are integrated element by element in a given structure. The independent variable is \( z \), the axis of the linac. The time \( t \), Lorentz factor \( \gamma \), the transverse coordinates \( x \) and \( y \) and their derivatives \( \frac{dx}{dt} \) and \( \frac{dy}{dt} \) are integrated for each particle.

The element by element structure is overlayed by the field of solenoid coils which may surround the equipment. External fields are calculated in a very sophisticated manner and collective forces of the other particles in the bunch are taken into account.

In order to speed up the integration of the trajectories, an analytical solution of the Lorentz force equation for the case \( \vec{E} \parallel \vec{B} \parallel z \) is used. In the major part of the experiment these are the dominant fields. This analytical solution can be derived without any further approximations. The forces of the transverse fields \( B_x, B_y, E_x \) and \( E_y \) are treated in a kick approximation: In each step, the momentum is corrected according to these fields. The step length may still be fairly large (up to 3 cm) as long as the transverse fields are small compared to the longitudinal fields. The kick approximation is no longer appropriate if the transverse fields are in the same order of magnitude as the longitudinal fields. In this case, a Runge Kutta integration scheme is used.

The choice of models for the calculation of external fields is governed by the needs for the simulation of the experimental set up. The solenoid field is calculated as a superposition of the fields of individual coils which may have different shapes and different currents. The field of each coil is calculated in a second order approximation near the axis. This fast evaluation is possible, as the radius of the coils in the experiment is about 10 times the radius of the hollow beam.

In those elements of the linear accelerator, where the field shape is determined by iron, it is calculated by PROFI. In our application, this code solves the magnetostatic field equations on a 2-dimensional, cylindrically symmetric r-z-mesh. This field is then implemented in WAKTRACK on a local mesh in the element and linearly interpolated between the meshpoints.

The RF cavity fields may be obtained in two different manners: A fast method is to use a simple model and to calculate the field acting on a particle at position \( z \) and time \( t \) as

\[
E_z = E_{z0} \sin k_z z \sin \omega t
\]

and the transverse fields correspondingly so as to fulfill Maxwell's equations. For more sophisticated investigations of the dynamics inside a cavity, the field shape of the accelerating mode in the cavity may be calculated by URMEL on a 2-dimensional r-z-mesh. The field acting on a particle is then given by

\[
E = E_\theta \sin \omega \nu t
\]

where the spatial part is interpolated between mesh points, and the frequency \( \omega \) is also given by URMEL.

Collective fields of the particles inside a bunch are space charge fields and wake fields. These are treated in a Greens functions approach. The folding of the actual bunch shape with Greens functions is done in a bin-bin method rather than calculating the particle to particle interaction. The charge distribution within a bunch is projected onto a 2-dimensional mesh. Then the field at a certain position inside this mesh can be calculated as superposition of the fields of the charges in the mesh cells.

For the special case of a ring-shaped charge in a long conducting pipe, the Greens function can be calculated analytically. For all other cases, space charge and wake fields in more complex structures, a pseudo Greens function is calculated by TBCI. In this application, TBCI calculates the wake potentials of a short rigid bunch (short as compared to the bunch simulated in WAKTRACK) which passes the given structure on a path parallel to the \( z \) axis with constant velocity.

The Greens functions approach in WAKTRACK implicitly uses several approximations: As \( z \) is the independent variable of the integration, a spatial distribution of the charge in the bunch must be calculated from the time and energy distribution of the particles. This implies that the particles pass the structure at constant velocity. The use of a Greens function is appropriate only if the relative position of the particles does not change significantly in the time period the field needs to travel from the source to the particle it acts upon. This can be assumed in the high energy region of the linac, where all the particles move on parallel trajectories at the speed of light. But the assumption is wrong in the low energy region, where major parts of the structure are designed to shape and bunch the ring. For more detailed investigations in this region, a particle-in-cell code has been developed.
WAKTRACK is used extensively as an operating tool for the experiment at DESY. It is fast enough (\textasciitilde 1 min CPU on an IBM 3084 Q for a typical run) to be used in parallel with the experimental work. The example run shown in Fig. 2 was used to maximize the charge passing through the transformer section in the stage 1 experiment. For more details on the experiment see \[1\]. Figure 1 shows a technical drawing of the experimental set up which is schematically repeated between the top and the centre part of Fig. 2. For this optimization the most interesting part is the central one, where the trajectories of the hollow beam particles are plotted in an \(r-z\)-frame. Note that the \(r=0\) line is suppressed. The particles move on spiral paths around a magnetic field line. In the projection these spirals appear as oscillations. The lower plot shows that about 70\% of the charge emitted by the gun reaches the transformer. In the top frame, the energy of the particles is plotted and their phase relative to a speed of light particle. In these plots, the acceleration can be observed as well as the bunch length.

Figure 1: Overview of the Wake Field Experiment at DESY

Figure 2: Example output of WAKTRACK
2 TBCI-SF

The program TBCI-SF is a particle-in-cell code. This method of solving Maxwell's equations and the Lorentz equation self-consistently has been developed in plasma physics [12] and recently is being used in accelerator physics for high current beams [13,14]. TBCI-SF has been developed as an extension of TBCI [10].

After the initial conditions have been fixed, the following three steps are carried out in turn:

- Calculate the current density at the mesh points which corresponds to the motion of the particles.
- Advance fields in time using this current density as a driving term. (equivalent to 1 step in TBCI)
- Advance particle trajectories according to the Lorentz force.

2.1 Field Evaluation

Using the finite integration theory [15], the fields and the current density are located in the mesh as shown in Fig. 3.

![Figure 3: Allocation of field components](image)

Putting all unknown electric field components into a vector

$$\mathbf{e} = (E_{r,1}, ..., E_{r,N}, E_{\phi,1}, ..., E_{\phi,N}, E_{z,1}, ..., E_{z,N})^T,$$

the magnetic field components into $\mathbf{b}$ and the current density into $\mathbf{j}$ leads to the following matrix equations (cf. [16,17]), replacing Maxwell's equations

$$\mathbf{R} \cdot \mathbf{e} = -\dot{\mathbf{b}}$$

(1)

$$\mathbf{R} \cdot \mathbf{b} = \mathbf{D} \cdot \dot{\mathbf{e}} + \mathbf{j}.$$ 

(2)

Breaking up the time axis into pieces with length $\delta t$, using the central difference operator for the time derivative with the notation $f^n := f(n \cdot \delta t)$ and equating $\mathbf{e}, \mathbf{b}$ at half time steps and $\dot{\mathbf{e}}, \dot{\mathbf{b}}$ at full time steps, we obtain an alternating explicit time scheme first introduced by Yee [18] (the leap frog scheme of Maxwell's equations):

$$b^n = b^{n-1} - \delta t R e^{n-1/2}$$

(3)

$$e^{n+1/2} = e^{n-1/2} + \delta t D^{-1}(R h^n - j^n).$$

(4)

Deeper discussions of this algorithm can be found elsewhere [10,19].
2.2 Particle Pusher

The charge distribution in the bunch is described in TBASI-SF by macroparticles which represent a rigid charge distribution in a volume corresponding to about one cell of the field mesh. These macroparticles are characterized by their position \( x, z \) and their rapidity \( u = (u_\perp, u_\parallel, u_z) = \frac{\beta_z c}{\gamma c} \). The position may be anywhere inside the region covered by the mesh, the rapidity is treated fully 3-dimensionally. The Lorentz force equation can be written as

\[
\frac{d}{dt} x = v
\]

\[
\frac{d}{dt} u = \frac{q}{mc}(E + v \times B).
\]

Similar to the Maxwell's equations, this system is solved by a leap frog scheme assigning the position to half time steps and the rapidity to full time steps.

\[
x^{n+1/2} = x^{n-1/2} + \delta t \cdot v^n
\]

\[
u^{n+1} = u^n + \delta t \cdot \frac{q}{mc} (E^{n+1/2} + \frac{1}{2}(v^{n+1} + v^n) \times B^{n+1/2}).
\]

On the right hand side of the second equation, a time average of the velocities must be used. Additionally, the magnetic field has been assigned to full time steps and therefore must be averaged here. The second equation is implicit. In TBASI-SF it is replaced by an explicit algorithm: In the first step, the rapidity is advanced by \( 1/2 \delta t \) using only the electric field. Then the rotation in the magnetic field is calculated and finally the second half step of acceleration is carried out.

\[
u^- = u^n + \delta t \frac{q}{2mc} E^{n+1/2}
\]

\[u' = u^- + u^- \times T
\]

\[u^+ = u^- + u^+ \times S
\]

\[
u^{n+1} = u^+ + \delta t \frac{q}{2mc} E^{n+1/2}.
\]

The following abbreviations were used:

\[T = \delta t \frac{qB^{n+1/2}}{2m\gamma^{n+1/2}} \quad \text{and} \quad S = \frac{2T}{1 + TT}.
\]

2.3 Weighting

In order to decrease noise amplitudes, pyramid-shaped particles are used. This allows a smooth approximation of any charge distribution at the cost of second order terms in the current density calculation.

A charge-conserving scheme is used for the determination of current densities in the mesh. This is the same one which is used in ISIS [21] and was first described by Buneman [20]. The current is calculated as a sum of charges which pass a cell wall during one time interval:

\[j^n = \frac{1}{\Delta r \delta t} \sum_i u_i q_i.
\]

The field at the particle position is calculated as a weighted mean of the fields at mesh points which are covered by the charge cloud represented by a particle. For test purposes, the field of the nearest grid point can be used as well as a linear interpolation.

2.4 Internal Tests

Only two of the four Maxwell's equations are needed to advance the fields in time. The others must be fulfilled implicitly.

\[\int_{V'} B \, dv = 0
\]

\[\int_{V'} D \, dv = \int_{V'} \rho dv
\]

The second of these equations, Gauss' Law, must be used to correct the fields if the current calculation is not charge conserving. In TBASI-SF, both are used to check the results every few time steps.
2.5 External Fields

External fields created by sources different from the bunch current itself often cause problems in particle-
in-cell codes. Sometimes, static fields are not foreseen and RF cavity fields can only be produced by
simulating the whole filling period or by using other approximations.

TBCI-SF allows external fields to be given as start values of the electromagnetic field implemented on
the mesh. Once they are set up, they do not need to be treated specially any longer.

Static fields may be precalculated by PROFI. The PROFI mesh must be identical to the TBCI-SF
mesh or to part of it in order to avoid numerical errors due to the interpolation. Resonant fields are
precalculated by URMELE with the same restriction on the mesh. Both electric and magnetic fields are
taken from URMELE results. Therefore, initial phase and amplitude of the RF field may be adjusted
separately.

2.6 CPU Time

The CPU time needed for the simulation is a function of the number of macroparticles used \( n_M \) and of the
number of meshpoints \( n_P \):

\[
t_{CPU} = (a \frac{n_M}{1000} + b \frac{n_P}{1000}) \cdot \frac{\text{number of steps}}{1000}
\]

Typically \( n_P \) and \( n_M \) are in the same order of magnitude. On an IBM 3084 Q the coefficients are \( a \approx 13.5\,\text{sec} \) and \( b \approx 160\,\text{sec} \).

2.7 Example output

![Example output of TBCI-SF](image)

Figure 4: Example output of TBCI-SF: Bunches are being formed in a cavity with drift.
The first example (Fig. 4) shows the bunching of the hollow beam in the buncher section of the DESY experiment. The cavity has initially been filled with a RF field calculated by URMEL. An overall solenoid field holds the particles on paths parallel to the z axis. The current snapshots in Fig. 5 show more qualitatively the bunching efficiency.

![Figure 5: Current snapshots in the buncher region.](image)

TBCI-SF can also be applied to other problems. Figure 6 shows a simulation of the SLAC lasertron. The electrostatic field in the gun was calculated by PROFI, the RF fields by URMEL in order to simulate the steady state. The results are in good agreement with a corresponding MDAK simulation [22].

![Figure 6: TBCI-SF: simulation of a lasertron.](image)
3 Summary and Conclusion

Two supplementary computer codes have been developed for future studies of a Wake Field Accelerator. WAKTRACK is a fast design tool for high current, high energy linear accelerators. The calculation includes external fields in great detail and collective fields in a high energy approximation.

The particle in cell code TBCL-SF has been developed for more detailed simulations of the low energy region of a high current linac. It is generally applicable to high current, low energy devices like guns, buncher, RF sources, etc.

The numerical results of both programs have been verified by experimental data. Together they provide the computational tools for the design of a whole linear accelerator from the gun up to the interaction point.

References


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FEASIBILITY STUDIES FOR THE SWITCHED POWER LINAC *)

J. Knott
CERN, Geneva, Switzerland

ABSTRACT

Some technical aspects concerning the realization of the switched power linac have been studied. We present experimental results on the possible voltage gain of this concept and summarize the present status of other related work going on at BNL and CERN.

1. INTRODUCTION

The Switched Power Linac (SPL) as proposed by W. Willis [1] may achieve very high accelerating gradients by switching an electron burst with a sufficiently fast laser pulse from previously charged photodiodes on the circumference of a disk structure (Fig. 1). The electromagnetic pulse increases in amplitude as it travels radially towards the centre, where it accelerates particles on the axis.

![Fig. 1 Principle of the switched power linac]

Assuming the photodiode to be charged with a 50 to 100 kV pulse for about 1 nsec and then discharged by a correctly timed laser pulse into a 1 mm wide gap, we can expect accelerating fields of the order of one MV per mm to be held for only 10 psec. This would result in a compact accelerator with small structures, featuring high peak power for low stored energy.

*) Work carried out in collaboration with S. Aronson, BNL, F. Caspers, H. Haseroth, W. Willis, CERN.
2. PROBLEMS RELATED TO THE SPL

A. High-voltage breakdown

Some data exist in the literature concerning the voltage hold-off limits for the switch and at the centre of the structure. Jüttner et al. reported gradients of 1.4 GV/m with 57 μ copper gaps and 3 GV/m on 27 μ tungsten electrodes for nsec pulses [2]. Recent measurements on pulsed r.f. at SLAC indicate peak fields of 500 MV/m at 10 GHz [3]. Properly scaled, this should allow to hold several GV/m for sub-nsec pulses.

Experimental verification of geometries similar to that of the SPL are actually under way at BNL and CERN. We hope to achieve pulses of 100 kV for less than 1 nsec. This will give straightforward results for the switch area and allow for extrapolation to the situation in the accelerating gap.

B. Fast switching

The switch requirements are quite severe as rise-times of a few psec will be necessary in order to achieve reasonably high transformer ratios. Further, the impedance of the structure at the periphery is only about one Q, and, due to the short rise-time, the width of the emitting surface may not exceed a few tenths of a mm. Therefore, current densities of the order of 100 kA cm⁻² are required to launch pulses of 100 kV into the structure.

These values are probably hard to achieve, but do not seem impossible at this moment[4]. Experimental studies are actually under way at BNL and first results will be reported at this workshop [5].

C. Propagation and enhancement

The gain of the radial line transformer depends on the geometry, as given by the outer radius R and the gap width s, as well as the rise-time of the exciting pulse. As long as the concentrically travelling pulse does not merge at or near the axis, the possible enhancement at a given radial position r is determined by the ratio of the respective impedances:

\[
\frac{V_r}{V_R} = \sqrt{\frac{Z_r}{Z_R}} = \sqrt{\frac{R}{r}} \\
\text{with } Z_r = \text{constant } \frac{s}{2\pi r}.
\]

Despite the overlap of wavefronts near the centre, the overall gain will be limited by finite rise-times. Several analytical studies have been carried out for the case of ideal
symmetric feeding [6,7,8] and experimental verification has been done.

Besides a possibly high enhancement the uniformity of the accelerating field obtained at the centre is very important, too. It will depend on regular excitation of the structure and the presence of non-accelerating fields as caused by defects from the switch or mechanical imperfections, like, for example, manufacturing tolerances or the supports required for the final SPL structure.

3. SPL MODEL MEASUREMENTS

A. Experimental set-up

For a detailed study of these problems a model has been built at CERN. It consists of two gaps forming a double-sided radial stripline (Fig. 2) scaled up by a factor of 10 in order to avoid problems arising from the possibly small dimensions of an SPL, and permitting the use of conveniently sized probes and commercially available high frequency instrumentation.

![Fig. 2 Cross section of the 10:1 model of the SPL](image)

The photodiode discharge is simulated by feeding pulses via a high bandwidth divider network over 64 equally spaced connectors on the circumference. One of the gaps is equipped with probes across the diameter, and exchangeable probes with closer spacing are used at the centre to obtain details of the field distribution in the supposed accelerating gap. Most of the measurements were done by using synthetic pulse techniques with a network analyser, able to present the results in the time domain. Complementary tests with a fast pulser and real-time oscilloscopes are in good agreement with the first method.

B. Propagation and enhancement

The enhancement across the structure as a function of the radius is shown on Fig. 3a. Measurements follow the theoretical line \( \frac{VR}{R} \) until pulses start to overlap near the axis. At the centre the gain is reduced as a function of the rise-time and the results come close to those predicted by Cassell and Villa [6], by taking into account the disk spacing and the rise-time \( t_r \):

\[
\frac{V_O}{R} = 2 \left( \frac{2R}{s + c t_r} \right)^{1/2}.
\]
On Fig. 3b the enhancement at the centre is plotted as a function of the rise-time. An empirically corrected curve, using the equivalent half-wavelength instead of c.t, gives a better fit to the measured values and permits an extrapolation to shorter rise-times. As a result enhancements around 15 seem feasible for a rise-time of 5 psec, but it also shows how important the stability of the rise-time will be for the repetitive performance of a future switched power linac.

C. Non-uniform feeding

Defects of the switch discharge are simulated by disconnecting or delaying some of the feeds. Dipole and quadrupole excitation have been used as extreme cases of asymmetric feeding. Apart from the loss caused by the missing feeds the distribution of the longitudinal field component as measured near the axis is quite smooth [9].

Unfortunately we have not yet succeeded in making probes with better directional capabilities in order to measure the resulting radial field components. This probably requires either improved probe design or better methods for calibration or interpretation of data.

4. CONCLUDING REMARKS

With the data obtained we can specify the geometry for the accelerating structure of the switched power linac. For charge voltages between 50 and 100 kV and enhancements from 12 to 20 according to the chosen R/s we can expect average accelerating fields ranging from 0.3 to 1 GV/m. Consequently the length of a 1 TeV accelerator would come down to 1 to 3.3 km. In order to achieve these performances we need of course to master the switch technology, in particular to demonstrate the required current densities and the short and stable rise-times. Other important aspects like the voltage hold-off and the measurements of non-accelerating fields need to be followed up. Assuming that the practical realisation of the structure and the alignment present the same degree of difficulty as other very high gradient accelerators actually under consideration, the switched power principle requires particular attention on how to illuminate uniformly kilometers of accelerating structure.
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7) I. Stumer. Presentation to the CLIC Committee, CERN (1986).
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* * *

Discussion

M. Cavenago, INFN, Pisa

Is the transmission line a Blumlein line? If not, how much power is radiated outward?

Reply

The SPL structure is a radial stripline which is excited at the periphery. The power is then expected to travel inwards and after crossing the centre it will arrive again at the boundary and some of it may be radiated to the outside. But our actual model is not a really open structure and does not permit to measure these losses.

G. Coignet, LAPP

Could you please comment on the precision uniformity of the circular discharge needed for particle acceleration.

Reply

Any perturbation in the discharge will reduce the accelerating voltage. Concerning the uniformity of the field distribution near the axis we have measured with as few as 16 (equally spaced) feeds without any noticable distortion of the longitudinal component. But this is not relevant for the radial field components which may deflect the accelerated particles. Therefore we need to improve our measurements for these transverse fields.
N.K. Sherman, NRC, Ottawa

How well does the impedance of the beam match the impedance of the hole in the plates? If the match is not good, power will reflect back outward, radially.

Reply (from W. Willis)

The beam loading will be limited to small values by considerations of preservation of emittance against wakefield effects, and energy will indeed be reflected. We have considered schemes to recover that energy by an appropriate switch.