A HEAVY ION INJECTOR AT CERN

H. Haseroth
CERN, CH-1211 Geneva 23, Switzerland

Abstract

The request of the nuclear and high energy physics community for high energy heavy ions at CERN has lead to a proposal to upgrade the present facilities for this purpose. This scheme uses the (improved) existing accelerators: the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS). The Linac, however needs a complete rebuild.

This paper reviews the early "ion history" at CERN, where Linac 1 was used to accelerate deuterons and alpha particles. The experience gained during these exercises resulted in the more spectacular production of oxygen and sulphur ions over recent years. This work is to be continued up till 1992.

The future goal of heavy ion acceleration requires a new linac and substantial improvements to the ion source and also to the down-stream accelerators. Details of the procedure for arriving at the linac specifications and special features, particular to the CERN accelerator complex, will be described.

Introduction

Ions, or more precisely heavy ions play a rather special part in the accelerator and also in the linear accelerator world. Though it is well known that the linear accelerator proposed by Ising in 1924 was to accelerate ions, and that also the experimental work by Wideröe used sodium and potassium ions, no further particular interest arose for the acceleration of heavy ions. The classical (Alvarez) linac is a proton machine. The very few exceptions (Hilac, Unilac ...) are rather the confirmation of this rule. Only in the last few years electron linacs made a major impact. What are the reasons for this? Of course, as in every free market system the "clients" determine what will be built for them. In the past protons dominated the floor and electrons only caught up because of the increased physics interest (studies of Z_0 e.g. in LEP, to name but one example) and also to a lesser degree because of industrial applications. Apart from some nuclear physicists, for whom some fairly special machines were built, there was no wide-spread interest for heavy ions, in particular at higher energies. It is only now that after some preliminary work with light ions interest is large enough to pursue the issue at CERN and also at BNL (RHIC).

Past Experience with Ions at CERN

Though the CERN machines (i.e. originally only the 50 MeV Linac and the Proton Synchrotron) were built for protons, trials were made in 1964 to accelerate deuterons with the Linac. They were repeated in later years with higher intensity, longer pulses and followed by acceleration in the PS. It must be stressed in this context that these experiments were pushed by the machine people to widen their understanding of beam dynamics in the accelerators and not requested by high energy physicists. Nevertheless as it happened that deuterons were available at high energy and (fairly) high intensities, they were also stacked (and accelerated) in the Intersecting Storage Rings (ISR)(1) and the experiments set up there for protons were also used to look at the collision of deuterons. The results prompted a request for the production of alpha particle beams, which are somewhat heavier ions and presumed to be cheap. Originally it was hoped to produce them with the normal proton source, which used to be a standard duoplasmatron. It was quickly understood that this way the intensity would be fairly low, probably too low for further acceleration in the PS. Therefore it was preferred to produce a He^{1+} beam with the full pre-injector voltage, applying subsequent stripping (with about 30% efficiency) to He^{2+} and then injection into the Linac - with the correct β-value for the $2\beta\lambda$ mode. Stripping was achieved with a pulsed gas jet stripper requiring no expensive additional pumping. The intensities obtained this way were practically identical to those of the deuterons(2) , especially as the PSB was used(3) (for the first time) for this purpose. It should be mentioned that all these modifications were substantially eased by the availability of Linac 2, which served as the "proton factory" leaving Linac 1 (the original one) for more sophisticated experiments. The $2\beta\lambda$ mode required RF levels similar to the proton RF levels and some change of the "tilt" of the first cavity.

Incidentally the $2\beta\lambda$ mode was an essential condition for the exercise: due to the fact that the deuterons move with half the proton velocity, the momentum (except for some minor relativistic effects) stays the same as that of the protons. As the charge is identical, the magnetic rigidity remains the same too. This means that all the quadrupole settings in the linac remain essentially untouched (or rather slightly lowered because of the reduced space charge effects).The same statement holds for the magnetic elements of the injection line and the emittance and spectrometer lines. At the time it would not have been feasible to upgrade all this expensive equipment including the kickers and bending magnets for splitting the Linac beam into the four PSB rings. Maybe there would be no ion programme at CERN without these particular properties of the $2\beta\lambda$ mode on Linac 1.

Light Ions

There was never, even in the case of the α-particle beams, a strong demand by the physicists for ions but rather the interest from certain individuals expressed with different arguments. The idea of achieving high energy densities with nuclear collisions was already expressed earlier but there was not a strong consensus, partially because there was still enough to do with protons, partially because the experiments were thought to be too difficult with ions.

The situation changed around 1980(4), when a strong group of nuclear physicists put forward a request for ions at PS energies demonstrating that they would be able to digest the expected "mess". Some work had been done already on the machine side in anticipation and some studies about the different possibilities were made(5). CERN was not able - against the strong proton lobby - to invest a substantial amount of money into providing somewhat heavier ions, and it was also felt that there was a lack of experience to deal with the problem.

The way out of this situation was to set up a collaboration between CERN, Gesellschaft für Schwerionenforschung and Lawrence Berkeley Laboratory (GSI and LBL), the latter ones not only having the interest in the final experiments but also having the particular know-how. To minimize the overall cost - it was planned at that time to run experiments with O-ions for about two times 10 days - it was thought to use the existing Linac 1 and just modify the front end. This new front end (Fig. 1) was composed of an Electron Cyclotron Resonance (ECR) source and a special Radio Frequency Quadrupole (RFQ), designed to inject again into the Linac in the $2\beta\lambda$ mode.This new equipment was provided for by GSI (with the source subcontracted to C.E.N. Grenoble) and LBL. CERN had to care about its existing

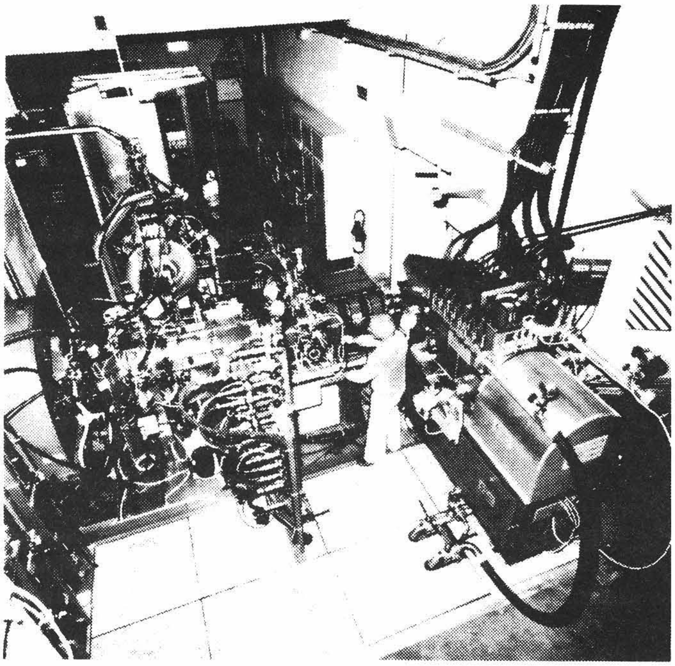

Fig.1. Front end of Linac 1.
Left: End of 1st cavity. Right: O-ion source.
Left center: O-ion RFQ; Left background: proton source and RFQ

accelerators and their "upgrading" to low intensities and had in particular to deal with the somewhat risky and ambitious plan to increase the focusing and accelerating fields of Linac 1 by some 33%. This increase was necessary to cope with O^{6+} ions expected from the source. Obviously O^{8+} ions could have been accelerated as easily as deuterons or α-particles but the intensity from the source would have been by far too low. O^{6+} seemed to be the correct compromise(6). The increase of the RF fields required, apart from more RF power, an improved vacuum on the first cavity (obtained with a cryo pump) and computer-controlled RF conditioning.The latter proved to be of vital importance for the successful completion of the programme(7,8).

Because Linac 1 had to serve also as injector to the Low Energy Antiproton Ring (LEAR), it was necessary to keep this facility and continue to inject protons or H^- beams into the Linac if required by LEAR.

The experimental programme has gained by now considerable momentum and has been extended to the acceleration of S^{12+} ions(9). Both O^{6+} and S^{12+} are accelerated by the Linac to 12 MeV/u and subsequently fully stripped by means of a carbon foil, hence for PSB, PS and SPS they look essentially like deuterons. As in the case of S^{12+} production the source produces also O^{6+}. Both of them are accelerated in the Linac in the same way. Even after stripping to 0^{8+} and S^{16+}, they are almost indistinguishable. This feature helps PSB and PS for their monitoring, especially for the RF beam control. Both species are only separated at PS transition. For source adjustments it is of course important to measure the relative intensities: this is done after the Linac by differential energy degradation, making use of the Z^2 dependence of dE/dx and allowing analysis in the spectrometer line after passage through a somewhat thicker "stripping foil" of 1.35 mg/cm^2).

Beam Quality and Measurements

As already mentioned, apart from the complications of 33% higher fields in the Linac and the special RF gymnastics (due to the lower β value) in the circular machines, the beam intensity - or rather the lack of intensity - is one of the major problems. Most of the measurements around the Linac and in the transfer line towards the PSB are made with current transformers and secondary emission monitors ("SEM"-grids and -wires). Depending on the environment, the resolution of the beam transformers goes down to the 1 μA level. The sensitivity of the SEM-grids is around 20 nA/strip, i.e. the profile of a beam well below 1 μA can be measured easily. After calibration these monitors have a very good long-term stability and are therefore also used for intensity measurements. As of course the sensitivity goes up with the Z of the ions, calibration must be made with the appropriate ion.

Future Plans for Lead Ion Acceleration

The present CERN Linac 1 has been pushed to its real limits with the acceleration of O^{6+} and S^{12+} ions. Any possible additional gain in terms of charge to mass ratio would remain very marginal without a substantial rebuild. As quite a few of the interesting phenomena in heavy ion physics are proportional to $A^{1/3}$ (A is the atomic mass number), it is also clear that another small factor gained for A would not help tremendously to discover the quark gluon plasma. The next step should be to accelerate really heavy ions like e.g. lead. Of course, if there would be ion sources available that could supply sufficiently high intensities of lead ions with a charge to mass ratio similar to O^{6+} on S^{12+}, Linac 1 would still be useful, provided some upgrading of the vacuum could be achieved. Unfortunately, this requirement means almost fully stripped ions for Pb: no ion source is available which can provide the required intensity. Therefore, a new Linac has to be built and some upgrading of the existing machines has to be done(10). A schematic layout is shown in Fig. 2.

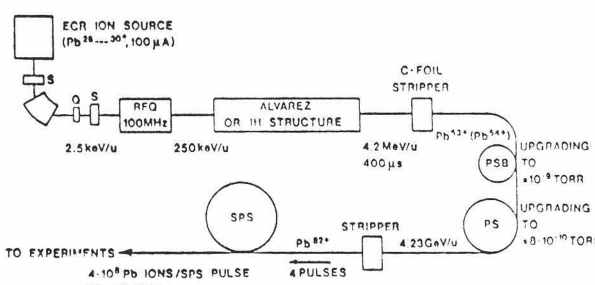

Fig. 2. Schematic layout of CERN's accelerator complex for Pb-ions

Specifications for a New Lead Ion Accelerating Facility

As mentioned already A must be of the order of 200. Lead has originally been chosen because it has a round nucleus - in contrast e.g. to uranium - but there is of course nothing magic in it. Au or Bi would be equally good, in a way even better, because in the case of Pb one would have to go to artificially enriched ^{208}Pb if one does not want to lose a factor of 2 by using natural lead.

The next important parameter is the required intensity. For fixed target experiments at the SPS this intensity originally has been specified as 5×10^7 ions per SPS pulse, i.e. per 10 ... 15 seconds with four pulses injected from the PS. Of course, very quickly afterwards different requests came up asking for more and this trend may continue.

Basically, two options are 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.

With the progress of modern high charge-state ion sources the second option is the more interesting one, the first option suffers anyhow from the fact that each intermediate stripping foil reduces the intensity by almost one order of magnitude. The next important parameter is the output energy of the Linac. A priori one would like it to be as high as possible, e.g. to do a 100% efficient stripping to Pb^{82+}. Unfortunately, the Linac would be a monster and the PSB would not be needed at all. For cost effectiveness the Linac energy has to be considerably lower. Which are the parameters of importance to determine how low the energy should be?

The future lead ion linac has to be integrated into the CERN accelerator complex. Both the charge-state and the velocity of the ions are important for the subsequent accelerators. The velocity of the ions determines the duration of injection and ejection into the synchrotrons and the required pulse length for all pulsed elements. The velocity range in the circular machines determines the necessary frequency swing of the RF or requires special RF gymnastics.

The obtainable velocity is of course linked to the charge-state. A higher charge-state (for the same β) results in a smaller magnetic rigidity and in a more efficient acceleration.

On the low energy end it is the ion source that determines the charge-state. With reasonable intensities it is possible to aim for 25+ to 30+ in the case of Pb ions. To keep maximum intensity it would be highly desirable to have no intermediate stripping. This would mean that the original charge-state would have to be kept through the PSB and the PS. The vacuum improvements needed in this case are prohibitive for both machines and the output energy of the PS would be rather on the low side for further acceleration in the SPS. One intermediate stripping is therefore needed and to avoid too difficult conditions for the PSB , the intermediate stripping should be after the Linac. To make life easy for the PSB, to get the maximum energy from PSB and PS and to reduce the stringent vacuum requirements in both machines, the conclusion is again that the charge-state after stripping and hence the energy of the Linac should be as high as possible. As for cost reasons it would be desirable to put the lead ion Linac into the buildings of the present Linac 1 and to use the same injection line into the PSB, which is also used for the 50 MeV protons from Linac 2. This fairly complicated line puts some limiting conditions on the ion energy.

As a final compromise we have chosen a Linac energy of 4.2 MeV/u yielding after stripping a charge-state of 53+. This corresponds to a magnetic rigidity which is about 13% higher than for 50 MeV protons and can be achieved with a fairly modest improvement of the present injection line. Due to the low velocity of the ions, pulses of about 400 μs (instead of 150 μs for protons) will be used for efficient injection into the PSB. This will require a more substantial upgrading of several pulsed elements. In spite of this "high" energy and high charge-state an improvement for the vacuum of PSB and PS by more than one order of magnitude will be necessary.

Vacuum Requirements

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[11] backed up by as yet unpublished calculations and measurements from LBL[12,13].

Vacuum improvements in PSB and PS will be needed to reach pressures below 10^{-9} mbar (Fig. 3).

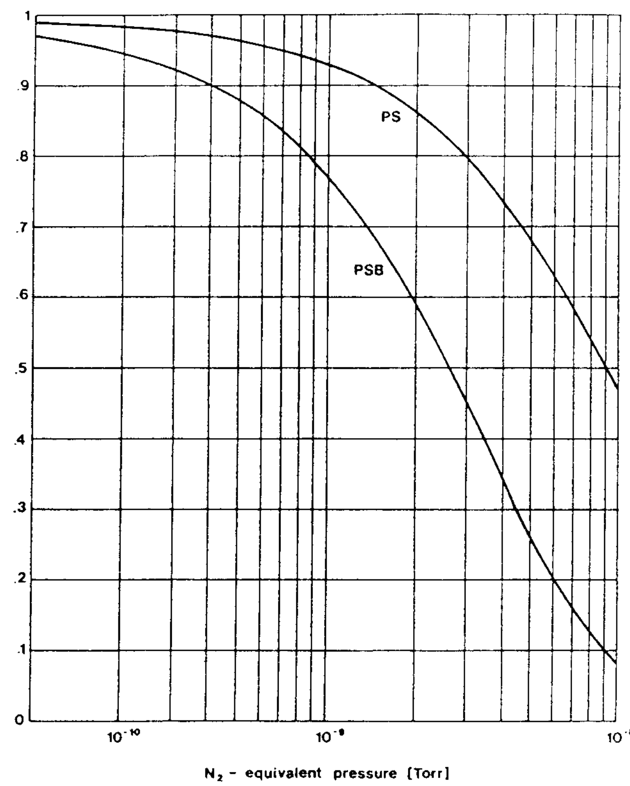

Fig. 3. Transmission losses of Pb^{53+} in PSB and PS as a function of pressure

Options for the Lead-Ion Linac

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).

Ion Source. Apart from the ECR source, already used at CERN for the oxygen and sulphur ion production, the EBIS has been envisaged as well as laser ion sources.For the moment these last two are not competitive when aiming for high intensities and heavy ions. Laser ion-sources have been studied e.g. at Munich and have been used at Dubna for light ions, where encouraging results were obtained for Mg ions. Studies are continuing, also at CERN, to try to answer the question whether they are also interesting for heavy ions. EBIS-sources still lack intensity but development is going on in several laboratories.

Low Energy Acceleration. The RFQ is here the only choice. The only options here are the frequency and the mechanical design: 4-rod or 4-vane structure.

High Energy Acceleration. Neglecting superconducting-, spiral- or other more exotic structures, it seems that there are only two promising alternatives: an Alvarez or an Interdigital H (IH) structure.

A possible option is a normal Alvarez structure operated in the $2\beta\lambda$ mode[14] at least at the low energy end. Unfortunately the number of quadrupole lenses implied in this solution is large. Another proposal[15,16] which reduces the number of quadrupoles and increases the acceleration rate, is the "quasi-Alvarez", a hybrid between a $2\beta\lambda$ and a $\beta\lambda$ structure. A model is shown in Fig. 4.

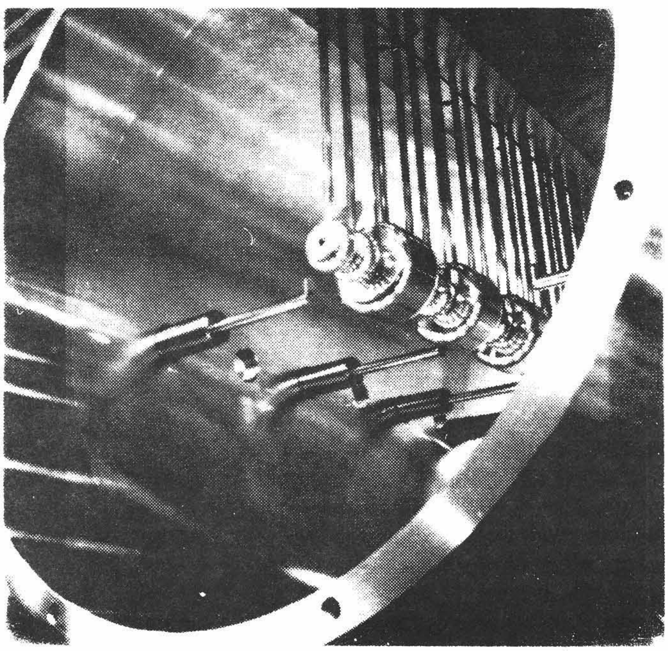

Fig. 4. Model of quasi-Alvarez with post-couplers

Interdigital H structures have been used successfully above 2 MeV/u as Tandem Van de Graaff post-accelerators[17]. 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. 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. These problems are being actively studied at CERN and GSI[18,19]. GSI is building an IH cavity that could be used for the CERN facility if it was followed by another two cavities to boost the energy from 1.4 MeV/u to 4.2 MeV/u.

The Present Linac Scheme

Ion Source. The source will be an ECR source with the following characteristics:

ion :	Pb^{28+}
current :	100 μA (electrical)
extraction voltage :	25 kV
normalized emittance :	0.6 π mm mrad (for 80% of the beam)
repetition rate :	10 Hz (≈1 Hz used initially)
pulse length :	≥ 400 μs

A preliminary design has the following parameters :

Low energy acceleration (RFQ):

Acceleration factor :	0.34
Focusing factor :	4.25
Voltage (kV) :	60.5
Aperture (mm) :	3
σ_{OT} (°) :	23
σ_{OL} (°) :	21
Length (m) :	5.30
Transmission (%) :	93.6
E_s/E_{KP} :	1.85

Required RF power : 100 kW at 101.28 MHz
Pulse duration : 500 μs

Another possible design would be very similar to one developed by IAP/Frankfurt for GSI/Darmstadt for use at the Unilac.[21]

Since Linac 1 and Linac 2 run with 202.56 MHz it would of course be of advantage to keep this frequency.However, in order to have a large enough acceptance[14], the frequency of the low energy part of the accelerator has to be lower. As the whole Alvarez and at least the high energy end of an IH structure can run at 202.56 MHz, the RFQ should operate at half this frequency.

High energy acceleration: For the Linac itself there are two competitive designs: for a quasi-Alvarez[15,16] and for an IH structure[18]. A final decision as to which one should be built, will be made by March next year.

The Basic Parameters of the Alvarez Design are :

Particle type : Lead Ions with A=208, q=25+
Frequency 202.56 MHz
Effective Synchronous Phase ($\phi_{s,eff}$) :
Tank 1 : $\phi_{s,eff}=A\ \beta^{(-0.27)} = -40$ deg at 0.24 MeV/u
Tank 2 : $\phi_{s,eff}= -30$ deg
Mean Electric Field (MV/m) :
Tank 1 : E = 2.09 + 0.278 z
Tank 2 : E const. with W' continuous between tanks
Acceleration Periodicity :
Tank 1 : 3 gaps/4 $\beta\lambda$
Tank 2 : 4 gaps/5 $\beta\lambda$

	TANK 1	TANK 2	
Energy	0.240 to 2.129	2.129 to 4.238	MeV/u
Length	7.684	6.634	m
No. RF Superperiods	31	12	
Mean E Field	2.090 to 4.152	3.960	MV/m
Aperture Dia.	12 to 16	18 to 20	mm
Quadrupole Length	51 to 125	145	mm
Quadrupole Grad.	170 to 61	46 to 41	T/m

In the case of the IH structure 3 cavities would be used, with the first one operating at 101.28 MHz and the others at 202.56 MHz.A detailed design is being worked out at GSI[18]. In case of the Alvarez solution simultaneous acceleration of several (three) charge-states and hence an increase in intensity seems to be possible.

The beam line after the Linac will contain the carbon stripper foil and a three magnet filter system to select the desired charge-state(53+). Emittance and energy measurements will be possible for the original as well as for the stripped beam.

Conclusion

It is perfectly feasible to upgrade the CERN accelerator complex for heavy ion acceleration. Further increases in intensity are possible which satisfy also LHC requirements[20]. The whole scheme is not yet in a project stage and it will not become a CERN project in the traditional sense but major contributions will come from other laboratories with which a collaboration will be set up in the near future.

Acknowledgements

The paper presented here is based on a thorough study presented in a report [10]. I would like to thank the authors of this report and also the numerous colleagues from other laboratories, especially from GSI (Darmstadt), LBL (Berkeley), IAP (Frankfurt), GANIL (Caen), C.E.N. (Grenoble), C.E.N. (Saclay) and MPI (Heidelberg). Their contribution to this project has been essential.

References

1. P. Asboe-Hansen, O. Barbalat, D. Boussard, M. Boutheon, J. Gareyte, H. Haseroth, J. Jamsek and S. Myers, "Acceleration and stacking of deuterons in the CERN PS and ISR", Proc. 7th Particle Accelerator Conf., Chicago, 1977 [IEEE Trans. Nucl. Sci. NS-24,1557 (1977)].

2. M. Boutheon, R. Cappi, H. Haseroth, C.E. Hill and J.P. Koutchouk, "Acceleration and stackingof α-particles in the CERN Linac, PS and ISR", Proc. 9th Particle Accelerator Conf., Washington, 1981 [IEEE Trans. Nucl. Sci. NS-28, 2049 (1981)].

3. K.H. Schindl, "Light ions via the PS Booster", PS/BR/Note 81-10 (1981).

4. R. Stock et al., "Study of particle production and target fragmentation in central ^{20}Ne on Pb reactions, at 12 GeV per nucleon energy at the CERN PS external beam", Letter of Intent to the PSCC, PSCC/80-129/I 56 (1980).

5. H. Haseroth, "Light ions at CERN", Proc. Workshop on Quark Matter Formation and Heavy Ion Collisions, Bielefeld, 1982, Eds. M. Jacob and H. Satz (World Scientific, Singapore, 1982), p. 557.

6. B.H. Wolf et al., "Heavy ion injector for the CERN Linac 1", Nucl. Instrum Methods A258, 1 (1987).

7. N. Angert, J. Klabunde, B. Langenbeck, K. Leible, P. Spädtke, J. Struckmeier, B.H. Wolf, S. Abbott, D. Brodzik, R. Gough, D. Howard, H. Lancaster, J. Staples, H. Haseroth, C. Hill, P. Têtu, M. Weiss and R. Geller, "A heavy-ion injector for CERN Linac. 1", Proc. Linear Accelerator Conf., Seeheim, 1984, Ed. N. Angert (Report GSI-84-ll, Darmstadt, 1984), p. 374.

8. H. Haseroth, C. Hill, P. Têtu, M. Weiss, B.H. Wolf, K. Leible, P. Spädtke, J. Klabunde, B. Langenbeck, N. Angert, R.A. Gough, J. Staples, R. Caylor, D. Howard, R. MacGill, and J. Tanabe, "Ion acceleration in the CERN Linac 1", Linear Accelerator Conf., Stanford, Calif., 1986 (SLAC-Report-303, Stanford, Calif., 1986), p. 355.

9. N. Angert, E. Brouzet, R. Garoby, S. Hancock, H. Haseroth, C.E. Hill, K. Schindl and P. Têtu "Accelerating and separating mixed beams of ions with similar charge to mass ratio in the CERN PS complex", Proc. European Particle Accelerator Conf., Rome, 1988, Ed. S. Tazzari (World Scientific, Singapore, 1988), vol. 2, p. 1367.

10. H. Haseroth (Ed.), "Concept for a lead-ion accelerating facility at CERN", CERN 90-01 (1990).

11. B. Franzke, IEE Trans. Nucl. Sci. NS-28, 2116 (1981).

12. H. Gould and B. Feinberg, LBL, private communication, 1988.

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

14. H. Haseroth, A. Lombardi and M. Weiss, "Feasibility study concerning a possible layout for a lead-ion injector for the CERN accelerator complex", Particle Accelerator Conf., Washington, DC, 1987 (IEEE Catalog No. 87CH2387-9), vol. 1, p. 296.

15. D. J. Warner, "Heavy ion acceleration using drif-tube structures with optimized focusing", Proc. Linear Accelerator Conf., Newport News, Va., 1988 (CEBAF-Report-89-001, Nat. Techn. Information Service, Springfield, Va., 1989), p. 109.

16. P. Lapostolle, E. Tanke, M. Vretenar, D. J. Warner, "Computer design and dynamics of the quasi-Alvarez Linac", This conference.

17. U. Ratzinger et al., "The upgraded Munich linear heavy ion post accelerator", Proc. Washington Conf. as in Ref. 14, vol. 1, p.367.

18. U. Ratzinger, Minutes of the 2nd Lead Linac Meeting, CERN Int. Rep. PS/DI/DS/Min. 88-2 (1988).

19. U. Ratzinger, "Interdigital RF Structures", This conference.

20. D. Brandt, E. Brouzet, R. Cappi, J. Gareyte, H. Haseroth, P. Lefèvre, S. Maury, D. Möhl, F. Pedersen, K. Schindl, T.R. Sherwood, L. Thorndahl, D. Warner, "High intensity options for the CERN heavy ion programme", To be published in the proceedings of the 2nd European Particle Acc. Conf. EPAC90, Nice, 1990.

21. Variable Energy and Heavy Ion RFQ's, A. Schempp, this conference.