CERN/PS 88-51 (DL)
September 28, 1988

23 MAI 1989

PLANNING AND PROPOSALS FOR THE CERN HEAVY ION INJECTOR

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Presented at the
Conference for Production of and Physics with Highly Stripped Ions
Grenoble, September 1988

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CM-P00059152

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Abstract - Already some decades ago CERN deviated from the sole acceleration of protons. Deuterons were accelerated in the Linac and in the PS (Proton Synchrotron) and finally stored and accelerated in the ISR (Intersecting Storage Rings). They were followed by alpha particles. Only minor changes were required in the accelerators. Some years ago heavier particles (oxygen ions) were accelerated in Linac, PSB (PS Booster), PS and SPS (Super Proton Synchrotron). Last year acceleration of sulphur ions was performed. The problems associated with the acceleration of heavy ions and the possible acceleration of lead ions will be discussed in this paper.

1 - INTRODUCTION

The programs of CERN's heavy ions started with deuterons some decades ago. Alpha particles followed after some years and only recently our machines have seen oxygen and sulphur ions. Obviously the problems gradually increased and required more and more sophisticated solutions.

Deuterons and alpha beams found an enthusiastic community in the previous ISR users. Problems at that time were mainly related with running the Linac in a special mode (2 $\beta\lambda$) and required one change of the harmonic number during acceleration in the PS, taken over by the Booster in the later runs. After a strong push from the (originally nuclear) physicists, a GSI, LBL, CERN collaboration was set up with the aim of accelerating oxygen ions in the CERN machines. Later this collaboration was extended to the acceleration of sulphur ions.

The successful acceleration of the oxygen and sulphur ions prompted a strong request for extension to the heavier ions, e.g. lead. At the moment CERN is studying actively the possibility of lead ion acceleration in its proton machines.

2 - SPECIAL PROBLEMS WITH THE PRODUCTION AND ACCELERATION OF IONS HEAVIER THAN PROTONS

The only difference between protons and other ions is their charge to mass ratio which can be equal to 0.5 in the case of light, fully stripped ions, but is usually much smaller because the heavier ions are normally not fully stripped.

2.1 - Ion Production

In general, ion sources use plasma hot enough to achieve the desired ionization state of the ions. Whilst a low current / low voltage discharge (e.g. 100 A, 100 V) with a correspondingly low electron temperature is sufficient in a duoplasmatron to produce protons with an ionization potential of 13.6 eV, heavier ions in higher charge states require considerably higher electron temperatures. It must be remembered that the ionization potential of the last electron scales with Z^2 . As an efficient acceleration of ions requires not too low a charge state, ion sources with high electron temperatures are desired for the production of heavier ions for use in accelerators.

Ion sources which are of interest in our context are mainly the following three:

a) Electron beam ionization source (EBIS). This ion source invented by Donets and now in regular use, e.g. at Saclay (CRYEBIS), is, in principle, perfectly suited for accelerator applications pulsed with a repetition rate of the order of some seconds. However, in terms of intensity for the usual injection times of the CERN Booster synchrotron its intensity is unfortunately still inferior to the ECR source. Development is, nevertheless, going on and future improvements may yield interesting results.

b) Electron cyclotron resonance source (ECR). It provided CERN with the oxygen and sulphur beams over the last few years and has proved to be fairly reliable. There is an extensive ongoing development at CEN, Grenoble, France and other labs have joined in, like Michigan State University, USA, and KFA, Jülich, Germany. At the moment there is a tendency to go to higher fields (superconducting coils) and higher frequencies. In this way, higher intensities may be obtained in the future. Though this source basically supplies a CW beam, its intensity is higher than present day EBIS sources, even when used only during the relatively short time of injection into the Booster.

c) Laser ion source. Theoretical and some experimental work has already been going on for many years. Large numbers of ions in high charge states are claimed with fairly heavy masses. As the pulse is inherently short, there are problems related to the high space-charge. Beam transport is a problem and emittance blow-up may occur. The lengthening of the pulse, necessary for injection into a synchrotron, may not be simple. For our purpose and for the time being the ECR source seems still to be the best choice. R. Geller, Grenoble, is confident that 30 μ A of lead ions with a charge state in the range of 25+ to 30+ will be achieved.

2.2 - Acceleration and Focusing

The smaller the charge to mass ratio, the more difficult is the acceleration and focusing of ions. In order to keep constant the acceleration rate and the particle trajectories, both the products of electrical fields times the charge to mass ratio and the magnetic fields times the charge to mass ratio must be kept constant. As magnetic and electric fields have technical limits, it is in general impossible to use a well designed accelerator for protons to accelerate heavy ions. Special designs are needed to cope with the low charge to mass ratio and the hence low acceleration rate. This latter does not only require long linear accelerators, but also long acceleration times in circular machines resulting in, nevertheless, lower velocities at ejection.

2.3 - Intensity Losses

Intensity losses in proton accelerators have different reasons like mismatch between acceptance of a machine and emittance of the beam coming from the upstream machine, space charge effects at higher intensities and different sorts of instabilities. All these loss mechanisms are, of course, also relevant for heavy ions. Additional losses occur for the latter due to capture or loss of electrons by interaction with the residual gas. Both effects change the charge to mass ratio and result in immediate loss of the particle concerned in a synchrotron and will spoil the beam quality in a linear accelerator. In general, loss of electrons is dominant at high energies and recombination is important at low energies, the transition between these two regimes depending on the ionization energy of the ion.

To evaluate the importance of the effect the cross-section for charge exchange reactions must be known. Its value depends on the ion, its charge state, its velocity and on the residual gas. In the range of interest are lots of theoretical calculations, but only very few experiments. Some data were available from GSI (Gesellschaft für Schwerionenforschung, Darmstadt, Germany) and also from LBL (Lawrence Berkeley Laboratory, Berkeley, USA). There are also empirical formulae from both laboratories for interpolation and extrapolation of the measurements. Comparing them one notices that LBL predicts larger cross-sections for energies below 12 MeV/u and vice versa above (Fig. 1). To determine losses in our machines we have been using the more pessimistic values. The most critical machine in terms of beam losses is the PSB, followed by the PS which is somewhat less critical because the cross-sections at higher energies are lower. The Linac itself is not a problem as the time the ions spend there is very short. Fig. 2 shows the result for calculations for the PSB and the PS. The pressure is defined as "nitrogen equivalent" pressure because the N_2 and the roughly equivalent CO molecules account for the quasi totality of the beam losses. For hydrogen the charge exchange cross-section is lower by about a factor 7. In the Booster we shall aim for a pressure of 1×10^{-9} Torr and for a slightly better one in the PS. Losses under these conditions should be tolerable (less than 30%).

Fig. 1 - Total Charge Exchange Cross-Sections as predicted by GSI (B. Franzke) and LBL (B. Feinberg, H. Gould)

Fig.2 - Transmission through PSB and PS as function of pressure

2.4 - Instrumentation and Beam Control

Basically all the instrumentation available for proton beams can be used for ion beams. The only drawback of course is the lower intensity that makes beam measurements and RF beam control difficult. The beam current usually accelerated in the Linac is well above 100 mA. The subsequent machines are fighting with instabilities caused by the high space charge. In case of highly ionized heavy ions typically some tens of μA may leave the Linac. Space charge problems are hence completely irrelevant. However, most of the instrumentation normally used will simply not work due to noise problems. Special high sensitivity instrumentation must be built to fit the requirements of the ions.

3 - EXPERIENCE AT CERN WITH DEUTERONS AND ALPHA PARTICLES

First machine experiments to accelerate deuterons with the CERN 50 MeV proton Linac were already carried out in 1964. As it was not possible to increase the electric and magnetic fields in the Linac by a factor two, the so-called 2 βA mode was used. In this mode the time needed for the ions to move from one gap to the next in the Alvarez structure does not take one RF period, but two. The kinetic energy of the deuterons is then only half that of the protons, this means the kinetic energy per nucleon is only a quarter. In principle, half the accelerating voltage would be sufficient, but the bad transit time factor, due to the low speed of the deuterons, makes the same RF levels necessary. At that time this test was merely a machine experiment with no apparent interest from the physics point of view. It took several years until the experiment was repeated with higher intensities and longer pulses and subsequent acceleration in the PS up to full energy. At that moment there was a certain interest from the Intersecting Storage Rings (ISR) community and deuterons were actually stored in the ISR and experiments were carried out with them /1/. On the Linac side, the usual duoplasmatron has been used for the production of the deuteron beams. Subsequently tests were carried out to produce alpha particles from the same source. Under these conditions, the main beam component was of course He^{4+} . As deuterium was used to set up the Linac a strong fraction of the assumed He^{4+} beam turned out to be deuterons. Nevertheless, a low intensity of alpha particles was accelerated in the Linac and subsequently in the PS. These results prompted a request from the ISR. The beam intensities achieved so far would have made their practical use in the ISR more or less impossible. Hence, some development work was carried out to produce He^{4+} beams and use subsequent stripping on a pulsed gas jet target to produce high intensity alpha particle beams. Thirty percent stripping efficiency at the energy of the pre-injector (260 keV/u) resulted in more than 10 mA at the output of the Linac /2/. With this intensity it was not too difficult to accelerate the beam in the PS. The main difference as compared with proton operation was the change of the harmonic number by a factor 2 (debunching/rebunching) in the course of the acceleration cycle. This was necessary because of the insufficient frequency swing of the PS RF cavities. Otherwise, it would have needed an increase by a factor 2 in order to cope with the lower velocity of the beam coming from the Linac. During the final runs for the ISR the Booster was used and took over the complicated RF manipulations.

It was quite clear, from that moment onwards, that this Linac was obviously able to accelerate any fully stripped ions (up to about calcium) as long as they could be provided for at the input (neglecting recombination losses in case of very heavy ions due to the imperfect vacuum). The subsequent machines had no major difficulties, except for the above mentioned change of the harmonic number and the lower intensity of the beams. Some work was started along the lines of the electron beam ionization source (EBIS) but dropped later on due to the apparent lack of physics interest.

The construction of the new CERN 50 MeV Linac (called Linac 2) eased considerably the ongoing development work on the old Linac (Linac 1).

4. RECENT PROGRAM WITH OXYGEN AND SULPHUR IONS

Some time later, however, the situation changed. Especially from the nuclear physics community the interest rose and the request for heavier ions at higher energies was formulated.

A detailed study /3/ was launched following a letter of intent addressed to the Proton-Synchrotron and Synchro-Cyclotron Committee (PSCC) at CERN. The study showed that it would be possible, with moderate investments, to accelerate ions considerably heavier than in the past, with the existing CERN machines.

The scenario envisaged consisted of an ion source yielding highly stripped ions at moderate intensity, an upgraded Linac 1 (capable of accelerating not-fully-stripped ions in the 2 βA mode), full stripping at the end of the Linac and improved instrumentation in the PS Booster

and in the PS itself /4/. The instrumentation was also improved in the SPS, because the experiments were finally carried out at higher energies than available at the PS.

Some major modifications of Linac 1, implemented for different reasons, proved very useful if not essential, to the planned conversion of Linac 1 to an ion injector. The installation of an RFQ /5/ which allowed the suppression of the conventional Cockcroft-Walton pre-injector, made it possible to shift back Linac 1 by some 12 m. The removal of the old pre-injector allowed easy installation of other possible sources because the additional complications with controlling and powering the source on an HT platform had disappeared. Another important factor was the regained accessibility of the Linac 1 equipment during PS operation which had to be abandoned in the past due to the ever increasing PS beam intensities and the crossing of the extracted beam through the Linac building.

To implement the required changes to the CERN accelerators, a collaboration was created between GSI (Darmstadt, Germany), LBL (Berkeley, USA) and CERN.

The plan was to use an electron cyclotron resonance source (ECR) capable of producing some 100 μA beam of O^{6+} ions, to accelerate this beam with a DC potential of 15 kV and to build an RFQ for further acceleration. Linac 1 needed a 33% increase in the RF accelerating fields as well as in the magnetic focusing fields. Some drastic improvements were required for the beam monitoring equipment in all the CERN machines to cope with this extremely low intensity.

GSI provided the ion source (built by R. Geller, Grenoble) and beam transport elements in the low energy area, LBL built the RFQ and CERN supplied matching cavities between the RFQ and the first Alvarez tank of Linac 1. CERN also dealt with the necessary upgrade of Linac 1 and with the instrumentation of the different accelerators.

The ion source and the RFQ were delivered to GSI, together with the CERN-built RF power amplifier, and tested there /6/. Subsequently, installation proceeded at CERN with an additional injection line for protons and H^+ ions joining (Fig. 3) the oxygen beam line before the last matching cavity mounted directly on tank 1 /7/. This arrangement was necessary because Linac 1 had frequently to supply beams to LEAR (low energy antiproton ring), both for testing the machine and for physics experiments.

One of the major problems proved - not unexpectedly - to be the RF voltage holding capability especially of tank 1. A 10,000 l/s cryopump had been installed on tank 1 to ease these problems. Nevertheless, pollution with pump oils showed up several times as a major difficulty. Conditioning of the tanks, and in particular of tank 1, was only possible by use of a computer program which would raise or lower the RF voltage as a function of vacuum pressure, breakdown rate and previous RF history.

The beam intensity at the end of the Linac was in the range of 30 μA , the emittance was similar to that of the usual proton beams. Stripping by means of a carbon foil was done yielding a fairly pure beam of O^{8+} . Apart from the intensity this beam was equivalent to deuteron or alpha particle beams for the down-stream machines. Beam measurements after the Linac were carried out by using secondary emission monitors, capable of measuring emittance and energy spread of beams with intensities well below 1 μA .

Part of the time the PS complex operated with higher intensity deuteron beams supplied by Linac 2, interlaced between oxygen ion pulses to allow the setting-up of the SPS. The intensities in the SPS were usually well above 10^{10} charges per pulse. Subsequent upgrading of the ion source resulted (1987) in a somewhat increased intensity for the oxygen beam with a large amount of S^{22+} ions. The majority of these ions was converted with the stripper foil at the end of the Linac to a S^{36+} beam and accelerated in the PSB together with the oxygen beam. The PS accelerated also both beams up to transition energy and was then able to selectively continue with the sulphur beam /8/.

5 - SCENARIO FOR A LEAD ION ACCELERATING FACILITY

The linear accelerator for this facility has to be a completely new machine and is the only one in our complex exclusively adapted to the heavy ions and cannot reasonably be used for protons. The subsequent machines need only certain improvements to cope with the lead ions.

Fig. 3 - The two beam lines joining in front of tank 1

5.1 - Pb Ions in the Linac

The lead ion Linac comprises the following main components:

- Ion source, including the electrostatic preaccelerator
- Low energy accelerator (RFQ)
- High energy accelerator (Alvarez or IH)

a) Ion Source

The preferred solution is the ECR (Electron Cyclotron Resonance) source. It will be an extrapolation from the O^{6+} and S^{12+} sources used on Linac 1 during the successful experiments with the SPS. A similar source for uranium ions is under development at C.E.N., Grenoble, for GSI and many of the technical details could be identical. The required performance for CERN is 30 μA (electrical) lead ions in one charge state between 25+ and 30+ at or above 625 keV total energy for 400 μs with a repetition rate of > 1 pulse / 1.2 s. For the specified current the normalized emittance should not exceed 0.5 π mm mrad.

b) Low Energy Acceleration

With the low energy available after the ion source the RFQ (Radio Frequency Quadrupole) with its electric focusing is nowadays the obvious choice. As in all RF accelerators the transverse

focusing is weakened by a defocusing effect which is a consequence of the phase stable acceleration. This defocusing is inversely proportional to the beam energy and hence most unfavourable at the low energy end of the Linac. To counter-balance this effect, operation at lower frequencies has to be envisaged where the focusing in terms of betatron phase advance per period is more efficient.

However, the present Linac 1 and Linac 2 operate at a frequency of 202.56 MHz and to keep this frequency for most or all of the RF equipment on a future lead ion Linac would be of great advantage in terms of spare parts and maintenance costs. The requirements for the RFQ depend on the input energy (≈ 2.8 keV/u), the output energy (> 250 keV/u) and the normalized transverse output emittance which we assume as $1 \text{ } \mu\text{m mrad}$.

In spite of the advantages when using the 202.56 MHz for the RFQ with the constraints mentioned above, one is forced to use, for this part of the machine, a lower frequency which can only be half the frequency in order to match the subsequent high energy accelerating structure which is supposed to run at the "normal" frequency. The choice of about 100 MHz is also reasonable because it allows to keep the peak surface fields below twice the Kilpatrick limit.

At the moment, the favoured RFQ design has the following parameters:

TABLE 1 : RFQ Parameters

Input energy	: 2.8 keV/u
Output energy	: 250 keV/u
Frequency	: 101.28 MHz
Normalized beam emittance (input)	: $1 \text{ } \mu\text{m mrad}$
Aperture	: 3 mm
Transverse phase advance per period	: 23°
Longitudinal phase advance per period	: 21°
Length	: 5.3 m
Transmission	: 94%
RF power	: ≈ 100 kW
Output beam:	
Normalized emittance	: $1 \text{ } \mu\text{m mrad}$
Phase spread	: 15°
Energy spread	: 3.8 keV/u
Longitudinal emittance	: $1.6 \text{ } \mu\text{s} \times 10^{-6} \text{ eV s}$

Fig. 4 - Output beam characteristics of RFQ

There is a choice between a 4-vane and a 4-rod RFQ, both having similar performances. A 4-vane RFQ, at 101.28 MHz, has a tank of about 0.6 m diameter and rather big and heavy vanes. A 4-rod RFQ can be housed in a tank of approximately half that size and has therefore some advantages. We intend to shape the "rods" in such a way as to be machined on a milling machine, rather than on a lathe.

The matching of the beam into the RFQ can, in principle, be achieved with two lenses, the beam from the ion source is rotationally symmetric. For more flexibility one usually uses three lenses, one einzel lens, incorporated in the electrostatic pre-accelerator and two solenoids. The einzel lens is efficient at low energies and its strength is proportional to q/A ; the solenoid is also efficient at low energies, but its strength is proportional to $(q/A)^2$, which is unfavourable. However, at energies of a few keV/u, the above scheme can work, as confirmed by computation. The fields in the solenoids are about 1 Tesla. The matching of the RFQ beam into the following drift tube Linac is more complicated. For the moment, the solution with a 202.56 MHz rebuncher and four matching quadrupoles has been retained. However, attempts to find solutions which eliminate these additional elements, are being made.

c) High Energy Acceleration

Two structures seem to be interesting for accelerating the ions after the RFQ: a more or less conventional Alvarez structure or the interdigital H structure. The latter has been successfully used, usually at higher energies as Tandem Van der Graaf post accelerator /9/. The attraction lies in the high shunt impedance which can be obtained (about 4 x that of the Alvarez structure) which comes from three main sources, the field mode (H instead of E), the acceleration mode ($\beta\lambda/2$ instead of $\beta\lambda$) and the low capacitive loading arising from very small diameter drift tubes. GSI is planning to build an accelerator using this structure for ions in a similar energy range and with charge to mass ratios similar to the CERN requirements. The operation of this structure relies at present on the sequence: acceleration at or near the RF peak, i.e. with no phase stability and no external focusing, followed by a focusing section (doublet or triplet) to provide a convergent beam and finally a longitudinal matching section (several drift tubes) to prepare the beam for the next "standard" accelerating section. This scheme presents many new problems concerning cavity calculations (in principle three-dimensional), tuning and field adjustments in a discontinuous structure and finally beam dynamics with complicated transverse fields perturbing the already quasi stable acceleration scheme.

Another variant of the Interdigital-H structure has been constructed as a tandem post-accelerator for ions with $q/A=1/4$ at Tokyo. The operating frequency is 48 MHz, input energy 0.25 MeV/u and the acceleration is phase stable with $\phi_s = -30^\circ$. The drift-tubes are alternately large (with quadrupoles) and small, which still gives a high shunt impedance at this low operating frequency. To flatten the electric field distribution large perturbing "wings" and flux deflecting slots are required, and these are adjusted empirically after assembly. This structure could not be scaled directly to 200 MHz without an unacceptable loss in transverse acceptance.

At the moment it seems that the selection of an Alvarez structure is the safest choice. Calculations are proven and straight forward and adaptations to special conditions are feasible. The output characteristics of the RFQ-beam determine the input conditions of the Alvarez structure. One important parameter needs still to be determined: the output energy of the Linac. In order to minimize the losses due to the residual gas in the PSB and the PS, the highest charge state would be desirable. As for intensity reasons the minimum number of intermediate strippers is foreseen, the only reasonable position for intermediate stripping is at the end of the Linac (final stripping will be done at the output of the PS). Hence the Linac energy determines the charge state in PSB and the PS. If the highest charge state is desirable, it means that the highest Linac energy is required. At present the injection line into the Booster and the Booster injection equipment is built to fit the magnetic rigidity of the 50 MeV proton beam. A substantial increase in the magnetic rigidity would require a major rebuild of very specialized and expensive equipment. In addition, the injection line has to be kept compatible with the 50 MeV proton beam coming from Linac 2, which is the standard "proton factory" of the CERN accelerator complex. If it would not be possible to increase the magnetic rigidity, the Linac energy would have to be limited to 2.8 MeV/u resulting in a charge state after stripping of about 48+. This combination would give the same magnetic rigidity as protons at 50 MeV. Under these conditions the vacuum requirements for the PSB and the PS would be more stringent and the injection energy into the SPS would be lower.

Choosing a Linac energy of 4.2 MeV/u results in a charge state of 53+ after stripping. This parameter combination yields about 13% of increase in magnetic rigidity as compared to 50 MeV protons. This increase can be dealt with by a modest upgrading of some of the power-supplies

in the injection line and in the Booster. Choosing this energy means that the Booster can reasonably use about 400 μ s Linac beam pulse length. So far, the Booster injection line had to cope with a maximum of 150 μ s, hence in order to make use of the 400 μ s some upgrading is also required in terms of the pulse length of certain pulsed elements. A lower energy of the Linac would make this upgrading more difficult because the pulse length would have to be increased by an even larger amount. The 4.2 MeV/u seem to be a reasonable compromise between the different constraints.

Fig. 5 - Types of focusing periods

Previously, in a preliminary study /10/, it was demonstrated that due to the very low charge to mass ratio the main difficulty when applying the Alvarez structure to heavy ions at low energy, concerned the quadrupole focusing. To fulfil the constraints a $2\beta\lambda$ structure would be necessary to house the strong quadrupoles at 0.25 MeV/u; this limits the accelerating rate and requires many quadrupoles especially if the structure reverts to the normal $\beta\lambda$ configuration at 2 MeV/u. A new type of structure has been proposed which is a sort of hybrid between a $2\beta\lambda$ and a $\beta\lambda$ structure /11/. Fig. 5 shows the type of focusing period which has been analysed; the period is $N \times \beta\lambda$ long with 2 quadrupoles in a FODO configuration, housed in drift tubes in the $2 \times \beta\lambda$ cells and separated by $\beta\lambda$ $(N-4)/2$ cells each containing an "empty" drift tube.

The following table shows the important parameters:

TABLE 2

TANK 1	Prov. Linac Cavity Param. "SAFE" DESIGN		"ECONOMICAL" DESIGN	
	input	output	input	output
W (MeV/u)	0.25	2.0	0.25	2.0
Ez (MV/m)	2.2	3.2	2.2	4.0
Es/EKP	1.0	1.0	1.0	1.25
ϕ_s (°)	-40	-30	-40	-30
TTF	0.65	0.73	0.65	0.73
Aperture Rad. (mm)	6	8	6	8
N	8		8	
No. $2\beta\lambda$ dts	$36 + 2(1/2)$		$32 + 2(1/2)$	
No. $\beta\lambda$ dts	74		66	
DT Outer Dia. (mm)	150,80		150,80	
Tank Inner Dia. (m)	1.05		1.05	
Tank Length (m)	9.3		8.2	
RF Power (MW)	1.2		1.4	

TANK 2				
W (MeV/u)	2.0	4.2	2.0	4.2
Ez (MV/m)		2.8		3.5
Es/EKP	1.2	1.0	1.5	1.25
φs (°)		-30		-30
TTF	0.83	0.82	0.83	0.82
Aperture Rad. (mm)	9	10	9	10
N		10		10
No. 2 βλ dts		15 + 2(1/2)		12 + 2(1/2)
No. βλ dts		48		39
DT Dia. (mm)		150,80		150,80
Tank Inner Dia. (m)		1.02		1.02
Tank Length (m)		9.4		7.5
RF Power (MW)		1.2		1.5

d) Instrumentation and Beam Transport

In the low energy area the beam has to be analyzed for correct source adjustment and stable operation. Undesired charge states have to be eliminated but must, nevertheless, be measured in order to be able to optimize the ion source. For this purpose the line will be equipped with several beam transformers, profile monitors, slits and TV-screens. A special Wien filter is foreseen to allow the selection of only one charge state. This is a necessary condition to make the measurements at the end of the Linac meaningful.

Most of the present equipment in the existing beam transport line to the Booster can and will be reused. Emittance measurements in this area are important and will be possible for the charge state as coming from the ion source (necessary for matching to the stripper foil to minimize transverse emittance blow-up) and for the charge states as coming from the stripper foil. The measurement will be done by varying the last quadrupole in the Alvarez tank and measuring the beam profile using several pulses from the Linac. Charge state separation will be achieved with a three magnet system (filter) taking into account the following boundary conditions:

- Correct matching of the charge state selected to the existing part of the Booster injection line
- Achromaticity of the filter
- Independent measurements of the charge state must be possible
- The first magnet will be used as a spectrometer magnet to measure the energy dispersion of the different charge states.

5.2 - Lead Ions in the Booster

a) Injection, Acceleration and Ejection

Injection into the Booster requires some upgrading of certain power-supplies as mentioned above. Acceleration in PSB is determined by the fastest possible rise of the magnetic field (which is in turn limited by the voltage induced) and by the maximum frequency swing of the RF cavities (2.95 - 8.05 MHz). Obviously the latter cannot cover the variation of β from 0.094 at 4.2 MeV/u to 0.42 at 96 MeV/u and a change of harmonic number from 17 to 10 involving debunching and adiabatic recapture on an intermediate flat top of the magnet cycle is required.

This technique has already been implemented to allow acceleration of oxygen and sulphur /17/. A notable difference consists in the transfer of 10 Booster bunches into 5 PS buckets to avoid further changes of the harmonic number. The nominal number of charges for Pb is comparable to that of the oxygen runs; in order to accelerate a maximum of particles the beam control should be able to cope with lower intensities. An improvement of 10 dB in the lower limit of the phase loop of the beam control seems possible. Another development presently discussed is the replacement of today's frequency programming from radial position by a synthesized signal derived from the magnetic field. At ejection the revolution time goes up by a factor 2 as compared to protons. Hence the ejection and transfer kickers have to supply 2 times longer pulses. Upgrading of the present equipment is possible.

b) Instrumentation

The most important modification envisaged is the replacement of the presently used processing of signals of the fast beam transformers which are entirely dependent on the bunch structure by DC beam current transformers similar to those installed in the PS. The new transformer would operate for all kinds of particles and all intensities will be covered with four ranges of sensitivity. In the injection line improvements are foreseen for the beam position monitoring.

c) VACUUM

The average pressure in the Booster is about 1 to 2×10^{-8} mbar with a typical average gas composition of 60-70% H_2 , 40-30% mass 28 (N_2 , CO). This situation is usually obtained after 1 to 2 months of ion pumping after a major shutdown, the machine being unbakable in situ.

For the lead ion acceleration we aim for an average pressure of $\sim 10^{-9}$ mbar to be achieved in about the same time with a similar residual gas composition. To achieve this, installation of titanium sublimation pumps is foreseen. In addition, vacuum firing of components and prebake of some of the highly outgassing machine devices will be necessary. Some preliminary tests done in the Booster in January 1988 have shown that it is possible to achieve this low residual pressure in 1 to 2 months.

The first stage of this improvement program would comprise the installation of 45 titanium sublimation pumps with associated equipment, ion gauges and residual gas analyzers, the change of turbo pumps prebake and general cleaning. To achieve a better safety margin and/or a shorter pump-down time, changes and modifications of kickers and septa will be required so that they can be baked in situ. This work would be done in a second improvement stage depending on the results of the first and on measurements of the beam losses.

5.3 - Pb Ions in the PS

The acceleration of Pb ions in the PS will be interleaved with other particles like protons, antiprotons, electrons and positrons. The transport line between the PSB and the PS cannot be changed from one pulse to the next. This imposes that the PSB to PS ion transfer has to take place at the same B_0 (5.634 Tm) as the standard 1 GeV proton transfer. This scheme excludes any stripping between PSB and PS.

The Main Parameters at the PS at injection and ejection can be seen from the following tables:

TABLE 3

PS Parameters at Injection

Q	= 53	(ion charge)
B_0	= 5.634 Tm	
B	= 803.9 Gauss	
dB/dt	= 0 T/s	
T	= 0.094 GeV/u	(kinetic en. per nucleon)
β	= 0.4169	
γ	= 1.10002	
$f(\text{rev})$	= 198.93 KHz	(revol. freq.)
h	= 20	
$f(\text{RF})$	= 3.978 MHz	(RF freq. = $h \cdot f(\text{rev})$)
Q_x	= 6.19	
Q_y	= 6.31	

The 40 bunches from the PSB will be captured by 20 buckets by using the standard ferrite tuned RF cavities in the PS ring (i.e. : two bunches into each bucket).

TABLE 4

PS Parameters at Ejection

Q	= 53	(ion charge)
B_0	= 51.6 Tm	
B	= 7363 Gauss	
dB/dt	= 0 T/s	
T	= 3.11 GeV/u	(kinetic energy per nucleon)

β = 0.9728
 γ = 4.318
 $f(\text{rev}) = 464.16 \text{ KHz}$ (revol. freq.)
 $h = 20$
 $f(\text{RF}) = 9.283 \text{ MHz}$ (RF freq. = $h \cdot f_{\text{rev}}$)
 $Q_x = 6.25$
 $Q_y = 6.30$

No transition crossing will be required. Extraction from the PS will be carried out as a standard single turn fast extraction. The stripping foil will be located in the transfer line PS - SPS.

The PS vacuum has recently been upgraded to make it compatible with the acceleration of leptons for LEP (Large Electron Positron Ring). The average base pressure is at present 7 to 9 times 10^{-9} mbar with a similar gas composition as in the Booster. This situation is usually achieved after 1 to 2 months of ion pumping following a major shutdown, because this machine, like the Booster, cannot be baked out in situ. To achieve an average base pressure of about 10^{-9} mbar in about the same time, with the same residual gas composition, the solution is, like for the Booster, to install about 150 titanium sublimation pumps, and a pressure monitoring system. The interleaved operation with leptons can, however, cause long lasting pressure increases. Hence, like in the case of the Booster, an additional upgrading may be necessary if cross-section estimates were too optimistic, or pumping-down time too long. This upgrading would again concern essentially kicker magnets and septa (some made out of ferrite and glued with araldite). On the other hand, the fact that the PS vacuum chamber receives high synchrotron radiation doses may also produce a cleaning effect which would be to its advantage. This effect, however, needs further study during operation.

5.4 - Pb Ions in the SPS

a) General

Four batches of lead ions from the PS will be used for 1 SPS filling. The relative velocity of the lead ions at transfer is $\beta = 0.983$. The change of β during acceleration in the SPS exceeds the frequency swing of 0.5%, for which the SPS travelling wave cavities have been designed. Allowing for some debunching at ejection, the 4 PS batches have a combined length of about 10 μs , leaving a combined length of 13 μs for the four holes. Because of the short filling time of the SPS travelling wave cavities, their phase can be adjusted during the passage of a hole in the beam if the hole is at least 2 μs long. To circumvent the limitations imposed by the limited frequency range of the SPS cavities, it is foreseen to operate the latter at a constant frequency and to adjust their phase after each revolution of the lead ions.

The previous operation with oxygen and sulphur ions was considered as exploratory running during a certain period which was exclusively dedicated to ions. If lead ions were to be accelerated at CERN, one has to envisage this as a regular program, interleaved with other particles, and the runs will be subject to the same demands for efficiency as the operation with protons. An additional complication stems from the fact that it will not be possible to set up the SPS with intense deuteron beams, as it was done for the light ion runs, because the charge to mass ratio of the heavy ions is different. Nevertheless, to make the lead ion program feasible, an intensive upgrading of the instrumentation will be required.

b) Instrumentation

The expected intensity in the SPS is about 10^8 lead ions, this means that beam monitors ought to be able to cope with 10^9 to 10^{10} charges. They have been designed for intensities in the range of 10^{11} to 10^{13} charges. Foreseen are drastic improvements to the 216 electrostatic pick-up stations in the ring, installation of a new current transformer, highly sensitive SIT (Silicon Intensifier Target) cameras and special thin scintillators placed in the external beams.

c) External Beams

The external beams, on their way to the experiment, have to pass through thin windows and also some air. A recent study indicates that the contamination of the beam caused by nuclear or Coulomb dissociation should not be larger than observed with oxygen and sulphur ions. However, because of the larger interaction cross-sections of lead ions compared to lighter ions, about 30% of the beam would be lost in traversing target stations and mobile dump regions. Both the thickness of the windows and the amount of air can and will be reduced to lower the beam losses to less than 10%.

Special instrumentation is under development to make possible the profile measurements and also the analysis of the beam in terms of ion species. "Blind" operation, like during the light ion runs of the past, is felt to be unacceptable for the future lead ion acceleration facility.

6 - OUTLOOK

The scheme proposed here should safely yield 5×10^7 lead ions from the SPS with an energy approaching 200 GeV/u. Higher intensities may be interesting in the future especially in case of colliding beams. The ultimate scenario that could be envisaged at the moment is certainly the LHC (Large Hadron Collider in the LEP tunnel) where energies of 3 TeV/u per beam could be reached.

Several options are open for intensity increases. A straightforward possibility is "funneling". In this scheme a second ion source and a second RFQ (running at 100 MHz) will be needed to fill the empty buckets of the 200 MHz DT Linac. Joining the two beams from the two RFQ's requires a 200 MHz deflector.

Another possibility for higher intensities is the use of several charge states coming from the ion source. Schemes to achieve this goal are under consideration.

The stripper at the end of the Linac causes high beam losses due to the fact that charge states in the vicinity of the desired charge state are also produced. Re-circulation of these undesired charge states through the same or another stripping foil could be another method to increase the beam intensity.

Storage schemes making use of the continuous beam which comes from the ECR source could drastically enhance the number of particles in our accelerators.

Progress in the ion source field is the most likely reason for intensity improvements. Development in the ECR field is ongoing and has a tendency to higher fields and frequencies. Higher currents will certainly be achieved in the not too distant future. Higher charge states may make obsolete the stripper at the end of the Linac. This would correspond to a gain of approximately a factor 6. The development of the EBIS sources has also to be followed. Laser ion sources as developed for example at Dubna and Munich seem to have a high potential of development.

7 - ACKNOWLEDGEMENTS

It is clear that the work presented here is the result of the collaboration of a large number of persons. More details can be found in a CERN paper which is in preparation: "Concept for a lead ion Accelerating Facility at CERN". I would like to thank all the co-authors of this paper, but also the persons inside and outside CERN who have contributed to our different meetings on this subject. It is due to their hard work and enthusiasm that we can now present a realistic and - I believe - good scenario for lead ion acceleration at CERN.

8 - REFERENCES

- /1/ ASBOE-HANSEN, P., BARBALAT, O., BOUSSARD, D., BOUTHEON, M., GAREYTE, J., HASEROTH, H. JAMSEK, J., MYERS, S., "Acceleration and Stacking of Deuterons in the CERN PS and ISR", Proc. 7th US Particle Accel. Conf. Chicago, IEEE Trans., NS-24, p. 1557 (1977).
- /2/ BOUTHEON, M., CAPPI, R., HASEROTH, H., HILL, C.E., KOUTCHOUK, J.P., "Acceleration and Stacking at α -particles in the CERN Linac, PS and ISR", Proc. 9th US Particle Accel. Conf. Washington, IEEE Trans., NS-20 p. 2049 (1981).
- /3/ HASEROTH, H., "Light Ions at CERN", Proc. of the Bielefeld Workshop on Quark Matter Formation and Heavy Ion Collisions, May 1982, p. 557, Edit. M. Jacob and H. Satz (1982)
- /4/ ANGERT, N., et al., "A Heavy Ion Injector for CERN Linac 1", Proc. of the 1984 Linear Accelerator Conf. Seeheim (Germany), p. 374, Edit. N. Angert, report GSI-84-11, GSI Darmstadt 1984.
- /5/ BOLTEZAR, E., et al., "Performance of the CERN RFQ1 Project", Proc. of the 1984 Linear

Accelerator Conf. Seeheim (Germany), p. 56, Edit. N. Angert, report GSI-84-11, GSI-Darmstadt, 1984.

- /6/ WOLF, B.H., et al. "Heavy Ion Injector for the CERN Linac 1", NIM A258,1,1987.
- /7/ HASEROTH, H., et al., "Ion Acceleration in the CERN Linac 1", 1986 Linear Accelerator Conf. Stanford, California, USA and BROUZET, E., and MIDDELKOOP, W.C., "Performance of the PS and SPS Accelerator Complex with Oxygen Ions", 1987 IEEE Part. Acc. Conf. Washington.
- /8/ ANGERT, N., BROUZET, E., GAROBY, R., HANCOCK, S., HASEROTH, H., HILL, C.E., SCHINDL K., TETU, P., "Accelerating and Separating Mixed Beams of Ions with Similar Charge to Mass Ratio in the CERN PS Complex", to be presented at EPAC, Rome 1988.
- /9/ U. RATZINGER et al., "The Upgraded Munich Linear Heavy Ion Post Accelerator", 1987 IEEE Part. Acc. Conf. Washington
- /10/ HASEROTH, H., LOMBARDI, A., WEISS, M., "Feasibility Study Concerning a Possible Layout for a Lead-Ion Injector for the CERN Accelerator Complex", 1987, IEEE Part. Acc. Conf. Washington.
- /11/ D.J. WARNER, to be publ. in Proc.of the 1988 Lin. Acc. Conf.,CEBAF