PB INJECTOR AT CERN

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ABSTRACT

For the CERN Lead Ion Accelerating Facility (achieved within a collaboration of several outside laboratories and with financial help of some member states) a new dedicated Linac has been built. This Linac has been installed in 1994 and served during two extended physics runs.

This paper reviews the main characteristics of this machine and describes the first operational experience. Emphasis is put on new features of this accelerator, its associated equipment and on the peculiarities of heavy ions.

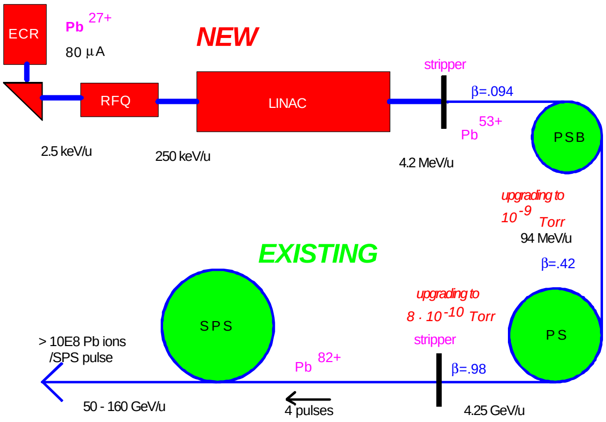

Fig. 1: Layout of the CERN Heavy Ion Accelerating Facility

INTRODUCTION

The Pb injector Linac is part of the Lead Ion Accelerating Facility at CERN [1] which has been described at different conferences [2,3]. This project has not been a CERN project but a joint project with several outside laboratories and helped also by outside financial contributions.

The work reported here is the result of a collaboration between different laboratories, namely GANIL (Caen, France), Legnaro (INFN, Italy), GSI (Darmstadt, Germany), Torino (University, Italy) and CERN (Geneva, Switzerland), supported by financial contributions from Sweden and Switzerland. and helped with software and some hardware from India (VECC, Calcutta, TIFR and BARC, Bombay), a debuncher from IAP (Frankfurt, Germany) and manpower for installation from Prague (Czech Academy of Sciences).

The Pb injector Linac (“Linac 3”) started operation in June 1994 and first results have been presented at the last Linac Conference [4], where also some papers on details of the machine were submitted[5,6,7,8].

DESIGN AND INSTALLATION OF THE LINAC

The design of this machine was decided to a large extent by the characteristics of the existing CERN machines and their auxiliary equipment and of course also by our collaborators, their experience and possibilities. Fig. 1 shows the layout of the whole facility. Several considerations determined the choice of the machine parameters. From the future experiments there was the request for a certain minimum intensity to be made available (5×10^7 ions per SPS supercycle) and the other important boundary was the cost factor. CERN had no major funds available for up-grading its machines to heavy ions and the future ion experiments were struggling with their own financial problems but several of the institutes involved were willing to contribute in kind. The choice for the machine parameters had to be made by taking into account these conditions. It was evident that a new Linac would be needed and to minimise its cost a source with a high charge state had to be selected. Given the good performance of ECR (electron cyclotron resonance) sources, the positive experience in using them at CERN and their availability from a collaborating lab (GANIL), the choice for the future linac was quite clear. A filter line to select the desired charge state and a RFQ for further acceleration were obvious choices (experience at INFN Legnaro). The linac itself has been an open question for some time and was finally determined by the positive results at GSI with their high charge state injector using an interdigital H structure (“IH”). Its compact design and - for its length - modest RF power requirements and the possibility to profit from GSI’s and its subcontractors experience made it an attractive choice for Linac 3. An important parameter was of course the final energy of the linac. It has been determined by careful consideration of:

- the maximum magnetic rigidity allowed in the (complicated and expensive to up-grade) injection line to the Booster
- the charge state achievable when stripping after the Linac
- the losses when stripping at lower energies
- the losses due to charge exchange reactions in the PSB and PS as a function of energy and charge state
- the energy at the top of the accelerating cycle in PSB and PS to make transfer to the next machine not too complicated

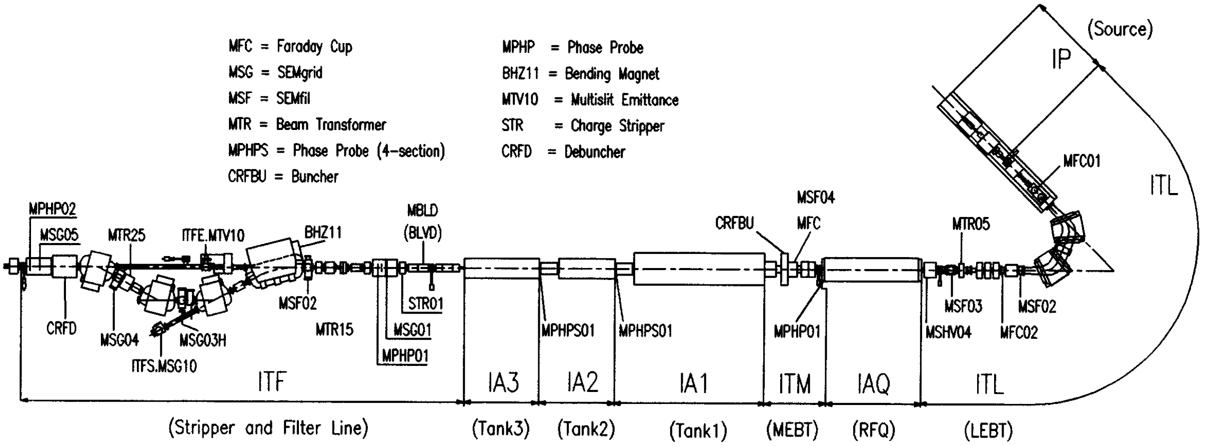

Fig.2 Layout of Linac3 with filter line

The final choice made here was 4.2 MeV/u at the output of the Linac and stripping at this energy to Pb^{53+}.

The ion source

The first element of the Linac is the ECR source delivering in a pulsed mode (the so called "afterglow") a current of 120 μA of $^{208}Pb^{27+}$. The source is operating at 10 Hz, the frequency chosen for future operation for the LHC (CERN's Large Hadron Collider) and compatible with all the new machine components. It maybe recalled that the original specification for this source was 30 μA and during its construction phase the afterglow mode was applied pushing its performance to above 80 μA. Careful tuning and some modifications resulted in the present intensity.

The Low Energy Beam Transport

To transport the beam from the ion source into the RFQ, a special line has been designed, which does not only match the beam into the RFQ. It acts also as a high resolution spectrometer (0.3 %), that eliminates the unwanted charge states and even the unwanted isotopes, if needed.

The RFQ and the Medium Energy Beam Transport

The RFQ is of the four rod type and has symmetric supports for the vanes. It accelerates the beam from 2.5 keV/u to 250 keV/u with a very good transmission. With one buncher cavity and two quadrupole doublets matching is achieved into the first IH tank.

The IH Linac

Three cavities accelerate the beam to 1.8, 3.1 and 4.2 MeV/u respectively. The first tank operates like the RFQ at 101.3 MHz, tanks 2 and 3 at 202.56 MHz. Transverse focusing is provided by quadrupole triplets, two in tank 1, one between tanks 1 and 2, and one between tanks 2 and 3.

Stripper and Filter Line

Another magnetic quadrupole triplet is employed after tank3 to focus the beam onto the carbon stripper foil to minimise the transverse emittance blow-up. An arrangement of four bending magnets is used with a slit in the middle to analyse the beam and to select the required charge state (normally Pb^{53+}). The first bending magnet is stronger, such as to allow spectrometer measurements even for the (un-stripped) Pb^{27+} beam.

Instrumentation

Instrumentation on Linac 3 is vital, not only because several different labs were involved in the construction, which meant that beam quality checks were important at the hand-over points, but also due to the additional complications when working with heavy ions. Beam current measurements are achieved by transformers and faraday cups. Profile measurements are done with secondary emission grids and the longitudinal beam characteristics are monitored with capacitive phase probes (some with four sectors to allow for position measurements) and a so called BLVD (Bunch Length and Velocity Detector) [9]. Apart from the existing emittance measuring lines a special multislit/scintillator screen device has also been set up [10].

Installation

Installation of the source had been achieved already at the end of 1992. In July 1993 the LEBT was used to measure the source characteristics. By then most of the filter line had been installed too. Tanks 2 and 3 arrived in December 1993, tank 1 in February 1994 and the RFQ in April 1994.

SETTING-UP AND OPERATIONAL PERFORMANCE

The somewhat hectic installation period in 1994 was followed by a very fast running in. This was necessary because it was clear that the subsequent machines, not used to partially stripped heavy ions, would require a fairly extended period for setting-up.

Conditioning of the RF cavities caused no major problems. Some days were in general sufficient to overcome problems. The buncher behind the RFQ, however, suffered from operating ion pumps and even from the very low intensity beam passing through the RFQ when it was not yet powered. This beam coming from the source before the maximum of the after glow pulse was finally suppressed to have reliable operation of the buncher. In spite of the fast running in careful measurements were done using the sophisticated equipment available for beam diagnosis. Provisional installation to measure the beam out of the RFQ and out of tank 1 were made to check the performance of the subsystems before injecting into the next unit. The BLVD in particular proved its value.

No major problems were encountered. Vacuum conditions throughout the linac were completely adequate. Some weak points on some RF amplifiers (failing HT components and insufficient cooling) have been corrected.

PRESENT PERFORMANCE AND IMPROVEMENTS

Work continued on different improvements concerning the ion source, triplet and tank alignment and also the field distribution in the tanks. Some problems with the mechanics of the stripper were also tackled.

Table 1 shows the original, the design and the present performance of Linac 3.

	Source current [µA]	Linac output current [µA]	Horizontal emittance (norm.) [π mm mrad]	Vertical emittance (norm.) [π mm mrad]	energy spread [keV/u]
design	80	65	.81	.80	2.1
1994	80	60	1.2	1.1	2.5
present	120	90	.85	.80	2.2

Table 1: Linac beam characteristics (Emittances are 4* the rms values, the energy spread is given after debunching)

Although it is true that the original specifications for the minimum intensity have been exceeded by a factor of eight, future physics experiments will probably require higher intensities (e.g. the search for strangelets). In any case the LHC (Large Hadron Collider) where lead ions will be accelerated to a few TeV/u will require higher intensities to achieve a reasonable luminosity.

Apart from intensity improvements on the source, which will reflect proportionally on the final intensities, and improvements in the transmission of the circular accelerators, several scenarios have been studied for the LHC [12]. Present planning calls for a faster (10 Hz) repetition rate of the linac and injection into LEAR (Low Energy Antiproton Ring). Accumulation of about ten pulses and electron cooling would provide for the intensities and emittances needed for the LHC [13].

First electron cooling tests were performed in LEAR with Pb^{53+} ions in December 1994. Considerably better lifetimes of the beam were achieved using Pb^{54+} ions [13]. The current after the stripper at the Linac exit for Pb^{54+} can be made equal to the normal Pb^{53+} current by optimising the stripper foil.

Another possibility, depending on ion source development [14], is a high current, short pulse, source (EBIS or Laser source) that could provide the necessary intensity and keep the required low emittance by mono turn injection into the PSB. Work in this field is going on in some labs, e.g. BNL (EBIS) and CERN (laser source, in collaboration with ITEP and TRINITI, [15]).

MACHINE EXPERIMENTS

Tests with Higher RF Power

Some interesting experiments were performed in collaboration with GSI. The IH structure shows very good voltage holding capabilities in spite of the small radius of curvature on the drift tubes. Tests were made on tank 2 with considerably higher RF powers than nominal. The normal operating level requires 346 kW. Test made in 1995 with 550 kW showed excellent behaviour. In 1996 an increased power level of 800 kW was successfully applied. The conditioning of the tank took about 18 hours with a repetition rate of slightly below 1 Hz and 200 µs pulse length. The radiation values during conditioning are presented in Fig. 3. The radiation is measured 90 cm from the tank axis.

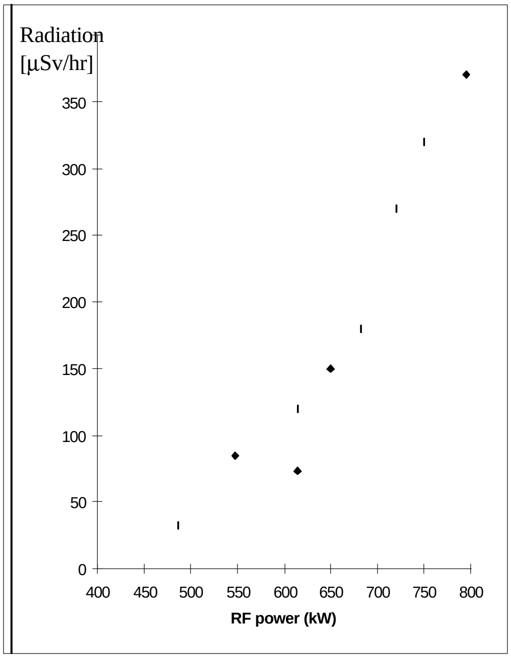

Fig. 3. Radiation levels near tank 2

The two points around 620 kW are taken at different times. Basically this figure shows the radiation increase as RF conditioning proceeds. These values are not to be taken as the values under normal operation.

The design and actually achieved fields in tank 2 are shown in table 2. It must be stressed that these values have been realised with a very short conditioning time and are certainly not yet the maximum levels that can be obtained. These levels were determined by the maximum RF power available with the present configuration.

	Design Fields [MV/m]	Scaled to 800 kW [MV/m]
Effective accelerating field	6.4	9.3
Average field in gaps with highest gradient	15.8	24.0

Table 2: Accelerating fields in tank 2 for the design conditions and scaled to 800 kW

We plan to have RF power available for further tests with up to 2 MW to reach (perhaps) the breakdown limit of the tank.

"Energy Ramping" During the Pulse

Multiturn injection into LEAR, to accumulate, cool and store ions for the LHC, maybe helped by an energy variation during the beam pulse. Requirements for this scheme are: a relative momentum variation of ± 0.4 % during a Linac pulse of 20 to 60 μs whilst keeping the beam momentum dispersion within 0.02 % at 1 σ. Several machine experiments ("MDs") were made to test the feasibility of this scheme.

Dynamic ramping with the debuncher phase alone did not give the required results. Additional ramping with the tank 3 amplitude (Fig. 4) yielded the necessary variations for the energy together with the required energy dispersion. Fig. 5 shows the energy dispersion in the beginning, the middle and the end of the ramp (superimposed pictures). The variation is ± 40 keV/u and the dispersion is about 10 keV/u.

Ramping with parameters of a machine, which is built to supply constant energy, means of course deviating from the optimum settings and results in a reduced stability and a more delicate operation. The best solution appears to be a dedicated energy corrector cavity:

- it allows for energy variation with a minimum alteration of other beam/machine parameters, since it can be placed close to the tank 3 output where the beam is very short. This would permit the Linac to be run with its optimum settings without spoiling its performance.
- stripping can then be performed at constant energy, hence constant distribution of the resulting charge states.

Another important application of special and dedicated hardware for the energy ramping for LEAR is to keep the injection energy into the Booster constant in spite of changes of or on the stripper foil. Stripper foils usually show some variations in thickness and replacing one foil produces inherently a change in the energy of the stripped beam. These changes are quite difficult to cope with on the Booster machine which requires a lengthy resetting of the injection and especially of the RF parameters. As the necessary stripper foil changes cannot always be predicted and preventive maintenance is hence excluded it is usually tried to trim the Linac energy to another value to compensate for the different stripper foil. It is clear, however, that this means - as a Linac is a fixed energy machine - deviating from the optimum settings. For this reason it is highly desirable to have a special energy corrector cavity after the Linac which allows energy corrections without touching the optimised parameters of the Linac itself. Another problem that could be eased by a dedicated cavity, is ageing of the stripper foil, which can result both in energy variations and in changes of the energy dispersion.

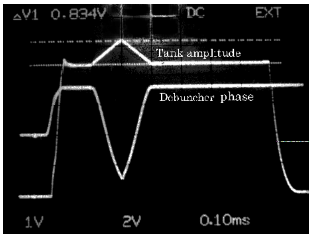

Fig. 4: Debuncher phase (lower), tank 3 amplitude (upper trace)

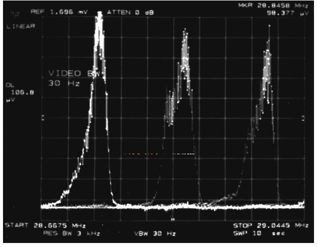

Fig. 5: Energy spectra during the ramping

Tests with Pb^{25+}

Although ^{208}Pb^{25+} had been foreseen as "nominal ion" right from the beginning, all the initial running including the physics runs of 1994 and 1995 had been done with Pb^{27+}. The high intensity the source was able to provide, and the lower RF power needed for the Linac cavities, made this a good choice. However if the source can give the same (electric) current of Pb^{25+} there is already a gain of some 8% in terms of number of ions. It must be remembered in this context, that the Linac accelerates to 4.2 MeV/u (by adjusting the field levels correspondingly) independent of the charge state of the ion. The output of the stripper in terms of Pb^{53+} is again independent of the charge state of the incoming ion and depends solely on its energy. Hence converting the same current of Pb^{25+} will result in 8% higher current after the stripper. Preliminary tests are under way to explore this possibility and have quickly produced an increase of the current by some 11%. The overall gain in terms of number of ions is hence about 20%. There is some hope that this mode of operation can be used for the physics run later this year and that further optimisation of the source can give even higher intensities.

Stripper foil ageing

The carbon stripper foils show a very good lifetime of several months. Some ageing effects have been observed that are of importance for the Booster synchrotron. Fig. 6 shows the energy spectrum (after the debuncher) with a stripper foil of a few months (note the Pb^{54+} on the right), fig.7 shows the same spectrum under identical machine conditions but with a new foil. With the old foil one can clearly see a low energy tail in the spectrum. Some curling of the foil maybe the reason. This effect reduces considerably the trapping efficiency of the Booster. Fortunately it is easy, if the effect is noticed, to put in a new foil.

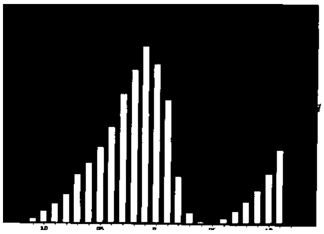

Fig. 6: Energy spectrum with old foil

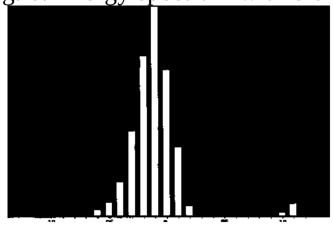

Fig. 7: Energy spectrum with new foil

CONCLUSION AND ACKNOWLEDGMENTS

The CERN Linac 3 put into operation in 1994 has been working very well and exceeding most of the specifications, in particular the ones relevant for the subsequent machines. It has been demonstrated that such a machine can be built by a large collaboration of several labs from different countries without making compromises for the final performance.

It is a pleasure to acknowledge here the enormous help given to this project by our friends from the collaborating institutions, in particular from GANIL, Legnaro, GSI and Torino, but also from IAP, CAT and Prague and of course also - last but not least - the financial contribution by Sweden and Switzerland. Thanks are of course also due to the CERN people in the different groups of the PS division, and likewise from the previous AT, MT, ST and TIS divisions.

Special thanks go to several of my colleagues in the PS for supplying material for this paper especially to C. E. Hill, A. Lombardi, E. Tanke and R. Scrivens.

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