FINAL DESIGN OF THE IFMIF-EVEDA LOW ENERGY BEAM TRANSPORT LINE

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Abstract

During the EVEDA (Engineering Validation and Engineering Design Activities) phase of the IFMIF (International Fusion Materials Irradiation Facility) project, a 125 mA/9 MeV accelerator prototype will be built, tested and operated in Rokkasho-Mura (Japan). The injector section of this accelerator is composed by an ECR source, delivering a 140 mA deuteron beam at 100 keV, and a low energy beam transport (LEBT) line to match the beam for the injection into the RFQ. The proposed design for the LEBT is based on a dual-solenoid focusing scheme. In order to take into account the space charge compensation of the beam induced by the ionization of the residual gas, a particle-in-cell code (SOLMAXP) has been used for beam dynamics calculations. The LEBT parameters have been optimized in order to maximize the beam transmission through the RFQ. The final LEBT design as well as the simulation results are presented.

INTRODUCTION

In the first phase of IFMIF, called EVEDA (Engineering Validation and Engineering Design Activities), a 125 mA cw/9 MeV deuteron demonstrator accelerator will be constructed, tested and operated at Rokkasho-Mura, in Japan [1]. This accelerator is composed by an ECR ion source, a low energy beam transport (LEBT) line, a RFQ (designed by INFL-Legnaro) [2], a matching section, a superconducting Half Wave Resonator cavities section, and finally a high energy beam line equipped with a diagnostic plate and a beam dump.

The purpose of the LEBT is to transport the 140 mA/100 keV deuteron beam extracted from the ECR source and to match it for its injection into the RFQ. A previous work [3] showed preliminary beam dynamics simulation results for the IFMIF-EVEDA LEBT. This paper present the final beam line design, specifically in the RFQ entrance region, in order to obtain the best RFQ injection.

LOW ENERGY BEAM LINE LAYOUT

ECR Ion Source and Extraction System

The IFMIF ECR source, based on the SILHI design, will operate at 2.45 GHz [4]. The extraction system has been optimized to increase the total beam intensity from 150 mA to 175 mA (in order to meet the required 140 mA D^+, as D_2^+ and D_3^+ are also produced in the ECR source) and the energy from 95 keV to 100 keV. A four electrode system has been calculated to minimize the D^+ divergence.

Table 1: Beam parameters after the extraction system.

Extracted Species	Intensity (mA)	Emittance (π mm.mrad)
D^+	141	0.064
D_2^+	26.5	0.043
D_3^+	8.8	0.042

The particle distributions after the source are derived from their tracking through the extraction system. Those beam distributions, of which main parameters are summarized in table 1, have been taken as inputs for the LEBT simulations.

Low Energy Beam Transport Line

The optics for the LEBT is based on two identical solenoids whose pole length is 240 mm (total length : 300 mm with the iron shielding). The magnetic field maps of the solenoids, computed by finite element method, have been included in the simulations. Compared to the preliminary layout [3], the second solenoid is now closer to the RFQ in order to obtain higher beam convergence at the RFQ entrance.

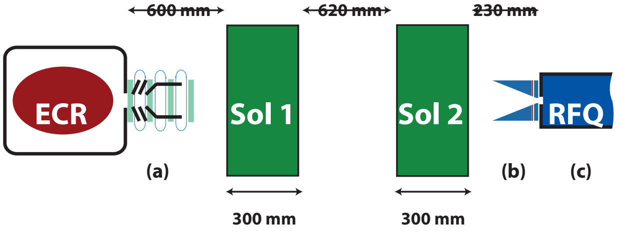

Figure 1: Scheme of the IFMIF-EVEDA LEBT. (a): ECR extraction system - (b): RFQ injection cone - (c): first RFQ segment.

The total length of the beam line, from the plasma electrode to the internal face of the RFQ entrance flange is 2.05 m (see Fig.1). A pumping system and beam diagnostics as movable Faraday cup and emittance measurement device are inserted between the two solenoids. A regulating valve is also foreseen in order to inject a controlled flux of a specific gas in the beam line.TRANS

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RFQ Injection Cone

Compared to the preliminary design [3], the RFQ injection cone has been completely redefined. The cone is about 150 mm length, with an half-angle of 8°. The cone injection hole is 12 mm diameter. A circular electrode polarized negatively, called electron repeller, is located 20 mm before the end of the cone. This electrode creates an electric field that repel the electrons created in the cone region in the LEBT so that they can contribute to the space charge compensation of the beam.

The new cone geometry has been included in our simulations, as well as the electric field map (computed by finite difference solver) of the electron repeller.

SIMULATION AND OPTIMIZATION

Codes

For this work, three different numerical codes have been employed.

First, the modeling of the extraction system of the ECR source has been done with a commercial code, called AXCEL-INP [5]. The electric field map of the source extraction system, which is included in the LEBT simulations to get relevant boundary conditions, is calculated with OPERA 2D.

In order to achieve realistic beam transport simulations in the 100 keV energy range and with such a high intensity, it is necessary to take into account the space charge compensation of the beam on the residual gas. For that, a 3D particle-in-cell (PIC) code, called SOLMAXP, has been recently developed at CEA/Saclay and has been used for this work. The basics of this code are briefly described in reference [3]. SOLMAXP has been implemented to run in parallel on a multiprocessor architecture, using a Message Passing Interface library.

Finally, the optimization of the LEBT optics parameters for the beam injection into the RFQ has been performed with TraceWin [6].

Optimization Method

The parameters of the IFMIF LEBT are optimized with the objectives of obtaining the best injection into the RFQ and keeping the emittance growth as low as possible.

A first calculation is made with TraceWin, considering around 70% of space charge neutralization, to find the beam transport and focalization that met the required Twiss parameters for the injection into the RFQ. In our case, the goal is to find the magnetic field values to be applied by the two solenoids.

Then, a calculation is made with SOLMAXP, with these magnetic field values, until the steady-state of the space charge compensation is reached. The code outputs are the particle distribution (ions, electrons, neutral atoms) and the electric field map derived from the potential created by the space charge along the beam line. A typical (r,z) space charge potential map coming from a SOLMAXP simulation is represented in Fig. 2.

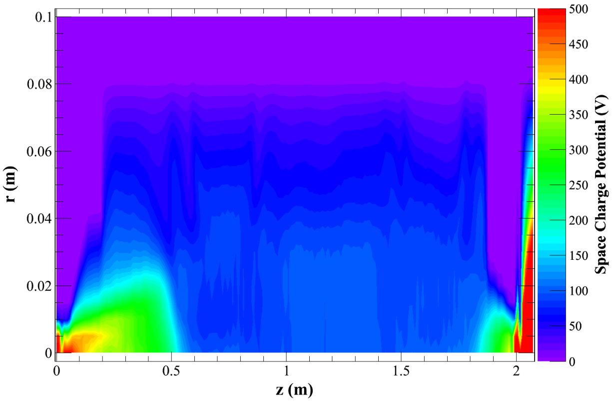

Figure 2: Two dimensions (rz) space charge potential map.

Coming back to the TraceWin code, the space charge electric field map is superimposed to those of the beam line elements. So, optimizations are now performed to find the best injection conditions into the RFQ, taking into account the space charge compensation through the LEBT. During that TraceWin optimization process, as the optics parameters are slightly modified, the space charge compensation should be modified too. Thus, another simulation has to be done again with SOLMAXP.

After a few steps of this back and forth process between the two codes, the convergence toward the optimized solution is reached.

SIMULATION RESULTS

In a preliminary work [3], two different beam focalization conditions have been studied: with or without a beam waist between the two solenoids (respectively called “strong” and “weak” focalization). The results showed that the “weak” focalization should be adopted to reduce the emittance growth along the LEBT.

RFQ Transmission

In order to be as close as possible to experimental conditions, the optimization in TraceWin are done by maximizing the transmitted current trough the RFQ.

For an injected D^+ beam of 141 mA (no losses on the beam pipe are observed in the LEBT) the best RFQ transmission that has been obtained is 96%.

At the RFQ entrance, the emittance is 0.13 mm.mrad and the Twiss parameters are : α=5.35 and β=0.23 mm/π.mrad (Fig 3 shows the particle distributions). This emittance value is below the IFMIF-EVEDA requirements (0.25 πmm.mrad) for the LEBT.

The mismatch factor [8], that gives the deviation of the obtained Twiss parameters to those of a perfectly matched beam, is around 8%. As the RFQ transmission remains maximal if the mismatch factor stay below 10%, it can

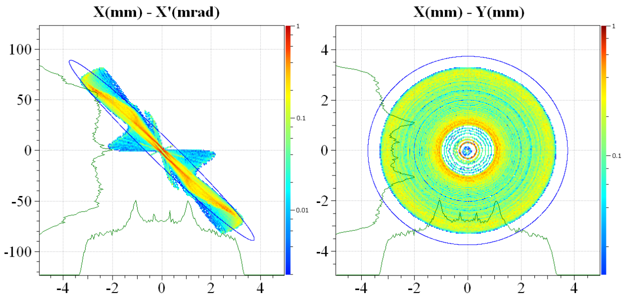

Figure 3: Particle phase space distribution (x,x') and (x,y) at the RFQ entrance.

be considered that the LEBT requirements for an optimal beam injection are reached.

The deuteron beam transport and density through the LEBT and in the first RFQ cells is shown on Fig. 4. The two solenoid magnetic field values on axis are respectively around 0.37 T and 0.47 T.

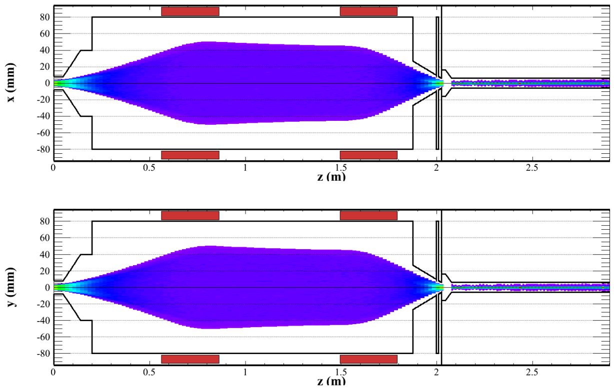

Figure 4: Beam transport and density in the LEBT and in the first cells of the RFQ. The red rectangles represent the solenoids.

The beam dynamics simulations showed that the role of the electron repeller in the injection cone is crucial to reach the best injection. If the electron repeller is switched off or even is not close enough to the RFQ, the electron density in the cone is too low to reach a satisfactory space charge compensation. In that case the space charge effect on the beam overwhelms the focalization forces induced by the solenoids.

Effect of Kr Partial Pressure In The LEBT

It has been qualitatively observed in preliminary calculations [3] (and also experimentally [7]) that the beam emittance can be improved by injecting some gas in the beam line. Furthermore, this improvement depends strongly on the gas species.

Assuming that the residual D_2 gas contribution (coming from the source and the beam neutralization) to the total pressure of the beam line is 10^{-5} hPa, the addition of a partial pressure of krypton appears to be an important parameter to reach the optimum RFQ injection.

The simulation results presented in the previous section have been obtained with a Kr partial pressure of 4×10^{-5} hPa. Then, the loss rate due to electron capture by the $D^+$is around 2.4%.

In order to reduce this loss rate and to evaluate the importance of the krypton injection in the beam line, a simulation has been done by reducing the Kr partial pressure in the LEBT by a factor of 2. In this case, the RFQ transmission drops to 93%, with a mismatch factor of 19%. The beam emittance is 0.19 πmm.mrad. Even if, with a Kr partial pressure of 2×10^{-5} hPa the loss rate by neutralization is only 1.3%, it is recommended to keep a higher pressure in order to limit the emittance growth and to have an easier beam matching.

CONCLUSIONS AND PERSPECTIVES

The beam dynamics simulations for the IFMIF LEBT have been achieved with the TraceWin and SOLMAXP codes developed at CEA/Saclay. In order to be closer to experimental conditions, the pressure profile along the LEBT still have to be included in our calculations.

With the proposed LEBT design, beam dynamics simulations showed that the beam can be transported thought the beam line and injected into the RFQ with optimized emittance and Twiss parameters. Under the present conditions, the beam intensity after the RFQ is 135 mA (96 % transmission). This results give a reasonable security margin compared to the IFMIF-EVEDA requirements which is 125 mA at 5 MeV at the RFQ output.

The present LEBT design has been adopted for the EVEDA project and is now under detailed mechanical studies.

REFERENCES

[1] A. Mosnier et al, *The IFMIF 5MW linacs*, Proc. of PAC 2009, Vancouver, Canada.

[2] M. Comunian et al, *The IFMIF-EVEDA RFQ*: Beam dynamics design, Proc. of LINAC 2008, Victoria, Canada.

[3] N. Chauvin et al, *Beam dynamics simulation of the low energy beam line for IFMIF/EVEDA*, Proc. of LINAC 2008, Victoria, Canada.

[4] R. Gobin et al., *A 140 mA cw deuteron electron cyclotron resonance source for the IFMIF-EVEDA project*, Rev. Sci. Instrum. **79** (2008) 02B303.

[5] INP, P. Spädke, Junkernst. 99, 65205 Wiesbaden, Germany, e-mail: p.spaedtke@inp-dme.com.

[6] http://irfu.cea.fr/Sacm/logiciels/index.php.

[7] P.-Y. Beauvais et al, *Emittance improvement of the ECR high intensity light ion source proton beam by gas injection in the LEBT*, Rev. Sci. Instrum. **71** (2000) 1413.

[8] T. Wangler, *RF Linear Accelerators*, Wiley-Interscience (1998).