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REDESIGN OF CERN LINAC3 RFQ FOR LEAD 29+

S. Benedetti *, A.M. Lombardi, G. Bellodi, J.B. Lallement, CERN, Geneva, Switzerland

Abstract

CERN Linac3 is at the heart of the CERN Heavy Ion Facility, providing 4.2 MeV/u ion beams to the Low Energy Ion Ring (LEIR). It mostly accelerates $^{208}Pb^{29+}$, though in recent years runs were performed with $^{40}Ar^{11+}$ and $^{129}Xe^{22+}$, in view of the raising interest of the physics community towards lighter ions experiments. In the framework of the LHC Injectors Upgrade (LIU) project, measurements and beam dynamics simulations showed that a transmission bottleneck of Linac3 is represented by the RFQ. As this accelerator was originally designed for $^{208}Pb^{25+}$, the lower beam rigidity of the heavy ions currently in used – and planned to be used – permits a redesign of the RFQ aimed at increasing its transverse acceptance, and thus the transmitted beam current. The methodology adopted and the results of this study are presented.

INTRODUCTION

Linac3 [1] is composed by an Electron Cyclotron Resonance (ECR) source producing heavy ion beams at 2.5 keV/u. The desired charge state is filtered by a Low Energy Beam Transport (LEBT) line and further accelerated by a 101.28 MHz RFQ to 250 keV/u. A Medium Energy Beam Transport (MEBT) line matches the beam, both longitudinally and transversally to an Interdigital H-type (IH) linac, which boosts the beam to 4.2 MeV/u. After the IH linac, the beam is stripped to a higher charge state and transported to LEIR. The layout of Linac3 is shown in Fig. 1.

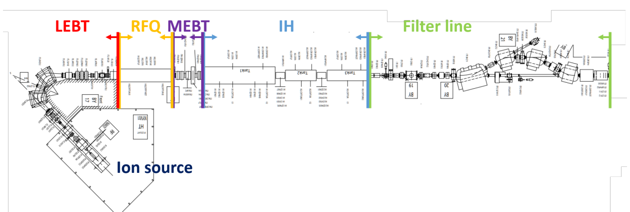

Figure 1: Linac3 layout, with the different sections marked.

In 2005, the original Linac3 ion source was replaced by a higher intensity 14.5 GHz room temperature ECR ion source (GTS-LHC) [2]. This source operates mostly in afterglow mode to produce $^{208}Pb^{29+}$, and in recent years, $^{40}Ar^{11+}$ and $^{129}Xe^{22+}$. This change called for a new study of the beam dynamics in Linac3 [3]. A major result is that the RFQ represents a bottleneck of the line, with transmission of 70 % or lower, depending on the accelerated ion species, while originally the transmission was higher than 90 %. The phase space orientation of the beam emittance appears to be reasonably well matched at the RFQ input, with the losses due to the input emittance larger than the acceptance (Fig. 2).

* stefano.benedetti@cern.ch

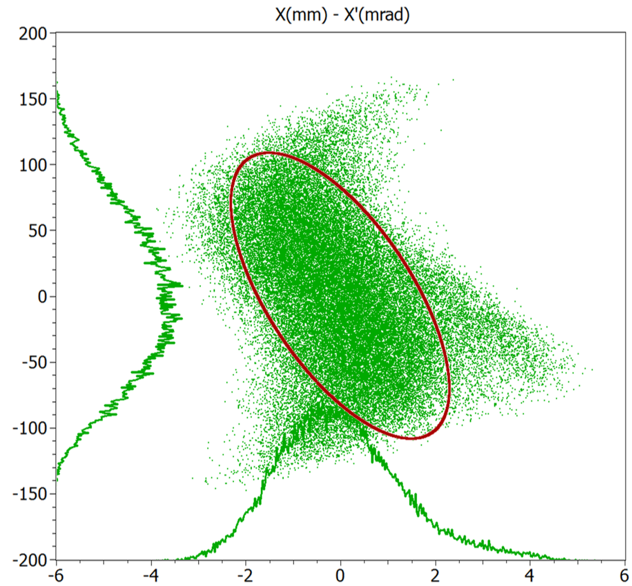

Figure 2: RFQ acceptance in red (0.45 mm.mrad 95 % beam) and simulated beam in green dots (0.97 mm.mrad 95 % beam) at the RFQ input for the the x-x' plane.

The lower beam rigidity of the currently accelerated ions with respect to the originally considered $^{208}Pb^{25+}$ permits to redesign the RFQ increasing its transverse acceptance. The redesign shall meet the constraints discussed in the following section.

CONSTRAINTS OF THE REDESIGN

The RFQ redesign had to meet three constraints: to maintain the same cavity length – 2.5 m – and operating frequency – 101.28 MHz, to maintain the same vane voltage V_0 – 71 kV – and maximum surface electric field – 23.9 MV/m, to maintain or decrease the output longitudinal emittance, 39 π.deg.keV/u for 95 % of the particles.

The first constraint guarantees a minimal change of the line, as only the rod modulation and aperture will change, while the outer tank and power supply would not be replaced. The second point ensures that the redesigned has the same Break-Down (BD) rate of the current one. Operating at 101.28 MHz, with a maximum surface electric field of nearly 24 MV/m, the cavity Kilpatrick factor is 2.1.

The last constraint – to maintain or decrease the output longitudinal emittance – is a consequence of the small longitudinal acceptance of the IH linac that follows the RFQ.

The transmission through the IH cavities was measured as a function of the phase of the input beam. This was achieved by changing the RFQ RF phase, which accepts a continuous input beam and it is thus unaffected by this modification. The phase of the buncher cavities between the RFQ and the IH were also changed accordingly, in order to guarantee

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that the same longitudinally matched beam reaches the IH input, though with the different RF phases. The result of the measurement is a very sharp drop in the transmission as soon as the RF phase of the beam changes (Fig. 3). The beam dynamics simulations agree with this measurement, as the beam phase space in the longitudinal plane at the IH input is just contained by the IH acceptance (Fig. 4). In conclusion, the longitudinal output emittance from the RFQ has to be preserved, if not reduced, to guarantee a good transmission through the IH linac.

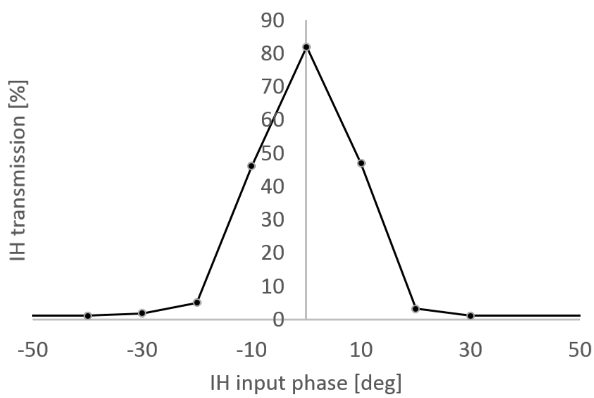

Figure 3: Measured transmission through the IH linac as a function of the IH input phase.

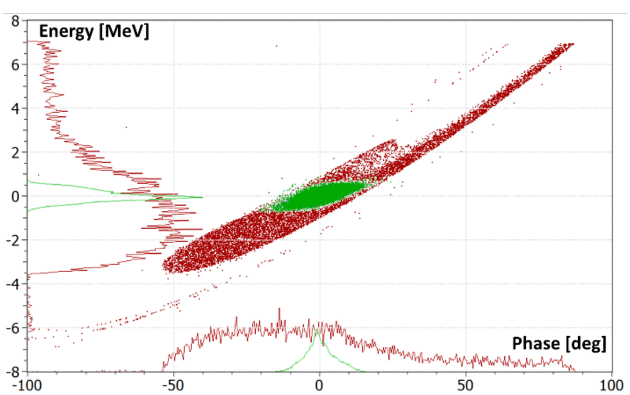

Figure 4: Simulated IH cavities longitudinal acceptance (red dots) and comparison with the simulated beam at the IH input (green dots).

The redesign specification parameters are summarized in Table 1.

CURRENT DESIGN

Linac3 RFQ became operational in 1994. It has been originally commissioned for a $^{208}Pb^{25+}$ beam, with 2.5 keV/u input energy and 250 keV/u output energy. This four-rod RFQ is characterized by a bunching section where the modulation m and the synchronous phase are quickly increased shortly after the RFQ input. The bunching section itself is relatively short with respect to a standard design. Therefore, the transverse acceptance is lower than that of a more standard RFQ. This peculiar design approach [4] is observable in Fig. 5 top.

Table 1: Main Design Specifications for The Linac3 RFQ Redesign

Parameters	Value
Input/Output energy	2.5/250 keV/u
Operating frequency	101.28 MHz
Length	2.5 m
Input transverse acceptance (95%)	> 0.5 mm.mrad
Output longitudinal emittance (95%)	< 40 deg.keV/u
Max surface electric field	24 MV/m

BEAM DYNAMICS REDESIGN

A standard RFQ design with the Los Alamos National Laboratory (LANL) codes [5] was adopted at the first stage of this study. Even with optimization of the gentle buncher, it was not possible to reach the required small longitudinal output emittance that represents the main peculiarity of the actual RFQ design. The main parameters that have been varied were the gentle buncher length - by setting the desired phase and energy at the end of this section - the average focusing strength B, the ratio between the rods transverse radius of curvature ρ and the average aperture r_0, and the vane voltage V_0.

As a second approach, it was decided to consider four reference designs, considering 71 kV vane voltage and a 0.95 ρ/r_0 as the reference design, and focusing strength B of 4.5, 5, 5.5 and 6, respectively. As a remark, the reference Linac3 RFQ has a focusing strength B=4. Considering the 16 % increase in q/m, this would translate in B=4.6 for the new redesign. In the redesigns, B<4.5 did not permit to have an RFQ length of 2.5 m, while B>6 had a too high maximum surface electric field E_s.

As a final step, the modulation and the phase of the buncher section were modified with the aim of reducing the longitudinal output emittance to the goal value. Designs exceeding Es of 24.0 MV/m were discarded. A lower modulation in the bunching section decreases the longitudinal output emittance, as well as the surface electric field Es and the transverse acceptance. The same behaviour is obtained by decreasing the synchronous phase. Goal of this redesign was to exploit the surface electric field limit – around 24 MV/m – throughout the whole cavity. The best result was achieved considering as a starting point a design with B factor 5.2, with a lower modulation in the bunching section and a slower increase of the synchronous phase (Fig. 5 bottom).

The main beam dynamics parameters of the two designs are summarized in Table 2.

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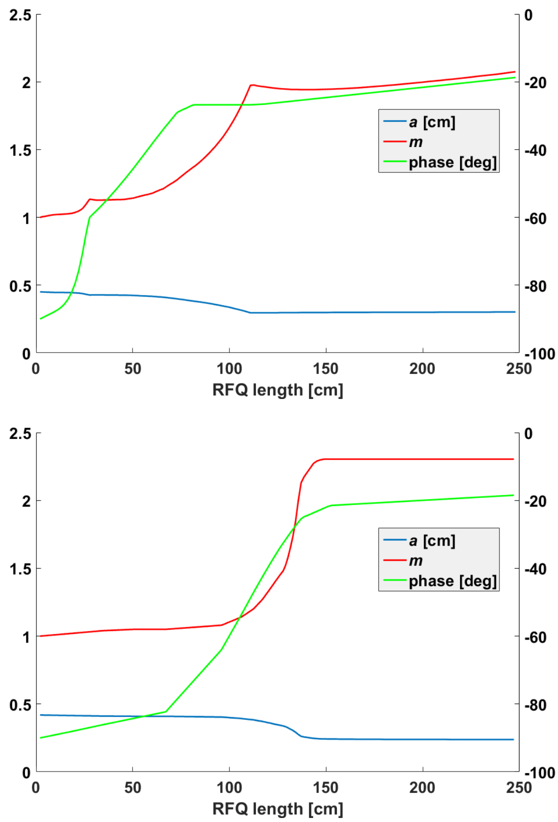

Figure 5: Minimum aperture a, modulation factor m and synchronous phase for the current Linac3 RFQ (top) and for the redesign proposed in this paper (bottom).

Table 2: Comparison Between the Main Beam Dynamics Parameters for the Two RFQ Designs

	$^{208}Pb^{25+}$ design	$^{208}Pb^{29+}$ design
Vane voltage	71 kV	
ρ / r_0	0.95	
Final synch. phase	18.5 deg	
Min aperture radius	3.0 mm	2.4 mm
Max modulation m	2.1	2.3
Number of cells	253	357
Output phase spread	± 12 deg	± 11 deg
Output energy spread	± 1.3 %	± 1.2 %
Input transv. accept. (95%)	0.45 mm.mrad	1.02 mm.mrad
Output long. emit. (95%)	39 deg.keV/u	34 deg.keV/u
Max surface E field	23.9 MV/m	

BEAM CURRENT INCREASE AT LINAC3 OUTPUT AND DISCUSSION

Parmteq [5] and Toutatis [6] were used to validate the new design of the Linac3 RFQ with multi-particle simulations. The beam phase space was reconstructed from beam profile measurements before the RFQ, and tracked through it until the MEBT Faraday cup (FC). With the current design, the simulated beam transmission is 68 %, in agreement with the measurements taken during the 2017 Xe run [3]. If the same beam is tracked considering the $^{208}Pb^{29+}$ redesigned RFQ, it shows a simulated transmission of nearly 100 %. As the redesign RFQ is nearly loss-free, the normalized transverse emittance is preserved, and thus the $^{208}Pb^{29+}$ redesigned RFQ has a larger output emittance than the current one. Thus this output beam has to be further simulated through the IH linac to obtain a complete comparison of the two scenarios. After the RFQ, the beam is transversally and longitudinally matched to the IH cavities by the MEBT line. Uncertainty in the quadrupoles calibration makes the beam dynamics simulations in this part of the line challenging [3]. For this part of the line the multi-particle code TRAVEL was used [7]. For all the simulations a complete beam aperture model is considered.

Adopting a conservative approach, the simulated transmission from the RFQ output to the IH output is 70 %. Thus the losses would increase in the MEBT line with respect to the current design, where the simulated transmission is 80 %. Overall, the simulated beam transmission from the LEBT to the IH linac output would however increase, thanks to the higher transmission through the RFQ, as summarized in Table 3

Table 3: Total Simulated Transmission from the LEBT Triplet to the IH Linac Output With the Current RFQ $^{208}Pb^{25+}$ Design and the $^{208}Pb^{29+}$ Redesign

$^{208}Pb^{25+}$ design	56 %
$^{208}Pb^{29+}$ design	69 %
Relative current increase at Linac3 output	23 %

The Linac3 diagnostic in the MEBT line has been recently improved. This should permit to estimate with more precision the final beam current increase to be expected.

SUMMARY AND OUTLOOK

A redesign study of the CERN Linac3 RFQ has been made profiting of the lower rigidity of the heavy ions nowadays accelerated with respect to the first conservative assumption, $^{208}Pb^{25+}$. The main RFQ parameters, cavity length, vane voltage and Kilpatrick limit, have been kept equal to the original design. The redesign was carried out only by modifying the rods shapes. From simulations, the RFQ transmission would increase from 68 % to nearly 100 %, and the current at the end of Linac3 would increase by 20 %.

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