ACCELERATION OF SEVERAL CHARGE STATES OF LEAD ION IN CERN LINAC3

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Abstract

CERN's LINAC3 is designed to accelerate a 100 μAe lead 25+ ion beam from 2.5 keV/u to 4.2 MeV/u. The beam is then stripped using a carbon foil and the resulting 25 μAe 54+ beam is accumulated and cooled in the Low Energy Ion Ring (LEIR) before transfer to the Proton Synchrotron (PS) and ultimately to the Large Hadron Collider (LHC). The lead 25+ ions are selected with a spectrometer from a mixture of ten charge states produced by an Electron Cyclotron Resonance (ECR) source.

In view of the fact that the stripping efficiency to lead 54+ is mostly dependent on energy and not on initial charge state, the feasibility of simultaneously accelerating to 4.2 MeV/u several charge states has been investigated. In this paper we report two possible technical solutions, their advantage in terms of intensity for the downstream machines and the experimental results supporting these conclusions.

MOTIVATION

LINAC3[1], the CERN lead ion injector has been operational since 1993 and providing an intensity of 25 μA of lead 54+ at 4.2 MeV/u to the Proton Synchrotron Booster (PSB). The beam is obtained by selecting a 2.5 keV/u 27+ lead ion beam from an ECR source and further accelerating it to 4.2MeV/u onto a 100 μg/cm^2 carbon foil. The acceleration is done in two stages: a 100MHz RFQ increases the beam energy to 250 keV/u and subsequently a system of three IH tanks (first one at 100MHz, the others at 200MHz) increases the beam energy to 4.2 MeV/u. The theoretical and experimental acceleration efficiency is around 85%, the stripping efficiency around 15% [2]. After stripping one charge state is selected and debunched to prepare for injection into the PSB. From 2006 the LINAC3 beam will be accumulated and cooled in a Low Energy Ion Ring (LEIR) before acceleration to LHC injection energy. The present set-up of LINAC3 is sufficient to meet the LHC needs [3]. Nevertheless, studies for exploring LINAC3 bottlenecks and possible improvements to its output current were pursued in the framework of the Ions for LHC (I-LHC) program. In view of the very good transmission of LINAC3 significant improvements can come either from a new source or from a new approach to producing lead 54+ at 4.2 MeV. In this paper we deal only with the second option. The efficiency of ionisation from lead 27 to lead 54 is quite low, because of the statistical nature of the interaction between charged particles and matter. This means that a good fraction of the intensity is lost due to the fact that more than 80% of the incoming ions are ionised to the "wrong" charge state. For this very same reason, a high charge state can be the result of the ionisation of a slightly different incoming charge state, i.e. lead 54+ can be obtained by stripping 25+ or 26+ or 27+ with the same foil thickness. Therefore, if we had more than one charge state simultaneously on the stripper within the nominal transverse emittance and energy spread, we could increase the overall useful current delivered by LINAC3. In the following we will report some theoretical and experimental observation on how to bring several charge states onto the LINAC3 stripper with minimum modification to the present set-up.

MULTICHARGE OPERATION

The ECR source of LINAC3 delivers, in the afterglow mode, 800 μA of lead shared between about 10 charge states. The source is optimised for delivering a maximum current made of 27+ lead ion and about 400μA of the total current is made of 24+,25+,26+, 27+ and 28+[4].

Low Energy Beam Transport (LEBT)

The LEBT is designed to select a pure single charge state lead ion beam. The 135 degrees spectrometer placed after the source is composed of two 67.5 degrees bending spaced by 700 mm. After the selection, a system of three quadrupoles and a solenoid matches the beam to the RFQ. We have analysed two solutions to bring several charge states at the RFQ entrance. The first one involves eliminating the spectrometer and putting the source in line with the RFQ: the new LEBT line, 2.4 m in length and equipped with three solenoids would allow all the charge states (5 of which also well matched) to the RFQ entrance. This solution, conceptually the easiest, involves major modifications to the present set-up and acquiring a new solenoid. It will be referred to as the "straight injection" solution and its beam dynamics can be seen in Fig. 1.

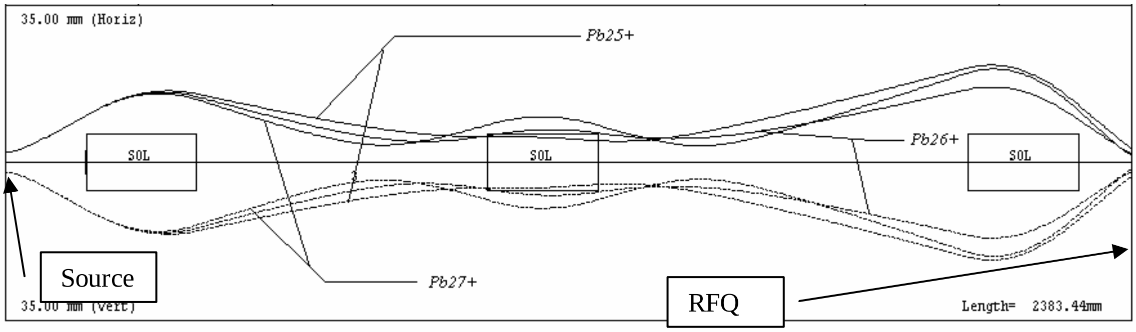

Figure 1: Beam dynamics in the LEBT for the straight injection solution.

An alternative solution aiming at nullifying the dispersion and its derivative without uprooting the present set-up involves adding a third magnet to the spectrometre with opposite bending field. In particular the following constraints were taken into account: that the total bending angle should be the same as the initial one, that the space available between the two nominal bending magnets is limited to about 200mm, and that the overall emittance of all the recombined charge states should be matched to the RFQ acceptance of 200 pi mm mrad. A magnet with an effective length of 80 mm and average field of 0.5 T placed between the two main spectrometre magnets would allow three charge states to be matched to the RFQ with an efficiency of 75% (9 % losses on the vacuum chamber 16% outside the RFQ acceptance). This solution, referred to as the "reverse bending", can cohabitate with nominal operation. The dynamics in the reverse bending and in the matching to the RFQ is shown in Fig 2 and 3.

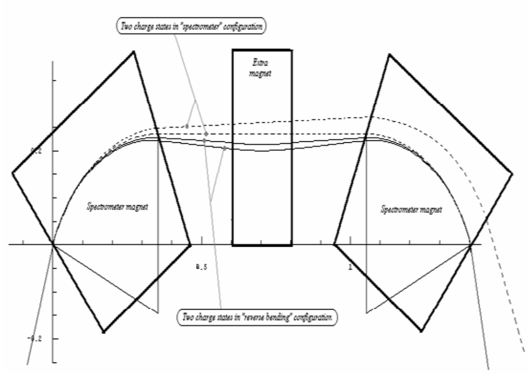

Figure 2: Principle of the reverse bending.

The proof of principle of the reverse bending solution was experimentally tried with a magnet which could give only 10% of the required field: a decrease of the dispersion was observed but stronger magnet is required for a fully conclusive experiment.

Radio Frequency Quadrupole (RFQ)

The LINAC3 RFQ is designed for a 25+ lead ion beam with excellent transmission and beam quality. We want to evaluate its efficiency when several charge states are injected simultaneously. The beam dynamics issues are the following: the different charge states have a different input longitudinal velocity and they receive a different acceleration per cell in the RFQ. Those two factors which are equivalent to a bigger overall input energy spread and a voltage jitter inside the RFQ have an impact on the overall output longitudinal emittance. The source extraction voltage and the RFQ vane voltage are the two parameters that can be used for the optimisation. Theoretical studies have shown that the minimum output longitudinal emittance for a population of three charge states is reached when the voltage in the RFQ is set correctly for the charge state with the biggest offset in input energy. The theoretical prediction was verified experimentally, by passing one charge state population at the time without changing the setting of the optics line matching to the RFQ. With these measurements we could verify the transmission of the nominal and adjacent charge state in presence of transverse mismatch and verify the prediction on the voltage settings. One should note that this procedure is valid if there are no collective effects, which is what we observe in simulations.

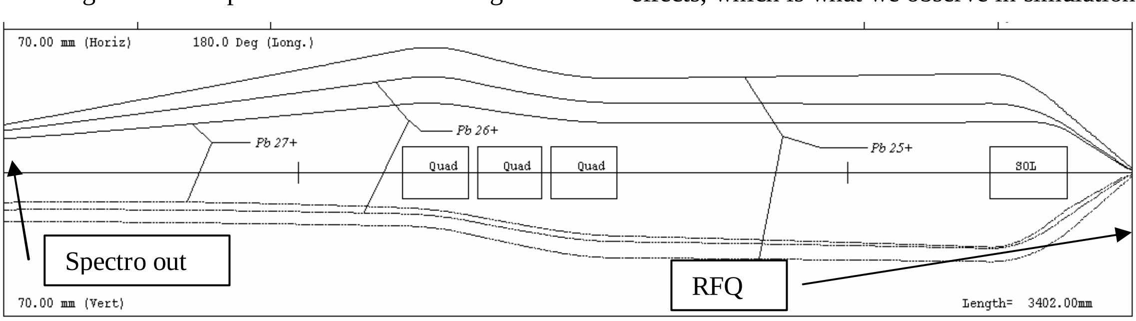

Figure 3: Beam dynamics in the LEBT for the reverse bending solution.

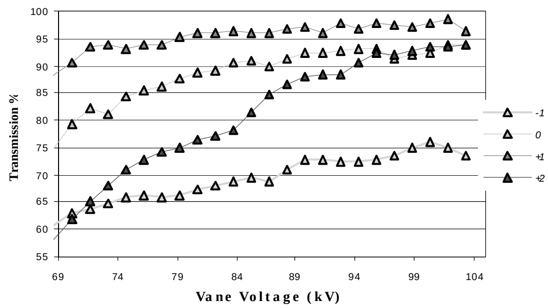

Figure: 4: Measured transmission vs. RFQ vane voltage for four adjacent charge states (0 is the charge state for which the matching to the RFQ has been optimised).

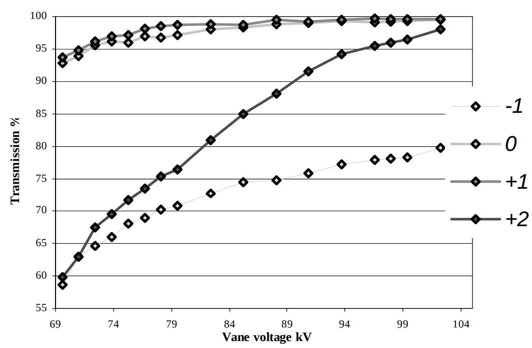

Figure 5: Calculated transmission vs. RFQ vane voltage for different charge states. Each charge state was individually matched to evaluate the effects of mismatch by comparison with the data on Fig4.

From Fig 4 and 5 we can learn that four charge states can be accelerated in the RFQ simultaneously, that the effect of mismatch for the adjacent charge state is noticeable only for one charge state and that it can be compensated by increasing the RFQ vane voltage.

Interdigital H-Structucture (IH)

The IH structure is very sensitive to any longitudinal mismatch and its acceptance is very tight hence particular care has been used to optimise the longitudinally matching of the three charge states from the RFQ. Designed for Pb25+, the IH Linac cannot accelerate lower charge states, while acceleration for two higher charge states is rather good. As lower charge states receive an energy gain less than the design one, they stay in an unstable area, and are lost already in the first tank. With these preliminary considerations we look at the possibility of accelerating simultaneously Pb25+, 26+ and 27+. The overall transmission for three charge states has been optimised both transversally and longitudinally [6]. In particular, quadrupoles are optimised for maximum possible total transmission and, RF phase and voltage in tanks are used mostly to ensure beam quality. Tank 1 and Tank 2 voltages are suitable for tuning the beam transmission and longitudinal parameters while the voltage in Tank 3 acts mainly on the output energy of the beam. Experimental results are reported in Fig. 6.

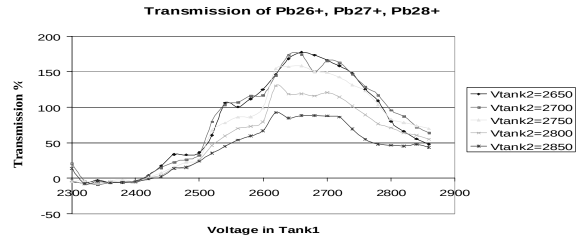

Figure 6: Transmission of three charge states through the LINAC3 IH. For reference the single charge state transmission is 85%.

Comparison of the Proposed Solutions

In order to estimate the advantages of the multicharge solution over the present single charge acceleration scheme, we have performed an end-to-end simulation of the different set-ups starting from the source up to the end of the line which selects the lead 54+ for injection into LEIR. We have used the same beam at the source and transported it through the optimised configuration for each case. The figure of merit is the intensity of lead 54+ inside the typical transverse emittances and momentum spread expected by LEIR (2.1 mm mrad rms and 0.1 % dp/p-5sigma) [7]. This figure of merit accounts for the losses in the accelerator as well as for any transverse and longitudinal emittance increase, resulting in the effective gain as seen from the downstream accumulator. The results are that both solutions give abut twice as much particles: 80% if the reverse bending solution is chosen or up to 150% more if the straight injection solution is chosen.

CONCLUSIONS

It is possible to accelerate simultaneously 3 charge states of lead ion through the RFQ and the IH of LINAC3. This possibility allows us to increase the intensity delivered to LEIR, the low energy ion ring for the LHC ion program, by a 80% or 150% depending on the technical solution chosen for the LEBT.

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