CERN/PS 88-67 (DL)
26.10.1988

CONCEPT FOR A LEAD ION ACCELERATING FACILITY AT CERN

R. Billinge, E. Boltezar, D. Boussard, E. Brouzet, R. Cappi,
B. de Raad, N. Doble, P. Grafström, H. Haseroth (Editor), C.E. Hill,
K.H. Kissler, J. Knott, T. Linnecar, F. Nitsch, A. Poncet, U. Raich,
N. Rasmussen, H. Schönauer, N.Siegel, T.R. Sherwood, U. Tallgren,
P. Têtu, D. Warner, M.Weiss

CONTENTS

Preface

This report presents a concept for a Lead Ion Accelerating Facility at CERN. It describes a possible scenario for this facility and points out the boundary conditions such a proposal has to comply with and discusses the technical, financial and manpower implications.

This concept is intended to present to the experimental physicists solutions which can achieve the desired goal.

The present proposal is based upon well proven technology and can be followed without any risk. Other schemes can be incorporated in the final design if further study demonstrates their feasibility and advantage. The probability to use the interdigital H structure for the high energy part of the lead Linac is very high if the ongoing calculations continue to confirm its usefulness. However, different approaches to the problem will not lower substantially the requirements for cost and manpower. The reasons for this are explained in the present report.

The work presented here is the result of a collaboration of a large number of persons. In order to study the overall possibilities and constraints, a workshop was organized in May 1987. Subsequently, a number of meetings were held to study different aspects of the problem.

We are grateful to all the contributors, inside and outside of CERN, for their effort and efficient collaboration.

Helmut Haseroth
Chairman of the Lead Ion Linac Study

The following persons have attended the meetings and/or have made contributions to our study (for special contributions please see the relevant minutes):

J. Alonso, LBL
N. Angert, GSI
H.W. Atherton
E. Baron, GANIL
R. Becker, Frankfurt
B. Bianchi
R. Billinge
E. Boltezar
M. Bouthéon
R. Brockmann, GSI
M. Brouet
E. Brouzet
A. Burlet
R. Cappi
T. d'Amico
H. Deitinghoff, Frankfurt
D. Dekkers
N. Doble
G. Dôme
Ch. Fabjan
B. Feinberg, LBL
A. Fiebig
B. Franzke, GSI
R. Garoby
G. Gelato
R. Geller, C.E.N.
R. Gough, LBL
H. Gould, LBL
P. Grafström
H.A. Gustafsson, Lund
H. Haseroth
H. Henke
C.E. Hill
R. Hohbach
A. Ijspeert
K.H. Kissler
J. Klabunde, GSI
H. Klein, Frankfurt
J. Knott
P. Krejcik
P. Lapostolle, consultant
T. Linnecar
A. Lombardi
L. Magnani
E. Malandain
G. Nassibian
F. Nitsch
M. Olivier, Saclay
P. Pearce
A. Poncet
N. Rasmussen
U. Ratzinger, GSI
G. Schaffer, KfK
A. Schempp, Frankfurt
K. Schindl
H. Schönauer
T.R. Sherwood
N. Siegel
D. Simon
J. Staples, LBL
H. Ströbele, GSI
P. Riboni
U. Tallgren
E. Tanke
P. Têtu
M. Thivent
R. Valbuena
S. Valero, Saclay
J.L. Vallet
A. Van der Schueren
F. Völker
M. Vretenar
D. Warner
M. Weiss
W. Willis
C. Zettler

1. Introduction and Summary

1.1 Introduction

Since the days of deuteron stacking and acceleration in the Intersecting Storage Rings interest in ion physics has increased continuously, not only on the nuclear physics, but also on the high energy physics side.

The successful acceleration of oxygen and sulphur ions during the last two years might have given the impression that a further increase towards heavier masses can be obtained by upgrading of the existing machines. This is not possible. Therefore, the interest in heavier ions has prompted this study on lead ion acceleration.

1.2 Summary

To accelerate deuterons, alpha particles and - more recently - oxygen and sulphur ions, required each time a modest upgrading of the CERN proton accelerators, mainly of the Linac. Heavy ion acceleration (like lead ions) will be possible only at the expense of a complete rebuild of the Linac and a major upgrade of the subsequent machines, schematically presented in Fig. 1.

The Linac part will consist of an ECR ion source providing 30 μA of Pb ions with a charge state of 25+ to 30+. The ions will be accelerated with a DC potential of 20 kV into an RFQ increasing their energy to 250 keV/u. Subsequent acceleration will be achieved with a special Alvarez (or possibly Interdigital H) structure up to 4.2 MeV/u. At this energy stripping will be done with a C-foil and a charge state of 53+ will be selected for further acceleration in the PSB (Proton Synchrotron Booster).*)

The pulse length of the beam as coming from the Linac will be 400 μs (about 3 times longer than for proton beams) and its magnetic rigidity is by 13% higher than for the usual 50 MeV protons. Upgrading of the injection line and of the injection elements in the Booster is therefore necessary. A substantial improvement in the vacuum of both

---

*) A charge state of 54+, as suggested by Becker (Frankfurt), is possibly more attractive because of its closed shell configuration. The final choice can be made when commissioning.

the PSB and the PS (to 10^{-9} Torr N_2 equivalent) is essential to keep the beam losses due to charge exchange reactions sufficiently low. This will be achieved mainly by increasing the pumping speed with additional titanium sublimation pumps. Transfer to and injection into the PS requires also upgrading of some elements due to the much lower energy (94 MeV/u instead of 0.800 or 1 GeV in the case of protons).

The lead ions will be ejected from the PS at 3.11 GeV/u. Stripping to Pb 82+ will be done immediately after ejection. Four PS pulses will be used to fill the SPS (Super Proton Synchrotron).

All machines will require improvements of their beam instrumentation to cope in a reliable way with the low intensities. The complicated RF gymnastics of debunching and rebunching of the beam, necessary due to the limited frequency range, will be made in the PSB. The SPS, having an even more limited frequency range, will apply a new method of accelerating the ions with a fixed frequency using a "non-integer harmonic number". This method should provide much better efficiency than applying the debunching/rebunching scheme several times as would be required when using the traditional "integer harmonic" accelerating method.

An intensity of 5 x 10^7 Pb ions per pulse can safely be expected from the SPS. Further improvements should be possible in the future.

2. Ions at CERN

In order to understand why a cheap upgrading of the CERN machines for heavy ion acceleration is not possible, it is instructive to discuss what has been done in the past to accelerate deuterons and alpha particles and how the upgrading to oxygen and sulphur was achieved.

2.1 History of Deuteron and Alpha Particles

First machine experiments to accelerate deuterons with the CERN 50 MeV proton Linac were already carried out in 1964[1]). As it was not possible to increase the electric and magnetic fields in the Linac by a factor two, the so-called 2 $\beta\lambda$ 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 that 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 as those required for protons. At the time this test was merely a machine experiment with no apparent interest from the physics point of view. It took several years before the experiment was repeated with higher intensities, 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 experiments were carried out with deuterons which were actually stored in the ISR [2]). 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^{1+}. As deuterium was used to set up the Linac, a strong fraction of the assumed He^{2+} beam turned out to be deuterons. Nevertheless, a low intensity beam of alpha particles was accelerated in the Linac and subsequently in the PS. These results prompted a request from the ISR users to store them in their ring. The beam intensities achieved would have made their usefulness in the ISR at that time somewhat marginal. Hence, some development work was carried out to produce He^{1+} 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 (130 keV/u) resulted in more than 10 mA at the output of the Linac[3]). 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[4]).

From that moment onwards, it was quite clear that this Linac was able to accelerate any fully stripped ions (up to about calcium) as long as they could be provided 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 towards an electron beam ionization source (EBIS)[5]), but dropped later on due to the apparent lack of physics interest.

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.

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

2.2 Present Set-Up for the Acceleration of Oxygen and Sulphur Ions

A detailed study[6]) of how to accelerate oxygen ions was launched following a letter of intent addressed to the Proton-Synchrotron and Synchro-Cyclotron Committee (PSCC) at CERN[7]). 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 partially-stripped ions in the 2 $\beta\lambda$ mode), full stripping at the end of the Linac and improved diagnostics in the PS Booster and in the PS itself[8]). 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[3]) which allowed the suppression of the conventional Cockcroft-Walton preinjector, 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. This had to be abandoned in the past due to the ever increasing PS intensities and the crossing of the extracted beam through the Linac building, resulting in increased radiation levels.

To implement the required changes to the CERN accelerators, a collaboration was created between GSI (Gesellschaft für Schwerionenforschung, Darmstadt, Germany), LBL (Lawrence Berkeley Laboratory, 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 to compensate for the incomplete stripping of the oxygen ions. To cope with the extremely low intensity, some major improvements were required in the beam monitoring equipment in all CERN machines.

GSI provided the ion source (built by R. Geller, C.E.N., Centre d'Etudes Nucléaires, 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 tank of Linac 1. CERN also dealt with the necessary upgrade of Linac 1 and with the instrumentation of the different accelerators[10]).

The ion source and the RFQ were delivered to GSI, together with the CERN-built RF power amplifier, and tested there[11]). Subsequently, installation proceeded at CERN with an additional injection line for protons and H^- ions joining the oxygen beam line in front of the last matching cavity mounted directly on tank 1[12]). 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. The very slow conditioning of the tanks, and in particular of tank 1, was made possible by means of a computer program which adjusted 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, with emittances similar to those of the proton beams. Stripping was done by means of a carbon foil 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 beam 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 10^9 charges per pulse. Subsequent upgrading of the ion source with the aim of producing sulphur ions resulted (1987) in a somewhat increased intensity for the oxygen beam with a large amount of S^{12+} ions. The majority of these ions was converted with the stripper foil at the end of the Linac to a S^{16+} beam and accelerated in the PSB together with the oxygen beam. The PS also accelerated both beams and was then able to select the sulphur beam[13]) at transition energy.

3. Reasons for a New Linac Dedicated to Lead Ions

Present day ion sources do not provide heavy ion beams with reasonable intensities and charge to mass ratios of 0.375 (like O^{6+} and S^{12+}) or higher. Linac 1 has been pushed up to its very limits with the required field increase of 33% to cope with the charge to mass ratio of .375.

There is no dramatic improvement in the field of ion sources which can be anticipated to take place in the near future. The only way to accelerate heavier ions at CERN is hence a rebuild of the linear accelerator to cope with charge to mass ratios that can be achieved with present ion source technology. Basically, two options are then open:

- a very low charge to mass ratio at fairly high current from the ion source, subsequently very long accelerators and possibly (to reduce the excessive length) intermediate stripping.

- a charge to mass ratio larger than 0.1 at an intensity that can still satisfy the users. A fairly short linear accelerator is then sufficient, but intermediate stripping must be kept to a minimum to limit intensity losses[14]).

3.1 Main Parameters

The main parameter is of course the beam intensity as desired by the final users. The request was for $5 * 10^7$ ions (corresponding to some $4 * 10^9$ charges). The intensity which can be offered is determined first by the ion source, then by how much of the offered transverse emittance and pulse length can be used by the following accelerators and how big the losses are during injection, acceleration and transfer in the different accelerators. Usually, the relevant parameters can be fixed only after some reiteration and optimization between the different machines.

In the case of the design of a Linac that has to be integrated into an existing accelerator complex it would seem that the Linac parameters can be fixed in a rather independent manner, or at least by considering only the input parameters of the subsequent machine. In the case of the Lead Ion Linac, however, it turned out that the choice of its final energy not only determines the charge state of the ions after stripping at the end of the Linac, but has repercussions throughout the subsequent accelerators up to and including the SPS. This fact, at first sight surprising, stems from the drastic difference between a partially stripped ion and a "normal" proton for which the different accelerators have been designed. For the same energy per nucleon, the lower charge of the lead ion increases drastically the magnetic rigidity compared with protons. Hence the output energy and the speed of the lead ions are quite different from the usual values in the CERN synchrotrons.

It was for this reason that the choice of an apparently simple parameter like the Linac energy required careful considerations of the whole accelerator complex. This required several iterations before converging to the selected energy (4.2 MeV/u). The following chapters will deal with this question in greater detail.

3.2 Transmission Losses from Interaction with the Residual Gas

Here we have to distinguish between losses inherent in the design of our accelerators and common to all species of particles to be accelerated and losses peculiar to the highly ionized heavy ions or to the very low intensity.

Amongst the losses specific for heavy ions the dominant mechanism is charge exchange between molecules of the residual gas and the passing ion, which captures or loses one or more electrons. Any of these events causes immediate loss of the ion concerned in a circular machine. In order to evaluate the probability of loss during the acceleration cycle we need to know the cross-sections for these processes as a function of the energies in the range of interest. Besides numerous theoretical calculations there are only few experimental fixed points to verify the former. We have used an empirical formula fitted to GSI data[15]) backed up by yet unpublished calculations from LBL[16]) Measurements at 4.66 MeV made at LBL[17]) add some confidence to our assumptions in the region of the early acceleration in the PSB where most of these losses occur. Comparing

LBL and GSI formulae for total cross-sections[18]) one notices that LBL predicts larger ones for energies below 12 MeV/u and vice versa above. The experimental point at 4.66 MeV seems to fall right in between the two. To be on the safe side, we always use the more pessimistic value for a given energy in the integration over the cycle. Within the frame of this model one can compute the probability of survival for a given (in practice the fastest possible) acceleration cycle as a function of vacuum pressure. The result is shown in Fig. 2 for the PSB and the PS. (Note that pressure is defined as "nitrogen-equivalent" pressure because nitrogen and the roughly equivalent CO molecules account for the quasi-totality of the effect compared with hydrogen, in which the charge exchange cross-section is much lower): in the Booster one should strive for $1 * 10^{-9}$ Torr N_2-equivalent since transmission falls off rapidly above that pressure. For this value a transmission of 0.76 is expected while in the PS, where $8 * 10^{-10}$ Torr is envisaged, the transmission should be 0.94. Total charge exchange effect for both machines results in a factor of 0.71. Losses and blow-up from single, multiple and nuclear scattering are negligible, compared to the charge exchange processes.

3.3 Estimated Final Lead Ion Beam Intensity at SPS

The previous oxygen and sulphur runs at CERN are interesting as a basis for comparison. The official figures were (with four PS batches injected into the SPS):

Oxygen, peak	$1.6 * 10^9$	ions / SPS pulse
Oxygen, average	$1.2 * 10^8$	ions / SPS pulse
Sulphur, peak	$5.6 * 10^7$	ions / SPS pulse
Sulphur, average	$9.7 * 10^6$	ions / SPS pulse

The factor of 10 between peak and average intensity for the oxygen ions at SPS had many causes: source instabilities, difficulties to measuring the beam with existing monitors in all the accelerators, insufficient experience with this type of operation, etc. It is intended that better instrumentation will be ready for lead ion runs, resulting in better optimisation of the conditions in the whole chain of accelerators. For the sulphur run, an additional difficulty existed due to the abundent presence of oxygen ions with the same charge to mass ratio as the sulphur ions. Hence it was difficult to measure with confidence the actual sulphur ion beam in the early stages of acceleration. For this reason, we make a comparison of predicted and actual values for the oxygen run:

Oxygen Ion ECR Source:

Output current:	100 μA (electrical)
Charge state:	6^+

Number of Oxygen Ions leaving the Source for One SPS Filling:

$$N = 4 * \frac{100 * 10^{-6} * 90 * 10^{-6}}{1.6 * 10^{-19} * 6} \approx 3.8 * 10^{10} \text{ oxygen ions}$$

The factor 4 comes from the fact that we use 4 batches from PS to fill SPS. The pulse length to fill PSB was 90 μs.

Particle Transmission:

RFQ:	0.9	
Linac:	0.3	(not designed for ion acceleration)
Stripping to 8+:	1.0	(no losses)
PSB:	0.35	(4 out of 5 bunches)
PS:	0.8	
SPS:	0.6	(incl. transfer)

Total Transmission Factor:

$$0.9 * 0.3 * 1.0 * 0.35 * 0.8 * 0.6 = 0.045$$

Estimated SPS Intensity:

$$0.045 * 3.8 * 10^{10} \approx 1.7 * 10^{9} \text{ oxygen ions / SPS pulse}$$

Compared with the measured peak intensity given above, the agreement is good. For the lead ion beam, we expect improvements arising from the specially designed lead Linac. The vacuum in the PSB and in the PS needs improving to reduce beam losses due to charge exchange reactions. The vacuum in the SPS has already been improved for the collider operation. However, the stripping to 53+ after the Linac is rather inefficient due to the simultaneous production of other charge states.

Lead Ion ECR Source:

Expected output current: 30 μA (electrical)
Charge state: 25+ to 30+

Number of Lead Ions Leaving the Source for One SPS Filling:

$$N = 4 * \frac{30 * 10^{-6} * 400 * 10^{-6}}{1.6 * 10^{-19} * 25} = 1.2 * 10^{10} \text{ Pb ions}$$

The factor 4 comes from the fact that we use 4 batches from PS to fill SPS. The pulse length to fill PSB is 400 μs.

Particle Transmission:

RFQ:	0.9	
Linac:	0.9	
Stripping to 53+:	0.16	(due to production of other charge states as well)
PSB:	0.25	(incl. losses due to residual gas)
PS:	0.7	(- " - - " - - " -
Stripping to 82+:	1.0	(no losses)
SPS:	0.4	(in case of acc. with phase jumps)

Total Transmission Factor:

$0.9 * 0.9 * 0.16 * 0.25 * 0.7 * 1.0 * 0.4 = 0.0090$

Estimated SPS Intensity:

$0.0090 * 1.2 * 10^{10} \approx 1.1 * 10^{8}$ Pb ions / SPS pulse

The transmission factor of the SPS has been lowered from 0.6, in the case of oxygen, to 0.4 for lead. The reason is, that in the latter case the injection energy is lower. In the case of acceleration in the SPS, not with phase jumps, but with several harmonic jumps, we could even expect a transmission of only 0.2, due to the losses at each harmonic jump.

At the "Discussion Meeting on Lead Beam Experiments at the SPS", held at CERN, 28 and 29 April, 1988, the user community expressed the wish for an intensity of:

$5 * 10^7$ Pb ions / SPS pulse

The estimated figure fits well with the desired intensity, but it must be kept in mind that many factors are not known with very high precision. With suitable instrumentation to detect low intensity ion beams, the efficiency of the SPS ejection process for lead ions is expected to become as high as for protons (above 90%). This was not the case, particularly for the sulphur run, where the ejection was performed rather blindly.

4. Design Proposal for the New Lead Ion Linac

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 µs Linac beam pulse length. So far, the Booster injection line had to cope with a maximum of 150 µs, hence in order to make use of the 400 µs 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.

4.1 Options

In this section a set of options for the main systems of the Linac between ion source and exit of the Linac (at 4.2 MeV/u) is given in order to place in context the choices which had to be made to develop a reference design. It is evident that the latter will be a "safe" design so as to ensure coherence with specifications, predicted performance, technical solutions and cost estimates. Alternative solutions could become part of the reference design once their technical and cost advantages have been demonstrated. In the following summary the presently preferred option or options are mentioned first with a brief indication of the specifications and predicted performance, where available. The starting point is that any proposed solution must be consistent with the specified beam at the output of the RF Linac including the stripping and debunching processes.

The Lead Ion Linac complex would comprise the following main components:

- Ion source, including the electrostatic pre-accelerator
- Low energy accelerator (RFQ)
- High energy accelerator (Alvarez or Interdigital-H).

a) Ion Source

i) Preferred Option

The preferred solution here is the ECR (electron cyclotron resonance) source. This would be an extrapolation from the oxygen ($O6^+$) and sulphur ($S12^+$) sources used on Linac 1 during the successful experiments with the SPS. A similar source for uranium ions is under development at Grenoble (Geller) for GSI and many of the technical details could be the same. Our specified performance is for 30 µA (electrical) lead ions in one charge state between 25+ and 30+ at or above 625 keV total energy and during 400 µsec at a repetition rate of $\geqslant$ 1 pulse/1.2 sec. Another important parameter which fundamentally affects the design of the following accelerators (here assumed to be an RFQ and a drift tube Linac respectively) is the maximum normalised emittance of 0.5 πmm mrad for the specified ion current (30 eµA). These parameters have been given in some detail as they refer specifically to the expected performance of an ECR source. Other source options might be better matched to other parameters but this would also affect the choice of design for the following accelerators.

ii) Other Source Options.

The EBIS ion source has been proposed as a possible source having the advantages of potentially very high charge states produced in a storage time well matched to the proposed repetition rate. No ready supplier has been found for this source, however. Laser sources are under study at Munich and are in use at Dubna. They can produce high charge states and acceptable numbers of ions per pulse but with a very short pulse length (several µsecs), somewhat dependent on the energy spread and allowable drift space before acceleration. This source is mechanically simple but somewhat variable in its output current. No experience is yet available with very heavy ions.

b) Low Energy Acceleration

At the low energy end of the Lead Ion Linac, the RFQ with its electric focusing is the natural choice. Due to constraints on the electrostatic pre-accelerator, the input beam energy is, however, very low: ≈ 2.8 keV/u. The mean transverse focusing in the RFQ (as in all RF accelerators) is weakened by a defocusing term, which is a consequence of the phase stable accelerator. This defocusing is inversely proportional to beam energy, hence most unfavourable at the lower energies. A counter measure is to operate at lower frequencies, where the focusing is much more efficient (in terms of betatron phase advance per period).

However, as will be emphasised for the further RF acceleration, there is a distinct advantage for spares and tried solutions to retain the Linac 1 and 2 frequency of 202.56 MHz if there are no strong technical reasons against it. The nominal performance requirements for the RFQ are an output energy between 0.25 MeV/u and 0.5 MeV/u depending on the relative costs of extending the energy upwards in the RFQ or downwards in the RF accelerator. For beam quality, a normalised transverse output emittance of 1 π mm mrad is assumed. Another constraint which can affect the choice of the output energy for the RFQ is the drift space between it and the following RF accelerating structure. If sufficient space is left for measuring equipment (e.g. for emittance) then the longitudinal phase spread increase which occurs may need to be corrected by one or more bunchers with their associated RF systems. To avoid this expense the drift space could be reduced to an acceptable minimum (of the order of 0.1 m) or more elegantly, the beam shaped longitudinally in the RFQ itself so as to be matched at the Linac input after the drift space. The RFQ structure can either be of the 4-vane or of the 4-rod type; this choice does not affect the beam quality.

i) Preferred Options

In spite of undeniable advantages of an overall 200 MHz RF system, one was obliged to prefer for the RFQ a lower frequency, i.e. 100 MHz. Only a 100 MHz RFQ could keep its peak surface fields below twice the Kilpatrick limit and allow at the same time an efficient acceleration ($\eta > 90\%$) of a beam with an emittance of 1 π mm mrad. The RFQ was optimised in the standard way and its length was computed as 5.25 m.

The longitudinal beam properties at the RFQ output are not strongly frequency dependent: the longitudinal emittance for ~ 95% of the beam is about $1.6\ \pi * 10^{-6}$ eV sec. This corresponds to 3.8 keV * 15° at 100 MHz.

ii) Other Options

Although at this stage of the project a standard 100 MHz RFQ has been preferred, 200 MHz RFQ's with special electrode modulation will continue to be studied. Such a special modulation can to a certain extent be compared to an Alvarez Linac operating in the 2 βλ mode.

c) High Energy Acceleration

i) Alvarez Type Drift-Tube Linacs.

In the 1987 IEEE paper^{14}) various focusing options were considered for drift tube Linacs giving 8 MeV/u lead ions (q/A = 1/7) and it was concluded that at least at the input energy a 2 βλ structure (at 200 MHz) would be necessary to house quadrupoles with an acceptably low pole tip field. Later work essentially confirmed this conclusion with the present beam parameters^{16}) and the drift tube Linac was selected for further close study compared to other options mentioned below. Nevertheless, it was recognised that the number of quadrupole lenses implied in this solution was large (175 drift tubes with quadrupoles for a Linac from 0.25 to 4.2 MeV/u). By concentrating on the beam transport aspects of the Linac at 0.25 MeV/u it was demonstrated that the distance between quadrupoles could be increased to give a betatron phase shift of about 90 deg. The beam envelope modulation increases but the maximum aperture remains acceptable and the required quadrupole field actually reduces^{32}). To satisfy the RF acceleration constraints the increased space between the 2 βλ cells (with quadrupoles) is "filled" with empty drift tubes having βλ periodicity. This arrangement allows the number of drift tubes with quadrupoles to be reduced drastically (from 175 to ≈ 50), allows the accelerating rate to increase safely above the 2 βλ level and using the empty drift tubes as variable elements allows an optimisation of shunt impedance (ZT^2).The reference design has a focusing period of 8 βλ up to 2 MeV/u and 10 βλ thereafter.

ii) Interdigital-H Structures.

These structures have been used successfully above 2 MeV/u as Tandem Van de Graaff post-accelerators^{19}). Their attraction lies in the high shunt impedances that can be obtained (about 4 times that of the Alvarez structure) which comes from three main sources, the field mode (H vs E), the acceleration mode (βλ/2 vs βλ) and the low capacitive loading arising from the very small diameter drift-tubes (no quadrupoles). It has been proposed to apply this principle at 0.25 MeV/u and 100 MHz operating frequency[20]. 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 sequence has been mentioned to show that the proposed scheme presents many new problems concerning cavity calculations (of necessity 3-dimensional), practical tuning and field adjustments in a discontinuous structure, and finally beam dynamics with complicated transverse fields perturbing the already quasi-stable acceleration scheme. These problems are being actively studied at CERN and GSI.

Another variant of the Interdigital-H structure has been constructed as a tandem post-accelerator for ions with q/A=1/4 at Tokyo Institute of Technology, Tokyo. The operating frequency is 48 MHz, input energy 0.25 MeV/u and the acceleration is phase stable with $\varphi s = -30°$. 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 which would otherwise fall to half its initial value along a tank, 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.

4.2 Ion Source

Production of multicharged ions by single step ionisation is generally not possible except for some low charge states. Thus, multistep ionisation processes must occur which take a time inversely proportional to the ionising particle density. In electron-bombardment ionisation, the incident electron must have an energy at least that of the ionisation potential (binding energy) of the last electron to be removed and for maximum efficiency of ionisation, between three and five times the minimum. For the desired lead ions this ionisation potential is around 1kV. At the present time, only two sources, the EBIS and the ECR[21] are capable of producing lead ions of the required charge state and will be the only two to be examined in detail.

In an Electron Beam Ion Source (EBIS)[22] a fast dense electron beam interacts with cold ions. Ions are trapped longitudinally in an electrostatic well and radially by the potential in the electron beam. Particles are ejected by lowering one end of the well. The minimum confinement time required to produce a given charge state is given approximately by:

$$t = 1.6 * 10^{-19}/(J * \sigma\ (q-1,q))$$

where J is the electron current density. Long formation times (low J) must be weighed against recombination losses in the rest gas, i.e. a low neutral density (good vacuum), and high density electron beams (low t) and their problems.

Without taking into account practical considerations, the maximum number of ions per pulse obtainable from an EBIS is $1.37 * 10^{12}/Q$ per meter of source length[23]). This converts into engineering units as $1.05 * 10^{7} * P * V * N/Q$ per meter where P is the electron gun perveance in microperv, V the gun voltage and N, the extraction efficiency[24]). In practice, N rarely exceeds 10% for heavy ions and stable high P guns are difficult to design. Higher current densities, and hence shorter formation times, are obtained by magnetic compression of the electron beam.

Whereas in an EBIS hot ionising electrons are injected into the source volume, an Electron Cyclotron Resonance source (ECR) makes use of the electron component of a plasma heated by microwave radiation[25]). A surface can exist in a multimode cavity immersed in a magnetic field where the electron cyclotron resonance condition exist for the injected microwave power (0.36 kGauss/GHz). Plasma electrons crossing this surface can, in general, be heated to higher energies thus increasing the degree of ionisation and the plasma density. In this case the formation time is given by:

$$t = 1/(V * N * \sigma\ (q-1,q))$$

where V is the electron energy and N their density, i.e. a high plasma density reduces formation times. However, the density is limited by the tendency of the plasma to become opaque to microwave radiation as the plasma frequency ($9 * \sqrt{(N)}$kHz) approaches the RF frequency. The microwave frequency can be increased, but this increases the ECR resonant magnetic field. RF power would decrease with the frequency but would be increased by a higher mean charge state in the plasma.

The magnetic field required for the resonance can be shaped to provide a magnetic mirror for longitudinal confinement with radial confinement provided by a multipole magnetic field. Particle extraction is by a traditional dc acceleration gap carefully positioned in the edge of the plasma volume.

A 5 μperv 5kV EBIS could produce about 2 * 10^{10} charges per pulse per meter with a 10% extraction efficiency. This perveance corresponds to an electron current of 1.75 A and to attain a formation time of 100 ms, the current density would need to be about 110 A/cm^2 giving a beam radius of 0.7 mm. The solenoidal field needed to confine the beam would be around 2 kG. Intensity could be gained by increased perveance (limit 25 μP) or by increasing the beam voltage (offset by the reduction of ionisation cross-section with electron energy). An EBIS is used at Dubna, Saclay and elsewhere and is proposed for RHIC, but it has gained the reputation of being a somewhat temperamental device. Both design and experimental effort would be needed to produce a source for this application.

The ECR source has been used at CERN both for the oxygen and sulphur runs at the SPS[26]) and a development has been proposed to obtain 30 μAe of lead 25+ to 30+ ions[27]). As compared to the sulphur source, which operated with a 15 GHz, 6.3 kG resonance and a plasma density of the order of 2 * 10^{12}/cm^3, a lead source could operate between 20 GHz / 8.4 kG and 30 GHz / 12.5 kG resonance conditions with a density of 4 to 9 * 10^{12}/cm^3. Formation times would be between 25 and 50 ms. RF powers are estimated to be between 6 and 3 kW and it is here that technological difficulties arise. The RF must be quasi CW. However, development of the ECR has not stopped, and there are indications that the use of a second resonance surface at a field corresponding to 2 times the cyclotron frequency can improve ion yields[28]).

Within the present restrictions on manpower, bearing in mind the continuing development of the ECR source and the difficulties mentioned above in EBIS output, it is felt that the ECR source would be a suitable choice for the Lead Linac Project, at least in the short term. Future development of the project could lead to a reconsideration of an EBIS if advances can be made in its performance, but development of a laser source may be more interesting[29]).

4.3 RFQ Preinjector

4.3.1 General Considerations

The acceleration of particles with a low charge to mass ratio always presents some problems, as high fields (electric in the case of RFQ) are required in the accelerators to contain the beam both radially (betatron motion) and longitudinally (synchrotron motion). The betatron and synchrotron motions are described with their relative phase advances over a structure period, i.e. σ_{0T} and σ_{0L}.

It is usually more difficult, in particular at lower energies, to establish a reasonable σ_{0T} within limits of maximum allowable surface fields. The expression for σ[14]) is :

$$\sigma^2_{0T} \simeq \overline{Q^2} - \frac{1}{2}\ \sigma^2_{0L}$$

- where $\overline{Q^2}$ describes the average focusing in a period, and 1/2 σ^2_{0L} is the defocusing due to the modulation of electrodes in the RFQ. The first term on the right hand side does not depend on energy, but scales with frequency as f^{-4}. The second term does not depend on frequency, but scales with energy as W^{-1}. It it clear, therefore, that at very low energies the defocusing term might become a problem. To ensure a certain σ_{0T} , one has to raise Q^2 and to do so without exceeding field limits, one has to lower the frequency. This is the case with the lead ion RFQ, where the imposed limit of

$$E_S \leq 2E_K \quad (E_K \ldots \text{Kilpatrick field limit})$$

could be satisfied only by lowering the RF frequency.

4.3.2 Design of a 101.28 MHz RFQ

For the design of an RFQ [30])[31]) one uses essentially two types of computer programs. With the first type one explores the RFQ parameter space and ends up, eventually, with an acceptable design. Afterwards one checks the validity of the design by particle simulation programs. When necessary, the whole procedure is repeated.

It was found that a judicious choice of σ_{0T} and σ_{0L} is of prime importance. One can find, as will be shown later, a set of these values which ensure a good transmission efficiency (> 90%), without exceeding the electric field limits. The length of the RFQ, however, cannot be imposed in addition and one has to accept lengths of the order of 5 m.

It was found also that the specified beam output emittance (normalised value 1 π mm mrad) played an important rôle in the design of the RFQ. If the emittance could be halved, a much shorter RFQ[14]) would be feasible.

The main specifications for the RFQ are the following:

Input energy : 2.78 keV/u
Output energy : 250 keV/u
Frequency : 101.28 MHz
Beam emittance, normalised : 1π mm mrad

In Table 4.3.I we represent several RFQ's, which differ slightly in their parameters, but which for one reason or another would not be accepted. These RFQ's, however, helped us to approach the optimised design, the parameters of which are presented in Table 4.3.II, together with the output beam characteristics. The output beam is presented also on Fig. 3.

For the following accelerator, operating at twice the frequency (202.56), the phase spread is doubled. The resulting value of ~ 30° is still quite acceptable.

4.3.3 RFQ Structure

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.

4.3.4 Matching at input and output of RFQ

The matching of the beam into the RFQ can, in principle, be achieved with two lenses as 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 effect is weakened proportionally to Q/A; the solenoid is also efficient at low energies, but its effect is proportionally weakened 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.

Table 4.3.I : Search for best RFQ parameters

Accel. Factor	Focus. Factor	Volt. (kV)	Apert. (mm)	σ_{0T} (deg)	σ_{0L} (deg)	Length (m)	Transm. (%)	E/Ek
.29	3.80	70.8	3.5	20	21	5.25	71.1	1.9
.36	4.75	81.1	3.2	25	25	3.70	90.6	2.3
.35	4.51	59.5	2.9	25	21	5.30	96.4	1.9

Table 4.3.II : Optimised RFQ and beam parameters

a) RFQ

Accel. Factor	Focus. Factor	Volt. (kV)	Apert. (mm)	σ_{0T} (deg)	σ_{0L} (deg)	Length (m)	Transm. (%)	E/Ek
.34	4.25	60.5	3	23	21	5.30	93.6	1.85

Required RF power : ~ 100 kW at 101.28 MHz; pulse duration ~ 500 μs.

b) Output beam

Normalised emittance	: 1 π mm mrad
Phase spread	: 15.2°
Energy spread	: 3.8 keV/u
Longitudinal emittance	: $1.6\ \pi * 10^{-6}$ eV sec

4.4 Linac

4.4.1 Starting Conditions and Constraints

In order to develop the Linac designs as described below, the input beam is taken to be 30 μAe of Lead ions at 0.25 MeV/u with A = 208 and q = 25. (Both of these latter two assumptions give some margin.) The normalised emittances assumed are 1 π mm mrad transverse and 1.6 π * 10^{-6} eV sec longitudinal. The Linac operates at 202.56 MHz with an output energy of 4.2 MeV/u.

Two tight constraints are the quadrupole pole-tip field less than 1.3 T and the peak RF electric field on the drift tubes not to exceed 1.5 times the Kilpatrick limit at 200 MHz (ie. 1.5 * 14 Mv/m). Weaker constraints are on the peak RF power requirement (assumes similar designs to Linac 2) and on the overall length which for 4.2 MeV/u should fit easily in the existing Linac 1 building.

4.4.2 Design Philosophy

A preliminary study had demonstrated that due to the very low charge to mass ratio the main difficulty when applying the drift tube structure to heavy ions at low energy concerned the quadrupole focusing. To fulfil the constraints of 4.4.1, a 2 βλ structure would be necessary to house the strong quadrupoles at 0.25 MeV/u; this limits the accelerating rate (less gaps/m) and requires many quadrupoles especially if the structure reverts to the normal βλ configuration at 2 MeV/u. The formulation used was that of a previous feasibility study for a lead Linac[14]). In the present study this formulation could be adapted to treat the less usual cases with the focusing period extending over many βλ periods (up to 12 βλ). The order in which the problems are treated in the following sections reflects this fundamental focusing difficulty ie. starting with the selection of the focusing period, then fitting an acceptable RF structure and finally generating a self consistent set of Linac parameters. Here only the main results and trends are given, (for more details see Ref.[32]) and Ref.[33])) to demonstrate the use of the design tools and to indicate how the reference parameters have been obtained.

4.4.3 Comparison of Focusing Periods

Fig. 4 shows the type of focusing period which has been analysed; the period is N x βλ long with two quadrupoles in a FODO configuration, housed in drift tubes in the 2 x βλ cells and separated by N/2 -2 cells each containing an "empty" drift-tube. The comparisons of different periodicities can be made with sufficient precision to choose the N-value using the analysis of Ref. [14]). For the results quoted here however, a matrix multiplication routine was used as this represents the motion of a synchronous particle with much better precision (assuming constant momentum over a period). The quadrupoles are "hard-edged" and the RF defocusing is represented by a thin lens at each mid-gap. The energy studied is mainly 0.25 MeV/u as this is the most difficult region for the quadrupole field limitation. It can be shown that the required field gradient varies approximately as $\beta^{-1.2}$ so that quadrupoles can be made in batches and the apertures can increase with beam energy whilst becoming less critical in design.

Another important energy to study is 2 MeV/u, nominally chosen at the end of the first accelerating section. Here one can reoptimise both the focusing period and the structure.

The parameter which best characterises the motion in transverse and longitudinal phase-space is the phase advance over one focusing period of the transverse (betatron) and longitudinal (synchrotron) motions denoted by σ_T and σ_L, respectively. Constant σ_T implies constant envelope amplitude whilst the σ_L varying along the accelerator (as a function of E,T,β and φs) generally reduces and the corresponding RF defocusing term in the transverse analysis decreases likewise. The two results given for the beam envelope are the maximum (increased by a nominal 25% to allow interpretation as the necessary beam aperture radius) and the maximum to minimum ratio (ψ). In order to keep a reasonable transit time factor at the beginning of the Linac (TTF > 0.65) the maximum tolerable aperture radius is taken as 6 mm and the corresponding quadrupole aperture as 7 mm, hence the interest in the magnetic field at 7 mm (B(7)).

TABLE 4.4.I: Aperture and Quadrupole Gradient vs Period Length

N	G' (T/m)	σ_{OL} (deg)	σ_{OT} (deg)	a (mm)	ψ	B(7) (T)
4	230	50	40	4.6	1.52	1.61
6	195	75	60	5.3	1.97	1.37
8	178	100	80	6.4	2.62	1.25
10	166	125	100	7.8	3.65	1.16

The results of Table 4.4.I show that for N=4 and N=6 the maximum aperture required is less than the 6 mm specified for satisfactory transit time factor, while for N=8 the aperture (with safety margin) is slightly greater than 6 mm and for N=10 the aperture required is nearly 8mm. As these computations were made with the "worst case" conditions as far as energy, charge to mass ratio (q/A), sychronous phase and accelerating rate are concerned, and satisfy the magnetic field constraint, we feel justified in choosing N=8 between 0.25 MeV/u and 2 MeV/u. The corresponding computations using the previous method[14]) are close to the above for N=4 and N=6 but give slightly smaller aperture and larger gradient requirements for N=8 and N=10. Note that the aperture depends on the assumed emittance, so that if later studies showed that 0.6 π mm mrad could be delivered by the RFQ, then N=10 would be a valid option.

Similar sets of results have been obtained at 2 MeV/u, and with the increased available aperture and smaller RF defocussing, N=10 is quite safe (pole tip field < 0.6T).

4.4.4 RF Structure Design

Before the Linac dimensions can be generated we must have a reasonable idea how the transit time factors vary with energy and also the way the peak surface electric field varies. The starting hypothesis is that the apertures should increase with energy to allow some margin for misalignments and emittance growth. However, the transit time factor (ZT^2) which is an important term as regards structure efficiency should not fall below 0.70 after the initial low value of 0.65 at 0.25 MeV/u. This will allow the aperture radius to increase from 6 mm to 8 mm between 0.25 and 2 MeV/u. The notion of increasing the distance between quadrupoles leads naturally to the idea of special "empty" drift tubes, being both smaller in diameter and simpler in contruction. When a quadrupole must be contained, a drift tube outer diameter of 150 mm is necessary (cf. 180 mm in Linac 2 with 10 mm aperture radius). But for the empty drift tube, an outer diameter of 80 mm suffices to keep essentially the same electric field distribution near the axis.

A small series of computations was made using the cavity program SUPERFISH, first of all to demonstrate the startling decrease in dissipation on the larger drift tubes when the effective drift-tube to drift-tube capacity was reduced (e.g. by increasing the number of gaps/m). Then the program was applied to the N=8 sequence to find the dynamics parameters (e.g. Transit Time Factor) and the power dissipation at W = 0.25, 0.50, 1.0, 1.5 and 2.0 MeV/u with fixed cavity diameter of 1.05m and the gaps varied to ensure f = 202.5 MHz.

It was assumed that a second tank would start at 2.0 MeV/u so another set of parameters was computed for N=10 at 2.0 MeV/u with the cavity diameter 1.02 m now corresponding to the reduced gap length.

These results, though not really optimised, gave enough information to generate the Linac dimensions and to estimate the power losses. Although the losses on the drift-tubes have been significantly reduced, there are the same losses on the support stems as in a conventional structure e.g. at the start of tank 1 these stem losses are greater than those on the drift-tubes they support. Similar losses will occur on post couplers but it is proposed to install only one post per two long drift-tubes.

4.4.5 Generation of "Safe" and "Economical" Linac Designs

Compared to a proton Linac the velocity gain per gap is small (1.1% compared to 3.9%) so that the simple formalism which uses the mean transit time factor is a good approximation to the transit time factor for the particle at the gap centre. Thus, there is no need to go to complicated programs for this first proposal. The constraints applied were for the "safe" design surface fields not to exceed the Kilpatrick Limit (EKP = 14MV/m), in the first tank, whereas for the "economical" design 1.5 x EKP = 21 MV/m was the upper limit. In addition, to allow a good margin of longitudinal acceptance without raising the RF defocusing term too drastically, the synchronous phase should start at - 40° and the accelerating rate at 0.125 MeV/u/m. The φs varies throughout tank 1 as β**n with n = - 0.28 so that φs = - 30° at 2 MeV/u. The mean field along the first tank increases linearly with distance to maintain the surface field near to 14 MV/m for the safe design and rising to 1.25 x 14 MV/m for the economical design.

In tank 2 the initial accelerating rate is the same as at the end of tank 1 (continuity condition), φs = - 30° throughout and the mean axial electric field is constant. It is evident that several iterations are required to generate the tank 1 dimensions but tank 2 is straight forward between 2 MeV/u and 4.2 MeV/u.

Numerical results are given in Table 4.4.II where nominal RF dissipations, allowing 25% extra for surface imperfections are also shown. It should be noted that the "economical" design requires fewer drift-tubes with quadrupoles, 44 compared to 51 but 20% more RF power.

TABLE 4.4.II: Provisional Linac Cavity Parameter

TANK 1	"SAFE" DESIGN input	"SAFE" DESIGN output	"ECONOMICAL" DESIGN input	"ECONOMICAL" DESIGN 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
φs (°)	-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 $\beta\lambda$ DTs	15 + 2(1/2)		12 + 2(1/2)	
No. $\beta\lambda$ 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	

4.4.6 Bunching, Debunching and Drift-Spaces

These three topics are closely related to the longitudinal acceptance and its evolution along the Linac.

To estimate the required bunching we use the accelerating rate and the synchronous phase at 0.25 MeV/u to deduce the nominal matched acceptance of the drift tube Linac in the near linear region viz. 30° by 8.8 keV/u semi-axes. The beam from the RFQ, of nominal emittance 30° * 3.8 keV/u at 200 MHz requires matching to the Linac acceptance, which is a right ellipse with semi-axes 20° * 5.9 keV/u. This can be done by a drift space of 0.33 m to a "rebuncher" which provides 11 keV/u modulation followed by another drift space of 0.28 m to the Linac. As mentioned in section 4.1(b) it may be possible to avoid this special (re)-bunching system by designing the RFQ to deliver a beam which would be matched after a drift space.

The debunching between tanks at 2 MeV/u gives less than 25% increase in phase extent if the inter-space is less than 0.3 m. Assuming a matched beam at 0.25 MeV/u and longitudinal emittance increase by a factor two, the output beam at 4.2 MeV/u has emittance 9° * 26 keV/u. This corresponds to a momentum spread of 0.3% which is greater than the 0.1% normally required for the Booster synchrotron following the Linac. Thus momentum spread reduction using a "debuncher" is required. As there is a long beam transport line, following that from the present Linac 1, a standard debuncher providing about 300 keV of modulation can be used, possibly the existing one.

4.4.7 Quadrupole Design

It seems possible to scale the Linac 2 pulsed quadrupoles (which are based directly on a BNL design) for use with the lead Linac[34]). They have good saturation, field harmonic and pulsing characteristics and would retain these properties if the aperture, pole shape and winding slot were reduced in the ratio 14/22 (as the aperture diameters). The maximum number of ampere-turns required would reduce from 6300 At to 3800 At in the lead Linac, corresponding to a gradient of 180 T/m and a pole tip field of 1.26 T. The length of winding slot can be chosen as a function of the number of turns and thus the inductance can be optimised according to the pulser requirements. For example a lead Linac quadrupole (at 0.25 MeV/u) could operate at 350V x 150A compared to the Linac 2 quadrupoles at 0.75 MeV which require 350V x 300A. Thus it should be possible to make simpler supplies or to reduce the number of supplies by powering the quadrupoles in batches. The mean power dissipation per quadrupole is about 7 W in the worst case (at 0.25 MeV/u).

4.4.8 Other Design Considerations

We expect to use the experience gained in the mechanical design of Linac 2, but with some simplifications particularly arising from the "empty" drift tube idea. As the beam envelope will be maximum in the quadrupoles, the necessary aperture in the "empty" drift-tubes can be less, which is equivalent to allowing larger alignment tolerences e.g. ± 0.5 mm radial compared to the normal ± 0.1 mm radial demanded for drift-tubes with quadrupoles. With the operating point and aperture we have chosen for the N = 8 focusing, the beam centroid deviation, due to misalignments, is less than for the N = 4 periodicity, due mainly to fewer quadrupoles. In addition, the proposed cavity diameters of 1.05 m and 1.02 m allow for somewhat easier drift-tube installation than Linac 2.

4.5 <u>RF Power</u>

The acceleration system consists of 3 or 4 acceleration cavities:

- RFQ
- Buncher (optional)
- Tank 1
- Tank 2

The concept of the RF system will be very similar to the one existing in the CERN Proton Linac 2.

Each of the acceleration cavities will be provided with its individual RF amplifier chain. The common drive for all chains is generated in a crystal-controlled master oscillator, amplified to approx. 250 W peak pulsed power, then fed to the inputs of the amplifier chains via a common phase reference line and individual 20 dB directional couplers. The pulse length of this drive signal is approx. 1 ms. Each amplifier chain will have its own fast acting closed loop feedback system, correcting tank amplitude and phase errors on the low level RF side. The input phase of the acceleration cavities will be set by digital phase shifters with a resolution of 5.6° at the input of each amplifier chain. Each cavity will have its individual automatic tuning system. Since variations of the tuning due to external influence are generally very slow, it is sufficient to provide a slow-acting tuning system.

The amplifiers used are standard-type amplifiers delivering the following max. pulsed output power:

- transistor amplifier	:	400 W
- 1st predriver	:	5 kW
- 2nd predriver	:	60 kW
- driver stage	:	2 MW
- final stage	:	2 MW

4.5.1 Amplifier Chain for RFQ (202.56 MHz)

The power requirement is approx. 500 kW pulsed RF power. The chain will consist of 4 amplifiers:

(i) Transistor amplifier, output 250 W
(ii) 1st predriver, air-cooled amplifier, using the RCA 7651 tetrode, output 2.5 kW
(iii) 2nd predriver, air-cooled amplifier, using the SIEMENS RS 2024 CL tetrode, output 50 kW
(iv) final stage, water-cooled using the TH 170 R triode, output 500 kW.

Should the power requirements be higher than 500 kW, a driver stage, identical to the final stage, could be inserted between 2nd predriver and final stage.

From the final stage the power will be carried to the cavity by a rigid feeder line of 4" or preferably 6" diameter with incorporated trombone section.

In the case of operating the RFQ at 101,28 MHZ and power requirements of approximately 100 kW, three amplifier stages will probably be sufficient.

These amplifiers will have to be bought or developed as well as the major part of the low level RF electronics.

4.5.2 Amplifier Chain for Buncher (optional)

The power requirement of about 50 kW is met with 3 amplifiers:

(i) transistor amplifier, output 250 W
(ii) 1st predriver, output 2.5 kW
(iii) 2nd predriver, output 50 kW.

For this amplifier chain water-cooled stages are not necessary.

4.5.3 Amplifier Chains for Tanks 1 + 2

These two identical chains have to furnish approx. 1.5 MW and consist of 4 amplifiers each:

(i) transistor amplifier, output 300 W
(ii) 2nd predriver, output 12 kW
(iii) driver stage, output 200 kW
(iv) final stage, output 1.5 MW

The amplifiers driver stage and final stage are identical and use the water-cooled TH 170 R triode. The amplifier driver stage could seem to be a little over-designed with only 200 kW of power requirement, but has the advantage of being relatively simple, using a tube with excellent lifetime (≈ 25.000 hrs), and makes another standard type amplifier with a different tube superfluous.

The final stage amplifiers will be linked to the tanks by 230 mm diameter feeder lines with incorporated trombone sections.

4.5.4 Power Supplies

The transistor amplifier, 1st predriver, and 2nd predriver have their individual DC power supplies. The driver stage and final stage amplifiers receive their plate voltage from one separate modulator per amplifier chain. These modulators consist of a number of L-C elements, forming a delay line. The charged delay line is discharged via a triggered ignitron onto the primary of a pulse transformer which boosts the voltage for plate powering up to ≈ 40 kV and matches the impedance of the amplifiers on the secondary to the characteristic impedance of the delay line on the primary. The number of L-C elements must be sufficiently big to allow for a usable pulse length of 500 μs.

4.5.5 Interlock and Control Systems

Switch ON/OFF sequences, detection of faults and status indication will be provided by hard-wired local interlock systems in each chain. A local/remote switch allows control to be taken over by the control room or the computer.

The equipment enumerated above will be modular to a great extent so that each of the chains is composed of basically the same building blocks.

4.6 Beam Instrumentation and Transport

The beam measuring equipment and the transport lines (source -

RFQ and Linac - Booster) will have to cope with very low intensity beams and with different charge states.

4.6.1 Beam Line Source-RFQ

In this line the beam (30 μA with a charge state between 25+ and 30+) has to be analysed 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 optimise 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.

4.6.2 RF-Accelerators

In the restricted space between the RFQ and the Alvarez tanks only a minimum of measuring equipment can be installed. Beam transformers, profile monitors and fast probes for bunch measurements are foreseen.

4.6.3 Beam Line after the Linac

Most of the present equipment in the existing beam transport line to the Booster can and will be re-used. Additional equipment is needed to join the new shorter Pb-Linac to the existing injection line. This is needed partially to ensure independent operation and setting up of the Pb-Linac, partially to allow for stripping, charge state measurements and selection. It will also enable energy correction to match the longitudinal beam characteristics to the acceptance of the Booster.

Emittance measurements are important and will be possible for the charge state coming from the ion source (necessary for matching to the stripper foil to minimise transverse emittance blow-up) and for the charge state(s) coming from the stripper foil. The measurements 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 system must be short, so as to fit the available space
- the first magnet will be used as a spectrometer to measure the energy dispersion of the different charge states.

Attention will be paid to the possible simultaneous acceleration of more than one charge state in the Alvarez Linac, which may be one way to increase the beam intensity.

4.7 Control System

4.7.1 The Control System for the Lead Linac

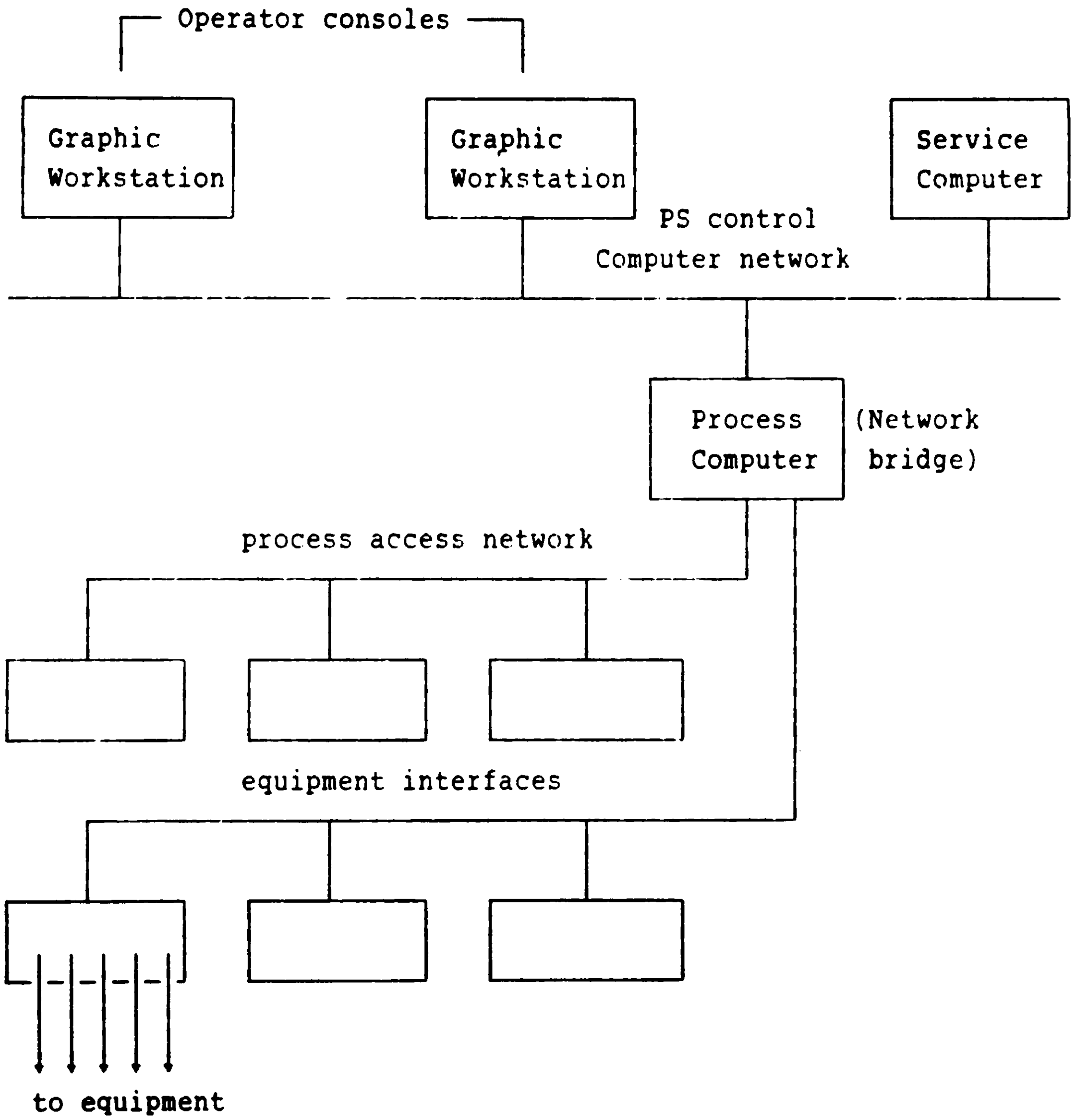
A basic layout for the lead Linac control system is given. The boundary conditions are explained and the cost of the system is estimated on the basis of the existing Linac 2 controls. Since the design of the Lead Linac is not definitive and the future development of computer hard and software may change the control system design the estimates may only be considered as approximate.

a) The Boundary Conditions

The lead Linac will replace the present Linac 1, which implies that the equipment used to control Linac 1 could be recuperated at least partially. However, the first tank of Linac 1 will be reinstalled to serve as an injector for LEAR. Since the source control, the RFQ control, the control for the beam transport constitute the major parts of the control system hardware and of course the computer is needed to drive this hardware, essentially all existing equipment will be needed to control this future LEAR injector. The Linac 1 control system was not accessible from the main control room, which can be considered a major drawback in view of regular operation of the machine. It seems desirable, therefore, to integrate the future lead Linac controls into the existing control system for the other PS accelerators.

b) The Control System Hardware

Because of the enormous changes in computer hardware during the last few years and which can be assumed to continue for the near future, it is very difficult to give a layout for a system that will be built in approximately 2 years from now. We therefore give a few ideas of how we see the system today. A general layout is given in the following figure.



This layout is quite similar to the existing control systems except for the fact that graphic workstations replace the well known "old" operator consoles. The process access network is presently implemented in serial Camac but may be replaced by another, more modern form of access if it will be available in time. It seems evident also that the process access computer (and the service computer) will be an up to date machine. This means that all computers, the networks and all installations (interfaces, cabling etc.) have to be new constructions. The total hardware cost of such a new system was estimated using the number of control channels of the Linac 2 control system as a base. This number is multiplied by the estimated cost per channel. We define a control channel to be the hardware needed to control or acquire one value.

Example: A power supply control needs:

1) control on/off
2) acquisition on/off
3) control value (current)
4) acquisition value

For a power supply we therefore count 4 control channels. The estimated cost per channel was calculated using the estimations for the KAON factory Vancouver (1) and the EHF (2) estimations and subtracting the software cost which is given separately here. These estimates were valid for rather big control systems (~ 40000 control channels) and the average price per channel might be higher for a medium size project as the lead Linac.

We find:

Timing:	200	channels
Source:	50-100	channels
RF:	270	channels
Vacuum:	100	channels
Power supplies:	640	channels
ca.	1600	channels
Instrumentation:	400	channels
total:	2000	channels

With an average price of 0.8 KSFR per channel the digital part of the system will cost approximatly 1.6 MSFR. This price includes the computers, the networks, the interfaces, the cabling etc. In addition to the digital part of the system we need the possibility to observe analog signals coming directly from the equipment. Linac 2 has ca. 400 analog signals where 4 signals may be selected for inspection on 2 oscilloscopes. The multiplexing network will cost approximately 700 KSFR including hardware (we count 400 KFSR only for cabling) and manpower cost.

The total hardware cost can therefore be estimated as

Total hardware cost: 2.3 MSFR

c) The Software

Until now 2 different control systems were available in the PS division. The Linac control system was specifically tailored to the Linac timing, with its very low duty cycle, while the PS system is more general allowing to run a very big range of different accelerators. Having two different control systems, however, inceases exploitation problems and we expect to unify them in the future. The system should be able to be accessible locally from the Linac control room during the running-in period and at machine startup, as well as from the MCR during normal physics runs. The software to be designed and implemented can be subdivided into 3 main categories:

1) console software (data representation and interaction)
2) the process access (equipment drivers)
3) the applications

On Linac 2 a total of 100 application programs are available at the moment. 80 of these applications are of synoptics type needing only limited control intervention (switching on/off etc.). These programs may easily be implemented using some type of synoptics editor. We estimate 2 man weeks per program. The other 20 applications mainly control measuring lines giving emittance, charge states etc. as results and providing complex graphic outputs. For this type of programs, 3 man months per program must be allowed. In addition, ca. 30 different equipment drivers have to be provided. Some of these drivers (especially instrumentation drivers) may be very complex. As an average we count 2 man months per driver. Some general purpose programs like log, alarms, archives, hardware diagnostics, hardcopy, are needed in addition. For the console we have to count for adaptation of a synoptic editor to our requirements and for some network interface routines. As a very rough estimate we give 40 man months for "general utilities".

Software manpower estimates:

Simple applications:	40 man months
Complex applications:	60 man months
Equipment drivers	60 man months
General utilities	40 man months
	200 man months

With the the extremely short manpower situation at CERN in mind we consider that only 30% of the software work could be done at CERN:

10%	Specifications of programs	(2 man years)
10%	Acceptance tests	(2 man years)
10%	for prototypes and special equipment	(2 man years)

Subcontracting the other software to software houses implies an additional cost of:

14 man years at 160 KSFR per man year = > 2.2 MSFR

d) Summary

The total cost of a control system for a lead Linac at CERN is estimated as:

Digital hardware	: 1.6 MSFR	
Signal Observation System	: 0.7 MSFR	
Software manpower at CERN	: 6 man years	
Software subcontracted	: 2.2 MSFR	
Total	4.5 MSFR	+ 6 man years

4.7.2 Proposal for the Lead Linac Timing

a) Requirements

The operational aspect of the Lead Linac will basically be the same as that of the present Linac 1, except that it will not have to provide particles for LEAR. The latter will be done by a dedicated injector, probably the actual tank 1 of Linac 1.

We, therefore, propose to use the same concept for timing as used for the existing Linacs. This structure will provide the required flexibility and the equipment is of proven reliability and cost efficiency. Furthermore, the system will remain compatible with

Linac 2, not only from the operational point of view, but also for the equipment and applications programmes. This because of the required direct exchange between these two machines, as Linac 2 will remain master in the overall pulse-to-pulse modulated operation for interleaved ion injection from the new lead injector.

b) Expenditure

Different scenarios are possible, depending mainly on where the future LEAR injector will be located:

- use the present Linac 1 control position for the lead Linac and install new controls for the LEAR injector.
- build two new control positions if the LEAR injector is located at the present Linac 1 control position.

As the timing systems for the future Lead Linac and a possible LEAR injector are similar in size to the present Linac 1, only new equipment and the infrastructure for one timing system will be required.

4.8 Mechanical Aspects and Vacuum

4.8.1. General

The following analysis concerns the part of the lead ion accelerating facility from the ion source to 4.2 MeV/u energy (Fig.5). From the design options offered for this energy range, the arrangement ECR ion source, four rod RFQ accelerator and a 202.6 MHz Linac is chosen for the analysis, although a different set of options would not essentially change the conclusions.

The installation is divided into four mechanically independent sections,

- the ion source with the accelerating column,
- the RFQ with beam transport and diagnostic equipment,
- tank 1 of the drift tube Linac and
- tank 2 of the Linac.

Each of these four sections is supported by a statically determined system so that the floor movement does not produce stresses in the accelerating structures and cause misalignment of the inner parts. This design feature is even more important given the fact that the installation site has three different types of building foundations.

The mechanical isolation of the sections is achieved through flexible connections between the sections, to the RF power supplies and for the electrical cables.

The sections are aligned optically via a sighting line parallel to the ion beam and given by the sighting monuments which already exist in the building. For this, each of the four sections is provided with a pair of optical targets and a spirit level.

The vacuum needed throughout the system is of the order of 10^{-7} Torr. With metal seals, no organic matter in vacuum and low gas charge from the ion source, the most suitable pumps would be the triode ion pumps. Their lifetime under the given conditions is almost unlimited and, what is more important, they are maintenance free so that the pressure cycling of the accelerator tanks is minimized. This helps to keep the RF stable and the alignment of the internal parts unchanged.

4.8.2. Drift Tube Linac

The values in the following table result from the beam optics and RF design of the Linac as given in the chapter 4.4. These values were used for the evaluation of the concept variants and the elaboration of the mechanical conceptual design.

- Tank 1 / tank 2 lengths	8.2/7.5 m
- Tank 1 or tank 2 inner diameter	1.05 m
- Tank 1 or tank 2 volume (approx.)	8 m^3
- Tank 1 or tank 2 inner surface exposed to vacuum	40 m^2
- RF losses on the tank walls	30 W/m^2
- RF losses on "full" DT body / quad / stem	5/7/3 W
- RF losses on "empty" DT body / stem	.3/2 W
- Alignment precision for "full" DT	.2 mm
- Alignment precision for "empty" DT	.5 mm

The "full" DT stands for the type of drift tube with a focusing quadrupole magnet in the DT body. The values concerning the tanks and the RF losses are preliminary design values and therefore approximate. They are also taken from "economical design" where the losses are higher (see chapter 4.4) than in the "safe" design.

Each of the two Linac tanks is made of five cylindrical sections bolted to the full tank length. The drift tubes are built into a tank section from the inside. They are fixed on the tank wall and not on a girder as on the CERN Linac 2 37)38). The sections are fully aligned and vacuum tested before they are built into the long tank.

The alignment method for the DTs is mechanical, with alignment jigs. For this purpose, the sections are provided with outside reference faces on the flanges; the faces are used for DT alignment as well as for section to section alignment. Optical targets are not used for this alignment.

All seals on the tank are in aluminium and are used as vacuum seals and/or as RF contacts. An important design requirement on the seals is that the assembly geometry must not depend on the sealing pressure. To give an example, the distance between two connecting faces should be given by the size of the shims and not by the seal.

The RF power and measuring loops are mounted on the tank from the outside. The same is valid for tuners.

The tank is water cooled by a tube near each tank end. Such a cooling arrangement produces a temperature gradient along the tank and not around the tank circumference. This is important for the alignment stability. The temperature rise water to tank wall is about 12 °C.

The "full" drift-tubes are similar to the DTs for the CERN Linac 2 with the difference that the vertical movement facility is suppressed. The horizontal movements are provided by a pendulum mechanism with the pivot point in the centre of the flexible bellows on the DT stem. It is possible to read the position of the DT and also to realign it from the outside without breaking the vacuum. The DT body, the quadrupole magnet and the copper stem are cooled by heat conduction to the support stem which in turn is water cooled. The deformation by thermal expansion is negligible.

The "empty" DT is rigidly bolted to the tank wall without an adjustment facility. The tube is cooled by heat conduction through the full copper stem onto the tank wall. The temp. rise is about 10 °C max. on the stem in the highest RF field region. The thermal expansion of the stem (about 35 microns) is well within the range of the required alignment precision.

Compared to the CERN Linac 2[38]), this Linac is much simpler in mechanical design due to shorter tanks, less severe alignment precision and less stringent safety features used in the design.

5. Lead Ions in the Booster

5.1 Injection

The higher magnetic rigidity (+ 12%) and longer revolution times (a factor 3,32) when injecting lead ions ($q = 53$) instead of protons into the Booster implies upgrading of a part of the power equipment of the injection line.

There are two items which need a major upgrading which has a considerable impact on the global cost estimate. These are the distributor plus some minor items and the kickers. (The septum magnets presumably can support the increased current and pulse length. Tests are being carried out to verify this.)

a) The distributor pulse-forming networks have to be lengthened and the switching sequence changed. Along with this, rewiring of one of the magnet modules and modifications in the power supply electronics and pulsers will have to be made. The equipment will be capable of working in PPM (Pulse to Pulse Modulation) with protons and ions in the same main cycle. The minor items are : modifications of the post deflector, exchange of a DC quadrupole magnet supply and extension of the low level electronics for the septa to allow PPM operation.

b) The injection kicker magnets have to be supplied with longer current ramps (45 μs → 140 μs) of higher amplitudes (charge supply output voltage 7000 V → 8000 V). It is foreseen to use the existing equipment, upgraded for higher charge delivery and complemented by an additional discharger to supply the longer pulses. The latter is operating only when lead ions are injected.

5.2 Acceleration

Acceleration in the PSB is determined by the fastest possible rise of the magnetic field, which is in turn limited by the induced voltage; we assume that the PSB will operate with four power supply groups, i.e. one more than at present, and by the maximum frequency swing of the RF cavities (2.95 - 8.05 MHz). Obviously, the latter cannot cover the variation of v/c 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[12]. A notable difference consists in the transfer of 10 Booster bunches into five 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 lesser intensities. An improvement of 10 dB in the lower limit of the phase loop seems possible by replacement of the present five phase pick-ups by one long (~ 1m) pick-up. A single pick-up avoids complications with harmonic numbers not compatible with the present multiple-of-five layout. The new pick-up type requires development of adequate head amplifiers. Another development presently discussed is the replacement of today's frequency programming from radial position by a synthesized signal derived from the guiding field. This is more appealing as any further improvement in sensitivity of the present radial pick-ups is practically excluded.

5.3 Ejection

At ejection the revolution time goes up by a factor 2 (623 ns → 1245 ns). Hence the ejection and transfer kickers have to supply 2 times longer pulses.

For the moment, the pulse forming networks of the kicker pulse generators consist of coaxial cables. If we keep this solution, new cables will have to be bought and connectors must be made (unless we find a cable which has the same dimensions as the one presently installed). This is quite expensive, so another solution with a lumped circuit delay line is under scrutiny. However, for the cost estimate the solution with cables is considered. This is also justified by the fact that it may be desirable to install new and better cables in order to reduce interference with the equipment which measures beam intensity and position in the PSB-PS transfer lines.

Also the thyratron switches which will be more stressed will have to be exchanged with more powerful types. This requires some mechanical work particularly because the tubes are mounted in coaxial arrangements.

5.4 Beam Instrumentation

5.4.1 Booster Rings

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 d.c. beam current transformers similar to those installed in the PS. This new transformer would operate for all kinds of particles and all intensities will be covered with four ranges of sensitivity. The possibility of measuring coasting beams is extremely helpful already when tuning injection and the transport line at ion intensities. Disposing of a transformer is enough to measure transverse emittances with Beamscope. Longitudinal emittances can already now be measured down to 10^8 charges. Working points are set up operationally with computed Q-values and require no beam.

5.4.2 Injection Beam Line

Beam current measurements will be possible with existing transformers when (as now in oxygen production) a few interfering elements as the injection kicker are delayed, but this technique stops the beam. In view of the notorious instability of ECR sources an operational beam current transformer capable of non-destructive monitoring is very much recommended. Its development may be time-consuming and might not succeed. Beam position monitoring is difficult with presently employed scintillator screens. Equipping the second screens with more sensitive material would be helpful. In the long run it would certainly pay off to have pulse-to-pulse plunging screens with processing of the video signals for better localization of the beam centre.

5.4.3 Transfer Beam Line

No useable beam transformer signals can be obtained in the transfer line to the PS, since interference from kickers completely swamps the weak signals. Improvement seems possible but again development may be lengthy. On the other hand, highly sensitive scintillator screens are already installed in this line and have sucessfully operated at oxygen intensities.

5.5. Vacuum

At present, the average pressure in the Booster is 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.

To achieve an average pressure of ~ 10^{-9} mbar in about the same time, with the same residual gas composition, an example can be taken from the SPS vacuum system with the installation of 45 titanium sublimation pumps in the free straight sections. Together with a general cleaning program such as Vacuum Firing of components, prebake of some of the highly outgassing machine devices, it will be possible, as some preliminary tests done on the Booster in January 1988 have shown, to achieve the desired low residual pressure in 1 to 2 months. This could be a first improvement stage:

1st stage:
- Installation of 45 titanium sublimation pumps with associated equipments, ion gauges and residual gas analysers, change of turbo-pumps prebake and cleaning.

This requires one year of specification, design and construction, and can be installed in a 2 months shutdown.

To achieve reliably a base pressure a factor of 10 to 20 lower than the present one, requires some safety margin that the above program will not give. The margin can be obtained by reducing the risk of a bad average pressure due to a single faulty component such as a kicker or a septum. Note that the Booster has a smaller circumference and more highly outgassing localised devices than the SPS. By changing or modifying the kickers and septa so that they can be baked in situ, the condition of better safety margin will be fulfilled.

This will not only consolidate the improved vacuum pressure, but it will also ensure a better availability of the accelerator (such as fast recovery from a leak or equipment failure and consecutive replacement), and speed up the pump-down time by a factor 4 to 5 (from 1 to 2 months, to 2 to 3 weeks) after the complete machine has been let up to air. With the following 2nd improvement stage, one can aim at an average pressure well in the 10^{-10} mbar range, with a better gas composition like 80% H_2 or more, the rest being mass 28:

2nd stage:

- modification of 4 kickers and septa tanks

(BI.KSW,BI.SMH,BE.KFA,BE.SMH) 665 k (with tanks rebuilt....)

A detailed study of required resources and construction planning for this 2nd improvement stage was not yet made. However, as for the PS, it could be envisaged as part of a long range replacement program.

6. Lead Ions in the PS

6.1 General

The PS machine will accelerate Pb^{53+} ions on cycles of 1.2 s four times per supercycle and in PPM (pulse-to-pulse modulation) mode, i.e. allowing for example on the remaining cycles : pbar production, e^+e^- acceleration, etc..

The transport line between the PSB and the PS cannot be pulsed in PPM. This imposes that the PSB to PS ion transfer has to take place at the same $B\rho$ as the standard 1 GeV proton transfer ($B\rho$ = 5.634 Tm).

This not only sets maximum energy of the ions in the PSB but also forbids any stripping between PSB and PS, imposing consequently the acceleration in the PS of ions charged 53+ and requiring the final total stripping (53+ to 82+) to take place in the transfer line between the PS and the SPS. Stripping before the PS would anyhow be undesirable because of additional intensity losses.

6.2 Injection

Injection into the PS machine will take place on a ~ 30 ms long flat bottom at B = 804 Gauss.

The 40 (= 4 * 10) bunches from the PSB will be captured into 20 buckets making use of the standard ferrite tuned RF cavities (i.e.: two bunches into each bucket) .

The main parameters of the PS injection are listed in the following table:

Q = 53 (ion charge)
$B\rho$ = 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 = 1.100
f_{rev} = 198.93 kHz (revol. freq.)
h = 20
f_{RF} = 3.978 MHz (RF freq.= $h * f_{rev}$)
Qx = 6.19
Qy = 6.31

Important remarks:

1) The revolution time will be 5 μs compared to the 2.5 μs for the proton injection, and will imply an important modification in the pulse length of the injection kicker. This appears to be the most important hardware modification in the PS machine.

2) The bunch spacing (head-tail) will be about 60 ns; with the estimated modified kicker fall time of ~ 80 ns (see below) the last injected bunch will be partially lost.

In the injection line of the PS, it is the kicker magnet and supply (PIKFA 45) which require major modifications. By changes in the connexion scheme of the modules of the magnet and, in the power and low level electronics, the pulse length is increased by the factor 2 required. However, the fall time of the kicker pulse becomes longer (80 ns). Development work is going on with an electronic switch which can reduce this fall time. Another implication is that there will be no spare magnet available for operation with ions.

6.3 Acceleration

After 30 ms spent on the flat bottom, about 100 synchrotron periods, the acceleration will take place on h=20 bringing, in about half a second (dB/dt = 1.5 T/s), the ion beam to the top kinetic energy of 3.11 GeV/u (γ = 4.318).

Some upgrading in the low level beam control will probably be necessary to cope with the low intensity ($\approx 2 \times 10^9$ charges/pulse beams. No transition crossing will be required (PS γ_{tr}= 6.12).

The PS main parameters at high energy are listed in the following table:

Q	= 53	(ion charge)
$B\rho$	= 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_{rev}	= 464.16 KHz	(revol. freq.)
h	= 20	
f_{RF}	= 9.283 MHz	(RF freq.= $h * f_{rev}$)
Qx	= 6.25	
Qy	= 6.30	

6.4 Ejection

Extraction from the PS machine will be carried out as a standard single turn fast extraction, no modification of the present hardware seems, for the time being, necessary.

The stripping foil will be located in the transfer line PS-SPS, downstream of the "loop" to AA, in order not to interfere with the operations with antiprotons.

6.5 Vacuum

The average base pressure in the PS is at present 7 to 9 * 10^{-9} 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 following a major shutdown, because this machine like the Booster, cannot be baked out in situ.

To achieve an average base pressure of ~ 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:

Stage 1: - 150 titanium sublimation pumps,
ion gauges

This can be done in a 2 months normal shutdown, after one year of design and construction.

The PS Vacuum system has recently been upgraded - thus giving it an advantage compared to the PSB as far as the safety margin is concerned. One of the very reasons for this change, is to open the possibility to accelerate, in PPM mode, not only high intensity protons but also leptons for LEP. In fact this mode is a disadvantage for the acceleration of partially stripped ions, due to the fact that the leptons cause long lasting pressure increases and gas composition changes.

Therefore, one has also to envisage a consolidation stage which, as for the PSB, will not only give some safety margin in terms of pressure, but also more reliability and availability of the machine:

Stage 2:

- Modifications to kickers (8 straight sections in the PS !) involving magnets, some ferrites, bakeout equipment and tanks

- Reconstruction of septum magnets (some glued with araldite, 7 straight sections in the PSR).

This is only a rough estimate, and particularly for the septum magnets, the number of critical places where a replacement would urgently be needed could be reduced to half the existing ones. However, it has to be stressed that this additional work would be a problem because of a shortage of staff and is rather independent of any time scale for replacement of the equipment considered.

Finally it has been mentioned that - unlike the PSB - the PS could receive large synchrotron radiation doses with special high intensity / high energy / long lepton cycles during dedicated periods. This would have a certain cleaning effect, which could lower the base pressure in the PS. This obviously would require a study before relying on it.

7. Lead Ions in the SPS

7.1 Introduction

On each cycle the SPS will accelerate simultaneously 4 batches of lead ions, injected consecutively from the PS at 1.2 s intervals. This repetition time, which is standard for proton injection at 14 GeV/c into the SPS, limits the magnetic field on the flat top of the PS magnet cycle to a maximum value corresponding to a proton momentum of 20 GeV/c. In the PS the lead ions have a charge Q = 53 +, but since they are fully stripped after extraction from the PS, they have a charge Q = Z = 82 + in the SPS. The SPS magnetic field at the injection of the lead ions therefore corresponds to a proton momentum of 53/82 x 20 = 12.93 GeV/c, well above the minimum of 10 GeV/c required from a magnetic point of view. The maximum magnetic field during the flat top of the SPS cycle depends on the desired duty factor. For operation with protons the maximum field is usually 2.025 T in the main dipoles. The latter value corresponds to a momentum of 450 GeV/c per proton or 82 x 450 GeV/c = 36.9 TeV/c per lead ion.

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 injection, the four 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 (1μs) 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 constraints on the SPS operation for lead ions will be much more severe than during the previous light ion runs for the following reasons:

i) The lead ion program will take place at a time when the SPS will be in regular service as injector for LEP and the proton-antiproton program will probably not yet have been completed. Therefore, machine time will continue to be in great demand and it must be assumed that the lead ions will have to be accelerated on interleaved magnetic cycles during periods of LEP operation. Whereas during the previous exploratory runs with light ions a certain lack of efficiency could be tolerated, the operation with lead ions will be subject to the same demands for efficiency as the operation with protons.

ii) Since the value of Q/A respectively Z/A for lead ions is different from that of deuterons, it is not possible to set up the PS and SPS complex with intense deuteron beams as was done for the light ion runs, even if machine time could be made available for this purpose.

Because of i) and ii) it is necessary to upgrade the beam monitoring in the SPS ring, the proton transfer lines and the secondary beams. Furthermore, a number of improvements to the external target stations and the mobile beam dumps of the secondary beams are required.

Beams of lead ions can be extracted simultaneously from the SPS towards the West and North Experimental Areas. The lead ions are transported to the Areas via the primary and secondary beam lines, after the external targets have been withdrawn. The primary beams to the West and North Areas are equipped, respectively, with one and two splitter stations which can provide beams to two and three different experiments. Thus the lead ions from the SPS can be shared simultaneously among 5 different beams. The sharing ratio between the two Areas and between the experiments in the same Area can be adjusted in the range 10% to 90%. Because of the long debunching time at top energy, the holes in the beam which are necessary for acceleration at constant frequency, will persist during slow extraction.

7.2 Capture and Acceleration

At the proposed injection energy, the revolution frequency of the lead ions with $\beta = 0.983$ is too low to allow acceleration in the usual mode with a variable frequency proportional to the instantaneous revolution frequency of the beam, since the useful frequency range of the SPS cavities is only 0.5%. Fortunately, the latter are travelling wave structures of which the filling time (≈ 1 μs) is much smaller than the revolution time (23 μs) of the particles. This feature opens the possibility of a new method of acceleration in which the 4 PS batches occupy a total of about 10 μs while the other 13 μs are taken up by 4 holes, possibly of different lengths. Whenever a batch passes through the cavities, the latter are powered at a constant frequency with maximum accelerating voltage. During the passage of each hole or of one hole per revolution, the instantaneous frequency of the cavities is briefly changed so that the RF phase matches the arrival time of the particles on their next passage through the cavities.

The short filling time of the SPS travelling wave cavities also permits an independent adiabatic capture of each of the 4 PS batches by means of amplitude modulation of the RF voltage. After a new PS batch has been injected, the RF voltage in the cavities is raised adiabatically during the successive passages of that particular batch only. The batches already injected continue to see a constant voltage which will hold them in their respective azimuthal positions. In this way, each batch will only be captured once, so that the overall capture losses are minimized.

To implement this new acceleration procedure, which will first be tested with protons, a number of electronic circuits for modulating the phase and amplitude of the accelerating voltage at the revolution frequency must be built. Some modifications to the transmitter plants are also necessary to cope with the fast 100% amplitude modulation. Furthermore, previous experience with sulphur ions has shown the necessity for a new high sensitivity phase pick-up.

7.3 Beam Instrumentation in the SPS Ring and Proton Transfer Lines

The beam monitors installed in the SPS ring and in the proton transfer lines have been designed for intensities in the range of 10^{11}-10^{13} charges. Although improvements to some monitors were made for the operation with oxygen and sulphur ions, most detectors cannot be used at the expected lead ion intensities of 10^9 to 10^{10} charges per SPS pulse without a drastic increase of their sensitivity.

In the SPS ring, the 216 electrostatic pick-up stations which are used for the closed orbit measurements will be equipped with 200 MHz resonators. A quality factor Q between 100 and 200 will guarantee a sufficient level of the output signal while maintaining the necessary bandwidth. Remotely controlled switches will make it possible to damp the resonant circuits during high intensity proton operation.

The 200 MHz resonators will be followed by pre-amplifiers located in the SPS tunnel close to the detectors. To avoid radiation damage of these pre-amplifiers during proton operation, they will be installed in the existing electronic pits which must be cleaned and equipped with hermetically tight plastic boxes for this purpose.

The circulating lead ion currents expected in the SPS are of the order of 7 µA to 70 µA. The Barkhausen noise in the magnetic material of the existing beam current transformers and the drift and fluctuations in their electronics are too high to permit a meaningful measurement of such low beam currents. A new current transformer must therefore be built with an improved geometry of the layers of magnetic material, an optimized modulator frequency and feedback. It is hoped to achieve a resolution of better than 1 μA for this high sensitivity beam current transformer.

The beam monitors in the injection transfer line, where the ion pulses are as short as 2 μs, can be adapted without much difficulty to the expected lead ion intensities. However, in the extraction channels and in the extracted beam transfer lines, the spill will have a duration of several seconds with correspondingly lower instantaneous ion intensities. Moreover, the total intensity is shared between the North and West Areas and between more than one experiment in each of these Areas. Therefore, the existing detectors in the extraction channels and in the transfer lines cannot be used for lead ions.

The secondary emission monitors for steering and intensity measurements of the extracted beams will be equipped with high quality integrating amplifiers which will be installed close to the monitors in the transfer tunnels in order to minimize the deterioration of the signals in the cables due to electrical noise and radiation-induced ionisation. These integrating amplifiers have already been designed and constructed for the oxygen operation in 1986 and can be re-used. They must be mounted and demounted before and after the lead ion runs to avoid damage during operation with high intensity proton beams.

Beam profile measurements are needed for setting-up of the extracted beams, for emittance measurements and for the adjustment of beam splitting. During operation with protons secondary emission grids are used for these measurements. However, at the expected lead ion intensities, the signals from the individual strips of a grid become so low that the required sensitivity cannot be achieved, even with high quality integrating amplifiers close to the monitor. It is therefore proposed to use, for the profile measurements, luminescent screen monitors of which the screens will be observed by highly sensitive SIT (Silicon Intensifier Target) cameras. The signals from the latter will be processed by VME-based electronics to obtain the desired beam profiles. Most of the required luminescent screen monitors, though equipped with standard Vidicon cameras, already exist and are installed in suitable positions, but additional monitors are needed in the two extraction channels and at the upstream ends of the beam transfer lines TT20 and TT60 to the North and West Areas.

The extracted lead ion currents are of the order of a few times 10^{-11} A. Therefore, highly sensitive detectors are required for the servo control of the slow spill. Such a detector will consist of a thin scintillator placed in the beam path and observed by a photomultiplier. The output current of the latter will be compared with a reference signal and the difference between the two signals will be fed, after amplification, into the power converter of a quadrupole in the SPS ring which controls the spill-out. With the exception of the thin scintillators for the spill control, all intercepting material of the transfer line monitors will normally be retracted from the external beams after setting-up.

7.4. Beams to the Experimental Areas

On their way to the experimental areas some of the lead ions will be absorbed in the steel septa of the splitter stations while all ions must pass through beam windows and air in the target stations and the mobile dump regions of the secondary beams. A first assessment of the effects to be expected because of nuclear and Coulomb dissociation ($\sim Z^2$) interactions of the lead ions has been made[40]. This study indicates that at the end of the beam lines the contamination of the lead ion beams by lighter nuclear fragments should not be larger than that which has been observed for oxygen and sulphur ions and which has proven not to be detrimental for the experiments[41]. However, because of the larger interaction cross-sections of lead ions compared to lighter ions, a larger fraction (about 30%) of the beam flux would be lost in traversing the target stations and the mobile dump regions. It seems prudent to reduce these losses by a substantial factor, since the beam intensity expected from the proposed lead ion source does not have much margin compared to the requirements of the experiments, as was already the case for the sulphur ions in 1987.

The losses can be reduced to less than 10% by reducing the amount of material in the beam path to the minimum which can realistically be achieved. The parts of the beam path traversing the target stations and mobile beam dumps which at present are in air, must be replaced by vacuum or helium gas contained between thin aluminium windows. All existing titanium or stainless steel beam windows and the sensing foils of the target monitors will be replaced by foils made of high strength aluminium alloy with minimum thickness. In principle, the best solution would be to have a continuous vacuum system during operation with lead ions. However, this is not a realistic proposition because of the design constraints imposed by the existing installations and the need to minimize the time of intervention when changing between proton and lead ion operation, because of the high level of radioactivity in the target stations. Under these conditions the solution described above is considered to be the best compromise.

In proton operation the profiles of the secondary beams are measured with wire chambers placed in air between beam windows. Since these measuring stations represent too much material in the beam path, they were replaced by a continuous vacuum pipe and the beams were operated "blindly" during the previous light ion runs. In this context it should be mentioned that the presence of material in the beam path downstream of the momentum analyzing sections cannot be tolerated since nuclear fragments produced at such places are not removed from the beam. For the operation with lead ions a number of wire chambers at critical locations in the different beams will be replaced by pairs (horizontal and vertical) of filament scintillation counters (FISC's) which are housed inside vacuum tanks and can be moved by stepping motors to measure the position and profile of the lead ion beams. A number of FISC's are already installed and the last pair in each beam line is equipped with a set of electronics for pulse-height analysis. For lead ions, however, a higher resolution is required to allow the composition of the beam to be verified in terms of ion species. Such measurements have proved to be extremely useful in the previous light ion runs[41]).

It should be noted that four out of the five locations available for lead ion experiments are in open, i.e. unshielded, experimental areas. They are, therefore, designed to receive beams at intensities per SPS pulse of $\sim < 5 \times 10^8$ elementary particles which corresponds to $\sim < 5 \times 10^5$ lead ions. Depending on the experiments approved, extensive shielding of the beam lines and associated modifications to the layout may be necessary. No cost estimates for such changes have been included.

8. Replacement Injector for LEAR

The present Linac 1 will have to be moved out of its building in order to provide the space necessary for the Lead Linac. Linac 1 has so far been operating mainly as a facility to supply test beams for LEAR as well as the acceleration of ions. Protons as well as H^- ions were requested. The future Lead Linac will not be an appropriate injector for LEAR. Hence, LEAR has to have its own injector. As the energy required for this purpose can be as low as 10 MeV, tank 1 of the present Linac 1 would be adequate. The RFQ1 would again be mounted directly onto tank 1, guaranteeing optimum beam matching and minimum losses. Although it must be admitted that Linac 1 showed some deficiencies in the vacuum tightness of the watercooling system, tank 1 would certainly meet the requirements as injector of protons or H^- ions and could be located in the vicinity of LEAR.

9. Possible Future Intensity Improvements of the LEAD Ion Beams

In the future, intensity increases are certainly of interest. A straight forward possibility is "funneling". In this scheme a second ion source and a second RFQ (running at 100 MHz) would be needed to fill the empty buckets of the 200 MHz DT Linac. Joining the two beams from the two RFQ's would require 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.

Development in the ion source field is the most likely reason for intensity improvements. Development in the ECR field is continuing with a tendency towards 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 in intensity. The development of the EBIS sources has also to be followed. Laser ion sources, as developed for example at Dubna and Munich, also seem to have a high potential of development.

10. References

1) Sluyters, T., "A Theoretical and Experimental Comparison of Proton and Deuteron Acceleration in the CERN Linear Accelerator", CERN 64-22 (1964).

2) Asboe-Hansen, P., Barbalat, O., Boussard,D., Bouthéon, 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).

3) Bouthéon, M., Cappi, R., Haseroth, H., Hill, C.E., Koutchouk, J.P., "Acceleration and Stacking of α-particles in the CERN Linac, PS and ISR", Proc. 9th US Particle Accel. Conf. Washington, IEEE Trans., NS-28, P. 2049 (1981).

4) Schindl, K.H., "Light Ions Via the PS Booster", PS/BR/Note 81-10 (1981).

5) Foegen, B., Sherwood, T.R., "The EBIS Program at CERN", Workshop on EBIS and related topics, Darmstadt (1977).

6) 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).

7) Stock, R., et al., "Letter of Intent to the PSCC-1980".

8) 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.

9) 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.

10) Wolf, B.H., et al., "Performance of the Oxygen Injector for the CERN Linac 1", Report GSI-86-2, ISSN:0171-4546, 1986.

11) Wolf, B.H., et al. "Heavy Ion Injector for the CERN Linac 1", NIM A258,1,1987.

12) 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.

13) Angert, N., Brouzet, E., Garoby, R., Hancock, S., Haseroth, H., Hill, C.E., Schindl, K., Têtu, P., "Accelerating and Separating Mixed Beams of Ions with Similar Charge to Mass Ratio in the CERN PS Complex", presented at EPAC, Rome, 1988.

14) 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.

15) B. Franzke, IEEE Trans. Nucl.Sci. NS-28, 2116 (1981)

16) H. Gould and B. Feinberg, LBL, Priv. Comm. (1988)

17) W.G. Graham et al., Phys. Rev. A30, 722 (1984)

18) Min. of the 5th Lead Linac Meeting, PS/DI/DS/Min 88-5, Figs. 1,2

19) U. Ratzinger et al., "The Upgraded Munich Linear Heavy Ion Post Accelerator", 1987 IEEE Part. Acc. Conf. Washington

20) U. Ratzinger in Minutes of the Second Lead Linac Meeting, PS/DI/DS/Min-88-2.
21) R. Geller et al., "Sources for Highly Charged Ions - The ECRIS Status", Proc. Linear Accel. Conf., Seeheim, 1984 (GSI-84-11, 1984)
22) E.D. Donets, "Review of the JINR Electron Beam Ion Sources", Int. Conf. Heavy Ion Sources, Gatlinburg, 1976 (IEEE Trans. Nucl. Sci. NS-23, 897, 1976)
23) J. Arianer et al., "The Orsay Electron Beam Ion Source", ibid. p979
24) M.C. Vella, "Physics of the High Current Density Electron Beam Ion Source (EBIS)", LBL-10611 (1980)
25) R. Geller et al.,"Status of the Multiple Charged Heavy-Ion Source MINIMAFIOS", Rev. Sci. Inst. 56, 1505, (1985)
26) B.Wolf et al., "Heavy Ion Injector for the CERN Linac 1", NIM A258, 1, (1987)
27) U. Tallgren (Ed.), "Workshop on a Lead-Ion Linac for the CERN Accelerator Complex", CERN/PS 88-10(DL) (1988)
28) B. Jacquot et al., "Source d'ions lourdes Caprice 10GHz 2ωWc", NIM A269, 1 (1988)
29) Y.D. Beznogikh et al., "Laser Multicharge Ion Source of the Dubna Synchrophasotron", Proceedings, High-Energy Ion-Atoms Collisions, Debrecen, Hungary 1987 (Lecture Notes in Physics 294)
30) C. Biscari, "Computer Programs and Methods for the Design of High Intensity RFQ's", CERN/PS 85-67 (LI).
31) C. Biscari and M. Weiss, "Choice of Parameters for the CERN High Intensity RFQ (RFQ2 Project)", Proceedings of the 1984 Linear Acc.Conf. Seeheim, Fed. Rep. of Germany.
32) Minutes of the 7th Lead Linac Meeting 2-June-88, PS/DI/DS/Min 88-7
33) D.J. Warner, to be publ. in Proc.of the 1988 Lin. Acc. Conf.,CEBAF
34) Damm, R., Oms, A., Lo Grasso, V., "Quadrupole Focusing System for the 200 MeV Linac", Proc. 1970, Proton Linear Accelerator Conf., NAL, p561 (1970)
35) W.K. Dawson, R.W. Dobinson, D.P Gurd, C. Serre, "A Conceptual Design for the Triumf Kaon Factory Control System", TRI-87-1
36) G.P. Benincasa, "The Control System for EHF (Basic ideas)", PS/CO/Note 87-002
37) E. Boltezar, H. Haseroth, W. Pirkl, G. Plass, T.R. Sherwood P.H. Standley, P. Tetu, U. Tallgren, D. Warner, M. Weiss, "Review and Status of the CERN new 50 MeV Linac and Project", Proc. 1976 Proton Linear Acc. Conf., Chalk River, AECL-5677
38) E. Boltezar, H. Haseroth, W. Pirkl, G. Plass, T.R. Sherwood U. Tallgren, P. Tetu, D. Warner, M. Weiss, "The New CERN 50 MeV Linac", Proc. 1979 Linear Acc. Conf., Montauk. BNL 51134.

39) C. Carter et al., 1987 PAC, Washington, and CERN/PS 87/35 (BR)

40) P. Grafström: "Note on the Possibility to Transport Lead Ions in the SPS Secondary Beams", Report to the SPSC by the Heavy Ion Discussion Group, CERN/SPSC 87-52, SPSC/T27, p. 43. 1 December, 1987.

41) H.W. Atherton et al., "Contamination of Nuclear Fragments in a 200 GeV per nucleon Oxygen Ion Beam at CERN", CERN/SPS/37-11 (EBS) and IEEE Part. Acc. Conf. Washington, 1987.

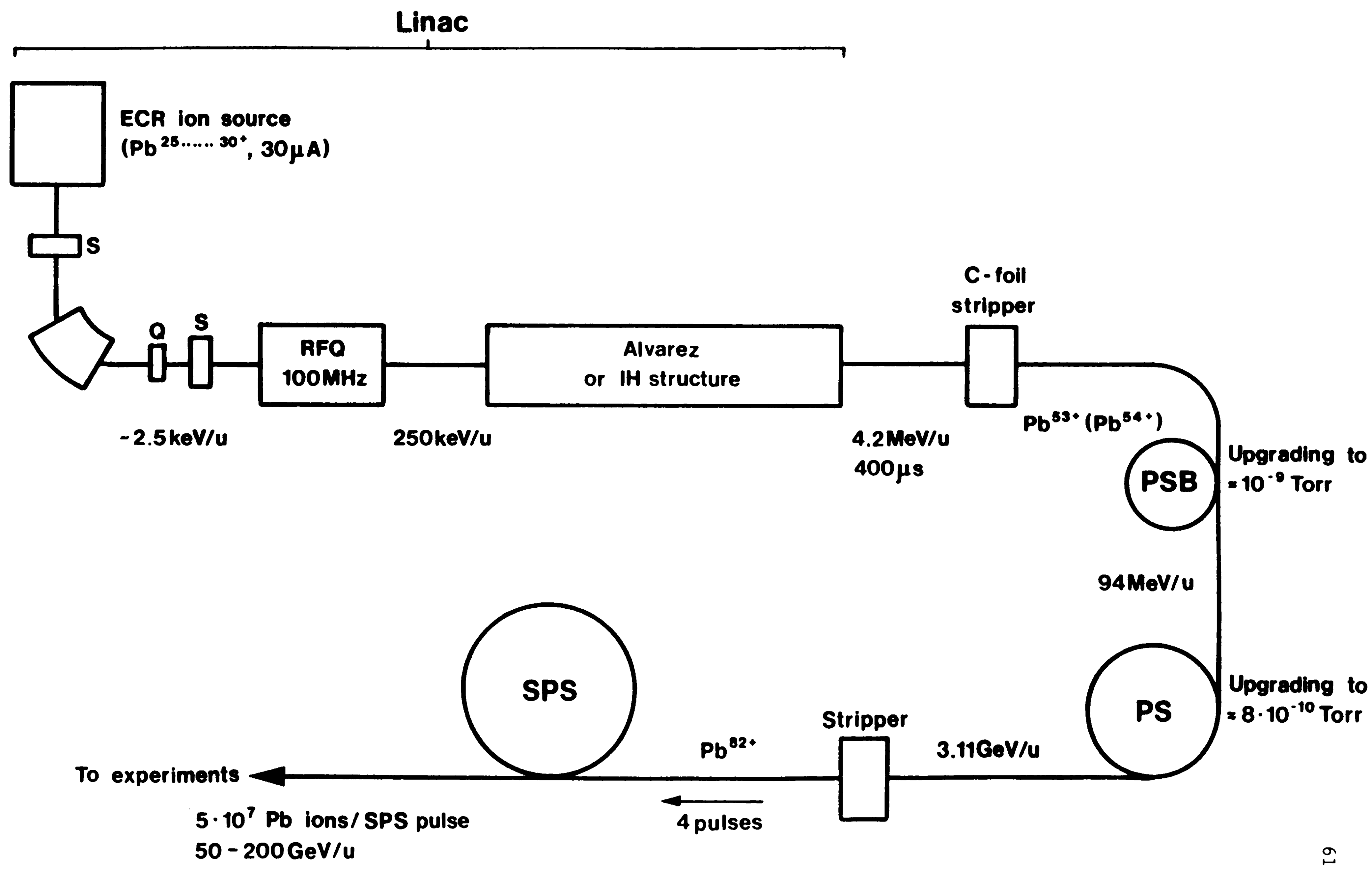


Fig. 1: Schematic layout of the accelerator complex

Fig. 2: Transmission of Pb^{53+} in PSB and PS

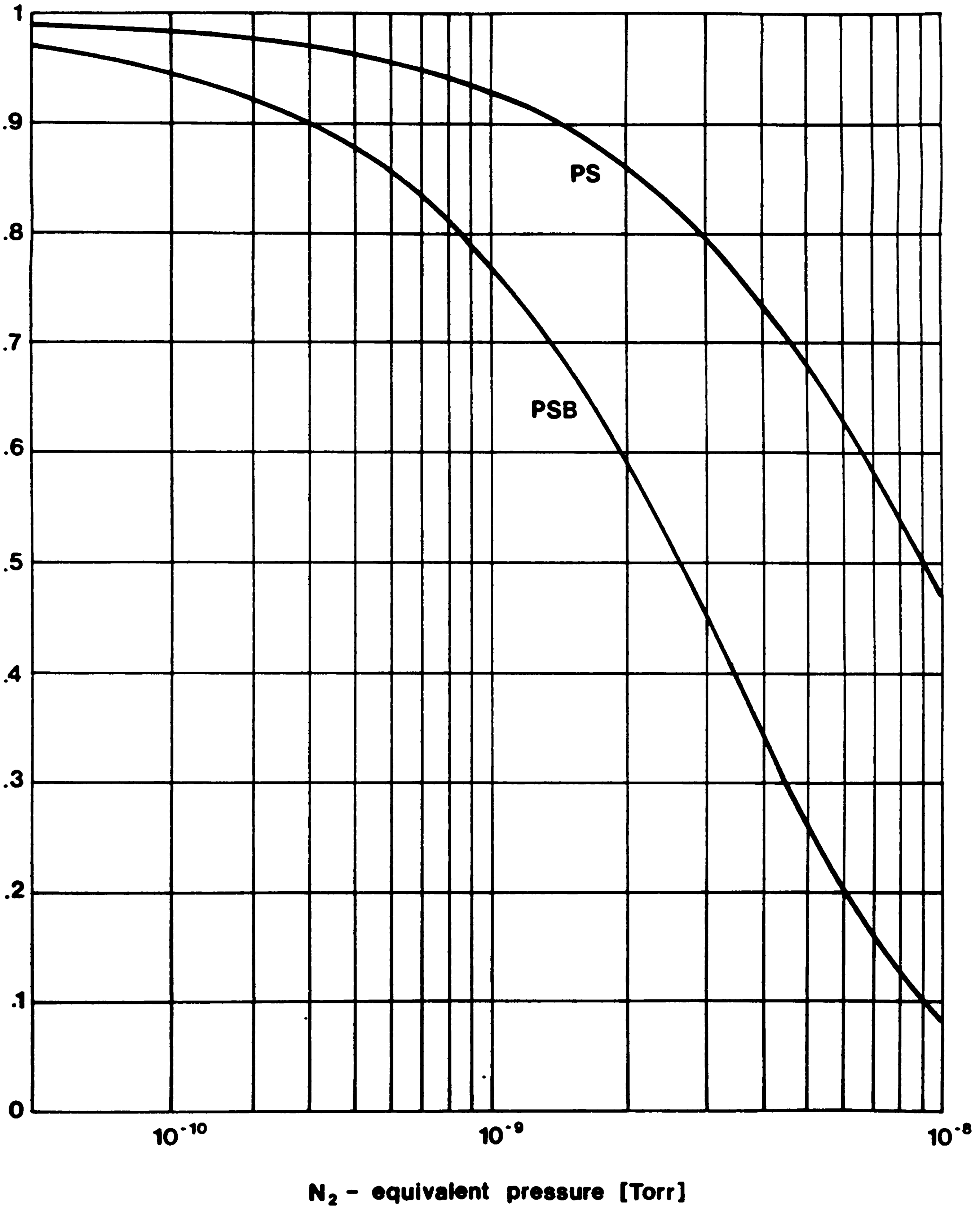


Fig. 3: Output beam of the RFQ

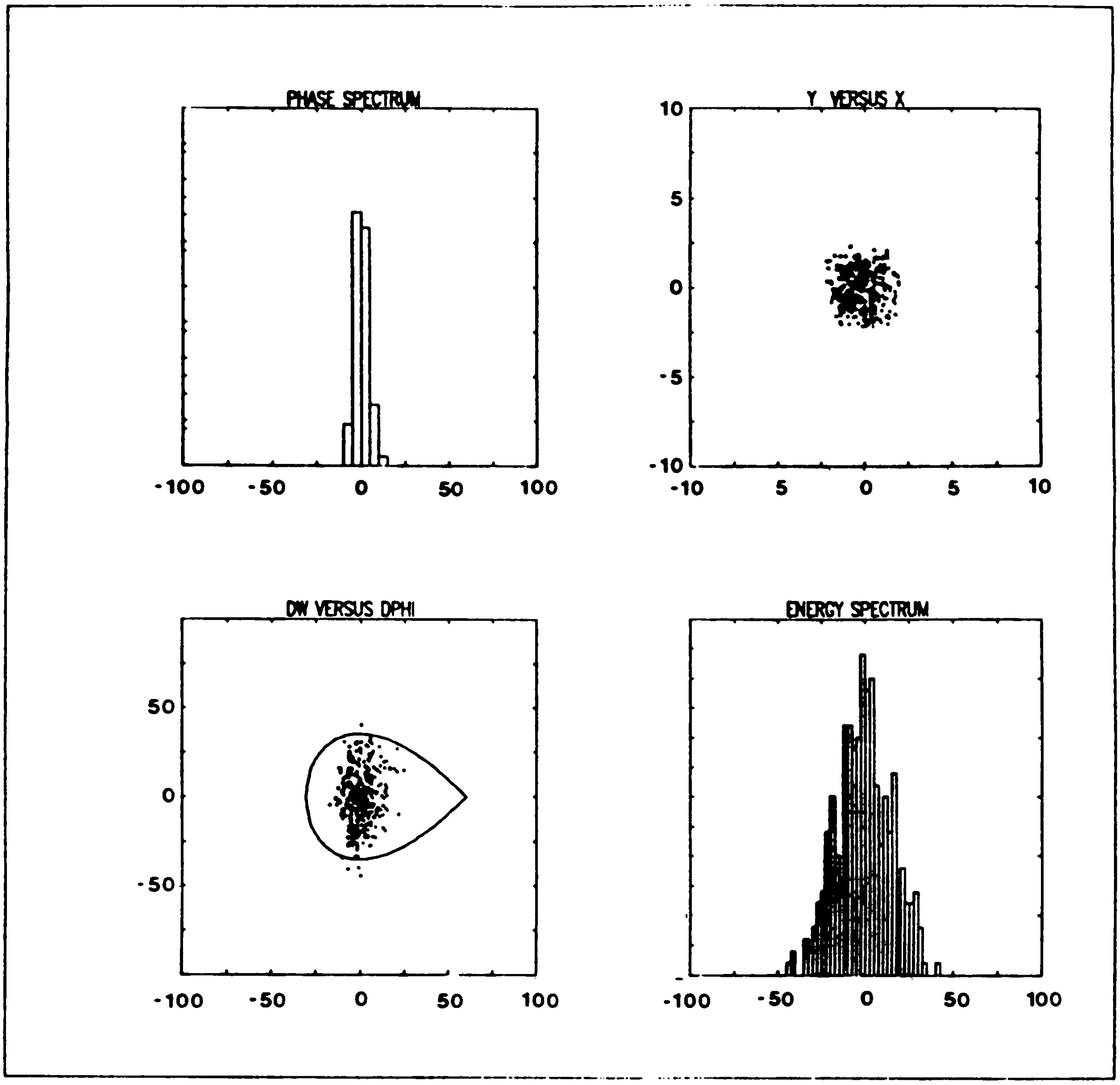
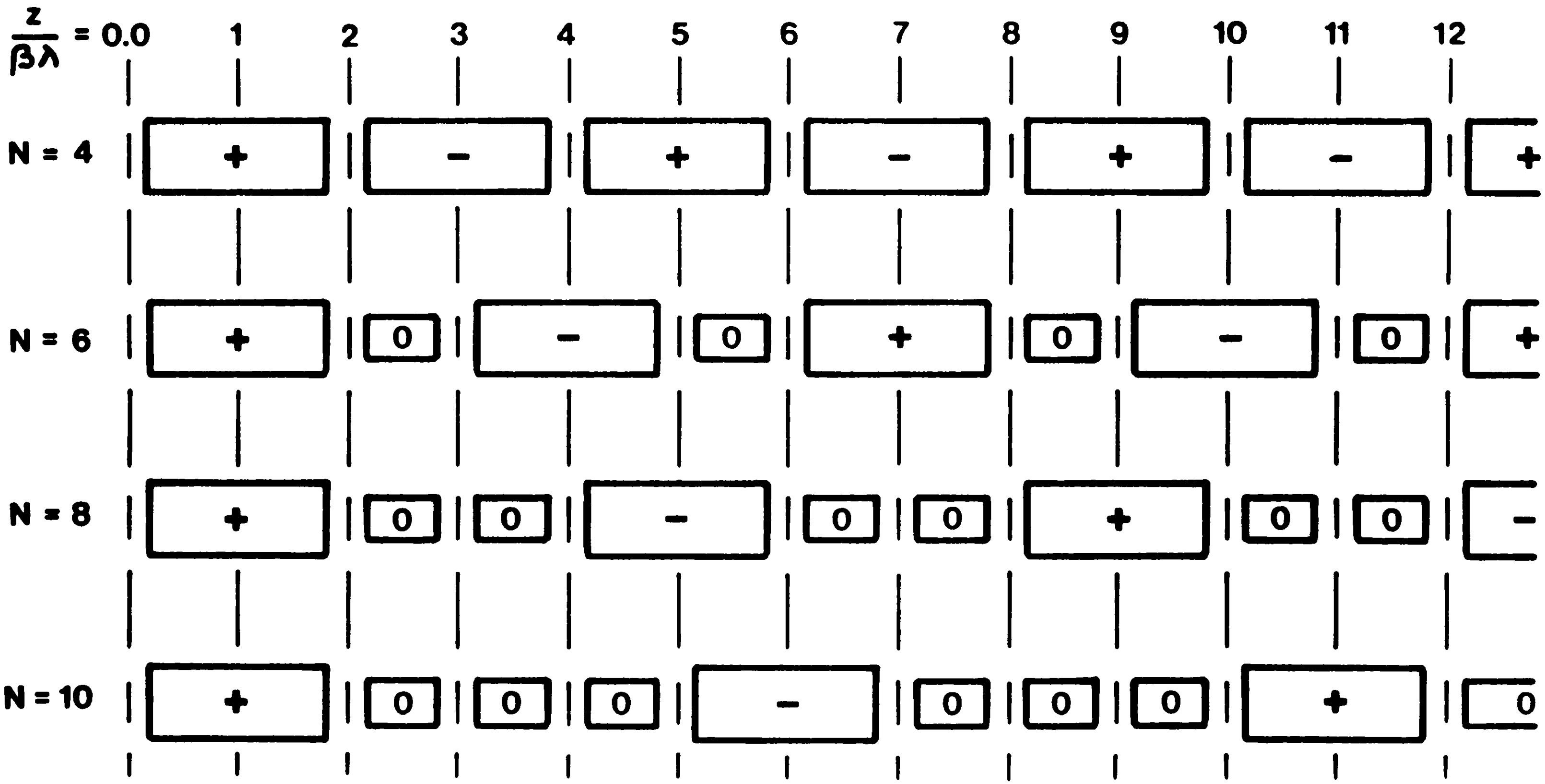


Fig. 4: Focusing periods with "empty" drift tubes: Nβλ is repeat length



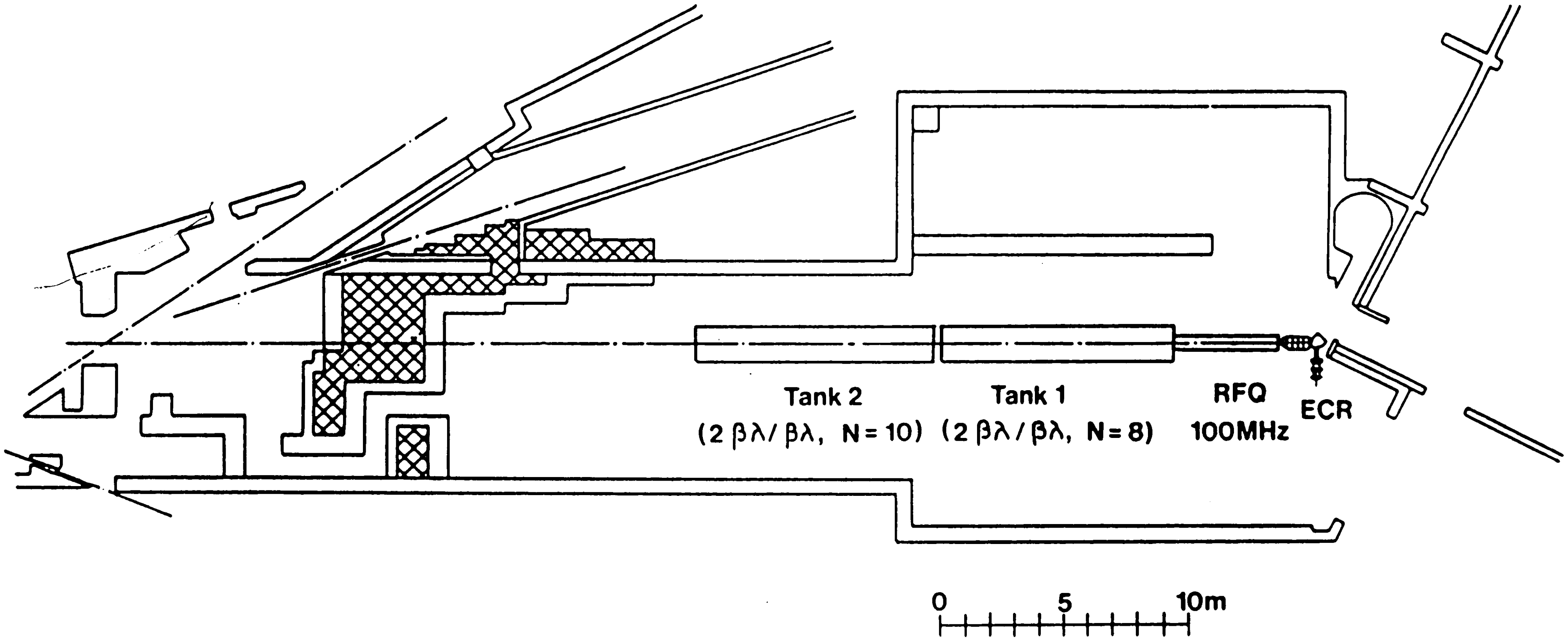


Fig. 5: 4.2 MeV/u Pb $^{25.......30^+}$ Linac (Drift-Tube version) in Linac 1 tunnel

APPENDIX

COST AND MAN-POWER ESTIMATE

1. Linac

	KSF (1988 prices)	CERN Staff (man-years) programmer	technician	engineer
- Source				
(present supplies re-used)	2,700			
Cabling and installation (incl. contract labour)	280			
	2,980		1.3	.2
- RFQ + beam transport				
Struct. fully equipped	410			
Vacuum system	240			
Cabling	50			
Beam transport + power suppl.	120			
Draughting (4 man-years)	320			
	1,140		1.5	1.5
- DT Linac:				
Structure, tanks equipped, intertank	1,600			
Vacuum system with drivers, gauges and controls	700			
Pulsed power supplies for quads (about 20 groups)	600			
Support structures with civil eng.	150			
Cabling and plumbing on structure	250			
Assembly and tests	200			
Draughting	200			
	3,700		6.0	8.0

	KSF (1988 prices)	CERN Staff (man-years) programmer	technician	engineer
- Controls:				
Digital hardware	1,600			
SOS (analogue signal transm.)	700			
Software subcontracted	2,200			
	4,500	4.0	1.0	1.0
- Timing	90	1.0	0.5	0.3
- Instrumentation and high energy beam transport:				
Low energy instrumentation	375			
Charge state separation	300			
High energy instrumentation	140			
High energy beam transport	465			
	1,280		4.0	2.0
- RF:				
Upgrading and adopting existing equipment	1,770			
Additional debuncher supply	350			
Modulator for debuncher	190			
RFQ supply at 101.25 MHz	750			
	3,060		6.0	6.0
- Building modifications, air conditionning, cooling	450			
Subtotal Linac	17,200	5.0	19.3	13.0

Above figures are based on the "economical" version of the DT Linac (see chapter 4.4.5). In case of the "safe" version, the expenses will not be considerably higher. A future decision in favour of the IH-structure (chapter 4.1) may result in savings for the Linac part, but those will, to a large extent, be compensated by additional expenses for a longer RFQ and/or for additional 100 MHz RF equipment.

	KSF	CERN Staff		
	(1988 prices)	(man-years) programmer	technician	engineer
2. Instrumentation PSB/PS, Beam Control and Stripping				
- PSB :				
phase pick-up and electronics	50			
DC beam transformer, mechanics	50			
DC beam transformer, electronics	20			
Injection line beam transformer	50			
Video signal processing	40			
Digital frequency program and separat. of the dedicated hardware for the heavy ions	120			
PS :				
PU signal processing	20			
Beam control: install. of dedic. ion equipment	50			
Beam transformer (external beam line)	50			
Stripper mechanism and controls	80			
Subtotal	530		5.0	2.3
3. Transfer Lines and Injection/Ejection PSB/PS				
Linac - Booster:				
Supplies for: distributor, post-deflector, septa, quadrupoles	560			
PSB injection kickers	100			
PSB ejection and recombination kicker supplies	900			
PS injection kicker (supplies and magnet connections)	200			
Subtotal	1,760		3.0	1.5

	KSF (1988 prices)	CERN Staff (man-years)		
		programmer	technician	engineer
4. Vacuum upgrading in PSB and PS				
PSB, first stage	400			
PS, first stage	300			
Subtotal	700		1.5	0.5
5. SPS upgrading				
Capture and acceleration:				
Electronics etc. for low level beam control	240			
Contract labour	60			
Beam instrumentation in SPS and transfer lines:				
Upgrading of 216 PU stations	270			
Beam current transformer	80			
Screen monitors	220			
SIT cameras	380			
Monitors for spill control	120			
Contract labour	260			
Beams to the experimental areas:				
Vacuum chambers helium gas enclosures in target stations	400			
Thin foil monitors	160			
Vacuum chambers in dump regions	200			
FISC monitors	250			
Electronics for pulse-height analysis	100			
Contract labour	240			
Subtotal	2,980		6.0	3.0

	KSF (1988 prices)	CERN Staff (man-years) programmer	technician	engineer
6. LEAR Injector				
Dismantling and re-installation	350			
Cabling	150			
Beam transport and instrumentation (3 bend. magnets, 6 quads with power supplies and meas. equipm.)	450			
Civil engineering	200			
Modif. of LEAR auxil. equipment	250			
Building for above equipment	200			
Subtotal	1,600		0.5	0.5
TOTAL	24,770	5.0	35.3	20.8
Contingency	2,500			
GRAND TOTAL	27,270			

N.B.: This estimate is based on certain assumptions on charge exchange cross-sections and pump-down time in PSB and PS rings. Additional upgrading (see chapters 5.5 and 6.5) may be needed (perhaps only partially):

Cost estimate for PSB : 1,055 KSF
" " " PS : 2,550 KSF

Total **3,605 KSF** + approx. 10 man-years

ESTIMATE OF THE CONSTRUCTION TIME

System	(years)
1. Linac	
- Source	2.5
- RFQ + Beam Transport	2.5
- DT Linac	3.0
- Controls and Timing	3.0
- Instrumentation and high energy beam transport	3.0
- RF	3.0
- Building modifications, air-conditionning	1.5
2. Instrumentation PSB/PS, Beam Control and Stripping	
- PSB and PS	1.5
3. Transport Lines and Injection/Ejection PSB/PS	
- PSB and PS	2.5
4. Vacuum Upgrading in PSB and PS	
- PSB and PS, first stage	1.5
5. SPS	
- Acceleration, beam instrumentation, experimental areas	2.5
6. LEAR Injector	1.5

The numbers given above are worst case figures and depend on the exact shutdown planning of our accelerators.

ESTIMATED TOTAL CONSTRUCTION TIME 3.0 YEARS