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ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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AT CERN

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ABSTRACT

After the successful acceleration of deuterons, alpha particles and in more recent years of oxygen and sulphur ions, interest arose for even heavier particles. This paper describes the problems associated with heavy ions. A proposal is made for a scenario which allows the CERN accelerators to cope with ions heavier than sulphur, e.g. lead. Discussed are the different options for the injector and the necessary upgrading for the circular machines.

PREFACE

This report presents a concept for a lead-ion accelerating facility at CERN. It describes a possible scenario for this facility, points out the boundary conditions such a proposal has to comply with, and discusses the technical 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 of using the interdigital H structure for the high-energy part of the lead-ion linac is very high if the ongoing calculations continue to confirm its usefulness. However, different approaches to the problem will not substantially lower the cost and manpower requirements. The reasons for this are explained in this 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 CERN, for their efforts and efficient collaboration.

Helmut Haseroth
Chairman of the Lead-Ion Linac Study

CONTENTS

FREQUENTLY USED SYMBOLS AND ABBREVIATIONS

β	particle velocity relative to that of light
λ	wavelength
q	charge state of ion (in units of elementary charge)
A	atomic weight (in atomic mass units u)
ϕ_S	angle of the stable phase in an accelerating structure
$\sigma_{q-1,q}$	cross-section for ionization from charge state q – 1 to q
eμA	*electrical* current in micro ampere contrary to particle current
σ_{0T}	transverse phase advance per structure period
σ_{0L}	longitudinal phase advance per structure period
$\overline{Q^2}$	average focusing per structure period
f	frequency
W	kinetic energy
E_S	electric field on the surface
E_z	electric field on the z-axis
E_{KP}	Kilpatrick field limit
T, TTF	transit time factors
B	magnetic induction
Z	shunt impedance of resonant accelerating structure
E_z	mean accelerating field
$B\varrho$	magnetic rigidity
γ	relativistic gamma-factor
γ_{tr}	γ at transition energy
Z	atomic number

1. INTRODUCTION AND SUMMARY

1.1 Introduction

Since the days of deuteron stacking and acceleration in the CERN Intersecting Storage Rings (ISR) 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 sulfur ions during the last few 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 sulfur ions, required in each case a modest upgrading of the CERN proton accelerators, mainly of the Linac. Heavy-ion acceleration (such as 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 electron cyclotron resonance (ECR) ion source providing 30 μA of Pb ions with a charge state of 25 + to 30 +. The ions will be accelerated with a d.c. potential of 20 kV into an RF quadrupole (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 Proton Synchrotron Booster (PSB)*).

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 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 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

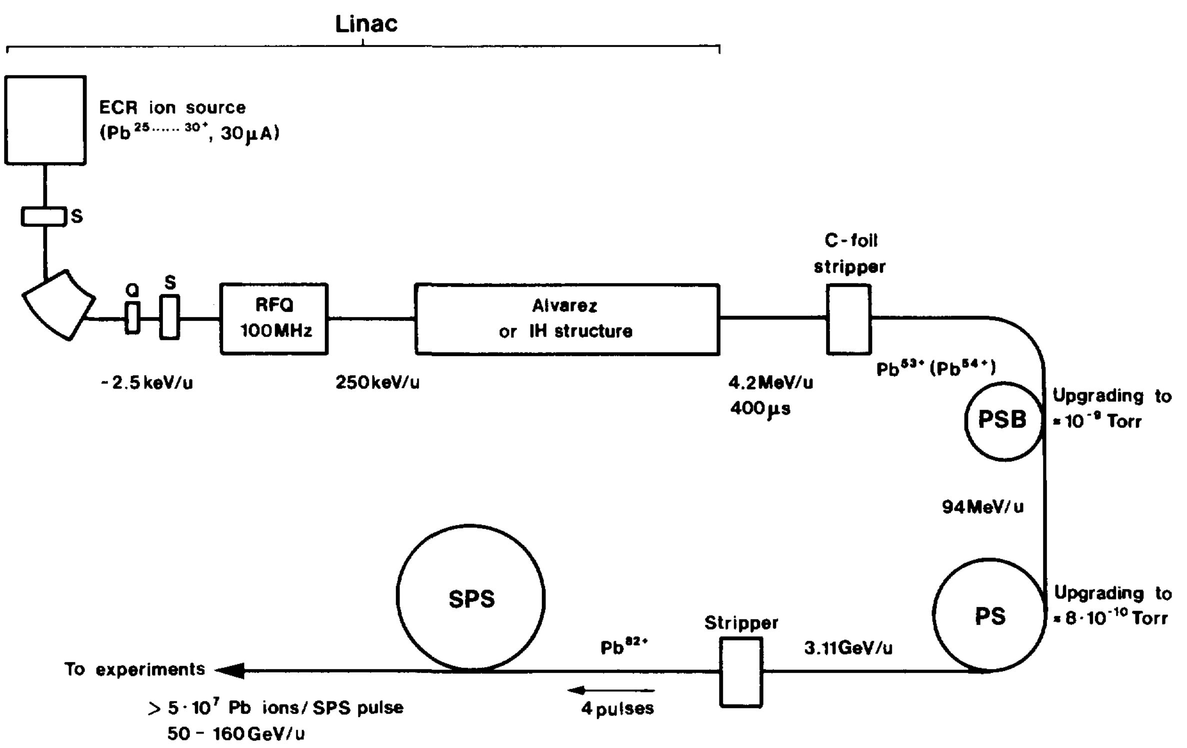

Fig. 1 Schematic layout of the accelerator complex

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*) 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.

achieved mainly by increasing the pumping speed with additional titanium sublimation pumps. Transfer to and injection into the PS require also the upgrading of some elements owing to the much lower energy (94 MeV/u instead of 0.8 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 Super Proton Synchrotron (SPS).

All machines will require improvements in 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 because of 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 that of applying the debunching/rebunching scheme several times as would be required when using the traditional 'integer harmonic' accelerating method.

An intensity of $\sim 4 \times 10^8$ Pb ions per pulse could 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 sulfur was achieved.

2.1 History of deuterons 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 of 2, 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, which is 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 time there was a certain interest expressed by the ISR community, and experiments were carried out with deuterons which were actually stored in the ISR[2)]. On the Linac side, the usual duoplasmatron was 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 per cent stripping efficiency at the energy of the preinjector (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 to proton operation was the change of the harmonic number by a factor of 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 of a factor of 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 due to the imperfect vacuum in the case of very heavy ions). 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 owing to the apparent lack of physics interest.

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

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

2.2 Present set-up for the acceleration of oxygen and sulfur 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 investment, 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 PB Booster and in the PS itself[8]. The instrumentation was also improved in the SPS, because the experiments were finally carried out at energies higher 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[9], 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 preinjector allowed easy installation of other possible sources because the additional complications with controlling and powering the source on a high-voltage platform had disappeared. Another important factor was the regained accessibility to the Linac 1 equipment during PS operation. This had to be abandoned in the past owing 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 the Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Fed. Rep. Germany, the Lawrence Berkeley Laboratory (LBL), Berkeley, USA, and CERN.

The plan was to use an ECR source capable of producing some 100 μA beam of O^{6+} ions, to accelerate this beam with a d.c. 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, Centre d'Études Nucléaires (CEN), Grenoble, France] 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 the Low-Energy Antiproton Ring (LEAR), 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 by 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 downstream 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 with 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 sulfur 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 sulfur 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 (such as 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 0.375.

No dramatic improvement in the field of ion sources can be anticipated in the near future. The only way to accelerate heavier ions at CERN is hence to rebuild 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:

i) 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.

ii) 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 most important 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 that 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 drastically increases 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 such as the Linac energy required careful consideration of the whole accelerator complex. This required several iterations before arriving at the selected energy (4.2 MeV/u). The following sections 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 to 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 a few experimental fixed points to verify the former. We have used an empirical formula fitted to GSI data[15] backed up by as yet unpublished calculations from LBL[16].

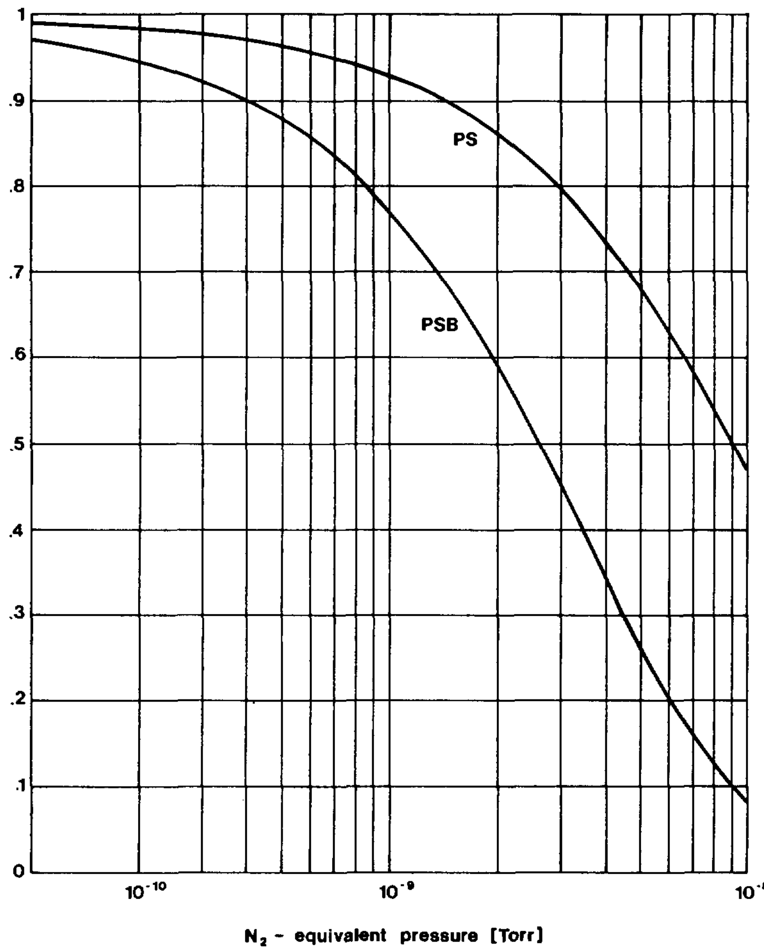

Fig. 2 Transmission of Pb^{53+} in PSB and PS

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 conversely 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. The 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 with those in charge-exchange processes.

3.3 Estimated final lead-ion beam intensity at the SPS

The previous oxygen and sulfur 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 per SPS pulse,
Oxygen, average:	1.2×10^8 ions per SPS pulse,
Sulfur, peak:	5.6×10^7 ions per SPS pulse,
Sulfur, average:	9.7×10^6 ions per SPS pulse.

The factor of 10 between peak and average intensity for the oxygen ions at the SPS had many causes: source instabilities, difficulties in 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 optimization of the conditions in the whole chain of accelerators. For the sulfur run, an additional difficulty existed owing to the abundant presence of oxygen ions with the same charge-to-mass ratio as the sulfur ions. Hence it was difficult to measure with confidence the actual sulfur-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*

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

  The factor of 4 comes from the fact that we use 4 batches from the PS to fill the SPS. The pulse length to fill the 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 (including transfer).

- *Total transmission factor*
  $0.9 \times 0.3 \times 1.0 \times 0.35 \times 0.8 \times 0.6 = 0.045$.

- *Estimated SPS intensity*
  $0.045 \times 3.8 \times 10^{10} \approx 1.7 \times 10^{9}$ oxygen ions per 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-ion 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 owing 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*

$$N = 4 \times \frac{30 \times 10^{-6} \times 400 \times 10^{-6}}{1.6 \times 10^{-19} \times 25} \approx 1.2 \times 10^{10} \text{ lead ions .}$$

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

- *Particle transmission*

RFQ:	0.9
Linac:	0.9

Stripping to 53+:	0.16 (owing to production of other charge states as well)
PSB:	0.25 (including losses due to residual gas)
PS:	0.7 (including losses due to residual gas)
Stripping to 82+:	1.0 (no losses)
SPS:	0.8 (in case of acceleration with phase jumps).

- *Total transmission factor*
  $0.9 \times 0.9 \times 0.16 \times 0.25 \times 0.7 \times 1.0 \times 0.8 = 0.018$.

- *Estimated SPS intensity*
  $0.018 \times 1.2 \times 10^{10} \approx 2.2 \times 10^{8}$ lead ions per SPS pulse.

Recent calculations have shown that the RFQ and the (Alvarez) Linac could simultaneously accelerate several charge states. If provisions are made for this facility an even higher intensity could be achieved:

$$\sim 4 \times 10^{8} \text{ lead ions per SPS pulse}.$$

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

$$5 \times 10^{7} \text{ lead ions per SPS pulse}.$$

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 sulfur 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 an increase of about 13% in magnetic rigidity, compared with 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 an ~ 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 the ion source and the exit of the Linac (at 4.2 MeV/u) is given in order to place in context the choices that had to be made to develop a reference design. It is evident that the latter is 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 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:

i) ion source, including the electrostatic preaccelerator,
ii) low-energy accelerator (RFQ),
iii) high-energy accelerator (Alvarez or interdigital H).

4.1.1 Ion source

a) Preferred option

The preferred solution here is the ECR source. This would be an extrapolation from the oxygen (O^{6+}) and sulfur (S^{12+}) 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 μs at a repetition rate of $\geqslant$ 1 pulse per 1.2 s. Another important parameter which fundamentally affects the design of the following accelerators (here assumed to be an RFQ and a drift-tube linac) is the maximum normalized emittance of 0.5π mm·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.

b) Other source options

The EBIS has been proposed as a possible source of ions, having the advantages of potentially very high charge states produced in a storage time well matched to the proposed repetition rate. However, no ready supplier has been found for this source. 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 μs), 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.

4.1.2 Low-energy acceleration

At the low-energy end of the lead-ion Linac, the RFQ with its electric focusing is the natural choice. Owing to constraints on the electrostatic preaccelerator, the input beam energy is, however, very low: $\approx$ 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 emphasized for the further RF acceleration, there is a distinct advantage for spare parts 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 normalized transverse output emittance of 1π mm·mrad is assumed. Another constraint that 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 that 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 be either of the 4-vane or of the 4-rod type; this choice does not affect the beam quality.

a) Preferred options

In spite of the undeniable advantages of an overall 200 MHz RF system, a lower frequency was preferred for the RFQ, 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 1π mm·mrad. The RFQ was optimized 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 $\sim$ 95% of the beam is about $1.6\pi \times 10^{-6}$ eV·s. This corresponds to 3.8 keV $\times$ 15° at 100 MHz.

b) Other options

Although at this stage of the project a standard 100 MHz RFQ has been preferred, 200 MHz RFQs 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 $2\beta\lambda$ mode.

4.1.3 High-energy acceleration

a) Alvarez type drift-tube linacs

In a paper[14] presented at the IEEE Conference in 1987 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 $2\beta\lambda$ 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[18] and the drift-tube linac was selected for further close study rather than the other options mentioned below. Nevertheless, it was recognized 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°. The beam-envelope modulation increases but the maximum aperture remains acceptable and the required quadrupole field actually decreases[19]. To satisfy the RF acceleration constraints the increased space between the $2\beta\lambda$ cells (with quadrupoles) is 'filled' with empty drift tubes having $\beta\lambda$ periodicity. This arrangement allows the number of drift tubes with quadrupoles to be reduced drastically (from 175 to $\approx$ 50), allows the accelerating rate to increase safely above the $2\beta\lambda$ level, and by using the empty drift tubes as variable elements allows an optimization of shunt impedance (ZT^2). The reference design has a focusing period of $8\beta\lambda$ up to 2 MeV/u and $10\beta\lambda$ thereafter.

b) Interdigital H structures

These structures have been used successfully above 2 MeV/u as Tandem Van de Graaff post-accelerators[20]. Their attraction lies in the high shunt impedances that can be obtained (about four times that of the Alvarez structure) and comes from three main sources, the field mode (H vs E), the acceleration mode ($\beta\lambda/2$ vs $\beta\lambda$), 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[21]. 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 the Tokyo Institute of Technology. The operating frequency is 48 MHz, the input energy is 0.25 MeV/u, and the acceleration is phase stable with $\phi s = -30°$. 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 ionization is generally not possible except for some low charge states. Thus, multistep ionization processes must occur, which take a time inversely proportional to the ionizing particle density. In electron-bombardment ionization, the incident electron must have an energy at least equal to the ionization potential (binding energy) of the last electron to be removed, and between three and five times this minimum for maximum efficiency of ionization. For the desired lead ions this ionization potential is ~ 1 kV. At the present time, only two sources, the EBIS and the ECR[22] are capable of producing lead ions of the required charge state and only they will be examined in detail.

In an EBIS[23] 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:

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

where J is the electron current density. Long formation times (low J) must be weighted 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 $1.37 \times 10^{12}/Q$ per metre of source length[24]. This converts into engineering units as $1.05 \times 10^7 \times P \times V \times N/Q$ per metre, where P is the electron gun perveance in μperv, V the gun voltage, and N the extraction efficiency[25]. In practice, N rarely exceeds 10 for heavy ions and stable high-perveance 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 ionizing electrons are injected into the source volume, an ECR source makes use of the electron component of a plasma heated by microwave radiation[26]. A surface can exist in a multimode cavity immersed in a magnetic field where the ECR condition exists for the injected microwave power (0.36 kG/GHz). Plasma electrons crossing this surface can, in general, be heated to higher energies, thus increasing the degree of ionization and the plasma density. In this case the formation time is given by

$$t = 1/[V \times N \times \sigma(q - 1, q)] ,$$

where V is the energy of the electrons 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 [$9 \times \sqrt{(N)}$kHz] approaches the RF. The microwave frequency can be increased, but this increases the ECR resonant magnetic field. Radio-frequency 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 d.c. acceleration gap carefully positioned in the edge of the plasma volume.

A 5 μperv 5 kV EBIS could produce about 2×10^{10} charges per pulse per metre 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 an increased perveance (limit 25 μperv) or by increasing the beam voltage (offset by the reduction of ionization cross-section with electron energy). An EBIS is used at Dubna, Saclay, and elsewhere, and is proposed for the Relativistic Heavy-Ion Collider 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 the sulfur runs at the SPS, and a development has been proposed to obtain 30 eμA of lead 25+ to 30+ ions[27]. As compared to the sulfur 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. Radio-frequency powers are estimated to be between 6 and 3 kW and it is here that technological difficulties arise. The RF must be nearly continuous wave (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 twice the cyclotron frequency can improve ion yields[28].

With 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-ion 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, since high fields (electric in the case of the 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

$$\sigma_{0T}^2 = \bar{Q}^2 - \frac{1}{2}\,\sigma_{0L}^2 ,$$

where $\bar{Q}^2$ describes the average focusing in a period, and $^1/_2\,\sigma_{0L}^2$ 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 is 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

$$E_S \leq 2E_{KP}$$

(where E_{KP} is the Kilpatrick field limit) could be satisfied only by lowering the RF.

4.3.2 Design of a 101.28 MHz RFQ

For the design of an RFQ one uses essentially two types of computer programs[30,31]. 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. As will be shown later, one can find 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 (normalized value 1π mm·mrad) played an important role 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, normalized: 1π mm·mrad.

In Table 1 we present several RFQs, which differ slightly in their parameters but which for one reason or another would not be accepted. These RFQs, however, helped us to approach the optimized design, the parameters of which are presented in Table 2 together with the output beam characteristics. The output beam is represented also in Fig. 3.

For the following accelerator, operating at twice the frequency (106.56), the phase spread is doubled. The resulting value of ~ 30° is still quite acceptable.

Table 1
Search for best RFQ parameters

Acceleration factor	Focusing factor	Voltage (kV)	Aperture (mm)	σ_{0T} (°)	σ_{0L} (°)	Length (m)	Transmission (%)	E_S/E_{KP}
0.29	3.80	70.8	3.5	20	21	5.25	71.1	1.9
0.36	4.75	81.1	3.2	25	25	3.70	90.6	2.3
0.35	4.51	59.5	2.9	25	21	5.30	96.4	1.9

Table 2
Optimized RFQ and beam parameters

a) RFQ

Acceleration factor	Focusing factor	Voltage (kV)	Aperture (mm)	σ_{0T} (°)	σ_{0L} (°)	Length (m)	Transmission (%)	E_S/E_{KP}
0.34	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

Normalized emittance	1π mm · mrad
Phase spread	15.2°
Energy spread	3.8 keV/u
Longitudinal emittance	$1.6\pi \times 10^{-6}$ eV · s

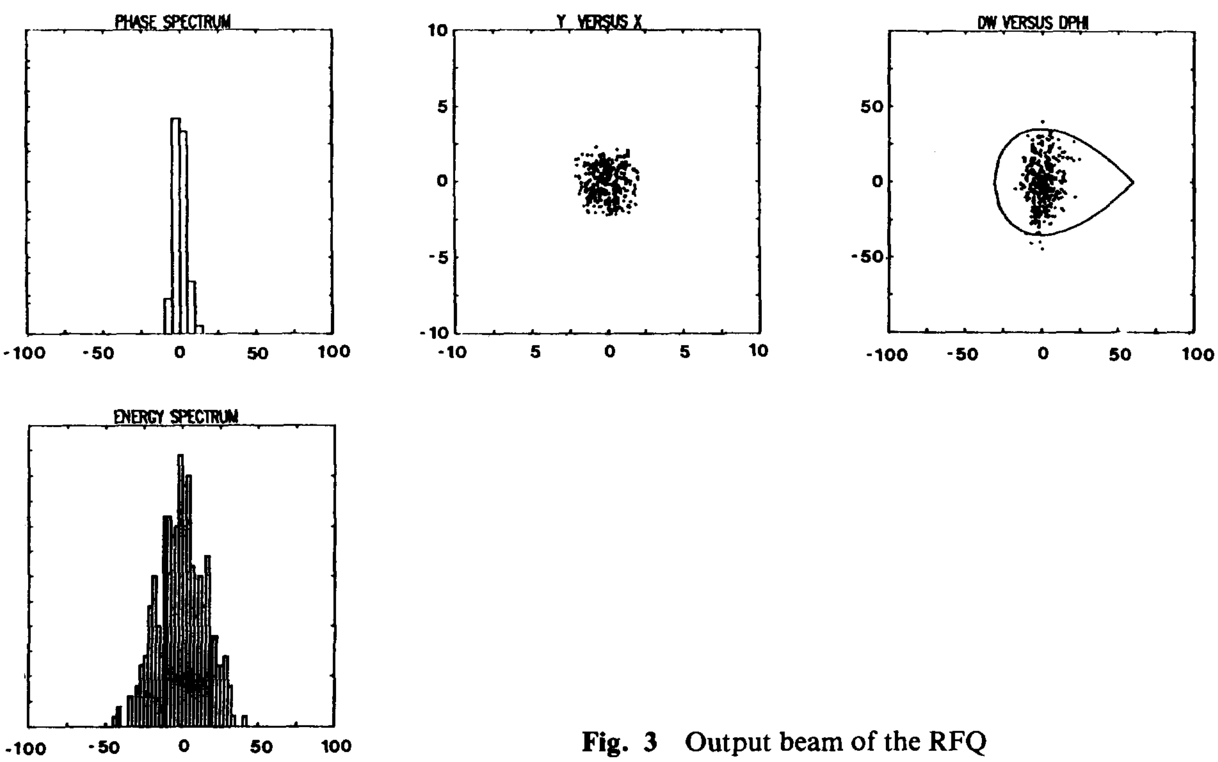

Fig. 3 Output beam of the RFQ

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 therefore has some advantages. We intend to shape the 'rods' in such a way that they can 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 since the beam from the ion source is rotationally symmetric. For more flexibility one usually used 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 T. 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 are being made to find solutions that eliminate these additional elements.

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 eμA of lead ions at 0.25 MeV/u with A = 208 and q = 25. (Both of these latter assumptions give some margin.) The normalized emittances assumed are 1π mm·mrad transverse and $1.6\pi \times 10^{-6}$ eV·s longitudinal. The linac operates at 202.56 MHz with an output energy of 4.2 MeV/u.

Two tight constraints are that the quadrupole pole-tip field must be less than 1.3 T and the peak RF electric field on the drift tubes must not exceed 1.5 times the Kilpatrick limit at 200 MHz (i.e. 1.5 × 14 mV/m). Weaker constraints are on the peak RF power requirement (assuming similar designs to Linac 2) and on the overall length, which for 4.2 MeV/u should fit easily into the existing Linac 1 building.

4.4.2 Design philosophy

A preliminary study had demonstrated that owing 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 subsection 4.4.1, a $2\beta\lambda$ structure would be necessary to house the strong quadrupoles at 0.25 MeV/u; this limits the accelerating rate (less gaps per metre) and requires many quadrupoles, especially if the structure reverts to the normal $\beta\lambda$ configuration at 2 MeV/u. The formulation used was that of a previous feasibility study for a lead-ion Linac[14]. In the present study this formulation could be adapted to treat the less usual cases with the focusing period extending over many $\beta\lambda$ periods (up to $12\beta\lambda$). The order in which the problems are treated in the following sections reflects this fundamental focusing difficulty: i.e. 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 Refs. 19 and 32) 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

Figure 4 shows the type of focusing period that has been analysed; the period is N × $\beta\lambda$ long with two quadrupoles in a FODO configuration, housed in drift tubes in the 2 × $\beta\lambda$ 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 since this represents the motion of a synchronous particle with much better precision (assuming constant momentum over a period). The quadruoles 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

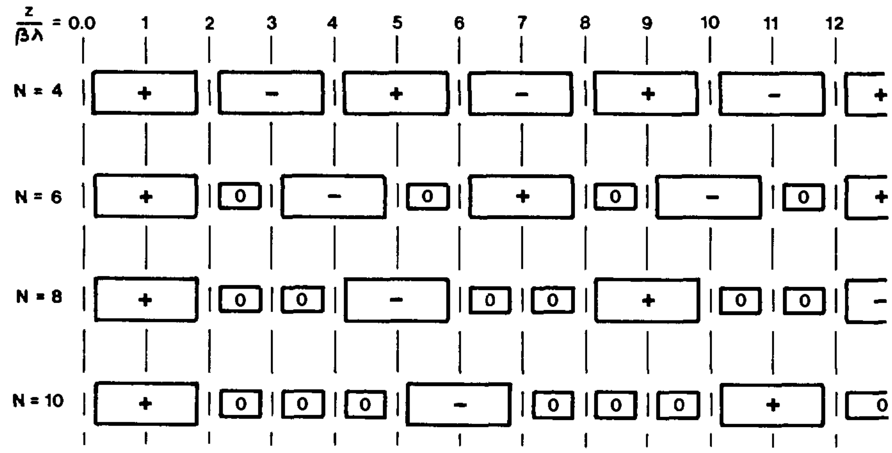

Fig. 4 Focusing periods with 'empty' drift-tubes: Nxβλ is repeat length

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 while 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 reoptimize both the focusing period and the structure.

The parameter that best characterizes 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 decreases 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 (> 0.65) at the beginning of the linac 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 3

Aperture (a) and quadrupole gradient (G') as a function of period length

N	G' (T/m)	σ_{0L} (°)	σ_{0T} (°)	a (mm)	ψ	B(7)
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 3 show that for N = 4 and N = 6 the maximum aperture required is less than the 6 mm specified for a satisfactory transit time factor, whilst for N = 8 the aperture (with safety margin) is slightly greater than 6 mm and for N = 10 the aperture required is nearly 8 mm. As these computations were made with the 'worst-case' conditions as far as energy, charge-to-mass ratio (q/A), synchronous 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 0.6π 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 defocusing N = 10 is quite safe (pole-tip field < 0.6 T).

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, which are both smaller in diameter and simpler in construction. When a quadrupole must be contained, the outer diameter of the drift tube must be 150 mm (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 per metre). 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 a fixed cavity diameter of 1.05 m 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 optimized, 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 with a proton linac the velocity gain per gap is small (1.1% compared with 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 (E_{KP} = 14 MV/m), in the first tank, whereas for the 'economical' design 1.5 × E_{KP} = 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 rises to 1.25 × 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 straightforward between 2 MeV/u and 4.2 MeV/u.

Numerical results are given in Table 4, 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.

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

Table 4
Provisional linac cavity parameters

	'Safe' design		'Economical' design	
	Input	Output	Input	Output
Tank 1				
W (MeV/u)	0.25	2.0	0.25	2.0
E_z (MV/m)	2.2	3.2	2.2	4.0
E_S/E_{KP}	1.0	1.0	1.0	1.25
ϕs (°)	−40	−30	−40	−30
TTF	0.65	0.73	0.65	0.73
Aperture radius (mm)	6	8	6	8
N	8		8	
No. $2\beta\lambda$ DTs	36 + 2(½)		32 + 2(½)	
No. $\beta\lambda$ DTs	74		66	
DT outer diameter (mm)	150/80		150/80	
Tank inner diameter (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
E_z (MV/m)	2.8		3.5	
E_S/E_{KP}	1.2	1.0	1.5	1.25
ϕs (°)	−30		−30	
TTF	0.83	0.82	0.83	0.82
Aperture radius (mm)	9	10	9	10
N	10		10	
No. $2\beta\lambda$ DTs	15 + 2(½)		12 + 2(½)	
No. $\beta\lambda$ DTs	48		39	
DT diameter (mm)	150/80		150/80	
Tank inner diameter (m)	1.02		1.02	
Tank length (m)	9.4		7.5	
RF power (MW)	1.2		1.5	

TTF = transit time factor
DT = drift tube.

region, i.e. 30° × 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 subsection 4.1.2 it may be possible to avoid this special (re)bunching system by designing the RFQ to deliver a beam that 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 interspace is less than 0.3 m. Assuming a matched beam at 0.25 MeV/u and a longitudinal emittance increase of a factor of 2, 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-ion Linac[33]. 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 (similarly to the aperture diameters). The maximum number of ampere turns required would decrease from 6300 At to 3800 At in the lead-ion Linac, corresponding to a gradient of 180 T/m and a pole-tip field of 1.26 T. The length of the winding slot can be chosen as a function of the number of turns and thus the inductance can be optimized according to the pulser requirements. For example, a lead-ion Linac quadrupole (at 0.25 MeV/u) could operate at 350 V × 150 A compared with the Linac 2 quadrupoles at 0.75 MeV which require 350 V × 300 A. 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 tolerances, e.g. ±0.5 mm radial compared with 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, owing mainly to there being fewer quadrupoles. In addition, the proposed cavity diameters of 1.05 m and 1.02 m allow for somewhat easier drift-tube installation than in Linac 2.

4.5 RF power

The acceleration system consists of three or four acceleration cavities:

i) RFQ
ii) Buncher (optional)
iii) Tank 1
iv) 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 ~ 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 ~ 1 ms. Each amplifier chain will have its own fast-acting closed-loop feedback system, which corrects 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 influences are generally very slow, it is sufficient to provide a slow-acting tuning system.

The amplifiers used are standard-type amplifiers delivering the following maximum 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 ~ 500 kW pulsed RF power. The chain will consist of four 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 requirement be higher than 500 kW, a driver stage, identical to the final stage, could be inserted between the second predriver and the final stage. From the final stage the power will be carried to the cavity by a rigid feeder line of 4 in. or preferably 6 in. diameter with an 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 by using three 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 and 2

These two identical chains have to furnish ~ 1.5 MW and consist of four 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 driver stage and final stage of the amplifiers are identical and use the water-cooled TH 170 R triode. The driver stage of the amplifiers could appear to be a little over-designed for a power requirement of only 200 kW, but it has the advantage of being relatively simple, using a tube with excellent lifetime (≈ 25000 h), 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, first predriver, and second predriver have their individual d.c. 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 large 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 that the ion source can be optimized. 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 reused. Additional equipment is needed to join the new shorter lead-ion Linac to the existing injection line. This is needed to ensure independent operation and setting up of the lead-ion Linac, as well as 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 minimize 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:

i) the selected charge state must be correctly matched to the existing part of the Booster injection line,
ii) the filter must be achromatic,
iii) independent measurements of the charge state must be possible,
iv) the system must be short, so as to fit the available space,
v) 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 will be one way to increase the beam intensity.

4.7 Layout of the lead-ion Linac control system

4.7.1 Introduction

In a modern control system we distinguish essentially two different functions: the operator interface to the system, classically implemented by the operator consoles; and the process access, which was supplied by the front-end computers (FECs). With the advent of low-cost graphic work stations the operator consoles, usually implemented on 16-bit minicomputers, became outdated. In the near future the consoles will therefore be implemented on the work stations. Because of the ever-increasing complexity in accelerator control (different modes of operation, more and more automatization) a single FEC became too limited in real-time response since it had to handle too many requests in parallel. Here, cheap microprocessor-based controllers allow us to distribute computing power right down to the equipment, and by multiplying the number of these controllers we considerably augment the total processing power. The problem left is the interconnection of these controllers with the work station, which can be accomplished by modern high-speed local area networks.

4.7.2 Requirements for the lead-ion Linac system

a) Overall layout

It was decided that the future consoles should be implemented as Unix-based work stations. Several DEC VAX stations have been purchased together with a file server to be used in the future PS control system. For the lead-ion Linac another six of these work stations and their associated file server resources will be needed. The real-time process access will be done by several device stub controllers (DSCs) running the OS–9 operation system.

The global layout of the control system will thus look similar to Fig. 5.

b) Work stations

In the PS control group two projects are currently under way, addressing the problem of using work stations as consoles in accelerator control systems. The two projects work together in tight

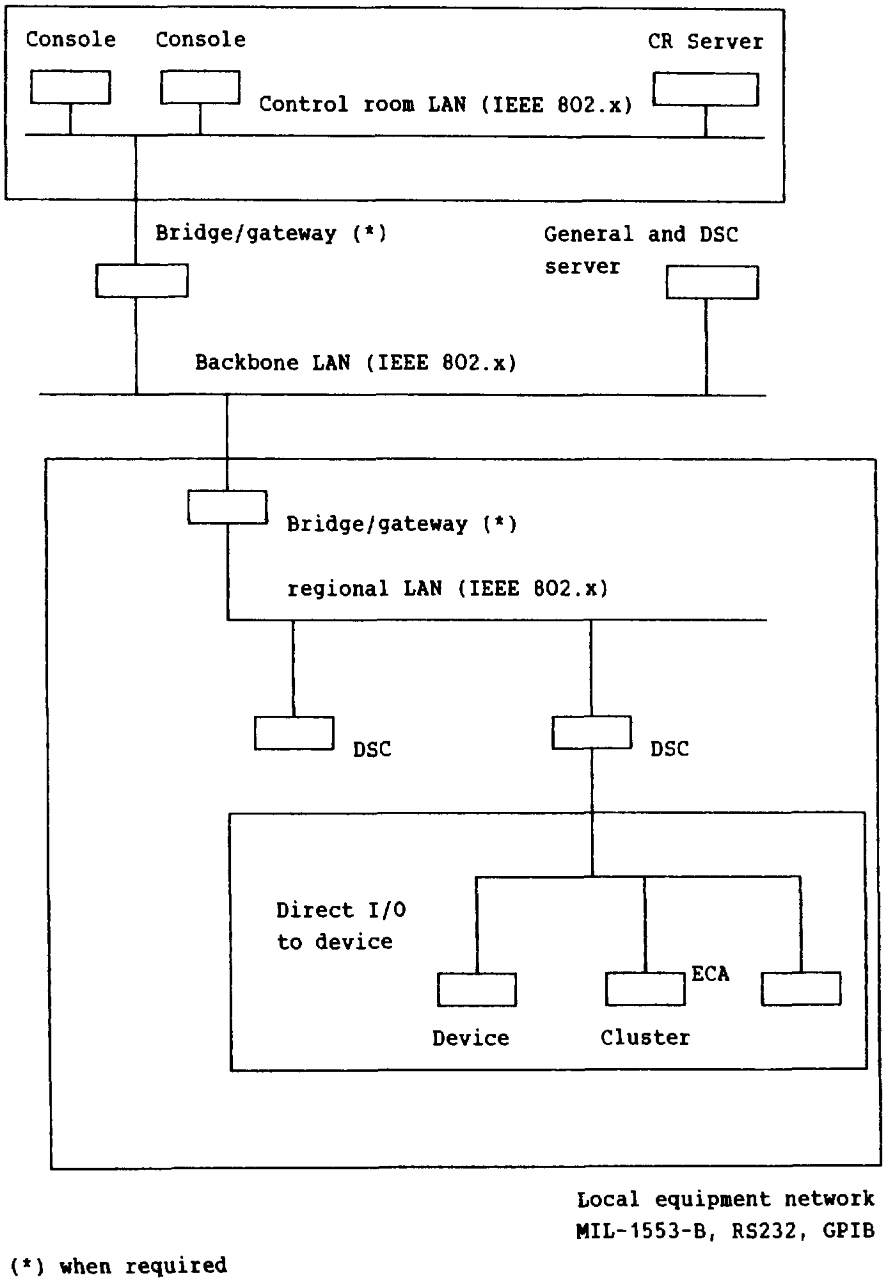

Fig. 5 Global layout of the control system for the Linac

collaboration for all aspects common to both. The final goal is to entirely replace the present consoles in the main control room and the Linac consoles and to give access to the parameters of all accelerators from the main control room. The work was divided into two projects because of the difference in parameter access (Linac real-time system on a PDP-11, equipment modules access for the others), where each of the projects has to go its own way.

The lead-ion Linac will directly benefit from the work done in these projects. Current ideas of what software for the work-station consoles should provide for are:

- to allow easy access to several parameters in parallel (~ 4–8 parameters as a minimum),
- to allow the parameters to be changed using absolute values or user-definable increments,
- to provide an easy and natural mechanism to select an application program or the parameter whose value is to be shown or changed,
- to be able to run several application programs in parallel, having the outputs on a single screen (for comparison).

These are the features the operator will see in his daily work. In addition to the above, the lead-ion Linac control system needs a means to access ~ 400 analog signals where any combination of four signals seems to be sufficient. The multiplexing of analog signals is not yet considered by the rejuvenation program of the PS controls. This means that, for the moment, we have to consider taking over the actual Linac 1 analog switching system for the lead-ion Linac.

c) The programming environment

The programmer generating application programs for the lead-ion Linac needs several tools for fast and reliable work. Many applications will simply show the status of a subsystem (synoptics) so a graphic editor allowing easy generation of this type of program is very helpful. In addition, there must be a means of inserting a new application program in the system giving the same type of access to all applications. A log must be provided showing all parameter values of a subsystem (or even the complete system). Industrial software products will be integrated as far as possible.

These tools will be developed in the work-station projects and we should be able to take over this work for the lead-ion Linac. The main effort will go into the generation of lead-ion Linac specific applications:

- the production of the synoptics,
- the writing of dedicated applications such as the selection of a certain charge state of ions for acceleration,
- the applications for beam instrumentation, which usually make up a big part of the effort to be put into the application software.

d) The process access

The application programs running on the work station make access to the process via DSCs. These devices are VME bus-based controllers having a CAMAC branch driver so that access to modern VME-type modules is possible as well as CAMAC access. The central processor unit (CPU) cards use the M680x0 family's CPU chips and run the OS–9 operating system. Fast access to the DSCs from the work stations can be provided using the TCP/IP protocol over Ethernet available for the VME bus.

Another project in the Controls Group, the DSC project, will provide the overall infrastructure, which includes network access, data saving and retrieval from archives, as well as the framework to build equipment access.

However, driver routines (equipment modules) needed for special lead-ion Linac equipment or instrumentation will have to be written.

4.7.3 Proposal for the lead-ion Linac timing

a) Requirements

The operational aspects of the lead-ion 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.

Therefore, we 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 application programs. This is necessary because of the required direct exchange between these two machines, since 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-ion 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.

Since the timing systems for the future lead-ion Linac and a possible LEAR injector are similar in size to those of 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. 6). From the design options offered for this energy range, the arrangement using an ECR ion source, a 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.

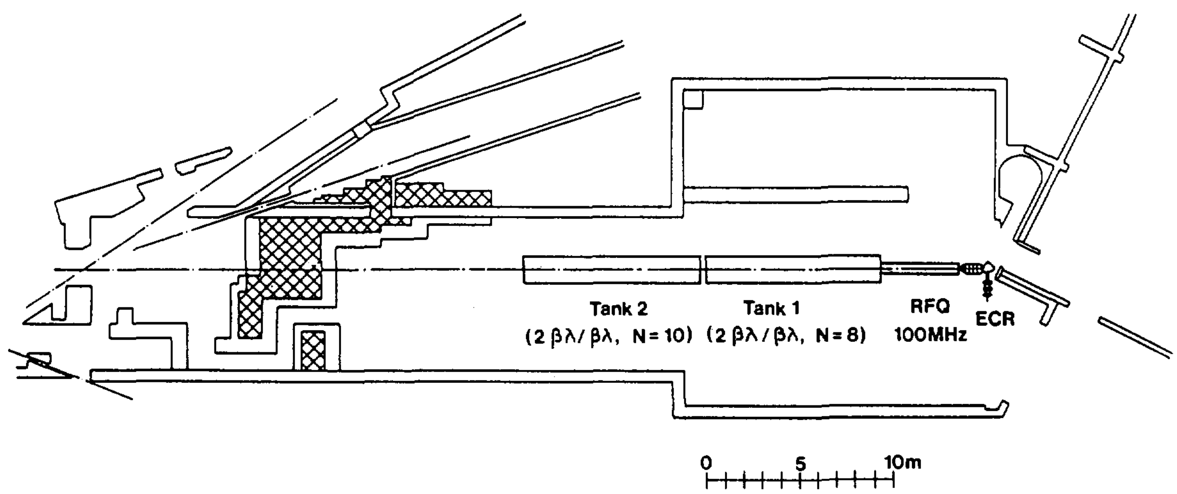

Fig. 6 Drift-tube version of 4.2 MeV/u $Pb^{25+ \text{ to } 30+}$ linac in Linac 1 tunnel

The installation is divided into four mechanically independent sections,

i) the ion source with the accelerating column,
ii) the RFQ with beam transport and diagnostic equipment,
iii) tank 1 of the drift-tube linac,
iv) 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 site of the installation has three different types of building foundations.

The mechanical isolation of the sections is achieved through flexible connections between the sections, to the RP 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 that 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 listed below result from the beam optics and RF design of the linac as given in subsection 4.4. These values were used to calculate the variants of the concept and the elaboration of the mechanical design.

- Tank 1 length: 8.2 m
- Tank 2 length: 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' drift-tube body: 5 W
- RF losses on 'full' drift-tube quadrupole magnet: 7 W
- RF losses on 'full' drift-tube stem: 3 W
- RF losses on 'empty' drift-tube body: 0.3 W
- RF losses on 'empty' drift-tube stem: 2 W
- Alignment precision for 'full' drift tube: 0.2 mm
- Alignment precision for 'empty' drift tube: 0.5 mm.

The 'full' drift tube means that type which has a focusing quadrupole magnet in its body. The values given for the tanks and the RF losses are preliminary design ones and are therefore approximate. Also, they are taken from the 'economical design' where the losses are higher (see subsection 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 at the CERN Linac 2[34,35]. The sections are fully aligned and vacuum tested before they are built into the long tank.

The alignment method for the drift tubes is mechanical, using alignments jigs. For this purpose, the sections are provided with outside reference faces on the flanges; the faces are used for drift-tube 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 for 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.

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

The 'full' drift tubes are similar to those for 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 drift-tube stem. It is possible to read the position of the drift tube and also to realign it from the outside without breaking the vacuum. The drift-tube 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' drift tube 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 maximum temperature rise is about 10 °C on the stem in the highest RF field region. The thermal expansion of the stem (about 35 μm) is well within the range of the required alignment precision.

Compared with Linac 2[35], this linac is much simpler in mechanical design owing to the 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 needing a major upgrading which have a considerable impact on the global cost estimate. These are the distributor plus some minor items and the kickers. (The septum magnets can presumably support the increased current and pulse length. Tests are being carried out to verify this.)

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

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). The use is foreseen of the existing equipment, upgraded for higher charge delivery and complemented by an additional discharger to supply the longer pulses. The latter will be 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 β from 0.094 at 4.2 MeV/u to 0.42 at 96 MeV/u, and a change of harmonic number from 17 to 10—involving debunching and adiabatic recapture on an intermediate flat top of the magnet cycle—is required. This technique has already been implemented to allow acceleration of oxygen and sulfur[36)]. A notable difference is the transfer of 10 Booster bunches into 5 PS buckets to avoid further changes of the harmonic number. The nominal number of charges for lead 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 (~ 1 m) 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 being discussed at present is the replacement of today's frequency programming from the 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 of 2 (623 ns → 1245 ns). Hence the ejection and transfer kickers have to supply two 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 now 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 being 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 that measures beam intensity and position in the PSB–PS transfer lines.

Also the thyratron switches, which will be more stressed, will have to be replaced by 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 system of processing the 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 type of transformer would operate for all kinds of particles and all intensities will be covered by 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 presently available equipment. 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 such 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 the 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 usable 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 successfully operated at oxygen intensities.

5.5 Vacuum

At present, the average pressure in the Booster is 1 to 2 $\times$ 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 unbakeable *in situ*.

To achieve an average pressure of $\sim$ 10^{-9} mbar in about the same time, with the same residual gas composition, an example can be taken from the SPS vacuum system where there are 45 titanium sublimation pumps installed in the free straight sections. Together with a general cleaning program such as vacuum firing of components and 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:

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

This requires one year of specification, design, and construction, and installation can be done during a 2-month 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 localized devices than the SPS. By changing or modifying the kickers and septa so that they can be baked *in situ,* there will be a better safety margin.

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 of 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 second improvement stage, one can aim at an average pressure well in the 10^{-10} mbar range, with a better gas composition such as 80% H_2 or more, the rest being mass 28:

Stage 2: Modification of 4 kickers and septa tanks (quite an extensive and expensive procedure).

A detailed study of required resources and construction planning for this second improvement stage has not yet been made. However, as for the PS, it could be envisaged as part of a long-range replacement programme.

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 mode, allowing for example $\bar{p}$ production, e^+e^- acceleration, etc., on the remaining cycles.

The transport line between the PSB and the PS cannot be pulsed in PPM. As a result, the PSB to PS ion transfer has to take place at the same $B\varrho$ as the standard 1 GeV proton transfer ($B\varrho$ = 5.634 T$\cdot$m).

This not only sets a maximum energy of the ions in the PSB but also forbids any stripping between the PSB and the PS, consequently imposing the acceleration in the PS of ions with a charge of 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 in any case 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 G.

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 below:

Q = 53 (ion charge)
$B\varrho$ = 5.634 T·m
B = 803.9 G
dB/dt = 0 T/s
T = 0.094 GeV/u (kinetic energy per nucleon)
β = 0.4169
γ = 1.100
f_{rev} = 198.93 kHz (revolution frequency)
h = 20
f_{RF} = 3.978 MHz ($f_{RF} = h \times f_{rev}$)
Q_x = 6.19
Q_y = 6.31.

Important remarks:

i) The revolution time will be 5 μs compared with 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.

ii) 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) that require major modifications. By changes in the connection scheme of the modules of the magnet and in the power and low-level electronics, the pulse length is increased by the factor of 2 required. However, the fall time of the kicker pulse becomes longer (80 ns). Development work is going on with an electronic switch that 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, for 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. No transition crossing will be required (PS γ_{tr} = 6.12).

The main parameters of the PS at high energy are listed below:

Q = 53
$B\varrho$ = 66.6 T·m (ion charge)
B = 9504 G
dB/dt = 0 T/s
T = 4.235 GeV/u (kinetic energy per nucleon)
β = 0.9834
γ = 5.5138
f_{rev} = 469.22 kHz (revolution frequency)
h = 20
f_{RF} = 9.384 MHz ($f_{RF} = h \times f_{rev}$)
Q_x = 6.25
Q_y = 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 necessary for the time being.

The stripping foil will be located in the transfer line PS–SPS, downstream of the 'loop' to the Antiproton Accumulator (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 $\times$ 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, similarly to 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, as for the Booster, to install about 150 titanium sublimation pumps and a pressure monitoring system:

Stage 1: Installation of 150 titanium sublimation pumps and ion gauges.

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

The PS vacuum system has recently been upgraded, thus giving it an advantage compared with the PSB as far as the safety margin is concerned. One of the very reasons for this change is to open up the possibility of accelerating, 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, since the leptons cause long-lasting pressure increases and gas-composition changes.

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

Stage 2: Modifications to kickers (eight straight sections in the PS!) involving magnets, some ferrites, bakeout equipment, and tanks. Reconstruction of septum magnets (some glued with araldite, seven straight sections in the PS ring).

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 possibly be halved. 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, but obviously would require a study before it could be relied on.

7. LEAD IONS IN THE SPS

7.1 Introduction

On each cycle the SPS will accelerate simultaneouly four 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 $53/82 \times 20 = 12.93$ 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 82×450 GeV/c = 36.9 TeV/c per lead ion.

The relative velocity of the lead ions at transfer is $\beta = 0.973$. 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 (1 μs) 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 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 programme 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 resp. Z/A for lead ions is different from that for 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 to three different experiments. Thus the lead ions from the SPS can be shared simultaneously between five 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 $\beta = 0.973$ 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 ($\simeq 1\ \mu s$) is much smaller than the revolution time (23 μs) of the particles. This feature opens up the possibility of a new method of acceleration in which the four PS batches occupy a total of about 10 μs while the other 13 μs are taken up by four 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 four 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 must be built to modulate the phase and amplitude of the accelerating voltage at the revolution frequency. Some modifications to the transmitter plants are also necessary to cope with the fast 100% amplitude modulation. Furthermore, previous experience with sulfur 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 sulfur 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 in their sensitivity.

In the SPS ring, the 216 electrostatic pick-up stations that 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 preamplifiers located in the SPS tunnel close to the detectors. To avoid radiation damage to these preamplifiers 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 ionization. These integrating amplifiers have already been designed and constructed for the oxygen operation in 1986 and can be reused. 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, the screens of which will be observed by highly-sensitive 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 only 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, whilst 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 has been made of the effects to be expected because of nuclear and Coulomb dissociation ($\sim Z^2$) interactions of the lead ions[37]. 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 sulfur ions and which has proven not to be detrimental for the experiments[38]. However, because of the larger interaction cross-sections of lead ions, compared with 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 with the requirements of the experiments, as was already the case for the sulfur 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 that can realistically be achieved. The air in the parts of the beam path traversing the target stations and mobile beam dumps 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 a high-strength aluminium alloy of 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 of the need to minimize the time of intervention when changing from proton to lead-ion operation and vice versa, 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-analysing 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 (FISCs), 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 FISCs 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[38].

It should be noted that four 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 $\leq 5 \times 10^8$ elementary particles, which corresponds to $\leq 5 \times 10^5$ lead ions. Depending on the experiments approved, extensive shielding of the beam lines and associated modifications to the layout may be necessary.

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-ion Linac. Linac 1 has so far been operating mainly as a facility to supply test beams for LEAR as well as to accelerate ions. Protons as well as H^- ions were resquested. The future lead-ion Linac will not be an appropriate injector for LEAR. Hence, LEAR will have 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 RQF1 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 water cooling-system, tank 1 would certainly meet the requirements as an 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 will certainly be of interest. A straightforward possibility is 'funnelling'. 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 drift-tube linac. Joining the two beams from the two RFQs 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 because charge states in the vicinity of the desired charge state are also produced. Recirculation of these undesired charge states through the same 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 of 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.

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