SIMULATION AND MEASUREMENTS IN HIGH INTENSITY LEBT WITH SPACE CHARGE COMPENSATION

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Abstract

Over the last years, the interest of the international scientific community for high power accelerators in the megawatt range has been increasing. One of the major challenges is to extract and transport the beam while minimizing the emittance growth in the Low Energy Beam Transport (LEBT) line. Consequently, it is crucial to perform precise simulations and cautious design of LEBT. In particular, the beam dynamics calculations have to take into account not only the space charge effects but also the space charge compensation of the beam induced by ionization of the residual gas.

The code SolMaxP has been developed in CEA-Saclay to perform self-consistent calculations taking into account space charge compensation. Extensive beam dynamics simulations have been done with this code to design the IFMIF LEBT (Deuteron beam of 125 mA at 100 keV, cw). The commissioning of the IFMIF injector started a few months ago and emittance measurements of H^+ and D^+ beams have been done. The first experimental results will be presented and compared to simulation.

INTRODUCTION

The International Fusion Materials Irradiation Facility 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. To reach such a challenging goal, 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 a first phase, called EVEDA (Engineering Validation and Engineering Design Activities), the 125 mA cw/9 MeV deuteron Linear IFMIF Prototype Accelerator (LIPAc) will be constructed, tested and operated at Rokkasho-Mura, in Japan [2]. This accelerator is composed by an ECR ion source, a low energy beam transport (LEBT) line, a RFQ [3], a matching section, a superconducting radio-frequency accelerator (based on Half Wave Resonator cavities), 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 [4] showed the beam dynamics simulations that have been achieved to perform the design and the validation of this LEBT. This paper will recall briefly the simulations that have been done and then presents the preliminary experimental results obtained during the IFMIF LEBT commissioning.

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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 [5]. 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, see Table 1) and the energy from 95 keV to 100 keV. A four electrode system has been calculated to minimize the beam 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

Low Energy Beam Transport Line

The LEBT is based on a dual solenoid focusing system to transport the beam and to match it into the RFQ. 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 (Faraday cup, Emittance Measurement Unit (EMU) and four-grid analyser) 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.

At the end of the LEBT, a cone with an half-angle of 8° is located just before the RFQ injection. The role of this cone is to allow the injection of the beam of interest (D^+) while stopping the other beam species (i.e. D_2^+ and D_3^+) to prevent their injection into the RFQ, that would cause subsequent beam losses. The cone injection hole is 12 mm diameter. A circular electrode negatively polarized, called

ISBN 978-3-95450-118-2

electron repeller, is located 20 mm before the end of the cone. This electrode creates an electric field that repels the electrons created in the cone and prevents them to be attracted by the RFQ field; that way these elctrons can contribute to the space charge compensation of the beam.

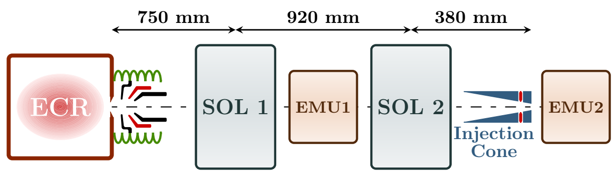

Figure 1: Scheme of the IFMIF-EVEDA LEBT. EMU 1 and EMU 2 are the two beam line positions where the Emittance Measurement Unit can be used.

During the injector commissioning, a second diagnostic chamber is placed after the injection cone, where the EMU can be used (position EMU 2 in Fig. 1). So, the beam emittance can be measured between the two solenoids and at the end of the beam line. The Emittance Measurement Unit that is used for the IFMIF injector commissioning is an Allison scanner [6].

SIMULATIONS OF THE IFMIF/EVEDA INJECTOR

Codes Used

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

First, the modelling of the extraction system of the ECR source has been done with a commercial code, called AXCEL-INP [7]. 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 with SolMaxP and TraceWin (see below). More precisely, the simulations start with a part of source extraction system, computed also with AXCEL-INP, in order to get relevant boundary conditions.

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 by ionization of the residual gas. For that, a 3D particle-in-cell (PIC) code, called SolMaxP, has been developed at CEA/Saclay and has been used for this work. The basics of this code are briefly described in reference [8]. 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 [9].

Simulation Conditions

The SolMaxP simulations presented in this paper have been done under the following conditions or hypothesis:

(i) D^+, D_2^+ and D_3^+ beams are transported through the IFMIF LEBT

(ii) the electric field map of the source extraction system is included to get relevant boundary conditions

(iii) the electric field map (computed by finite difference solver) of the injection cone electron repeller is included.

(iv) magnetic field maps (computed by finite difference solver) of the solenoids are included.

(v) the gas pressure is considered to be homogeneous in the beam line

(vi) the gas ionization is produced by ion beam and electrons impact

(vii) no beam scattering on gas is considered

(viii) no secondary electrons are created when the beam hit the beam pipe

SolMaxP Outputs

The SolMaxP codes tracks the particles of the incoming beams as well as the secondary particles that can be crated by ionization of the residual gas, for instance. So, all particles (ions, electron neutral atoms) distributions are accessible as a result of the calculations.

Another output of great interest is the overall potential map created by the space charge (and the space charge compensation) along the beam line [4]. From that potential map the space charge electric field map and the space charge compensation degree in the LEBT, that both can be used in TraceWin, can derived.

BEAM DYNAMICS RESULTS

The method to compute, with SolMaxP, the space charge compensation degree along the IFMIF LEBT is explained in reference [10]. The result is showed Fig. 2. In this plot, the abscissa z=0 represents the position of the repelling electrode of the source extraction system, while z=2.05 m is the RFQ entrance. It can be observe that in the ion source extraction region and after the repelling electrode at the RFQ injection, the SCC is poor because the electrons are attracted out of the beam. In the central part of the LEBT, where the solenoids and a drift are located the SCC degree reach around 95%.

The beam dynamics simulations showed that the IFMIF deuteron beam can be transported and injected into the RFQ with optimized emittance and Twiss parameters. Under these conditions, the IFMIF RFQ transmission is above 95 % [10].

ISBN 978-3-95450-118-2

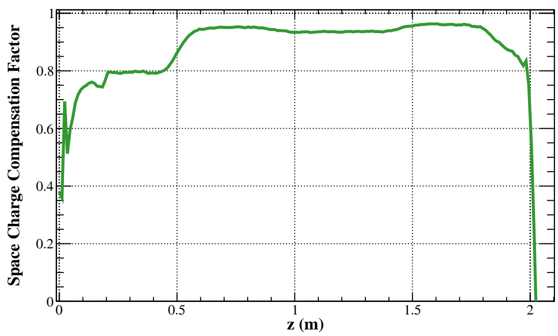

Figure 2: Space charge compensation degree along the IFMIF LEBT.

IFMIF INJECTOR PRELIMINARY EXPERIMENTAL RESULTS

The IFMIF injector commissioning is done in CEA/Saclay and started several month ago. In order to avoid activation of the beam line material with a 100 keV/140 mA deuteron beam, the commissioning is mainly done with a proton beam, at half current and energy (70 mA at 50 keV). That way, the proton beam has the same perveance has the nominal deuteron beam. Nevertheless, the ion source extraction has been modified to extract a lower beam intensity: during commissioning, the source plasma electrode has a diameter of 8 mm (instead of 12 mm for the nominal extraction system).

Gas Injection in the LEBT

It has been experimentally shown that the beam emittance can be improved by injecting gas in the LEBT. [11]. Besides, the nature of the injected gas has an influence on this emittance improvement. An emittance reduction of a factor of three has been reported with by replacing the H_2 gas by the same partial pressure of Kr [12].

The same experiment has been reproduced on the IFMIF injector. The beam emittance is measured between the two solenoid (position EMU 1) without Krypton and with a partial Kr pressure of 2×10^{-5} hPa in the beam line (pressure measurement is done between the two solenoids). The results are summarized in Table 2.

Table 2: Beam Emittance With and Without Kr Injection in the LEBT

Gas in LEBT	ϵ (π.mm.mrad)
Residual Gas (H_2)	0.53 ± 0.10
Krypton injection	0.54 ± 0.10

In this experiment, no emittance improvement has been observed with Kr injection. This can be explained by the fact that the residual pressure in the beam line, before Kr injection, is already quite high: around 1.5×10^{-5} hPa between the two solenoids and probably one order of magnitude more in the source extraction. So, the beam space charge compensation may have reached an optimum level only with the residual gas and the krypton injection can not improve it.

Emittance Measurements

The beam emittance has been measured between the two solenoids (position EMU 1) and after the RFQ injection cone (position EMU 2). The results are presented in the second column of Table 3.

The beam emittance measured at the end of the LEBT is lower than between the solenoids. This result will be explained and discuss, by using beam dynamics simulations, in the next section. It has to be noted that the beam emittance value at the end of the beam line meets the IFMIF specifications.

Simulation and discussion

In order to simulate our experiment, a beam dynamic calculation has been performed with Tracewin using a space charge compensation profile (see Fig. 2) calculated beforehand with SolMaxP.

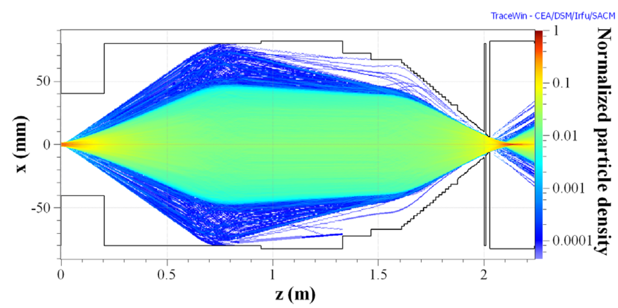

Figure 3: Beam density along the the IFMIF LEBT, for a 70 mA proton beam at 50 keV.

The simulated transport of a 70 mA proton beam at 50 keV through the LEBT (see Fig. 3) shows an important halo. Such a halo is created in the ion source extraction, which is not optimized for for a 50 keV proton beam but for the IFMIF nominal beam. In Fig. 3, it can be observed that after the cone (after z=2 m, EMU 2), the beam halo is reduced compared to the position between the two solenoids (around z=1.1 m, EMU 1). Indeed, the simulations shows around 1.5 percent of beam losses at the end of the cone and consequently an emittance decrease of around 35% (the beam halo has an important contribution to the emittance).

The measured and simulated emittance values at the two EMU locations are summarized in Table 3. The simulated emittances are in agreement with the measured ones. Furthermore, it has been experimentally observed that the proton beam transmission through the beam line (and especially through the cone) is almost 100% which is also compatible with the simulated losses (around 1.5%).

ISBN 978-3-95450-118-2

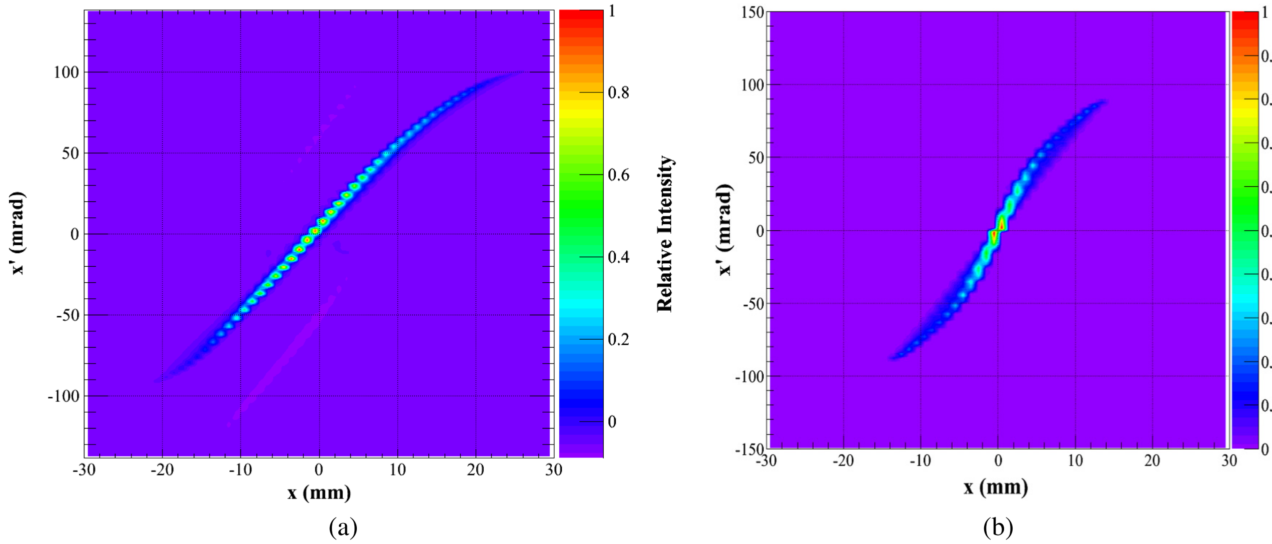

Figure 4: Transverse emittance at the end of the IFMIF LEBT (EMU 2): (a) Measured emittance – (b) Simulated emittance.

Table 3: Simulated and Measured Beam Emittance (in π.mm.mrad) at Two Position of the IFMIF LEBT. The emittance values are RMS and normalized.

Location	Measurement	Simulation
EMU 1	0.53 ± 0.10	0.48
EMU 2	0.29 ± 0.08	0.36

Finally, measured and simulated transverse emittances are compared in Fig. 4. The simulated beam distribution in the transverse phase space does not accurately reproduce the measurement. The experimental beam dimension and divergence are slightly higher than the simulated ones. Furthermore, the beam density of the simulated distribution is more important on the axis.

Some work remains to be done to improve the beam dynamics simulations and especially from the source extraction point of view, which is critical for the beam distribution and its evolution during the transport.

CONCLUSION

It has been demonstrated that a self-consistent PIC code like SolMaxP that takes into account space charge compensation by ionisation of the residual gas by the beam, can be used for injector design.

Beam dynamics simulation results are in agreement with the first experimental results obtained during the IFMIF injector commissioning. Nevertheless, more simulations are needed to reproduce more correctly the experimental emittance distribution.

The preliminary results of the IFMIF injector commissioning are encouraging since the transmission in the beam line is satisfactory (around 98%) and the emittance at the end of the LEBT meets the specifications. Nevertheless, further work is necessary to improve the beam intensity extracted from the source. Commissioning activities of the injector with a deuteron beam are planned in the next months.

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ISBN 978-3-95450-118-2