IFMIF-EVEDA RFQ, MEASUREMENT OF BEAM INPUT CONDITIONS AND PREPARATION TO BEAM COMMISSIONING

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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 of source LEBT RFQ will be reported with the corresponding set of measurements done on the Ion source and LEBT.

THE IFMIF-EVEDA PROJECT

The Linear IFMIF Prototype Accelerator (LIPAc) is an 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 IFMIF-EVEDA RFQ

The Radio Frequency Quadrupole (RFQ) 0.1 - 5 MeV, 130 mA, is an Italian in-kind contribution to the IFMIF-EVEDA project, under the INFN responsibility.

The RFQ design method has been aimed to the optimization of the voltage and R0 law along the RFQ, the accurate tuning of the maximum surface field and the enlargement of the acceptance in the final part of the structure. As a result, a length shorter than in all previous design characterizes this RFQ; very low losses (especially at higher energy) and small RF power dissipation [6].

In Table 1 and Fig. 1 are reported the main RFQ parameters along its length.

LAYOUT OF INSTALLED 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 that will transport and match the beam into the RFQ thanks to a dual solenoid focusing system with integrated H/V steerers.

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Table 1: RFQ Main Parameters

Length	9.814	m (5.7λ)
Total Cell number	489	
Voltage Min/Max	79.29/132	kV
Max modulation m	1.8	
Min aperture "a"	3.476	mm
R0 min/Max	5.476/7.102	mm
Ratio ρ/R0 (constant)	0.75	
Final Synch. phase	-35.5	Deg
Max Surf. Field (1.76 Kp)	24.7	MV/m

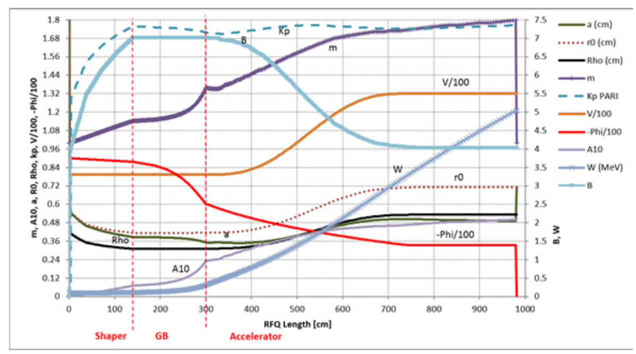

Figure 1: Parameters evolution along the RFQ.

The components of the LEBT are:

- Two solenoids with integrated steeres.
- Injection cone with repeller electrode after the two solenoids.
- Middle solenoids diagnostic box equipped with Doppler Shift Spectrometer instrumentation, Farady cup, Four Grid Analyser and Residual Gas Analyser.
- End diagnostic box after the solenoids, with an Allison scanner and self-polarised beam stop.

The commissioning is started in 2015 and will continue in 2016 interleaved with the RFQ installation in order to optimize the project schedule.

Design simulations show that to have less than 10% losses in the RFQ, the injected D+ beam must be 140 mA/100 keV CW with a normalized RMS emittance of 0.25 mm·mrad.

Commissioning activities use an equal generalised perveance H+ beam at RFQ injection, which consists of half current and half energy compare to deuterons at nominal conditions. This is done to allow hands-on maintenance activities since the activation power of 50 keV protons is negligible. Moreover, an electrostatic chopper has been implemented in between the two solenoids to provide sharp beam pulses of short length (~ 50-100 μs) for machine protection system in view of the RFQ com-

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missioning. Typically commissioning activities are done at 10% of duty cycle.

BEAM DYNAMICS SIMULATION AND MEASUREMENT OF SOURCE AND LEBT

The simulation was divided in two parts.

The first one deals with the extraction system and the plasma meniscus estimation (AXCEL-INP [7] program was used). The AXCEL simulation gave first estimation of the Twiss parameters and the emittance. Then, the input beam parameter was fine-match to an emittance measurement, via the neutralisation level given by FGA.

The second part deals with the LEBT: the software used was TraceWin[8]. Field map of the solenoids and of the repeller electrode in the RFQ injection cone were used. The input beam studied [9] is an H+ beam at 50 keV and 55 mA ($Q = 3.23\times10^{-3}$ generalised perveance) with a ratio of 75% compared to H2+ and H3+. The simulated input beam follows an uniform transverse 4D distribution with 5 eV as energy spread and with the input parameters found with the procedure defined above.

The TraceWin simulation starts 200 mm from the source extraction hole after the electrodes.

The distribution at the output of the source is not generally in an equilibrium state and the few betatrone oscillations along the LEBT are not enough in order to relax it. It will relax along the 9 meters' length; therefore, the main critical part is at the RFQ injection.

The matched beam follows the Eq. 1, where the ε_x is the total emittance given from ε_x=a $\varepsilon_{x,rms}$ (a is an arbitrary costant) 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.

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

The key parameters are the space charge defocusing term and the emittance defocusing term. In particular, the ratio between these two terms can help us to determine if the LEBT is emittance or space-charge dominated.

In simulations, static neutralisation was used in order to speed up calculations during the commissioning and its limitations were explored (see table 3).

From indirect calculation the exit of the extraction source seems to produce a too divergence beam at the first solenoid. Thus, the emittance growth is given mainly by the coupling from the solenoid nonlinearities and space charges.

The emittance trend was confirmed experimentally and by simulations during the March 2016 campaign, as in Fig.2 and Fig. 3 can be seen.

In fact, the neutralisation level of more than 95% between the solenoids implies an emittance-dominated beam (comparing the space-charge defocusing and thermal term from Eq. 1).

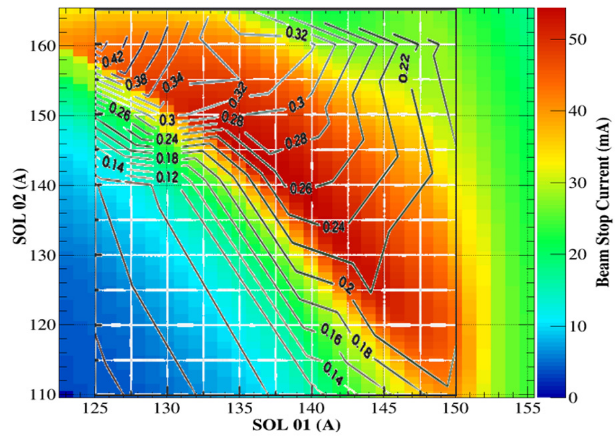

Figure 2: Beam stop current scan plot and rms norm. iso-emittance areas (black lines), measured at March work point. It is possible to identify the almost monotonic emittance trend from lower right corner to left upper corner.

Another degree of freedom found in the simulation was the neutralisation after the beam cone: the vacuum level is normally about 10^{-7} torr. Therefore, the contribution of the generated electrons from the residual gas is lower compared to the emitted electrons from the tungsten shield of the emittance meter.

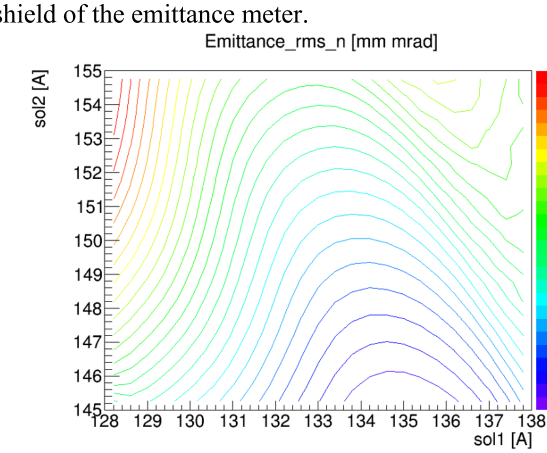

Figure 3: Particular of simulated rms norm. emittance gradient in the strong focusing zone (i.e. Sol1 from 120 A to 140 A, and Sol2 from 140 A to 165 A).

The electron cloud is attracted from the positive potential of the beam and neutralises. The overall effect of this neutralisation was estimated comparing with the BS (which is self-polarised) transmission and the emittance measurement.

As shown in the following table 2, there are two different regimes of neutralisation, which determine the current read by the BS and the emittance measurement, which needs to be taken into account.

The electron cloud dynamics is fairly complex and it is under study with another code (Warp[10]).

Another evidence seen by the measurement, foreseen by the simulation studies [11] and the theory is the dependence of the neutralisation level from the beam envelope.

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Table 2: Example of Parameter Changes in the Neutralisation after the Cone for the Solenoid Point (128 A, 158 A)

EMU in/out	Sim. neut. after the cone	Meas.	Simulation
in	87%	0.38 mm mrad	0.36 mm mrad
in	0%	0.38 mm mrad	0.43 mm mrad
out	0%	49 mA	46 mA
out	87%	49 mA	55 mA

This fact limits the approximation of the same level of neutralisation in confined zones of the scan plot, which was also a part of the study.

Table 3: Neutralisation Results and Input for the Three Zones

Scan plot zone limit approximation zone	N. before the cone	N. after the cone
134-145 A sol1 135-145 A sol2	96%	80%
127-138 A sol1 145-155 A sol2	99% (from measurement)	80%
125-135 A sol1 155-165 A sol2	99%	87%

This approximate but almost complete description of the LEBT dynamics allows us to estimate the mismatch at the RFQ input, which stays 300 mm before the emittance meter. See Fig. 4 as an example.

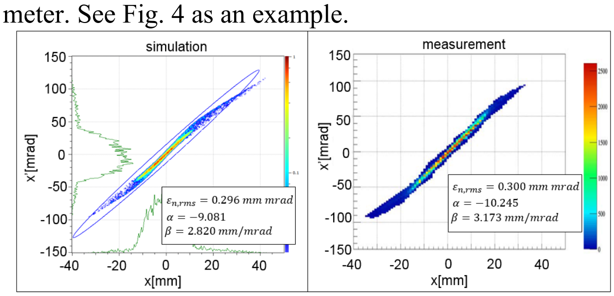

Figure 4: Simulated vs measured phase space at emittance meter for the point (130 A, 150 A).

From previous studies [12] the 30% mismatch zone[13] should be found in the upper left quadrant of Fig. 2. This fact was confirmed by the post analysis of the March campaign, as shown in Fig. 5. Once the 30% zone was identifying with an emittance around 0.3 mm mrad, it was possible to test the RFQ transmission and its output beam parameters.

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 position, at the end of the matching line. Before that the quadropoles and bunchers must be set in order to maximise transmission

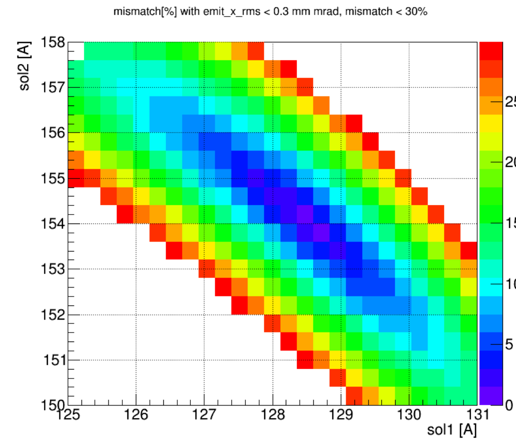

Figure 5: 30% mismatch zone located within the upper left quadrant of the scan plot (165-140 A sol2 and 124-140 A sol1).

In order to decuple the effect 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, respect to the LEBT solenoid values in the minimum mismatch zone (Fig. 5).

The Fig. 6 shows the current transmitted by the RFQ, without the not accelerated particles.

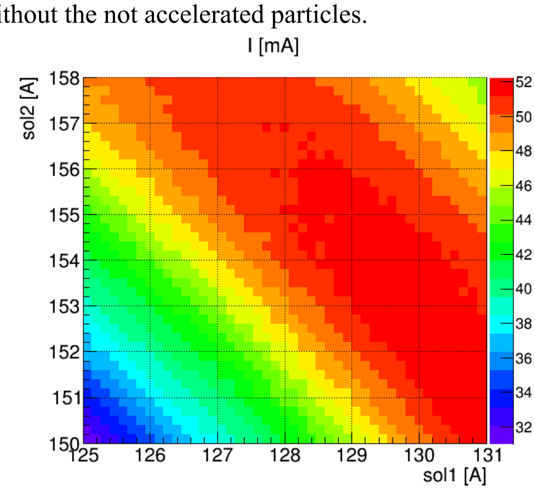

Figure 6: Current plot without the not accelerated particles in the scan plot zone with smaller mismatch.

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. 7.

Within the maximum transmission area, the rfq output beam does not show significant changes in terms of Twiss parameters. The emittance may change of about 10% depending on the solenoid value.

On the contrary, 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.

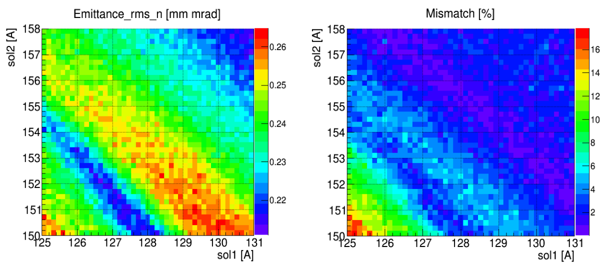

Figure 7: RFQ output beam parameters (mismatch and emittance) with the change of the lebt solenoids.

However, it would be useless to maximise the MEBT transmission in this zone, due to the fact that the rfq transmission would not be optimised. The simulation results shown by Fig. 6 and Fig. 7 evidence this fact.

Therefore, the MEBT quadrupole values should not affect the beam losses while moving the LEBT solenoid in the matching zone, but they need to be set with the simulation foreseen maximum transmission point of the accelerated particles.

SOURCE AND LEBT COMMISSIONING STATUS

At the state of the art the source is under commissioning at Rokkasho site, where the parameters still to be achieved are 65 mA H+ at 50 keV and 130 mA D+ at 100 keV with 0.25 mm mrad emittance in the equivalents strong focusing areas.

The LEBT behaviour is almost well understood and simulated, while the source needs a deeper beam dynamics studies and measurements for matching the QA requirements.

Some minor effects, which deal with secondary electrons, need to be fully understood but will require a different software to be managed.

CONCLUSION

The March campaign shows how strong can be the support given by the simulation even in such complex systems.

The results of the simulation and measurement from March 2016 are well in agreement, while they could effectively predict the area for matching the RFQ parameters. The prerequisites needed are:

- Measurements should be linked to all set of parameters of the LEBT, like gas pressure, solenoid settings extracted current, proton fraction. In this way it is possible to have under control all the observables of the many physical phenomena undergoing.
- the simulations must be performed taking into account their limit and their prerequisites.

On the contrary, the source presents many difficulties from the physics-modelling point.

Therefore, the extraction system simulation needs some extra caution: as an example, the presence of contaminants can affect the plasma state and deflect the beam from the expected trajectories.

Much effort should be put to this topic in order to start the RFQ commissioning.

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