

HIGH INTENSITY BEAM PRODUCTION AT CEA/SACLAY FOR THE IFMIF PROJECT

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Abstract

At CEA/Saclay, IRFU institute is in charge of the design, construction and characterization of the 140 mA continuous deuteron Injector for the IFMIF project. This injector is composed of the source and the low energy beam line (LEBT) with its own diagnostics. The Electron Cyclotron Resonance (ECR) ion source operates at 2.45 GHz and the 2 m long LEBT is based on 2 solenoids. Krypton gas injection in the beam line is foreseen in order to reach a high level of space charge compensation for the beam matching at the RFQ entrance. During the last months hydrogen beam has been produced in pulsed and continuous mode and the beam diagnostics have been installed and commissioned. Recently a 125 mA-100 keV pulsed deuteron beam has been produced with a 1% duty cycle. In this article, the high intensity proton and deuteron beam characterization will be presented.

That is why a prototype is presently under construction. This prototype consists of only the front end of one of both accelerators made of the ion source with its associated LEBT, a 10 meter long RFQ operating at 176 MHz and a first cryomodule with 8 HWR superconducting cavities. This cryomodule will allow reaching about 9 MeV beam energy.

Table 1: Summary of the IFMIF Injector Requested Parameters at the RFQ Entrance Flange

Requirements	Target value
Particles	D+
Output energy	100 keV
Output D+ current	140 mA
D+ fraction	99 %
Beam current noise	1 % rms
Normalized rms transverse emittance	0.25π mm mrad
Duty factor	CW
Beam turn-off time	< 10 μ s

INTRODUCTION

For several decades numerous HPPA (High Power Proton Accelerator) projects are based on high intensity beam interaction with different targets, either for industrial applications or research facilities. Even if the IFMIF (International Fusion Materials Irradiation Facility) machine [1], dedicated to irradiation materials for future fusion reactors will accelerate deuteron instead of protons, this project is also ranked in the HPPA family.

The aim of the IFMIF machine is to produce a high flux of neutrons with energy spectrum comparable to next fusion reactors like DEMO. To reach this goal, the IFMIF layout is based on 2 deuteron accelerators able to simultaneously produce 125 mA at 40 MeV. The 2 combined beams will impact a liquid lithium target flowing down in front of the test cells where future studied materials will be installed for neutron irradiation.

The total power delivered in continuous mode by the accelerators at the target interaction will be 10 MW. Nevertheless, despite such high beam power, the maintenance of the machine leads to imperative very low beam losses. One could consider this machine as the accelerator of all the records: the highest intensity, the highest beam power, the highest space charge and the longest RFQ.

To reach the requested beam intensity and considering a RFQ transmission of about 92 %, the deuteron beam at the RFQ entrance should reach a minimum of 140 mA with 100 keV energy. Table 1 summarizes the injector requests. Such demands are very challenging and push to a design based on the SILHI source operating at CEA/Saclay for more than 10 years [2]. A LEBT (Low energy Beam Transport) follows the source and will allow matching the beam at the entrance of the RFQ. As a consequence, like for other HPPA, while designing an injector, one has to consider the ion source, the extraction system and the LEBT as a whole [3].

ION SOURCE AND LEBT DESIGN

The source design is based on a 2.45 GHz frequency magnetron which transfers the RF power to the plasma chamber via waveguides and a RF window. A 3 step ridged transition located between the window (protected behind a bend to avoid backstreaming electron damages) and the plasma chamber. A boron nitride disk, located at the end of the ridged transition determines the barrier between the waveguide and the plasma chamber. The cylindrical plasma chamber, made of water cooled copper, is 90 mm inner diameter and 100 mm long. A second

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boron nitride disk covers the plasma electrode. In such high intensity source, the 2 boron nitride disks, bearing important impact of the plasma, are the only parts which need systematic change (roughly twice a year). Specific Boron Nitride has to be chosen to avoid high outgassing under plasma bombardment. For such a 2.45 GHz frequency, the electron resonance occurs when the magnetic field reaches 875 Gauss in the plasma chamber. The magnetic field is provided by 2 independently tuneable coil associated with iron shielding (Fig. 1).

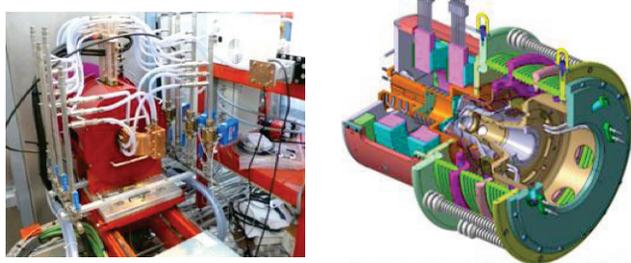


Figure 1: Picture and 3D view of the IFMIF injector ion source with coils and initial 4 electrode extraction system.

In order to minimize the beam divergence (by reducing the space charge effects) at the accelerator column exit, it has been initially decided at first to increase the plasma electrode aperture up to 12 mm. Then the overall extraction system length has been shortened by installing a 4 electrode accel-decel system. Such system allows keeping meniscus tuning with a puller for minimizing beam losses on the electrodes. Then the puller is followed by the electron repeller and the grounded electrode. Beam extraction simulations have been performed with the 2D Axcel code (Fig. 2) [4].

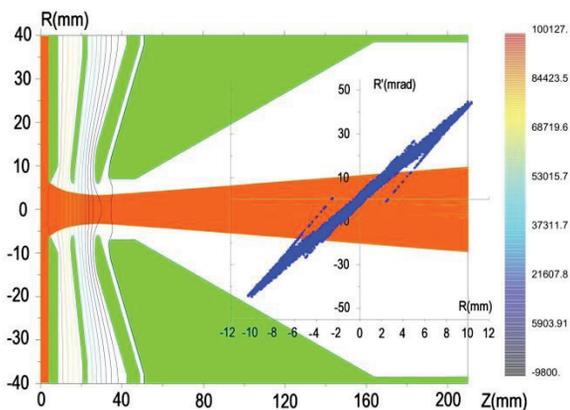


Figure 2: 140 mA D+@100 keV 4 electrodes extraction system Trajectories (r,r') beam emittance at z = 200 mm.

In the low energy transport line based on 2 solenoids, the space charge is partially compensated by the interaction of the beam with the residual gas. Secondary electrons are maintained into the beam core while secondary ions are repelled towards the walls. To minimize emittance growth in the LEBT, the length of the line has been reduced as short as possible. The use of short solenoids (310 mm long with shielding and H/V

steerers located into the solenoids) allows limiting the total LEBT length at about 2.0 m. Beam transport simulations at low energy have been performed with the TraceWin code [5]. In addition, numerous simulations were performed with the SOLMAXP home-made code to better understand the space charge compensation evolution in the beam line and to improve beam transport simulations. Addition of heavy gas like krypton in the LEBT is expected for increasing the space charge compensation and for reducing emittance growth.

Along the 2 m long beam line, the following equipments have to be integrated: the accelerator column, the 2 solenoids and steerers, 2 pumping systems with their associated valves and gauges, diagnostics and security beam stopper, RFQ entrance cone, alignment devices and supports.

To characterize and to follow the beam evolution, free spaces allowing diagnostics installation are very limited. As a consequence, only several CID cameras, a deported spectrometer (using a radiation resistant fiberscope [6]), an Allison scanner emittancemeter, a ACCT and a movable beam dump are installed between the source and the RFQ entrance. The Allison scanner has been developed for being able to bear more than 15 kW continuous beam. Thermal simulations have been performed to design the thermal screen (which is used as entrance slit) made of tungsten tiles brazed on a water cooled copper block. Then a classical varying electric filed allows analysing the selected beamlet through a second slit.

EXTRACTED BEAM ANALYSIS

The first hydrogen plasma and the first beam were produced in May 2011 in pulsed mode [7]. Then up to 75 keV continuous beam has been extracted with intensity of about 100 mA through a 10 mm diameter aperture. With beam energy higher than 70 keV, the spark rate increases dramatically and X-ray production also increases.

After the Allison emittance scanner commissioning the first emittance measurements have been done between both solenoids with a 80 mA total hydrogen beam extracted at 50 keV. Emittance value reaches (rms norm.) $0.46 \pi \text{ mm mrad}$ (Fig. 4a). Then after beam tuning in order to optimize the transmission through the RFQ entrance cone, only 42 mA of proton beam has been measured on the beam stop and the emittance value (rms norm.) reaches $0.29 \pi \text{ mm mrad}$ (Fig. 4b). The low transmission through the cone may be due either to the poor proton fraction extracted from the source or to the high beam divergence at the source exit caused by the 8 mm plasma electrode diameter.

By changing the plasma electrode diameter from 8 to 10 mm, hydrogen beam has been produced in pulsed mode (10 % duty cycle and 10 Hz pulse repetition). In these conditions, up to 140 mA have been extracted at 50 keV while more than 80 mA were crossing the cone (Fig. 5).

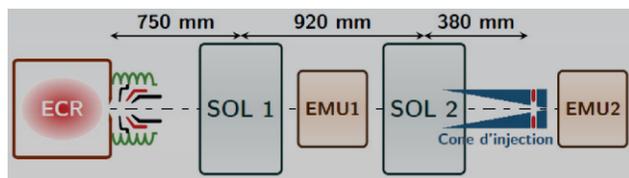


Figure 3: Both locations of the Allison emittance scanner (diagnostic box between solenoids and after RFQ entrance cone).

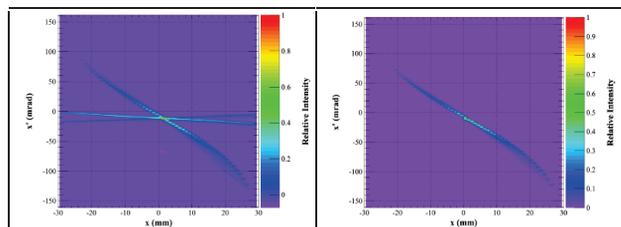


Figure 4a: emittance figure between both solenoids.

Figure 4b: emittance after RFQ entrance cone.

In addition, a pulsed Deuteron beam (125 mA) has also been produced at 100 keV with a 1% duty cycle. Up to now, with D^+ beam, the duty cycle is limited for neutron production and activation reasons.

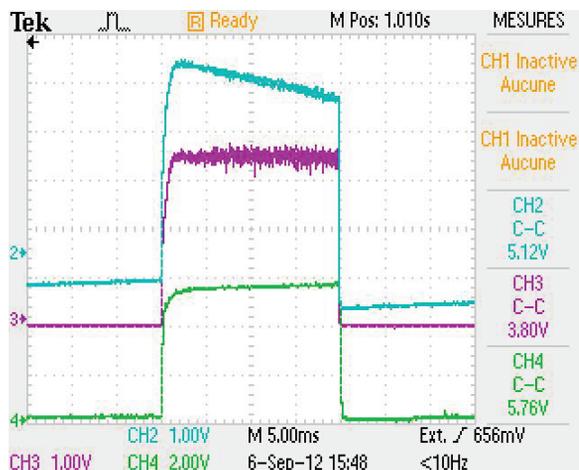


Figure 5: 50 keV extracted beam through a 10 mm diameter aperture i) green : 140 mA total hydrogen beam, ii) blue: 88 mA H^+ beam through the cone measured with ACCT, iii) magenta: 72 mA measured on beam dump.

FUTURE PLANS

As preliminary results demonstrated a quite high spark rate, the addition of a 5th electrode (as grounded electrode between puller and electron repeller) is presently underway. Figure 6 presents the recent simulations for the new extraction system. The addition of the 5th electrode would lead in higher beam divergence than with the initial 4 electrode extraction system.

This 5 electrode extraction system has been installed on the IFMIF injector mid of September 2012. As a consequence, after extraction gap conditioning, beam extraction and optimization will be performed within the next few weeks with hydrogen beams. Then, deuterium will be injected into the plasma chamber and beam characterization will be performed in pulsed mode before

switching to continuous mode for a short period (neutron production limitation).

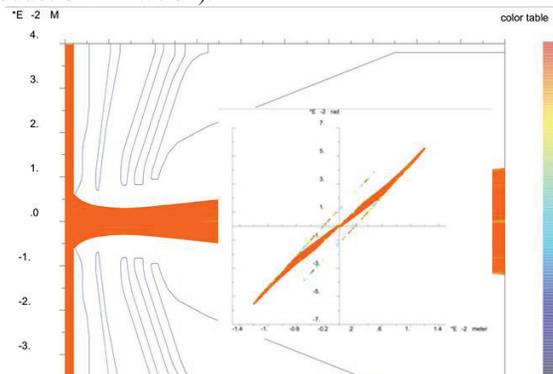


Figure 6: Simulations of beam trajectories with the new 5 extraction system.

Due to the high power beam, for use of interceptive diagnostics after the first accelerating cavities for machine commissioning, a slow chopper will be added between both LEBT solenoids.

CONCLUSION

The preliminary measurements performed with the IFMIF injector proton beams proved the expected challenges start immediately at source extraction and beam transport at low energy.

Important work still remains in beam optimization and understanding before reaching the requested beam performance at the RFQ entrance. This work will be performed at CEA/Saclay before the transfer of the whole injector on the Rokkasho site in Japan, foreseen in beginning 2013.

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