General design of the International Fusion Materials Irradiation Facility deuteron injector: Source and beam line[a)]

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In the framework of the International Fusion Materials Irradiation Facility-Engineering Validation and Engineering Design Activities (IFMIF-EVEDA) project, CEA/IRFU is in charge of the design and realization of the 140 mA cw deuteron Injector. The electron cyclotron resonance ion source operates at 2.45 GHz and a 4 electrode extraction system has been chosen. A 2 solenoid beam line, together with a high space charge compensation have been optimized for a proper beam injection in the 175 MHz radio frequency quadrupole. The injector will be tested with proton and deuteron beam production either in pulsed mode or in cw mode on the CEA-Saclay site before to be shipped to Japan. Special attention was paid to neutron emission due to (d,D) reaction. In this paper, the general IFMIF Injector design is reported, pointing out beam dynamics, radioprotection, diagnostics, and mechanical aspects. © *2010 American Institute of Physics.* [doi:10.1063/1.3257998]

I. INTRODUCTION

The International Fusion Materials Irradiation Facility (IFMIF) is dedicated to material irradiation for fusion reactor development; it is designed to operate with 2 continuous wave (cw) 175 MHz linear accelerators, each providing a 125 mA, 40 MeV deuteron beam.[1] Each accelerator is a sequence of acceleration and beam transport stages. A CW 140 mA deuteron beam is produced and extracted from an electron cyclotron resonance (ECR) ion source, installed on a HV platform. A low energy beam transport (LEBT) section transports and matches the deuteron beam from the source to the radio frequency quadrupole (RFQ) accelerator.

In a first phase (called EVEDA), a full scale prototype accelerator will be built in Japan (on the Rokkasho site) in the next 4–5 yr. It will deliver a cw 125 mA D+ beam with energy in the range of 10 MeV. In this framework, CEA/IRFU is in charge of the design and the realization of the injector[2] including the 140 mA cw deuteron source and its associated LEBT. It will be built and tested at CEA-Saclay before being shipped to Japan. The prototype injector aims to demonstrate that the performances (Table I) expected for the final IFMIF injector can be met, with high reliability and long lifetime (longer than 8000 h). It has to deliver sufficiently high current to the RFQ to achieve a 125 mA RFQ output current. Due to the beam losses in the RFQ, this current value requires that the ion source has to produce a 140 mA deuteron beam with excellent beam quality (transverse emittance).

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II. SOURCE AND EXTRACTION SYSTEM DESIGN

In order to reach the ECR in the plasma chamber, with 2.45 GHz rf wave, the needed magnetic field is 0.0875 T. The axial magnetic field is provided by 2 coils and iron shielding to obtain the 1st ECR zone located just at the rf entrance in the plasma chamber while pushing away the second one in the extraction system (able to reach 15 000 At). The 2.45 GHz rf power produced by a magnetron is injected in the source through standard rectangular waveguides, an automatic tuning unit, a ridged transition and a quartz window. The breaking of the window through the bombardment of backstreaming electrons is avoided by an additional bend. The cylindrical plasma chamber, made of water cooled copper, is 100 mm long. A first disk, located at the end of the ridged transition is used as the barrier between the waveguide and the plasma chamber and a second disk covers the plasma electrode. In such a high intensity source, both disks undergo an intense plasma bombardment. These are made of low outgassing rate boron nitride but need to be periodically changed (roughly twice a year).

Taking into account the Saclay source extracted H+ beam results and previous computations[3] for 125 mA total beam current at 95 eV, a new extraction system is proposed for the IFMIF D+ source. A 4 electrode extraction system designed for high current extraction focalization is adopted. Special attention should be paid to the electrode design in order to minimize the electric field and the spark risks. Since the vacuum pressure is as high as 10^{-2} Pa in this area, a maximum electric field of 100 kV cm^{-1} has been fixed. The plasma electrode is 12 mm diameter with a 45° angle, followed by the intermediate electrode for plasma-beam interface fine adjustment. The third electrode is the electron repeller (15 kV negative power supply) and the fourth one is the grounded electrode. The simulations have been per-

TABLE I. IFMIF RFQ entrance beam requirements.

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	0.25 π mm mrad
Duty factor	CW
Beam turn-off time	<10 μs

formed with a total extracted beam current of 175 mA ($J=155$ mA/cm^2), with standard species proportions (140 mA D+, 26 mA D2+, 9 mA D3+). The simulations results (Fig. 1) have been obtained using AXCEL code in two-dimensional (2D) with axisymmetrical geometry. The rms emittance at the exit of the extraction system deduced from trajectory calculations is $\varepsilon_{rms}=0.12$ π mm mrad. With a 12 mm diameter plasma electrode and 100 kV extraction voltage, the optimized beam radius is 10 mm for a beam divergence of 42 mrad at 200 mm from the plasma electrode.

The AXCEL trajectory simulations and OPERA-2D electrostatic simulations are carried out in parallel. A maximum electric field value of 98 kV/cm is predicted in the second accelerator gap.

III. LEBT DESIGN

A. Beam dynamics

The beam dynamics simulations for the IFMIF LEBT have been achieved with TRACEWIN and SOLMAXP codes.[4] The three-dimensional 3D code SOLMAXP has been developed at CEA/Saclay to compute the beam space charge compensation due to electrons coming from residual gas ionization. The parameters of the IFMIF LEBT are optimized with the twofold objective of reaching the matched Twiss parameters for the injection into the 176 MHz RFQ and keeping the emittance growth as low as possible.

Measurements performed with the SILHI source and LEBT (Ref. 4) showed that beam emittance can be improved by injecting some additional gas in the beam line. Furthermore, this improvement seems to depend on the gas species.

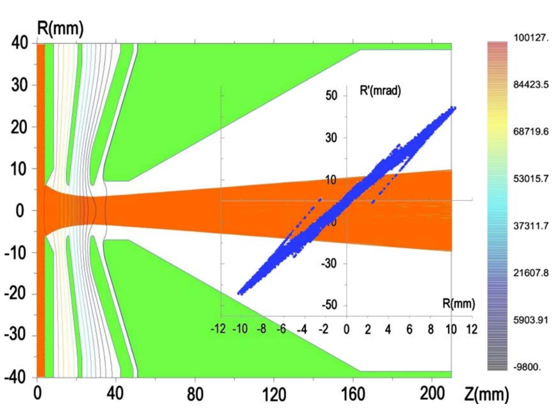

FIG. 1. (Color online) 140 mA D+ @ 100 KeV 4 electrode extraction system trajectories (r,r') beam emittance at $z=200$ mm.

Simulations were done for different pressure values and by adding krypton to the deuteron residual pressure. These simulations confirm that the emittance is lowered with higher gas pressure and with krypton injection.[3] Assuming that the residual D_2 gas contribution to the total pressure of the beam line is 10^{-5} hPa, a partial pressure (4×10^{-5}) of krypton would have to be added in the beam line. Under these pressure conditions, the loss rate is around 2.4%, due to the D^+ beam neutralization by the gases.

Another calculation shows that the Twiss parameters required for the beam injection into 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). The results show that the "weak" focalization should be adopted in order to reduce the emittance growth along the beam line. The two solenoid magnetic fields are around 0.37 and 0.47 T.

In order to be as close as possible to experimental conditions, the optimizations in TRACEWIN are done by maximizing the transmitted current trough the RFQ. Finally, for an injected D^+ beam of 141 mA, the best RFQ transmission obtained is 96%. At the RFQ entrance, the emittance is 0.125 π mm mrad and the Twiss parameters are: $\alpha=5.35$ and $\beta=0.23$ mm/π mrad.

B. Mechanical assembly

The optimal location of the solenoids was determined by beam dynamics simulations which showed that the LEBT length has to be short in order to limit the emittance growth. From the source plasma electrode to the RFQ entrance, the total length is 2.05 m. Along this short distance, the following equipments have to be implemented: the accelerator column, 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. Both solenoids are independently tunable in position (precise alignment). In addition, the injector will be first connected to a diagnostic box instead of the RFQ during the commissioning phases.

C. Diagnostics

For the IFMIF injector, classical interceptive diagnostics cannot be permanently used because of the high current power deposition. As already demonstrated, optical beam diagnostics based on the observation of the fluorescence induced by the excitation of residual gas molecules can be used. For the deuteron production required by IFMIF, deuterium gas will replace the hydrogen gas. As the emission spectrum of deuterium slightly differs from hydrogen, optical diagnostics (camera, spectrometer equipped with optic fibers) will be installed on the IFMIF injector. The neutron production forces to use radiation resistant devices. As a consequence, classical charge coupled device cameras will be replaced by charge injection device cameras able to support 10^3 gray/h. In the same time, the use of coherent optic fibers is expected for image transport up to the spectrometer.[5]

In addition, an Allison scanner emittance unit is under development. The high power deposition leads to highly wa-

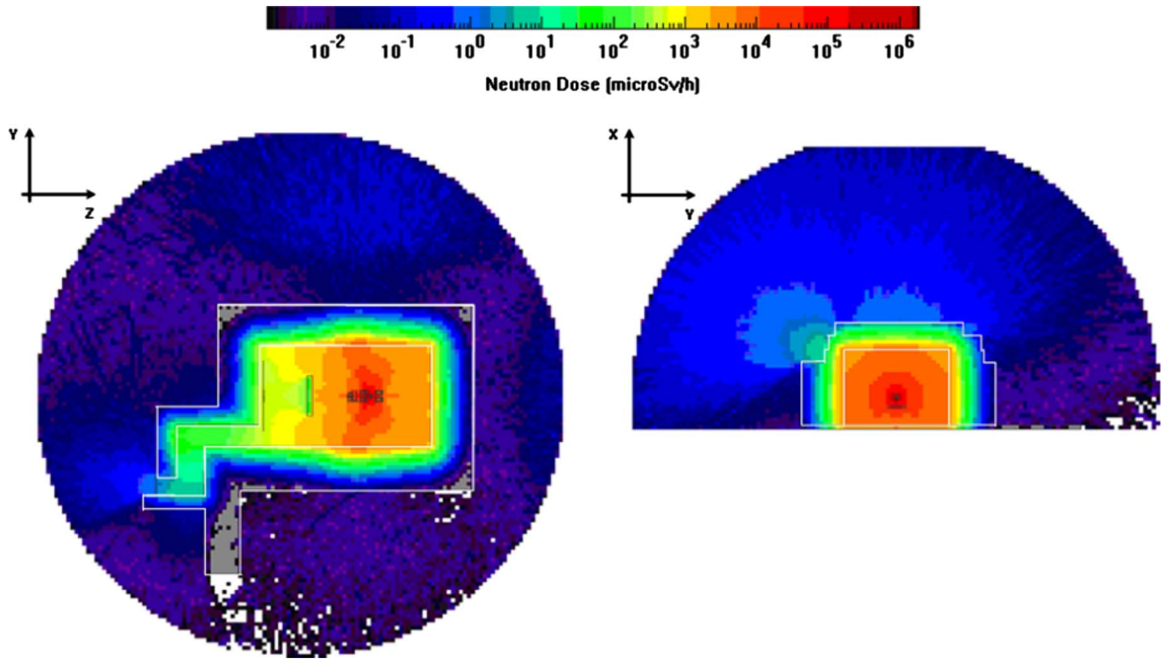

FIG. 2. (Color online) Top view (left) and side view (right) of the vault with the calculated 2D neutron dose distribution.

ter cooled equipment. In addition, to keep a reliable first slit, the large screen (sustaining more than 99% of the power) will be made of a tungsten-copper assembly, asking for a specific technical development.

Moreover, classical highly water cooled Faraday cup or beam stopper will be used for intensity monitoring and security aspects. Toroids will also be installed for intensity and beam noise measurements. Finally, a 4 grid analyzer will allow space charge compensation analysis.

IV. SAFETY AND RADIOPROTECTION

Preliminary neutron transport calculations have been performed in order to check that the present design of the Saclay injector blockhouse is in agreement with radioprotection constraints during the tests in Europe. The dose rate must be lower than 0.5 μSv/h outside the blockhouse.

Calculations are based on the estimation of neutron source term due to d-D fusion reactions after implantation of the accelerated deuterons in LEBT materials.[6] It must be pointed out that the process of deuteron implantation and especially its dependence on the temperature have been studied during a dedicated experimental campaign using Saclay source. Consequently, the accuracy in the estimation of the associated neutron source term has been significantly improved. By using this new source term, the calculated neutron flux in the regions where the detectors were located during the experiments agrees with the measured values. However, some conservative assumptions are still considered, mainly related to the temperature of the stopping material.

For the calculations, the major contributors to neutron flux attenuation, such as concrete shielding, polyethylene wall and metallic components, have been represented. In addition, potential neutron leakage areas such as entrance chicanes or ducts inside the wall have been accurately modeled at this stage. The neutron source has been placed at the position corresponding to the movable Faraday cup. The composition of concrete is mainly characterized by a low hydrogen content (700 ppm). The thickness of the walls is 2 m and of the roof is 1.2 m. For a beam intensity of 165 mA, corresponding to a 9 10^8 neutrons/s flux, the simulations show (Fig. 2) that the neutron dose rate outside the shielding is below the targeted value of 0.5 μSv/h (public dose).

In addition, activation calculations have been performed with a nominal elapsed running time operation with deuteron beam production. This operation period took into account sufficient high intensity beam production with pulsed and cw modes to characterize the deuteron beam. As a result, 2 weeks after the end of beam production, the residual activation of all the equipments would not exceed 1 Bq/g.

V. CONCLUSION

The requirements of the IFMIF injector are quite challenging in terms of beam extraction and beam dynamics. To minimize the emittance growth, the beam line length has been dramatically reduced, leading to difficulties in the mechanical integration.

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