BEAM COMMISSIONING OF THE LINEAR IFMIF PROTOTYPE ACCELERATOR INJECTOR: MEASUREMENTS AND SIMULATIONS

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Abstract

EVEDA (Engineering Validation and Engineering Design Activities) phase of the IFMIF (International Fusion Materials Irradiation Facility) project consists in building, testing and operating, in Japan, a 125 mA/9 MeV deuteron accelerator, called LIPAC, which has been developed in Europe.

The 140 mA cw D^+ beam that has to be delivered by the LIPAC injector is produced by a 2.45 GHz ECR ion source based on the SILHI design. The low energy beam transfer line (LEBT) relies on a dual solenoid focusing system to transport the beam and to match it into the RFQ [1]. The beam line is equipped by several diagnostics: intensity measurement, emittance measurement unit, profilers and beam proportion analysis. During the LIPAC injector beam commissioning performed in CEA-Saclay, the deuteron beam intensity transported at the end of the LEBT reached an unprecedented value of 140 mA at 100 keV. In this paper, the results obtained during the commissioning are presented. In particular, beam emittance measurements as a function of duty cycle, extracted current from the ion source and solenoids tuning are exposed. The experimental results are discussed and compared to beam dynamics simulations.

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 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 assemble, tested and operated at Rokkasho-Mura, in Japan [2].

This paper focuses on the experimental results obtained during the beam commissioning of LIPAC injector (ion source and LEBT) which took place in CEA Saclay in 2012.

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THE LIPAC INJECTOR

The purpose of the injector is to produce a 140 mA/100 keV deuteron beam and to transport and match it for its injection into the next accelerating section (RFQ). At the end of the LEBT, the emittance has to be lower than 0.3π mm.mrad (with a target value of 0.25π mm.mrad).

A scheme of LIPAC injector layout with the available beam diagnostics and their position is shown on Fig. 1 but a more detailed description can be found in reference [1].

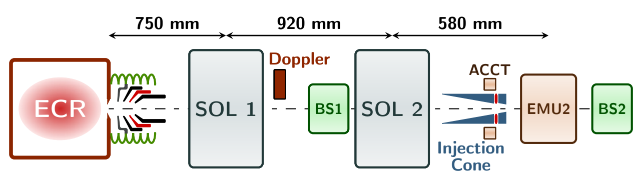

Figure 1: Scheme of the LIPAC injector.

Injector Layout

The LIPAC ECR source, based on the SILHI design, is operating at 2.45 GHz that has been optimized to extract, at 100 keV, a total beam intensity from 150 mA to 175 mA in order to meet the required 140 mA of D^+, as D_2^+ and D_3^+ are also produced in the ECR plasma.

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. At the end of the LEBT, a cone with an half-angle of 8° is located just before the RFQ injection to allow the injection of the beam of interest (D^+) while stopping the other beam species (i.e. D_2^+ and D_3^+).

Beam Diagnostics

Beam intensity can be measured at three locations: between the two solenoids with a beam stopper (BS1), at the end of the injection cone with an ACCT and after the cone with a second beam stopper (BS2) which is auto-polarized.

Emittance Measurement Unit (EMU) that is used for the LIPAC injector is an Allison scanner [3]. Beam emittance

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can be measured between the two solenoids and also at the end of the LEBT: during injector commissioning, a diagnostic chamber is placed after the injection cone, where the EMU can be inserted (position EMU2 in Fig. 1).

The total beam intensity extracted from the ion source is given by the current output of the main high-voltage power supply (100 kV).

The beam species fraction (D^+, D_2^+ and D_3^+) is measured by Doppler shift analysis [4].

EXPERIMENTAL RESULTS

Important Parameters

The main parameters of the injector that have been studied and varied during beam commissioning were: source duty cycle (from 10% to continuous wave); total extracted current from the ion source (noted I_{Tot}); the potential difference between the plasma electrode and the intermediate electrode (puller electrode) of the extraction system (noted U_{EI}); solenoids magnetic fields B_1 and B_2.

For each set of parameters the D^+ beam fraction, intensity on beam stop 2 (I_{BS}) and emittance (RMS normalized) at the end of the LEBT were recorded.

Experimental Results at 10% Duty Cycle

Table 1 summarizes the experimental results that have been obtained with a 10% beam duty cycle (pulses of 10 ms with a repetition rate of 10 Hz). The total extracted beam current I_{Tot} has been increased by increasing, from around 400 W to 600 W, the RF power injected in the ion source. By doing so, ion source plasma becomes more efficient for ionization and for breaking the D_2 molecule; that's why the D^+ fraction in increasing as well.

Table 1: Experimental Results at 10% Duty Cycle (Measurements performed with a constant U_{EI} value of 40 kV)

I_{BS} (mA)	**I_{Tot} (mA)**	**$D^+_{\%}$(%)**	ϵ (**π mm.mrad**)
100	125	80	0.14
110	133	83	0.15
120	141	85	0.16
130	148	88	0.17
140	155	90	0.2
150	165	91	0.26

It can be noted that beam emittance increases with the total extracted current. A higher beam intensity in the extraction system implies a higher beam beam divergence; consequently, the beam size is bigger in the solenoids and particles travel in non-linear magnetic field regions that can cause emittance growth.

Experimental Results at Higher Duty Cycle

During beam commissioning, duty cycle has been gradually increased from 10% to continuous wave. Some of the most representative results are presented in Table 2.

Table 2: Experimental Results at Several Duty Cycle

I_{BS} (mA)	**I_{Tot} (mA)**	**U_{IE} (kV)**	**d.c (%)**	ϵ (**π mm.mrad**)
140	155	40	10	0.2
120	151	40	30	0.19
140	170	43	30	0.32
140	170	43	50	0.33
140	176	42	cw	–

The emittance value in continuous wave was difficult to evaluate because of a measurement artifact: in cw, the very high beam power (14 kW) deposited on the entrance slits of the Allison scanner leads to their dilatation and the signal of selected beam is to small to be measured.

When the duty cycle increase, it is necessary to extract more current from the source to reach 140 mA at the end of the beam line. It was observe, with Doppler shift measurement, that the D^+ fraction is lower as the duty cycle increase. This is due to a different operating regime of the ion source at higher duty cycle, that is not yet well understood; one may suspect different pressure conditions in the source plasma chamber that lower D^+ fraction.

Experimental results indicate, when all the parameters are correctly tuned, that emittance at the end of the LEBT depends mainly of the total extracted current. As it was observed at lower duty cycle, the higher extracted current (because of a higher beam divergence), the higher emittance growth. However, this effect can be counteract, to some extent, by increasing the potential gap U_{EI} of the extraction system. Unfortunately, it was impossible to reach U_{EI} values above 43 kV because of high voltage sparkling.

Finally it is worth noting that an unprecedented 140 mA/100 keV D^+ beam as been produced and transported with the LIPAc injector.

Experimental Results: Solenoids Tuning

Solenoids magnetic field values have been systematically varied and for each pair of values, beam intensity after the injection cone has been recorded. The results of this experiment is presented on Fig. 2. Inside the maximum transmission area (red central zone), three "tuning points" have been chosen and beam emittance has been measured. The results are reported in Table 3.

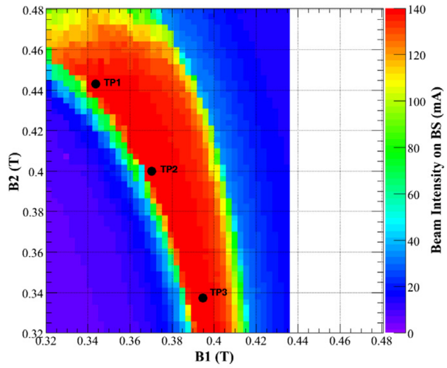

Figure 2: Experimental results: beam intensity at the end of the LEBT as a function of solenoids magnetic field.

SIMULATIONS RESULTS

Codes Used

First, the modelling of the extraction system of the ECR source has been done AXCEL-INP [5]. The particle distributions after the source are derived from their tracking through the extraction system.

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 residual gas. For that, a 3D particle-in-cell (PIC) code, called SolMaxP [6], has been developed at CEA/Saclay and has been used for this work.

Finally, the beam transport with different sets of LEBT parameters has been performed with TraceWin [7] using the space charge compensation profile along the beam line calculated beforehand with SolMaxP [8].

Simulation Results: Solenoids Tuning

The above described solenoids tuning experiment has been simulated. Transmission results are presented on Fig. 3 and simulated emittance values are reported in Table 3.

Table 3: Simulated and Measured Beam Emittance at Two Position of the IFMIF LEBT

TP	B1 (T)	B2 (T)	ϵ_{Exp} (π mm.mrad)	ϵ_{Sim} (π mm.mrad)
TP1	0.35	0.44	0.36	0.38
TP2	0.37	0.40	0.26	0.29
TP3	0.40	0.34	0.23	0.25

From LEBT beam transmission point of view, simulation results are compatibles with the experimental ones. The slightly smaller maximum transmission area in the experimental case (Fig. 2) can be explained by a small beam misalignment that is corrected by sterrers; on the contrary, the beam is perfectly aligned in simulations.

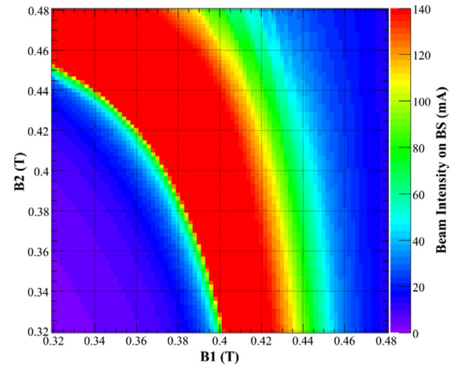

Figure 3: Simulation results: beam intensity at the end of the LEBT as a function of solenoids magnetic field.

The experimental and and simulated beam emittance values are also in good agreement. Different emittance values for the three solenoids tuning points are easily explained with the help of particle tracking simulations: in the TP3 case, the beam size in the second solenoid is significantly smaller than in the TP1 case (thanks to a higher magnetic field applied by solenoid 1) and subsequent emittance increase due to solenoid non linearity is also smaller.

CONCLUSION

Experimental results obtained during LIPAc injector commissioning meet the specifications at low duty cycle and are very close to them in cw. The injector recommissioning in Rokkasho will start at the end of 2013 and more experiments as well as some improvements are foreseen. Preliminary simulations results that have been obtained are encouraging but further work is still needed to achieve a better understanding of the phenomena that occur in high intensity LEBTs.

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