INSTALLATION AND COMMISSIONING OF THE 1.1 MW DEUTERON PROTOTYPE LINAC OF IFMIF

J. Knaster, IFMIF/EVEDA Project Team, Rokkasho, Japan
P. Cara, A. Mosnier, F4E, Garching
S. Chel, CEA, IRFU, Gif-sur-Yvette, France
A. Facco, INFN, LNL, Legnaro, Italy
J. Molla, CIEMAT, Madrid, Spain
H. Suzuki, JAEA, Rokkasho, Japan

Abstract

IFMIF, the International Fusion Materials Irradiation Facility, is projected to generate materials irradiation test data for design, licensing, construction and safe operation of a fusion demonstration power reactor, such as DEMO. In particular, the study of the material behaviour under irradiation conditions similar to DEMO in terms of primary recoil spectrum (PKA), important transmutation reactions, and gas production (He, H) is essential. The fusion relevant neutrons are produced in a liquid Li jet flowing at 15 m/s impacted by 2 parallel 125 mA CW deuteron beams at 40 MeV. The IFMIF/EVEDA project, by its engineering validation activities, will install and commission in Rokkasho a 125 mA, 175 MHz deuteron LINAC at 9MeV that will validate the concept of IFMIF accelerator, LIPAc. The ion source will inject 140 mA deuterons at 100 KeV in a normal-conducting RFQ that will deliver the bunched beam at 5MeV to be accelerated up to 9 MeV thanks to 8 half-wave superconducting resonators. The installation and commissioning of LIPAc at Rokkasho (Japan) is sequential and the first stage is starting now; the strategy to overcome potential difficulties is detailed.

IFMIF

A fusion relevant neutron source is a more than three decades long pending step for the successful development of fusion energy. In DEMO, like in future fusion power plants, the deuterium-tritium nuclear fusion reactions will generate neutron fluxes in the order of 10^{18} $m^{-2}s^{-1}$ with an energy of 14.1 MeV that will collide with the reactor vessel. Its first wall, a complex combination of layers of different materials that aims to maximizing the conversion of neutrons into thermal energy and breeding tritium, will be worst exposed undergoing potentially >15 dpa_{NRT} per year of operation [1,2]. Degradation of materials under neutrons bombardment, also called "Wigner disease", is a phenomenon anticipated by E.P. Wigner in the 40s with his assessment of the possibility of displacing atoms by irradiation with neutrons [3], with continuous world efforts implemented since then to unravel the physics. Through inelastic collisions, nuclei absorb neutrons and transmute the constituent elements changing the material inherent properties; in addition, the transmuted nuclei decay typically channelled through (n,p), (n,α) or (n,γ) (it is to be noted that the latter reactions, though presenting a significantly higher cross section, show negligible impact in the metallic lattice). Combined with this, primary recoil knock-on atoms (PKA) through elastic collisions generate a cascade of Frenkel vacancy-interstitial pairs with threshold energies as low as 40 eV for Fe and Cr [4] that accumulate the gas molecules from the decayed transmuted nuclei, which can also accumulate in the dislocations and in intergranular space leading to swelling and presence of internal stresses that might cause a dramatic increase of the ductile to brittle transition temperature (DBTT). Safe design, construction and licensing of a nuclear fusion facility by the corresponding Nuclear Regulatory agency will demand the understanding of the materials degradation during the life-time of the fusion reactor. The complexity of the degrading mechanisms, combining transmutation processes together with damages in the metal lattice, demands experimental observations in as close as possible to realistic conditions to develop models and tune computational algorithms. The number of variables playing a significant role (neutron flux, spectrum, fluence, material temperature, stress, microstructure, thermal-mechanical processing history, lattice kinetics…) makes the experiments with fusion relevant neutron sources unavoidable.

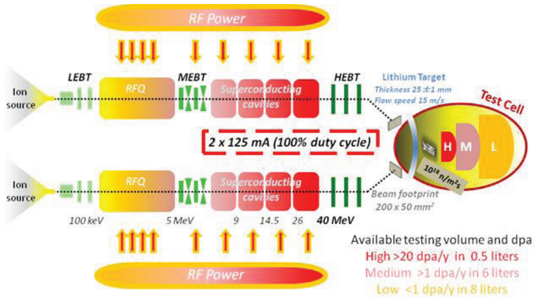


Figure 1: Schematic of IFMIF.

IFMIF, the International Fusion Materials Irradiation Facility, will generate a neutron flux with a broad peak at 14 MeV by Li(d,xn) reactions [5] thanks to two parallel deuteron accelerators colliding in a liquid Li screen with a footprint of 20 cm x 5 cm. The energy of the beam (40 MeV) and the current of the parallel accelerators (2 x 125 mA) have been tuned to maximize the neutrons flux and reach 10^{18} $m^{-2}s^{-1}$) to get irradiation conditions comparable to those in the first wall of a fusion reactor in a volume of 0.5 l that will house around 1000 small specimens [6] (see Fig. 1).

LIPAC, THE PROTOTYPE OF IFMIF ACCELERATORS

IFMIF, presently in its engineering validation and engineering design activities (EVEDA) phase will demonstrate the feasibility of its 5 MW deuteron accelerators thanks to the operation of a deuteron accelerator with 125 mA current in CW and one superconducting accelerating cryomodule to 9 MeV, cloning IFMIF accelerators layout up to the first of its four accelerating stages within the Broader Approach Agreement between Japan and EURATOM (see Fig. 2).

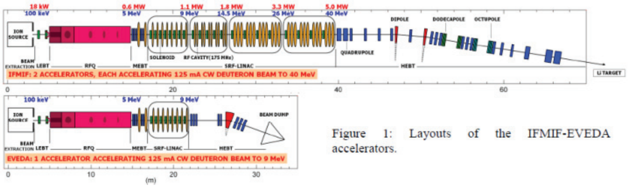
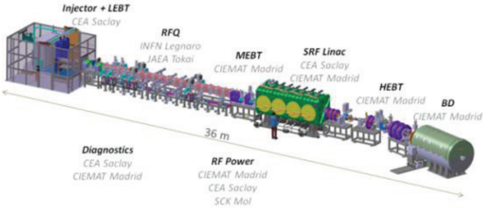


Figure 1: Layouts of the IFMIF-EVEDA accelerators.

Figure 2: Comparative layout of LIPAc and IFMIF accelerators [7].

The construction of the equipment of the Linear IFMIF Prototype Accelerator (LIPAc), is mainly accomplished in European labs, and its installation and commissioning will take place in Rokkasho (Japan) [8]. The sharing of the construction of the accelerator components across European labs is apparent in Fig. 3



.

Figure 3: Layout of LIPAc and its construction sharing.

The installation of LIPAc has started in spring 2013 following the successful tests of the injector and its LEBT in November in CEA Saclay (France) and the delivery to Rokkasho in spring 2013 [9]. The injector follows the 2.45 GHz and the 875 Gauss Electro-cyclotron resonance concept of Chalk River [10] (and successfully operated in SILHI [11]) at 140 mA and 100 kV with a 5 electrode beam extraction system. Two boron nitride disks, typically with low outgassing rates, protect the entrance of the waveguide and the plasma electrode from ion bombardment. The extracted beam is matched to the RFQ entrance thanks to a dual solenoid focusing scheme. The acceptance tests successfully complied with the specified transverse emittance values at the output of the LEBT < 0.3 π mm·mrad measured with an Allison scanner [12] and 95% D^+ fraction.

The RFQ follows the four vanes design [13] successfully operated in Europe in IPHI and TRASCO [14] accelerating the beam to 5 MeV along its 9.8 m length. The enhancement of space charge shortcomings at low energies led to the high input energy of 100 keV with the aforementioned challenging emittance values that will keep losses below 10% [15] until the end of 'gentle buncher' and below 10^{-6} in the high energy part (activation by deuterons, with significantly higher activation cross sections than protons, will be within hands-on maintenance limits). The validation of the tuning and stabilization procedures were established following low power tests on an aluminium real-scale RFQ [16], which determined the mode spectra and the electric field distribution with the bead pulling technique based on Slater perturbation theory [17].

Five quadrupoles and two 5-gap IH cavity [18] bunchers in the MEBT fulfil the transverse and longitudinal matching conditions of the RFQ output beam to the SRF input [19]. Two movable scrapers capable of withstanding up to 500 W will stop the beam halo and out-of-energy particles coming from the RFQ. The last accelerating stage till 9 MeV in LIPAc will be accomplished by the first cryomodule of the IFMIF SRF, which contains eight superconducting 175 MHz half-wave resonators (HWR) working at 4.5 MV/m accelerating field. The beam focusing and orbit corrections are performed by eight sets of superconducting solenoids/steerers and beam position monitors, located before each HWR. Successfully tested mono-crystalline CVD (chemical vapour deposition) diamond based µloss monitors will detect beam losses at $<10^{-6}$ beam current range.

The HEBT and beam dump are the responsibility of CIEMAT and have been described elsewhere [8].

LIPAC INSTALLATION AND COMMISSIONING

The unprecedented expected performance of LIPAc (125 mA CW deuteron beam at 9 MeV) will break through the scientific borders defined by the successful experience of LEDA (proton beam of 100 mA CW at 6.7 MeV) at the beginning of last decade [20]. In high current hadron Linacs, beam halo is the major cause of beam loss and activation. Though its clear definition is not agreed (one talks about 'halo', as long as there are significant tails outside the beam core), its presence in high power Linacs was shown in LEDA to be mainly driven by resonances between individual particles and the beam core oscillations due to optical mismatches in transition regions [21]. A carefully designed fiducialisation of the accelerator hall, taking into account the potential masking of certain fiducials by auxiliary equipment combined with a Leica AT401LT 401 Laser tracker guarantees an uncertainty of the measurements < 30 µm (indispensable if precisions of 0.1 mm are targeted); this will allow the alignment and determination of positioning of critical equipment within the specified accuracy.

The commissioning exercises will be mainly performed with H^+ beams given that at half energy and half intensity present same speed and space charge than D^+ beams at nominal energy and intensity. The low energy of protons will allow hands-on maintenance if beam time with deuterons is limited. Four stages are foreseen following the schedule indicated in Fig. 4. The full commissioning of Injector + LEBT at expected operational values will be repeated in 2013 in Rokkasho following its re-assembly. A second stage will include the RFQ + MEBT at full intensity but with a reduced duty cycle (0.1% is targeted). A temporal diagnostic plate placed at the output of the MEBT will allow the measurement of beam current, phase, position, transverse and longitudinal profiles, transverse halo, mean energy and energy spread, transverse and longitudinal emittance and beam losses [22]. Installation and commissioning of cryomodule, HEBT and Beam Dump will follow. Once LIPAc is fully assembled, full current in pulsed mode will be achieved with a final stage of a slow ramping up of duty cycle, with a close monitoring of the beam halo evolution, to reach the specified 100%.

The way ahead is not totally paved but the soundness of the accelerator layout, the high quality of the equipment under construction, the experience gained in LEDA, IFMIF's relevance for the world nuclear fusion program and the existing international enthusiasm are strong reasons for a bright future of the project.

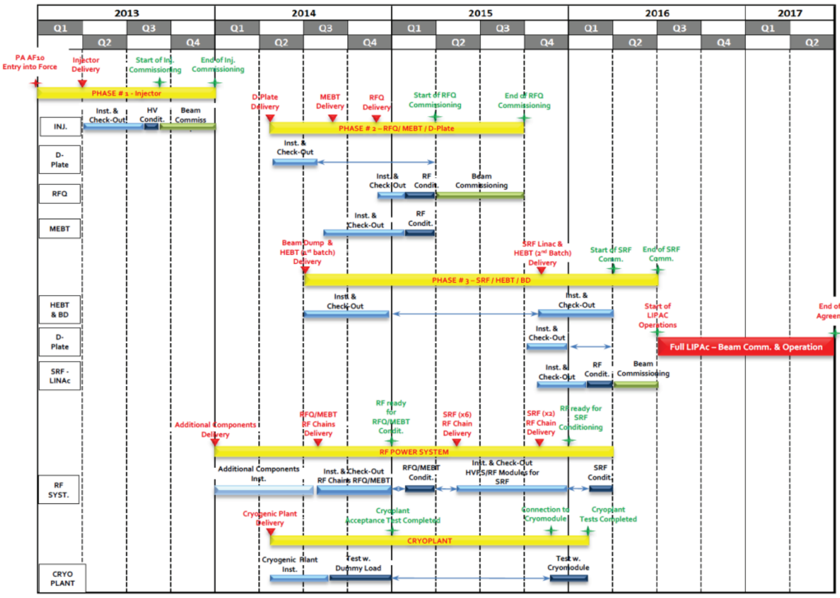


Figure 4: Schedule of the LIPAc Installation and Commissioning.

REFERENCES

[1] M.R.Gilbert, "An Integrated Model for Materials in a Fusion Power Plant: Transmutation, Gas Production, and Helium Embrittlement under Neutron Irradiation", Nucl. Fusion 52 (2012).

[2] M.I. Norgett et al, "A Proposed Method of Calculating Displacement Dose Rates", Nucl. Eng. Des. 33 (1975) 50.

[3] E.P. Wigner, "Theoretical Physics in the Metallurgical Laboratory in Chicago", J. Appl. Phys. 17 (1946).

[4] M.T. Robinson, "Basic Physics of Radiation Damage Production", J. Nucl. Mat. 216 (1994) l-28.

[5] M. Hagiwara et al., "Measurement of Neutron Emission Spectra in Li(d,xn) Reaction with thick and thin targets for 40 MeV deuterons", Fus. Sci. Techn. 48 (2005) 1320-1328.

[6] IFMIF Int. Team, "IFMIF Comprehensive Design Report"; http://www.iea.org/Textbase/techno/technologies/fusion/

[7] P.A.P. Nghiem et al., "The IFMIF-EVEDA Challenges in Beam Dynamics and their Treatment", Nucl. Inst. Meth. 654 (2011) 63–71.

[8] A. Mosnier et al., "The Accelerator Prototype of the IFMIF/EVEDA Project", IPAC 2010, Kyoto.

[9] H. Shidara et al., "Installation of D+ Injector of IFMIF Prototype Accelerator in Japan", IPAC 2013, Shangai.

[10] G.M. Arbique et al., "Multi-beamlet Injection to the RFQ1 Accelerator: a Comparison of ECR an Duopigatron Proton Sources", PAC 1991, San Francisco.

[11] R. Gobin et al., Saclay High Intensity Light Ion Source – Status, EPAC 2002, Paris.

[12] N. Chauvin et al., "Beam commissioning of the Linear IFMIF Prototype Accelerator Injector: measurements and simulations", IPAC 2013, Shangai.

[13] A. Pisent et al., "IFMIF-EVEDA RFQ Design", EPAC 2008, Genoa.

[14] A. Pisent at al., "TRASCO 100 MeV High Intensity Proton Linac", EPAC 2000, Vienna.

[15] M. Comunian et al., Beam Dynamics redesign of IFMIF-EVEDA RFQ for a Larger Input Beam Acceptance, IPAC 2011, San Sebastián.

[16] A. Palmieri et al., "The IFMIF RFQ real scale Aluminium Model: RF Measurements and Tuning", IPAC 2010, Kyoto.

[17] T. Khabiboulline, "A new Tuning Method for Travelling Wave Structures', IEEE Particle Accelerator Conference. 1-5 May 1995, Dallas.

[18] A. Lara, "RF Design for the Re-buncher Cavities for the LIPAc Deuteron Accelerator", IPAC 2011, San Sebastián.

[19] T. Weis, "A Highly Efficient Interdigital H-Type Resonator for Molecular Ions", IEEE Trans. Nucl. Sci., Vol. NS-30, No. 4, August 1983.

[20] L.M. Young, "High Power Operation of LEDA", XX International Linac Conference, Monterey.

[21] C.K. Allen et al., "Beam Halo Measurements in high current Proton Beams", Phys. Rev. Lett. 89, 214802.

[22] I. Podadera et al., "A Diagnostic Plate for the IFMIF-EVEDA Accelerator", IPAC 2008, Genoa.