

SIMULATION AND MEASUREMENT CAMPAIGNS FOR CHARACTERIZATION AND PERFORMANCE IMPROVEMENT OF THE CERN HEAVY ION LINAC3

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Abstract

In the framework of the LHC Injector Upgrade programme (LIU), several activities have been carried out to improve the GTS-LHC ion source and Linac3 performance (Linac3 providing the charged heavy ion beams for CERN experiments). A restudy of the beam dynamics and transport through the linac was initiated, through a campaign of systematic machine measurements and parallel beam simulations, generalising techniques developed for beam characterization during Linac4 commissioning. The work here presented will review the most relevant findings and lessons learnt in the process.

INTRODUCTION

The Linac3 linear accelerator is the first element of the CERN heavy ion injector chain, providing highly charged heavy ion beams for the CERN experimental program.

The ion beams are produced with the 14.5 GHz room temperature Electron Cyclotron Resonance (ECR) ion source GTS-LHC, which is based on the Grenoble Test Source (GTS) developed at CEA (France). Lead is the predominant ion beam delivered by the source, though production of argon and xenon beams for fixed target experiments has also been performed.

The GTS-LHC source was installed in 2005, replacing the original ECR4 ion source with the goal to increase the beam current delivered by Linac3. However, the projected gain was not reached due to a lower than expected transmission through the linac.

Linac3 itself has been operational since 1993, accelerating heavy ions from 2.5 keV/u to 4.2 MeV/u for injection and accumulation into the Low Energy Ion Ring (LEIR). Charge state selection is first carried out on the beam extracted from the source via a 135° spectrometer bend. Acceleration is then done in two stages: first a 101.28 MHz Radio-Frequency Quadrupole (RFQ) increases the beam energy to 250 keV/u; then a system of 3 Interdigital-H tanks (the first one at 101.28 MHz, the other two at 202.56 MHz) takes the beam to 4.2 MeV/u. The beam is then stripped in passing through an amorphous carbon foil, and a new charge state is selected for injection in LEIR. Here the beam is accumulated and cooled before being transferred to the Proton Synchrotron (PS), the Super Proton Synchrotron (SPS), and ultimately the Large Hadron Collider (LHC).

Typical currents delivered for Pb⁵⁴⁺ ion beams at the end of Linac3 before 2015 were approximately 20-25 μAe, with a stripping efficiency from Pb²⁹⁺ to Pb⁵⁴⁺ of 15% and

a cumulative acceleration efficiency through RFQ and IH of 55-60%. This corresponds to a Pb²⁹⁺ current at the source of ~150 μA.

An in-depth restudy of the Linac3 beam extraction and transport was initiated a few years ago in the context of the LHC Injector Upgrade (LIU) programme, with the aim of improving the performance of the accelerator chain for future high luminosity operation of the LHC. The target parameter of 8x10⁸ Pb⁵⁴⁺ ions/bunch extracted intensity from LEIR was comfortably exceeded in 2016 operation thanks to the combined improved performance of both Linac3 and LEIR (+40%) and mitigation of the main intensity limitations.

The Linac3 performance upgrade campaign was articulated around a comprehensive restudy of the beam formation from the GTS-LHC ion source and of its transport through the Low Energy Beam Transport (ITL) section, RFQ and IH linac. Previous simulation studies had been carried out either with TRACE2D envelope tracking or with multi-particle tracking with PATH using ideal input beam distributions. Focus was only recently placed on a more rigorous modelling of the beam extraction from the source, with the aim of providing more realistic input beam conditions for tracking studies. A systematic campaign of machine measurements was also launched to provide input and cross-check for the simulation results. In this paper we review the current understanding of beam dynamics in Linac3 and the limitations still affecting the present modelling.

SOURCE EXTRACTION SIMULATIONS

The GTS-LHC ion beam extraction has been simulated with the ion optical code IBSimu [1], with 3D magnetic field maps and electrode geometry. The afterglow discharge is modelled by assuming an increased plasma potential of 200V and low 10eV temperature cold electron population. The initial ion species distribution was defined based on the measured Charge State Distributions (CSD). The simulation assumes full space charge in the extraction region, due to the presence of strong electric fields preventing the accumulation of low-energy electrons and consequent compensation mechanisms.

Extraction simulations were carried out for all operational beams: lead, argon and xenon [2]. In the case of Pb beams the strong charge-over-mass dependent focusing effect causes the formation of a beam waist inside the grounded electrode and envelope separation of the different ion species. For Ar and Xe this effect is mitigated and the transverse distributions are more uniform (see Fig. 1). In all cases, due to the lack of additional focusing elements

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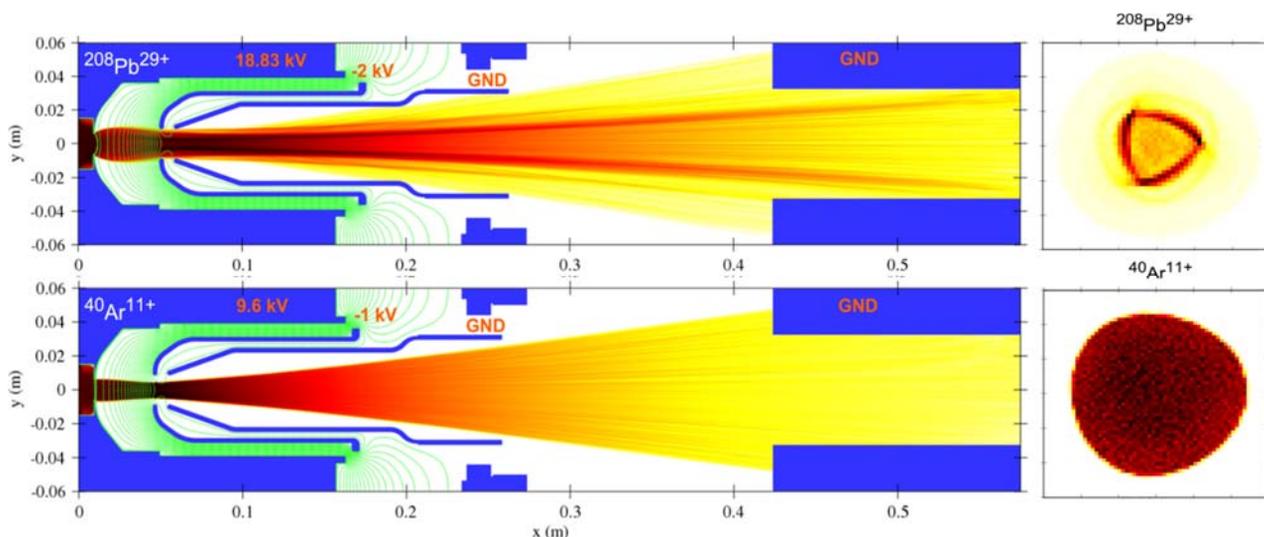


Figure 1: Beam extraction simulations with IBSimu: trajectory densities (left) and transverse beam profile distributions (right), taken at the axial location $x=0.423$ m.

in the extraction region, the beams are highly divergent, causing significant beam collimation on the walls of the extraction pumping chamber and downstream solenoid beam pipe. This was confirmed by a visual inspection of the GTS-LHC extraction system, showing clear beam-induced markings at the location predicted by the simulations (see Fig. 2).

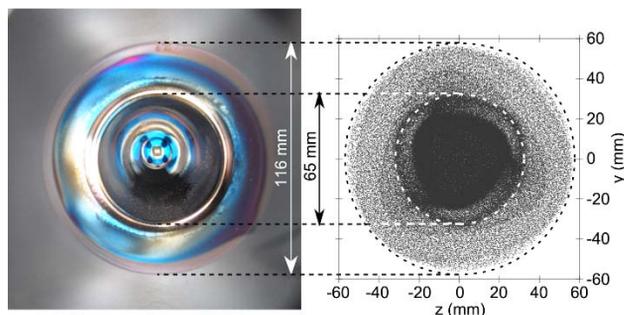


Figure 2: Observed beam induced markings from beam scraping (left) compared to the transverse distribution at the same location obtained with IBSimu (right).

A redesign of the beam extraction region was prompted by these studies, with the aim of reducing the losses due to beam scraping and improve transmission from the source. Two main modifications were put in place: 1) the aperture restriction was mitigated by increasing the beam pipe diameter at extraction and through the first solenoid from 65 to 100 mm; 2) a bipolar Einzel lens was installed to provide additional beam focusing and matching. The first action alone yielded a gain of +20% in the transmitted beam current from the source to the exit of the spectrometer bend. The second modification, on the other hand, did not prove to be beneficial in the end, and the lens was subsequently removed.

The IBSimu extraction results were used to define the initial beam distribution for input to beam dynamics studies in Linac3 with the 3D multiparticle tracking code PATH [3]. Machine operational settings and beam aperture model were used in the simulations to allow direct comparison with beam measurements. All the measurements and simulations reported in the following refer to the 2017 operation with xenon beams at Linac3.

EMITTANCE MEASUREMENTS

A layout of Linac3 is presented in Fig. 3. No beam diagnostics is available between the source and the spectrometer magnets. The first instruments are located after the slit (a Faraday cup) and quadrupole triplet (profile harp) downstream of the bend, before entering the RFQ. As will be shown later, this is at present one of the main limitations to any further progress in the understanding of the beam dynamics at Linac3.

The available diagnostics consists in several Beam Current Transformers (BCT) and Faraday cups for beam intensity measurements and harps (SEM grids) for transverse profile measurements. These are placed at several locations along the machine: 1) at the end of the ITL (LEBT) line, before entering the RFQ, 2) at the RFQ output, in the MEBT; 3) at the exit of the IH tanks, after the stripper foil and 4) finally in the ITF filter line selecting the charge state for injection in LEIR.

A pepper-pot device is installed after the spectrometer bend just downstream of the slit selecting the nominal charge state. After long and unsuccessful commissioning efforts, however, it was concluded that the beam characteristics at the installation location are not adapted to detection with this device. If measurements in the horizontal plane were indeed possible, the large beam divergence causes a superposition of beamlets in the vertical plane and

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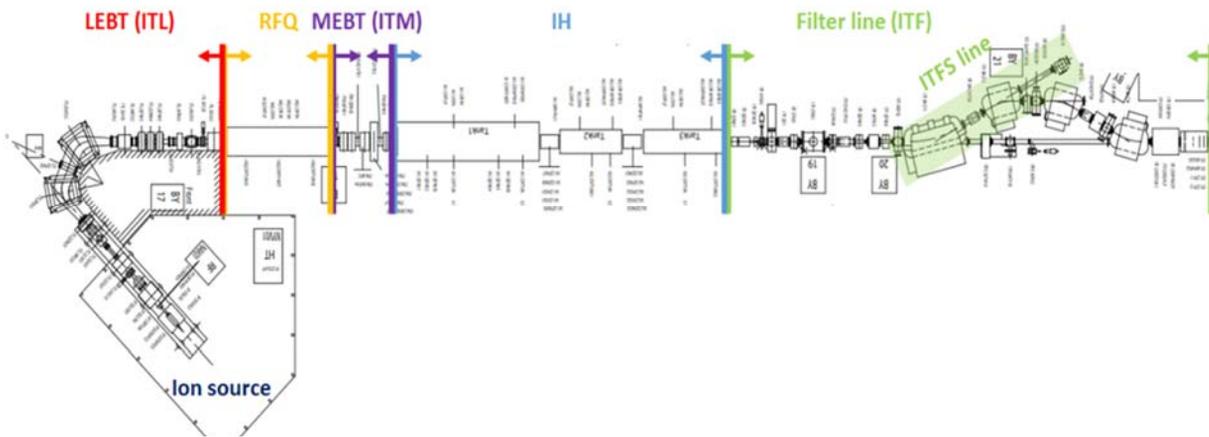


Figure 3: Linac3 layout.

makes virtually impossible the correct association between beamlets and pepper pot mask holes where they originate, which is at the basis of the data analysis process.

Beam transverse emittance has been measured indirectly from profile measurements via a quadrupole scan technique, using two independent methods originally developed during Linac4 commissioning [4]. The “forward method” technique builds up on the classical analytic calculations using transfer matrices: it consists in iteratively varying the Twiss parameters of the beam at the reconstruction point, tracking it to the measurement location taking into account space charge effects and comparing the measured and simulated RMS beam sizes. The method is relatively simple, since it deals with RMS beam sizes calculated from the measured profiles. This implies however a loss of information on the beam distribution, as only a

projection of the phase space is measured. A more sophisticated method is the phase space tomography, which is based on linear mapping of the measured beam profiles onto the initial phase space to estimate the particle density distribution. The projections of the reconstructed phase space are then compared to measured data and the initial distribution is modified iteratively until agreement is reached with the measured profiles.

The results of several emittance measurements taken during the year at different machine locations are listed in Table 1: values show a good reproducibility over time and agreement between analytical and tomographic technique of reconstruction, within a 15% range. The only exception is given by the vertical emittance measurements in the MEBT section. Here the insufficient resolution of the profile harp had a great impact on the quality of the measurements and yielded overestimated emittance values. At the

Table 1: Reconstructed Normalized RMS Emittance Values for Xenon Beams in the ITL, ITM and ITF Lines

		ϵ_x π mm mrad	ϵ_y π mm mrad	α_x	α_y	β_x m/rad	β_y m/rad		
ITL	<i>Analytical reconstruction</i>	0.13	0.15	-3.90	-1.59	1.32	0.57		
		0.14	0.18	-3.49	-2.50	1.15	0.72		
		0.13	0.18	-3.37	-2.77	1.08	0.83		
		0.11	0.18	-3.39	-2.67	0.96	1.11		
	<i>Tomographic reconstruction</i>	0.11	0.14	-4.68	-1.73	1.65	0.97		
		0.11	0.15	-3.98	-2.57	1.37	0.88		
0.12		0.16	-4.02	-2.54	1.41	0.89			
ITM	<i>Analytical reconstruction</i>	0.08	0.21	0.05	3.63	0.06	0.79		
		0.07	0.20	0.18	4.87	0.10	1.07		
	<i>Tomographic reconstruction</i>	0.08	0.29	0.07	2.38	0.06	0.63		
		0.08	0.36	0.25	3.04	0.09	0.80		
		ITF	<i>Analytical reconstruction</i>	0.13	0.16	-2.76	-1.75	6.17	1.56
				0.12	0.13	-1.82	-1.25	4.87	1.07
<i>Tomographic reconstruction</i>	0.14	0.17	-2.38	-1.81	5.17	1.58			
	0.12	0.15	-2.09	-1.60	5.04	1.30			

RFQ exit the beam should be approximately anti-symmetric, hence transverse emittance values should be similar in both planes.

SIMULATIONS

These emittance values and other beam measurements taken at Linac3 were used both as input and feedback for simulation studies, in an effort to validate our modelling of the machine. In particular, the particle distribution reconstructed tomographically from beam profiles in the LEBT was compared to the result of tracking the input beam obtained by IBSimu at source extraction all through the spectrometer line (consisting of one focusing solenoid, a quadrupole and two bending magnets). As shown in Fig. 4, agreement is fairly good in the horizontal plane, but not in the vertical one. Transmission values are also more pessimistic in the IBSimu-simulated case than in reality.

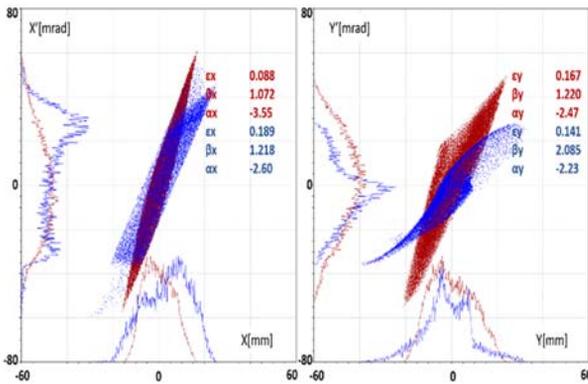


Figure 4: Comparison between beam phase space tomographic reconstruction from measurements (red dots) and simulation results (blue dots) in the ITL line [5].

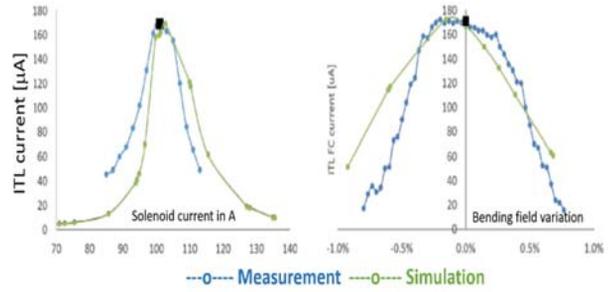


Figure 5: Comparison between measurements and simulation results for the transmitted current in the ITL Faraday cup when scanning: the solenoid current downstream of source extraction (left) and the spectrometer magnet current (right). The black marker indicates the operational point [5].

The absence of diagnostics in the spectrometer line and the difficulty in making diagnostics that distinguish between the many species in this zone makes it impossible to validate the assumptions taken in the simulation of the beam extraction from the source. A scan of beam intensity as a function of magnetic strength values for either the solenoid or the dipoles (Fig. 5) could only give agreement between measurements and simulations after some parameter rescaling, thus pointing at the fact that some of the values assumed in our modelling are not correctly known.

Simulated transmission values through the RFQ are also considerably more pessimistic than in reality. For all these reasons and difficulties it was decided to use as input for tracking studies the beam distribution reconstructed tomographically after the spectrometer bend, and focus on the beam dynamics downstream of this location. The beam was transported through the RFQ and IH cavities, and the

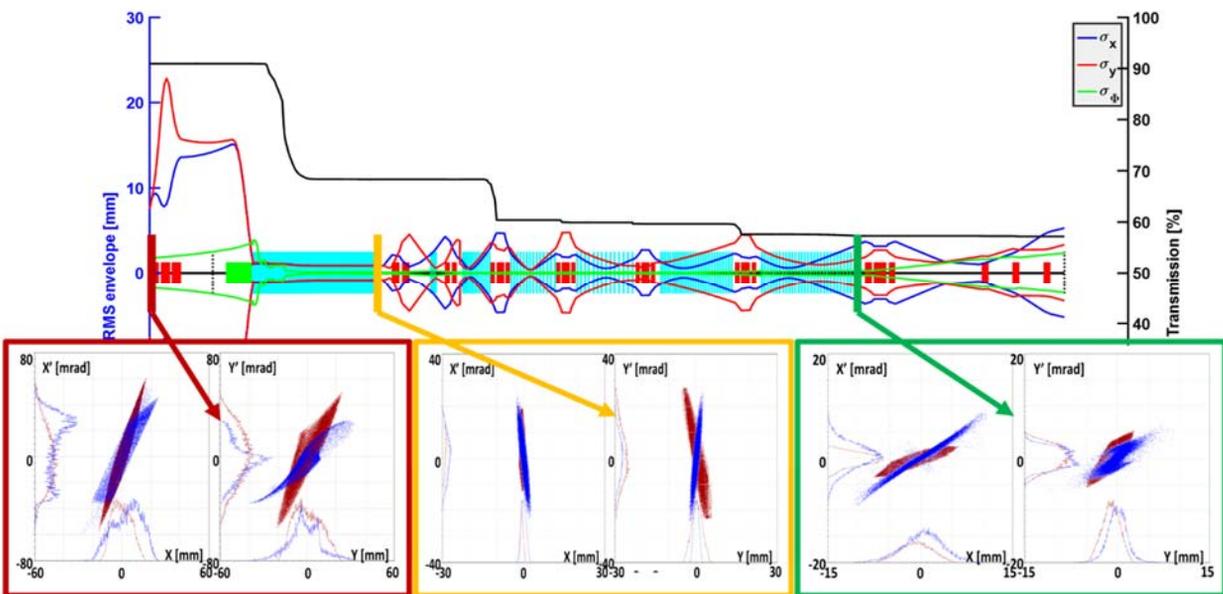


Figure 6: Summary of beam dynamics simulations: RMS envelopes, transmission and simulated vs measured beam distributions at selected locations along Linac3 [5].

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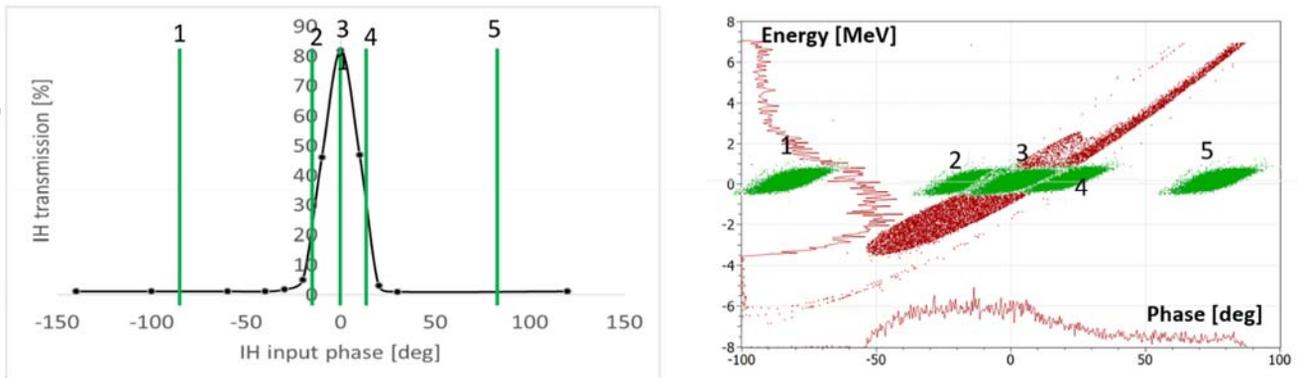


Figure 7: Measured transmission through the IH as a function of the input RF phase (left). Simulated IH longitudinal acceptance (red) in comparison with the longitudinal IH input beam for several input RF phases (in green)[6].

simulation results were again validated through comparison with measurements. As shown in Fig. 6, the operational beam current transmission through the RFQ was confirmed in simulations to be around 70%. The beam distribution at the exit of the RFQ (yellow box in the figure) was found to be in very good agreement in the horizontal plane with the corresponding tomographic reconstruction. The mismatch in the vertical plane is most likely due to an insufficient resolution of the profile harp, affecting the precision of the beam measurements, possibly combined with an uncertainty in the calibration curves of the quadrupoles scanned due to magnetic cross-talk. The short distance between the diagnostics device and the quadrupoles also causes larger fluctuations in the results.

The description of the IH cavities and the KONUS beam dynamics simulation results were also validated by beam profiles and transmission measurements. The reconstructed phase space at the IH output is quite similar to the simulated one (see Fig. 6 in the green box). The dependence of beam transmission on several machine parameters (tank amplitude and phase setpoints, IH quadrupole gradients etc) was measured through variable scans and well reproduced in simulations. The overall ~80% transmission through the IH was also confirmed by beam tracking.

Comparing this value with transport efficiency at lower energy showed that the RFQ remains the main bottleneck for beam transmission. This prompted research into a possible re-design of the cavity, with the aim of increasing its transverse acceptance while maintaining cavity length and field and constant or lower output longitudinal emittance. The latter constraint comes from the necessity to fit the beam in the small longitudinal acceptance of the IH, thus avoiding to just shift the bottleneck problem downstream. This acceptance was measured by detecting the change in transmission through the IH while scanning its input RF phase. A sharp drop is measured as soon as the input RF phase deviates from the nominal value (Fig. 7 left). This is confirmed by beam simulations, as the IH input beam phase space in the longitudinal plane is tightly contained in the IH acceptance (Fig. 7 to the right). A redesign solution was eventually found on paper: a new rods design fitting in the same footprint that could increase the transmission through the RFQ by 20% [6].

SUMMARY AND LESSONS LEARNT

A thorough restudy of the beam dynamics and transport through Linac3 was carried out, through a campaign of systematic machine measurements and parallel beam simulations.

For the first time beam production from the source was the object of detailed studies with the help of the IBSimu ion optical code. The absence of diagnostics immediately downstream of beam extraction severely affected the capacity of achieving a realistic initial beam distribution. Some input assumptions of the simulations would still need further tuning and optimisation before reaching full validation. An important result of these studies was however to confirm the performance limitation induced by beam scraping at extraction from the source. Reduction of these losses by an increase of the beampipe aperture diameter could gain a 20% improvement in transmitted beam intensity.

Emittance measurement techniques, which were initially developed for beam characterization during Linac4 commissioning, were successfully applied to Linac3. They also allowed the reconstruction of the beam phase space from profile measurements, and the distributions found could be used as input for tracking studies and cross-check of simulations. End-to-end beam tracking from the LEBT to the output of the IH gave results consistent with the observed beam transmission and profiles, thus providing a full validation of the models and machine description used. This allowed the possibility to conduct further studies and improve the understanding of beam dynamics in Linac3. A first conclusion reached was the identification of the RFQ as main bottleneck for beam transmission, due to its limited transverse acceptance compared to the emittance of the beam extracted from the GTS-LHC ion source. A dedicated study showed a possible mitigation could be put in place by a redesign of the RFQ geometry, with a 20% scope of increased beam transmission downstream through the IH.

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