# SOURCE AND LEBT BEAM PREPARATION FOR IFMIF-EVEDA RFQ

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## Abstract

The commissioning phase of the IFMIF-EVEDA RFQ requires a complete beam characterization with simulations and measurements of the beam input from the IFMIF-EVEDA ion source and LEBT, in order to reach the RFQ input beam parameters. In this article, the simulations results of the complex source-LEBT with the corresponding set of measurements and their impact on the commissioning plan will be reported.

## THE IFMIF-EVEDA PROJECT

The Linear IFMIF Prototype Accelerator (LIPAc) is a high intensity deuteron linear accelerator [1]; it is the demonstrator of the International Fusion Material Irradiation Facility (IFMIF) machine within the Engineering Validation Engineering Design Activities (EVEDA) scope. It is presently in an advanced installation phase at Rokkasho under the Fusion Energy Research and Development Directorate National Institutes for Quantum and Radiological Science and Technology (QST), in the prefecture of Aomori, Japan. LIPAc has been designed and constructed mainly in European labs with participation of JAEA in the RFQ couplers. It is composed of an injector delivered by CEA-Saclay [2], a RFQ [3] designed made and delivered by INFN on April 2016, a superconducting Linac designed by CEA-Saclay [4], RF power, Medium and High Energy Beam Transfer lines and a beam dump designed by CIEMAT [5]. The coordination of the European activities is managed by F4E and, on Rokkasho site, the Project Team supported by QST is responsible for coordination, integration and commissioning.

## SOURCE AND LEBT

The injector is composed of a 2.45 GHz ECR ion source based on the CEA-Saclay SILHI source design and a LEBT line of about 2.05 m (distance from plasma electrode to RFQ entrance flange). The LEBT is composed of two solenoids with H/V integrated steerers, two diagnostic boxes (one between two solenoids and the second one after the injection cone) and the RFQ injection cone, equipped with repeller electrode. The first diagnostic box contains the following devices:

- Self-polarized Faraday Cup,
- Doppler-Shift Spectroscopy diagnostic,
- Neutralising gas injection device (H2 or Kr gas),
- Chopper

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- 4-Grid analyser, for space charge compensation measurement.

The diagnostic box is equipped with:

- Allison-Scanner emittancemeter, placed 300 mm after the RFQ injection point (it will be placed between the two solenoids during RFQ commissioning),
- ACCT for pulsed current diagnostic at RFQ entrance (it will be placed at the end of the RFQ during commissioning),
- Self-polarised beam stop for current measurement.

The diagnostics employed in this section may be biased due to the beam power (14 kW for deuterons) and to the large quantity of electrons inside the beam pipe. Distributed power deposition along the LEBT components may induce thermal effects, which induce deformation on the diagnostics. Moreover, the electrons in the LEBT produced by residual gas ionization and collisions, can give rise to over/under estimation of the beam current reading. Both these effects may be a significant source of errors in beam parameters measurements. Therefore, it is very important to compare the diagnostics output and the simulations prediction, in order to check the understanding of the physics behaviour. The target values are 140 mA (70 mA proton) deuteron beam @ 100 keV (50 keV proton) with $\varepsilon_{n,rms}$ = 0.25 mm mrad and a correct converging beam at RFQ input: mismatch factor [6] lower than 10%. A pulsed beam will be used for RFQ commissioning, so the reproducibility of LEBT beam at different duty cycle up to cw is necessary. Finally a proton beam (50 keV, 70 mA) well characterized would help for beam commissioning.

## BEAM DYNAMICS SIMULATION AND MEASUREMENT OF SOURCE AND LEBT

The simulation results presented here are relative to an 86 mA (read from the power supply) hydrogen beam extracted beam at 50 keV, with an estimated proton fraction of 72% (from Doppler shift spectrometer) respect to H2 and H3 measured between the two solenoids of the LEBT (Q = $3.23\times10^{-3}$ generalised perveance, 55 mA proton beam at beam stop). The emittance measurement done within the maximum transmission area of the BS and the simulation with AXCEL-INP [7] program were used in order to find the Twiss parameter and emittance after 20 cm from the plasma electrodes. The software used for LEBT simulation was TraceWin[8], which is a PIC code with single species transport of 55 mA proton beam. 10000 macroparticles were used and the mesh was
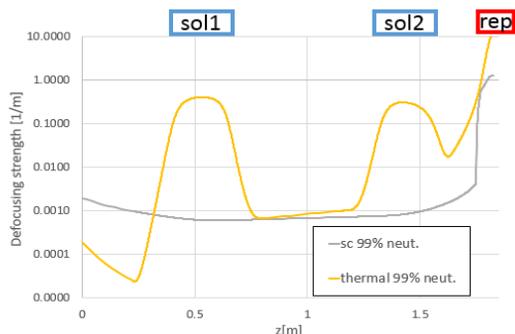
adapted following [9].



Figure 1: Defocusing strengths of thermal and space charge terms with 99% of neutralisation within the LEBT and 0% in the repeller electrode zone.

Its fast run capabilities allow following the commissioning operations. In simulations, static neutralisation was used: constant value (from the 4-Grid analyser measurement) for large part to the LEBT and then a decreasing ramp approaching the repeller electrode up to 0. The beam envelope follows the Eq. 1, where the $\varepsilon_x$ is the total emittance given from $\varepsilon_x = a\ \varepsilon_{x,rms}$ (a constant which depends from the input distributions) which is not normally constant along the line. The generalised perveance term is not constant also because the space-charge defocusing term depends on the neutralisation level.

$$r''(s) + k_x(s)r_x(s) - \frac{Q(s)}{r_x(s)} - \frac{\varepsilon_x^2(s)}{r_x^3(s)} = 0 \qquad (1)$$

This non-constant behaviour of the Eq. 1 defocusing terms leads to a very complicate description from the beam dynamics point of view. The emittance growth (given by the coupling from the solenoid nonlinearities and space charges) and the neutralisation level of more than 95% between the solenoids imply that the beam becomes more emittance dominated along the LEBT (see Fig. 1). The effect of the solenoid couplings can be seen by the dependence of the emittance from the solenoid values. In the strong focusing zone (upper left quadrant of the Fig. 2, solenoid 02 > 140 A and solenoid 01 < 140 A) it is expected a larger emittance than in the weak focusing zone (solenoid 02 < 140 A and solenoid 01 > 140 A). The trend was confirmed experimentally during the March '16 campaign (see Fig. 2 and Fig. 3 simulated emittance) and some initial trend in the lower left quadrant was seen with 110 mA @ 100 keV deuteron beam in December '15 [10]. The simulations help to identify the effects which contribute to the iso-transmission lines of the BS current scan: different beam dimensions at the BS, misalignment effects from the source and losses along the line in case of too strong focusing (losses located at the cone hole) or too weak focusing (losses located along the cone). The neutralisation after the beam cone is another issue: the vacuum level is normally about $10^{-6}$ torr, therefore another order of magnitude smaller than the rest of the LEBT,

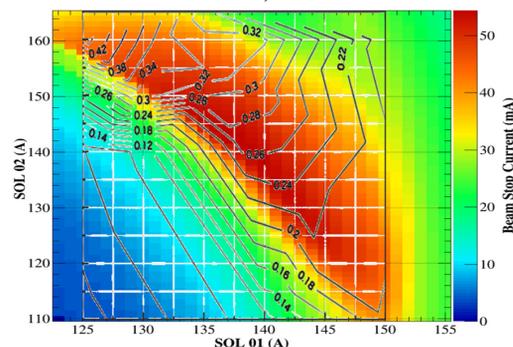which implies order of 100 µs for stable neutralisation (in case of H2 main contribution).



Figure 2: Beam stop current scan plot and rms norm. iso-emittance areas (black lines), measured at March work point. It is possible to identify the almost monotonic emittance trend from lower right corner to left upper corner.

Therefore, it is important to take also into account the effect of the emitted electrons, due to beam collisions, from the tungsten shield of the emittancemeter. A first rough estimate form indirect measurement and simulations was done in [11]. In the next campaign [10], Kr gas is foreseen in this LEBT zone, in order to try to improve the neutralisation. Some evidences have been observed with 50 keV proton beam as described [10].
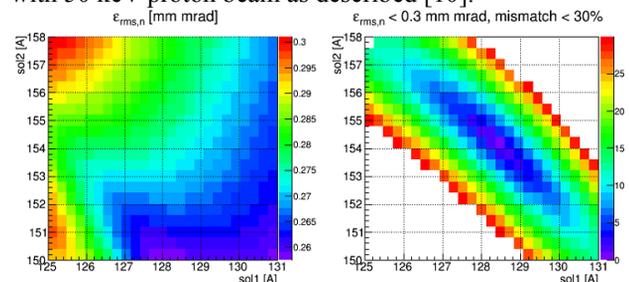


Figure 3: Right: Particular of simulated rms norm emittance at the RFQ injection point. Left: 30% mismatch zone located within the upper left quadrant of the scan plot (165-140 A sol2 and 124-140 A sol1) at the RFQ injection.

Foreseen by the simulation studies and the theory is the dependence of the neutralisation level from the beam envelope. This fact limits the approximation of the same level of neutralisation in confined zones of the scan plot, as reported in [11].

Table 1: Experimental and simulated trend of the emittance 300 mm after the RFQ injection from different solenoid values, from a weak focusing zone to strong focusing at RFQ injection.

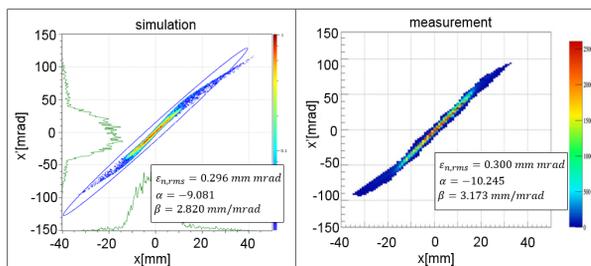| Sol1-Sol2 [A] | Meas. $\varepsilon_{n,rms}$[mm mrad] | Sim. $\varepsilon_{n,rms}$[mm mrad] |
|---|---|---|
| 143-130 | 0.227 | 0.241 |
| 138-142 | 0.271 | 0.286 |
| 135-150 | 0.299 | 0.300 |
| 131-159 | 0.354 | 0.363 |

Figure 4: Simulated vs measured phase space at emittance meter for the point (130 A, 150 A).

This description of the LEBT dynamics allows us to estimate the mismatch at the RFQ input, which stays 300 mm before the emittancemeter (see Fig. 4 as an example). From previous studies [11] the 30% mismatch zone should be found in the upper left quadrant of Fig. 2 (140 A – 125 A, 140 A -160 A). This fact was confirmed by the post analysis of the March campaign, as shown in Fig. 5.

Once the 30% zone was identified with an emittance around 0.3 mm mrad at RFQ injection, it was possible to test the RFQ transmission and its output beam parameters for these intermediate commissioning results.

## RFQ SIMULATIONS

The RFQ is matched to the superconductive cavities with a MEBT line. The current of the accelerated particle can be seen at the low power beam dump, at the end of the matching line. Before that, the quadrupoles and bunchers must be set in order to maximise the transmission of the accelerated particles. In order to decuple the effects of bad MEBT quadrupole settings, the effect of not accelerated particles, injector problems and RFQ issues, it is important to estimate the output beam parameters (without the not accelerated particles) at the exit of the RFQ, with respect to the LEBT solenoid values in the minimum mismatch zone. Figure 5 shows the current transmitted by the RFQ, without the not accelerated particles, for the LEBT solenoid settings of the matched beam. The maximum transmission results to be 93%. We can define the mismatch compared to the output Twiss parameters for the point with maximum transmission. The results can be seen in terms of output transverse beam emittance and mismatch in Fig. 6. Within the maximum transmission area, the RFQ output beam does not show significant changes in terms of Twiss parameters. On the contrary, the emittance increases of about 10% at the RFQ exit, moving the solenoid settings from the matching values (i.e. from the centre of the plot to the lower right corner).

This emittance growth is due to the mismatch at the RFQ input. From the output Twiss parameters point of view, if we move far away from the minimum mismatch zone, we may find zones with more than 16% of mismatch that couples with a smaller transmission to the RFQ.
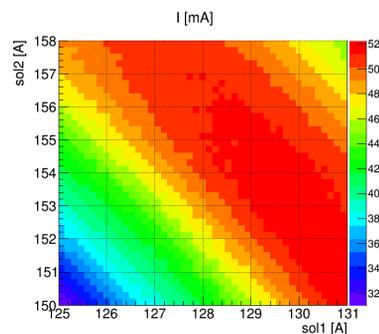


Figure 5: Current plot at RFQ output without the not accelerated particles (scan plot zone with smaller mismatch)
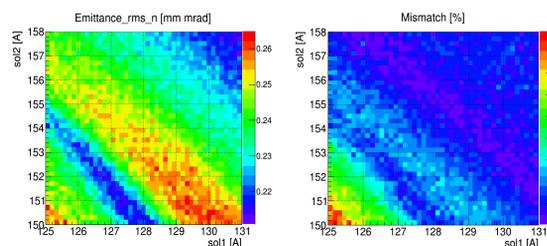


Figure 6: RFQ output beam parameters (mismatch and emittance) with the change of the LEBT solenoids.

However, it would be useless to maximise the MEBT transmission in this zone, because the RFQ transmission would not be optimised. The simulation results shown by Fig. 5 and Fig. 6 underline this fact.

## CONCLUSION

If we can ensure in the strong focusing area a normalized rms emittance < 0.3 mm mrad (at the emittancemeter), we can safety search the matching (<30%) keeping at the same time the beam quality. The simulations will be used to find the 30% mismatch zone (which position depends on the extracted Twiss parameters) @ RFQ input, with a similar procedure followed in this paper. The results of simulations and measurements can effectively help the commissioning, decoupling the effect of the different part of the machine: source, LEBT, RFQ and MEBT. In this article, a method for ensuring at the same time the emittance and the Twiss is proposed and partially tested. Deep understanding and modelling of the dynamic neutralisation is an ongoing work [12-14] and further studies are planned with other softwares [15] in order to check these results and the commissioning plan.

## ACKNOWLEDGMENT

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