

# BEAM DYNAMICS SIMULATION AND MEASUREMENTS FOR THE IFMIF/EVEDA PROJECT

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## Abstract

In the framework of IFMIF/EVEDA project the source and RFQ are ready to be tested with beam. In this article the beam dynamics simulation and the measurement performed in preparation of the first beam injection are presented. The installed line is composed by the proton and deuteron Source with the LEBT composed of two sole-noids that inject in the 10 meters long RFQ, the MEBT, diagnostic plate and the beam dump. The line is prepared to be tested with protons of 8 mA in pulsed mode (up to 0.1%).

## INTRODUCTION

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. It is composed of an injector delivered by CEA-Saclay [2,3], a RFQ [4] designed, manufactured and delivered by INFN on April 2016, a superconducting Linac designed by CEA-Saclay [5], RF power, Medium and High Energy Beam Transfer line (MEBT) and a high power Beam Dump supplied by CIEMAT [6]. The coordination of the European activities is managed by F4E and, on Rokkasho site; the Project Team supported by QST is responsible for integration. The beam that will be produced will be a 125 mA CW D<sup>+</sup> beam at 9 MeV after the SRF cavities, delivered onto the high-power beam dump. Because of the large power deposition, several commissioning stages were foreseen, each one involving a specific part of the machine.

The nominal D<sup>+</sup> input current to the RFQ is 135 mA.

This paper is divided into two parts: the first part concerns the effect of the residual beam potential after the neutralization process onto the input distribution of the RFQ and the response of it; the second part is dedicated to a different scenario, which is to foresee the behaviour of the RFQ and MEBT with lower current beam. The voltage characterization for different Courant-Snyder parameters of the beam were studied to identify the main characteristics of the beam.

## SPACE CHARGE NEUTRALIZATION

In the low energy high intensity transfer line from the source to the RFQ, the beam transport is affected also by other species: the space charge compensation phenomena, s.c.c. (or space charge neutralization) can occur with the generation and superposition to the primary beam by opposite charge particles with a net reduction of the space charge effects.

Therefore, an important part of the beam dynamics characterization of this kind of transfer line concerns the estimation of the so-called secondary plasma effect.

Two s.c.c. models are considered in the simulation: the constant/static and dynamic model. In a constant model of neutralization, the perveance is simply reduced by a factor that is called the space charge compensation ratio, this Beam dynamics model is implemented on the TraceWin code.

In dynamic model of neutralization, the s.c.c. is calculated directly from the electron charge distribution that is superimposed to the ion distribution. Therefore, for the model both the ions and electrons dynamics need to be calculated, this Beam dynamics model is implemented on the Warp code.

## BEAM DYNAMICS SIMULATION AT HIGH CURRENT WITH DYNAMIC MODEL OF SSC.

The method applied is using the following assumptions:

- The space charge compensation is a result of a Monte-Carlo process where each secondary particle is generated via a defined cross section, which depends on the energy of the incident particle.
- The secondary particle, electron, is governed by the self and applied field.
- The WARP code can transport all the multiple species.

This model of the dynamic space charge compensation requires extremely time demanding simulations with serial core processing. To reduce the time needed for a run, the parallelized version of the software was used: the 2 m length simulation was subdivided in 20 longitudinal domains, limited by the max core number at disposal of the machine. Anyhow, the simulations required times is the order of weeks to be performed to arrive at an almost steady stationary regime, see Fig. 1.

This framework does not foresee any arbitrary change of neutralization level. The process itself will determine it.

The steps used for the BD simulation are:

1. First set of  $\epsilon_{rms,n}$ ,  $\alpha$ ,  $\beta$  was calculated via the AXCEL software. The rms quantities were assigned to a parabolic beam distribution placed at the extraction column repeller position.
2. All the line optical elements such as the solenoids and the repeller were set as in reality, with the same applied field.
3. The distribution is transported up to the emittance meter. If the parameter triad agrees within 30% and the simulation current within 20% the mean value of the error bar, the method proceeds with the next measured point. If not, only the Twiss parameters and the emittance are changed.
4. When a rough agreement is obtained, the process is concluded.

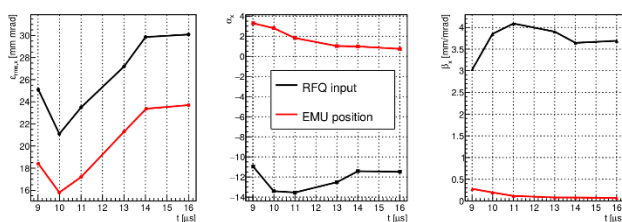


Figure 1: Twiss parameters evolution along the simulation time.

## COMPARISON OF SIMULATION AND MEASUREMENT

The simulation consists of 2.397 m long LEBT, starting from the repeller electrode up to the emittance meter (EMU). The repeller electrode is critical for the simulation, because it contributes to the longitudinal boundary of the electrons and cannot be neglected. The initial guess for the beam Twiss were obtained via AXCEL simulation which stops at the repeller position. The WARP software simulates the beam propagation through the LEBT. It was decided to use the multigrid Poisson solver routine to manage the space charge beam dynamics. All the simulations were performed with full 3d geometry to check if the formation of circular structures in the spatial domain. The BD envelope is shown on Fig. 2.

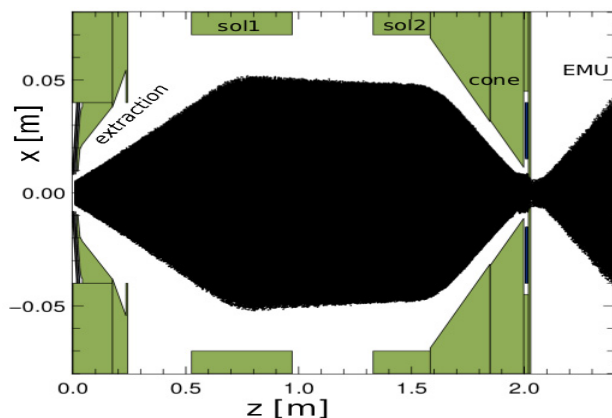


Figure 2: BD simulation from the injector to the EMU.

Respect to the measurement done very interesting results were obtained. Figure 3 shows the comparison between the experimental and simulated phase space.

The simulated point is quite near to the matched point for the RFQ injection Sol2=305 A, Sol1=262 A.

This dynamics model allows to follow the beam profile modifications due to the solenoid strength change with enough precision (less than 5 % difference in the rms quantities between the simulation and the experiment). The central peak position however is not in agreement.

The comparison involves the measured and simulated values with complete model with electron secondaries from wall collisions and with electrons belonging to ionization of the residual gas.

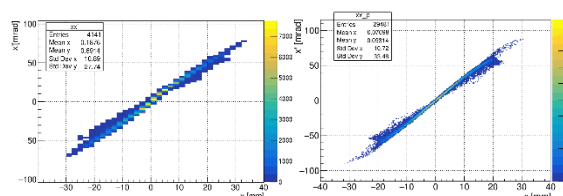


Figure 3 Measured and Simulated Phase Space at EMU position.

## RFQ BEAM DYNAMIC SIMULATION

The simulated point was transported through the RFQ to study the transient phenomena by using the same emittance of 0.25 mm mrad and the same Twiss parameters.

The main approximation is the different residual potential (thus s.c.c.) at the RFQ injection: as it was explained before, the simulations were performed with phase A2 layout (i.e. with a diagnostic box after the LEBT cone); therefore, the electrons presence in the region of RFQ injection may not be representative of the real RFQ boundary conditions. However, this problem affects just few mm length of simulation.

Up to three meters, there is the generation of longitudinal emittance and, at the same time, fast oscillations of the transverse emittances caused by the mismatch.

After the gentle buncher, the beam gets to an equilibrium state, with few oscillations on the transverse emittance.

The main losses are concentrated before the 3 m, which corresponds to the end of the gentle buncher section. The integrated power deposited in case of CW beam is 2.9 kW.

Normally the RFQ-designer uses "standard" distributions to predict the RFQ under study, such as the quasistatic waterbag and gaussian. It is worth to compare the predicted losses of these type of distributions with the same Twiss parameters of the WARP simulation, and the relative estimated real distribution. Table 1 shows the transmission, the total kW lost into the RFQ and the Halo parameter relative to each distribution: truncated gaussian at  $3\sigma$ , quasistatic waterbag and simulated one with WARP. It is possible to see that the approximation holds quite good for the W lost into the RFQ and the losses. However, the estimates with the standard distributions result optimistic as far as the losses are concerned of 2.3%. Therefore, for a fine estimate

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of the transmission it is necessary to study the RFQ acceleration and transport with the realistic distribution. The last but not the least aspect refers to the transient transmission and parameters change due to the build-up of space charge compensation. The RFQ model includes the measured geometry of the cavity [7] and the voltage profile from bead-pull measurements were also implemented in the code TOUTATIS by using a perturbed Vanes file [8]. In Fig. 4 is reported the emittance along the RFQ with Warp result as input distribution.

Table 1: Beam Distribution Effects at End of RFQ

Dist. Type	Tr. Out Emit.	Long. Emitt.	Halo	Losses	Losses Power
Unit	mmrad	MeVdeg		%	W
Warp	0.20	0.17	3.3	16.0	2.9
Gaussian	0.26	0.20	0.8	16.6	3.0
Waterbag	0.27	0.21	0.4	15.7	2.9

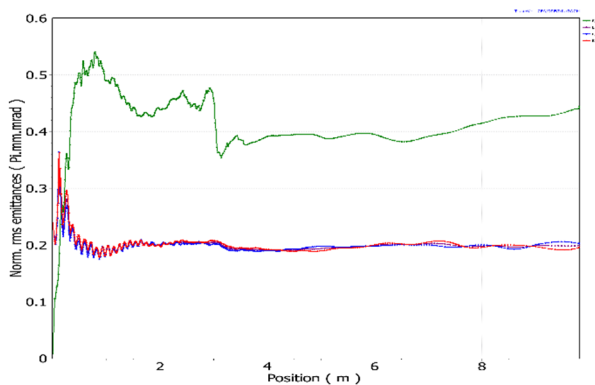


Figure 4: Emittance inside RFQ with real vanes and warp result as input distribution. Green Curve is longitudinal Emittance. The other curve the transverse Emittances.

## BD CHARACTERIZATION AT LOW CURRENT

### First Beam Operation

The first commissioning stage will involve the injector source, the RFQ and the MEBT with a low power beam dump in pulsed mode, up to 0.1% DC. Due to the potential damage even at low DC that may come from the deuteron beam, and the debug of the Low-Level RF system, it was decided to inject a low current proton beam of 7-9 mA at 50 keV, to avoid large power deposition and to maximize the RFQ acceptance with respect the input mismatch.

### Injector Input

The source extraction was designed for a maximum 155 mA deuteron total current beam at 100 keV ( $D^+$ ,  $D_2^+$ ), extracted from an extraction hole of the plasma electrode of 6 mm radius. In January 2018, we tested several configurations at different proton currents at 50 keV, to test the best extraction conditions, reducing the extraction hole down to 3 mm radius.

The results, in agreement with simulations and calculation, consisted of a beam of 13 mA total extracted current

(proton and molecular hydrogen ions) with approximately 7-8 mA proton current. Figure 5 shows the simulated phase space at 20 cm from the extraction hole of the plasma electrode, performed with AXCEL, of the beam above considered.

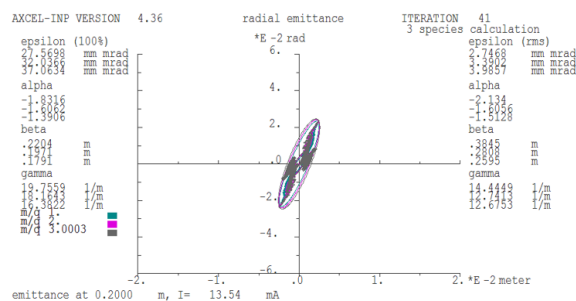


Figure 5: Output at 20 cm from the plasma electrode aperture for 13 mA proton beams.

The divergence of the whole beam is constrained between  $\pm 30$  mrad, while the dimension is in between  $\pm 5$  mm. The extraction is behaving like an electrostatic lens decreasing the divergence also of the molecular ions of the hydrogen.

Since the beam generalized perveance is one order of magnitude smaller with respect the deuteron beam ( $10^{-3}$  for D beam and  $10^{-4}$  for low proton current beam), the space-charge effects in the low energy beam transfer line are depressed with respect to the deuteron case.

In such condition, the trace-forward method, applied in previous studies [9], Fig. 6 shows the results for a certain couple of solenoid field, was chosen to retrieve the beam evolution along the LEBT up to the RFQ. This step is preliminary with respect the study of the voltage characterization.

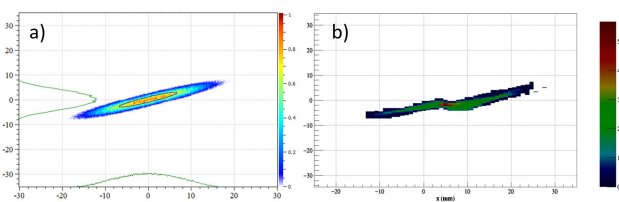


Figure 6: 7 mA proton beam distribution in phase space at the low energy beam transfer line emittance meter position (between the two LEBT solenoids). a) simulated distribution in phase-space, with the same set of solenoid strength b) Measured distribution in phase-space with the same set of solenoid couples. The simulated normalized rms emittance is 0.075 mm mrad, while the measured one is 0.08 mm mrad.

### RFQ and MEBT Behaviour

The software used for the transfer lines simulation is TraceWin: the LEBT was implemented in the code with solenoid field-maps; the space-charge compensation trend along  $z$  was inserted from a WARP simulation. The RFQ was modelled with TOUTATIS code. The RFQ model includes the measured geometry of the cavity [7] and the

voltage profile from bead-pull measurements were also implemented in the code [8]. Figure 7 shows the reconstructed macro particles density along the accelerator with respect the beam axis for the matched beam. Once the nominal solution is retrieved, it is possible to study the voltage characterization of the RFQ.

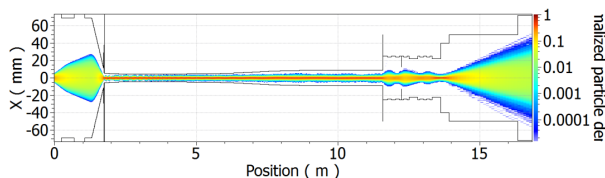


Figure 7: Macro particles densities with respect the beam axis, starting outside the extraction column and up to the LPBD.

Figure 8 shows the voltage calibration of the RFQ with respect to different input mismatches. The transmission is calculated looking at the RFQ input current, measured by an ACCT, at the RFQ output current, measured by another ACCT at the RFQ exit and at the end of the line, at the low power beam dump, equipped like a Faraday Cup. The MEBT quadrupoles (one triplet and one doublet) were set as for the matched beam. The first results is that the 7 mA proton beam will be 100% transmitted even with a mismatch of 220%, confirming the RFQ low sensitivity to solenoid fields setting with respect to the 135 mA D<sup>+</sup> case, where a mismatch of 20% can cause more losses than 20%. Different curves with respect to different input matching.  $\alpha$  indicates a converging or diverging beam at the RFQ input. The different matching was obtained changing the solenoid values in the LEBT model. The difference between the ACCT and the LPBD currents are due to the not accelerated particles, which are not transmitted along the MEBT section due to a sort of energy selection done by the quadrupoles and appropriate placed scrapers.

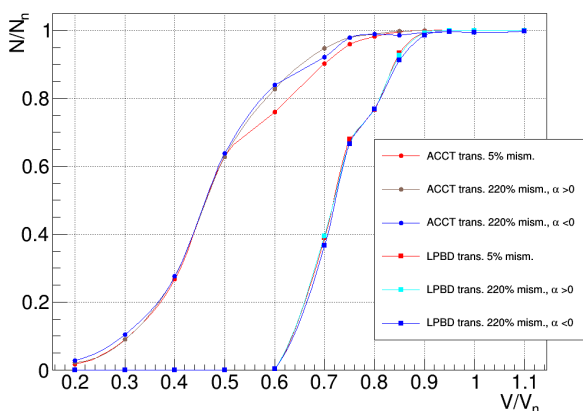


Figure 8: Normalized transmission ( $N/N_n$ ) with respect to the matched value transmission ( $N_n$ ) from the RFQ input current (LEBT ACCT) to the output of the RFQ (ACCT) and to the end of the line (LPBD) with respect to different RFQ voltage ratios ( $V$ ), normalized to the nominal voltage value ( $V_n$ ).

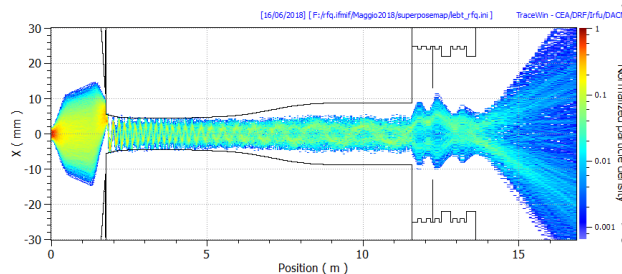


Figure 9: Macro particles density when the second solenoids is off-axis on X of 6 mm.

With the nominal voltage if is present a misalignment of the RFQ respect to the LEBT of 6 mm only on X, without any correction by using the steerers, the 86% of the beam is lost, as reported in Fig. 9.

In Table 2 is reported the effects of the two LEBT solenoids misalignment, without the use of the steerers, at the RFQ exit. The performed statistics is with 100 cases, considering only the maximum displacement on X and Y. Almost all the beam is lost if there is a misalignment of more than 4 mm.

The first days of beam operations have confirmed the results of these simulations, for what the optimum values of the lenses (solenoids) is concerned. An important misalignment between the LEBT and RFQ requires a high value of steerers and requires further tuning work to recuperate the nominal beam transmission (present value is 85%).as well as an upgrade of the model with the extraction region included.

Table 2: Solenoids Misalignment Effects at End of RFQ

Misalignment [mm]	Losses [%]
+/- 1	15.5
+/- 2	45.1
+/- 3	79.1
+/- 4	93.6

## CONCLUSION

The space charge neutralization is key phenomena that dominates the beam dynamics of the high intensity LEBT. In this paper, a method was applied to achieve an enough robust model to describe the input of the RFQ: the preliminary study shows that despite the very similar power deposition and losses, the second order moments may vary with respect to the standard design distributions (with the same Courant-Snyder parameters in case of mismatched beam. Further studies are foreseen as well as an upgrade of the model with the extraction region included.

The first beam input of IFMIF-EVEDA RFQ has been chosen and deeply studied. Thanks to its robust beam dynamics, it will allow to debug any possible issue of the RFQ in a safety environment. The current of the beam will be then ramp up to 30 mA, to study the effect of the growing space-charge term in the accelerator.

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## DISCLAIMER

Views and opinions expressed herein do not necessarily reflect those of QST, Fusion for Energy, or of the authors' home institutions or research funders.

## REFERENCES

- [1] P. Cara *et al.*, “The Linear IFMIF Prototype Accelerator (LI-PAC) Design Development under the European-Japanese Collaboration”, in *Proc. IPAC'16*, Busan, Korea, May 2016, paper MOPOY057, p. 985.
- [2] R. Gobin *et al.*, “Final Design of the IFMIF Injector at CEA/Saclay”, in *Proc. IPAC'13*, Shanghai, China, May 2013, paper THPWO003, p. 3758.
- [3] N. Chauvin *et al.*, “Final Design of the IFMIF-EVEDA Low Energy Beam Transport Line”, in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper TH5PFP004, p.3190.
- [4] M. Comunian and A. Pisent, “Beam Dynamics Redesign of IFMIF-EVEDA RFQ for a Larger Input Beam Acceptance”, in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper MOPS031, p. 670.
- [5] H. Dzitko *et al.*, “Technical and Logistical Challenges for IFMIF-LIPAC Cryomodule Construction”, in *Proc. SRF'15*, FRBA01, Whistler, Canada, Sep. 2015, p. 1453.
- [6] I. Podadera *et al.*, “The Medium Energy Beam Transport Line (MEBT) of IFMIF/EVEDA LIPAc”, in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper WEPS058, p. 2628.
- [7] A. Palmieri *et al.*, “Tuning the IFMIF 5MeV RFQ Accelerator”, in *Proc. LINAC'16*, East Lansing, MI, USA, Sep. 2016, paper THPLR049, p. 969.
- [8] L. Bellan *et al.*, “Source and LEBT Beam Preparation for IFMIF-EVEDA RFQ”, in *Proc. LINAC'16*, East Lansing, MI, USA, Sep. 2016, paper TUPRC005, p. 420.
- [9] L. Ferrari *et al.*, “Production quality controls and geometric characterization of the IFMIF-RFQ modules via the usage of a Coordinate Measuring Machine”, *Fusion Engineering and Design*, vol. 115, pp. 23-32, 2017.