BEAM DYNAMICS SIMULATION OF THE LOW ENERGY BEAM TRANSPORT LINE FOR IFMIF/EVEDA

N. Chauvin*, O. Delferrière, R. Duperrier, R. Gobin, P.A.P. Nghiem, D. Uriot,
CEA, IRFU, F-91191 Gif-sur-Yvette, France.

Abstract

The purpose of the IFMIF-EVEDA (International Fusion Materials Irradiation Facility-Engineering Validation and Engineering Design Activities) demonstrator is to accelerate a 125 mA cw deuteron beam up to 9 MeV. Therefore, the project requires that the ion source and the low energy beam transport (LEBT) line deliver a 140 mA cw deuteron beam with an energy of 100 keV and an emittance of 0.25 π.mm.mrad (rms normalized) at the entrance of the RFQ. The deuteron beam is extracted from a 2.45 GHz ECR source based on the SILHI design. A LEBT with a two solenoids focusing system is foreseen to transport and adapt the beam for the RFQ injection. In order to validate the LEBT design, intensive beam dynamics simulations have been carried out using a parallel implementation of a particle-in-cell 3D code which takes into account the space charge compensation of the beam induced by the ionization of the residual gas. The simulations results (in particular from the emittance growth point of view) performed under several conditions of gas species or gas pressure in the beam line are presented.

INTRODUCTION

The International Fusion Materials Irradiation Facility (IFMIF) will produce a high flux (10^{18}n.m^{-2}.s^{-1}) of 14 MeV neutron dedicated to characterization and study of candidate materials for future fusion reactors. A solution based on two high power cw accelerator drivers, each delivering a 125 mA deuteron beam at 40 MeV to a liquid lithium target, is foreseen [1].

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 [2]. This accelerator is composed by an ECR (Electron Cyclotron Resonance) ion source, a low energy beam transport (LEBT) line, a RFQ (100 keV to 5 MeV) [3], a matching section, a superconducting Half Wave Resonator cavities section (5 MeV to 9 MeV), and a high energy beam line equiped with diagnostic plate and a beam dump. This paper will focused on the LEBT section of the EVEDA project.

The purpose of the LEBT is to transport the 140 mA/100 keV deuteron beam extracted from the ECR source to the RFQ. In order to design the LEBT parameters and to optimize the beam injection in the RFQ, beam dynamics simulations have been performed.

* Nicolas.Chauvin@cea.fr

LOW ENERGY BEAM LINE LAYOUT

ECR Ion Source and Extraction System

The beam intensity and reliability required for the IFMIF project have lead to the choice of an ECR ion source to produce the deuteron beam. The IFMIF 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 140 mA D^+ requirements, as D_2^+ and D_3^+ are also produced in the ECR source. The extraction energy has also been increased from 95 keV to 100 keV, and a four electrode system has been calculated to minimize the D^+ divergence. In order to decrease the risk of high voltage breakdown, the maximum of the extraction electric field has been kept around 100 kV/cm.

Table 1: Beams 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. More precisely, the simulations start with a part of source extraction system, computed with AXCEL-INP [5], in order to get relevant boundary condition.

Low Energy Beam Transport Line

The optics for the LEBT is based on a dual solenoids system. The 3D magnetic field maps of the solenoids (pole length: 300 mm), computed by finite elements method, have been included in the simulations.

The total length of the beam line, from the plasma electrode to the RFQ entrance is 2.05 m (see Fig.1). A pumping system and beam diagnostics as movable Faraday cup and emittance measurement could be 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.

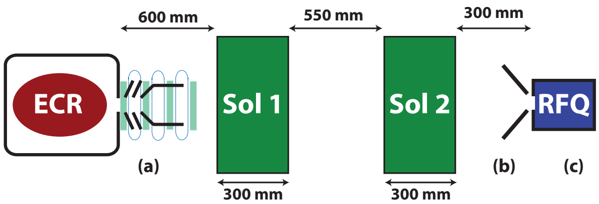

Figure 1: Scheme of the IFMIF-EVEDA LEBT. (a): ECR extraction system - (b): RFQ injection cone - (c): first RFQ segment.

SIMULATION AND OPTIMIZATION

Codes Used

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.

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), called SOLMAXP, has been recently developed at CEA/Saclay and has been employed for this work. The basics of this code are briefly described in the next section.

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

SOLMAXP: A 3D PIC Code

In this code, the motion of the macro-particle (each of them carrying an equal fraction of the overall beam intensity) is integrated on a time step basis. The simulation region is divided into a 3D grid. At each time step, the following procedure is done:

- weighting of the position of the particle to assign a charge density on the grid nodes.
- calculation of the potential and electric field from the charge density, by solving the Poisson equation.
- weighting of the forces (from the **B** and **E** self-generated fields and external fields) at the position of the particles.
- calculation of the new velocity and the position of the particles by integration of the equation of motion.
- simulation of collisions (ionization and neutralization) between particles, with the help of a Monte-Carlo algorithm.

This procedure is repeated until the emittance at the end of the LEBT has reached its steady-state.

Optimization Method

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 in the RFQ. In our case, the goal is to find magnetic field values applied by the two solenoids of the LEBT.

Then, a calculation is made with SOLMAXP, with the beam line parameters found with TraceWin. SOLMAXP is run 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 projection of a space charge potential map is represented in Fig. 2.

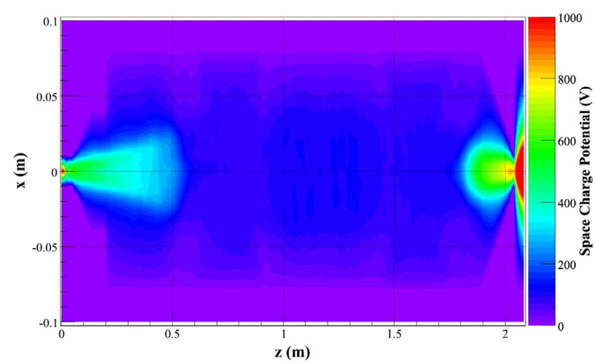

Figure 2: Two dimension projection in (z0x) plane of a space charge potential map.

For the TraceWin calculation, this space charge electric field map is then superimposed to those of the beam line elements. So, the RFQ injection optimization is now performed with space charge compensation through the LEBT. During that TraceWin optimization process, the optics parameters are modified and consequently, the space charge compensation should vary, because of the new particle distribution. Thus, another simulation has to be done with SOLMAXP.

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

SIMULATION RESULTS

One of the most critical beam parameter in the IFMIF LEBT, is the emittance growth. The emittance values presented in the following section are derived from the particle distributions calculated with SOLMAXP.

Gas Pressure

Previous measurements performed with the SILHI source and LEBT [7] showed that beam emittance can be improved by injecting some gas in the beam line. Furthermore, this improvement seems to depend strongly on the gas species.

Preliminary simulations were done, with a shorter and simplified beam line, for pressure values of deuteron gas of 4×10^{-4} hPa and 4×10^{-5} hPa. The results showed clearly that with the higher pressure, the obtained emittance is 45% lower.

But, in the IFMIF LEBT, the pressure has to be kept around several 10^{-5} hPa to minimize the high voltage breakdowns and ion losses on neutral gas. Then, we chose a total pressure value of 5×10^{-5} hPa. Nevertheless, according to reference [7], a lower emittance could be obtained by adding a heavier gas like krypton in the beam line.

Assuming that the residual D_2 gas contibution to the total pressure in the beam line is 10^{-5} hPa, two simulations were done by adding a partial pressure (4×10^{-5}) of either D_2 or krypton, all the other parameters remaining constant. The results are presented in table 2.

Table 2: Simulations Results for Two Gas Species Injected.

D_2 partial pressure (hPa)	Kr partial pressure (hPa)	Final Emittance (π mm.mrad)
5×10^{-5}	0	0.41
1×10^{-5}	4×10^{-5}	0.31

These simulation results confirm that the emittance is lowered with kryton injection, as it has been observed experimentally. Then, we can recommend that some krypton has to be injected in the IFMIF LEBT.

Finally, we have to consider the loss rate due to the D^+ beam neutralization by the gases. With these pressure conditions, the loss rate is around 2.4%.

Focalization

In the preliminary optimization process, it has been determined that the Twiss parameters required for the beam injection in the RFQ could be reached with two different beam focalization types: with or without a beam waist between the two solenoids (respectively called "strong" and "weak" focalization).

Simulations have been performed for these two cases, with a gas pressure of 5×10^{-5} hPa (D_2 and Kr). Fig. 3 shows the emittance results.

This results shows that the "weak" focalization should be adopted for the IFMIF LEBT in order to get a final emittance value of 0.31π mm.mrad. The magnetic field values on the two solenoids are respectively 0.36 T and 0.4 T

Space charge compensation steady-state

The simulations with SOLMAXP make possible to determine when the space charge compensation steady-state

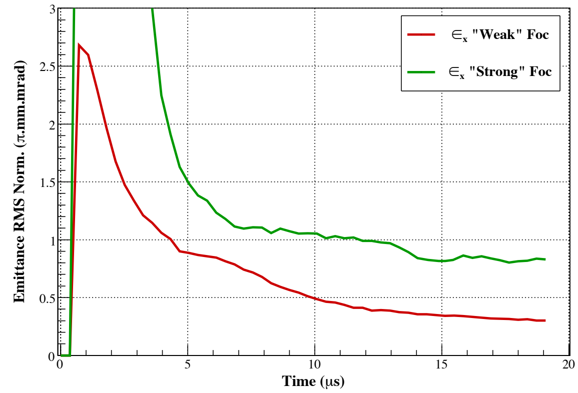

Figure 3: Emittance evolution as a function of time, for the two type focalisation conditions. The simulation starts at time t=0.

is reached. This information can be useful for an operation in pulsed mode, during the commissioning phase, for example. In this case, the pulsed mode has to be representative of the cw mode from the space charge compensation point of view.

From Fig 3, one can deduce that the space charge compensation steady-state is reached after around 15 μs.

CONCLUSIONS AND PERSPECTIVES

The beam dynamics simulations for the IFMIF LEBT have been achieved with a 3D PIC code developed at CEA/Saclay to compute the space charge compensation of the beam by the ionization of the residual gas.

The calculated beam emittance value at the end of the LEBT is still higher than the RFQ requirements. However, the optimization process, in order to adapt the beam for its injection in the RFQ is currently in progress. The preliminary results are promising and further optimization may lead to a lower beam emittance value than the current one. Otherwise, the final beam emittance can also be lowered by increasing slightly the krypton pressure in the beam line or by reducing the distance between the two solenoids.

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