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IFMIF/EVEDA, essential step towards a fusion relevant neutron source

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A fusion relevant neutron source for the characterization and qualification of materials capable to withstand the severe irradiation conditions of the plasma facing components in a fusion power plant is a more than three decades old worldwide pending step for the successful development of fusion energy. In fusion power plants, the fusion of deuterium and tritium will generate neutrons with fluxes in the order of 10^{18} $m^{-2}s^{-1}$ and energies of 14.1 MeV; their safe design, construction and licensing demands learning the irradiation impact in the structural materials during the life-time of the fusion reactor. The first wall of the reactor vessel will be most exposed undergoing potentially >15 dpa_{NRT} per year of operation. The understanding of the degradation of the mechanical and physical properties beyond the defined operational thresholds driven mainly by nuclear safety reasons, but also by investment protection aspects, will determine the operational program of the fusion power plant; in turn, the understanding of the physical phenomena will allow the design of suitable radiation hard and low activation materials enhancing the efficiency and economical interest of fusion energy. Nuclei are transmuted through nuclear interactions with the incident neutrons to stable or radioactive nuclei via (n,α), (n,p), (n,γ) or other reaction channels. Through elastic and inelastic collisions neutrons initiate primary recoil knock-on atoms (PKA) with a cascade of Frenkel vacancy-interstitial pairs with threshold energies as low as 40 eV for Fe and Cr. The damage in the microstructure of the metal contributes to the material embrittlement through the internal pressure of accumulated gas molecules resulting from the nuclear reactions at a rate of about 11 appm He/dpa_{NRT} for fusion neutrons spectrum. The accumulation of helium leads to a significant mechanical impact even with low concentrations. The materials do not show the same dpa_{NRT} cross-section under the same neutron irradiation conditions; in addition, the dpa_{NRT} concept neglects relevant factors such as recombination, migration, and coalescence of radiation defects; representing thus an incomplete atom-based approximation of the neutron radiation induced damage to materials. For fusion materials irradiation experiments it is therefore essential that the gas to dpa_{NRT} ratios and the PKA spectral distribution be similar to that of a fusion environment. The number of variables that plays a primary role (neutron flux, spectrum, fluence, material temperature, mechanical loading conditions, microstructure, thermo-mechanical processing history, lattice kinetics…) makes a fusion relevant neutron source become an indispensable step in the different world fusion power roadmaps. Tuned Li(d,xn) nuclear reactions have been considered for last three decades to be the most efficient way to simulate the neutronic conditions inside the reactor vessel. Different concepts have been proposed throughout years; the first initiative took place in the 70s in the United States of America (USA) with the “Fusion Materials Irradiation Test” project (FMIT), which aimed at obtaining a neutron flux of 10^{19} $m^{-2}s^{-1}$ in a 10 cm^3 volume by means of a deuteron accelerator of 100 mA in CW and 35 MeV of beam energy, but the project was cancelled in 1984. A few years later, JAERI proposed the “Energy Selective Neutron Irradiation Test Facility” program (ESNIT) with 50 mA CW 40 MeV deuteron beam and a 125 cm^3 testing volume with a neutron flux of 3 x 10^{18} $m^{-2}s^{-1}$. Since 1994, the “International Fusion Materials Irradiation Facility” (IFMIF) is the baseline within the Nuclear Fusion community. Presently in its “Engineering Validation and Engineering Design Activities” phase (EVEDA) under the frame of the Broader Approach Agreement between Japan and EURATOM signed in February 2007, has the mandate to produce an integrated engineering design of IFMIF, and to validate continuous and stable operation of each IFMIF sub-system. IFMIF will generate a neutron flux with a broad peak at 14 MeV by Li(d,xn) nuclear reactions thanks to two parallel deuteron accelerators colliding in a liquid Li screen with a footprint of 200 mm x 50 mm. The energy of the beam (40 MeV) and the current of the parallel accelerators (2 x 125 mA) have been tuned to maximize the

neutron flux (10^{18} $m^{-2}s^{-1}$) to get suitable irradiation conditions in a volume of 0.5 l that can accommodate around 1000 small specimens [1]. The design of IFMIF plant is intimately linked with the validation activities carried out over the first 6 years of life of the IFMIF/EVEDA phase. The accomplishment of the Engineering Design Activities arrived on schedule in June 2013 with the delivery of an “IFMIF Intermediate Engineering Design Report” describing the five major systems: 1) the Accelerator Facility; 2) the Li Target Facility; 3) the Test Facility, 4) the Post-Irradiation and Examination (PIE) Facility, and 5) the Conventional Facility compliant with international nuclear facility regulations. The validation activities have focused on the main technological challenges of the accelerator [2], target and test facilities with the construction of the following prototypes: 1) an Accelerator Prototype (LIPAc) mainly designed and constructed in Europe and to be installed in Rokkasho, fully representative of the IFMIF low energy (9 MeV) accelerator (125 mA of D^+ beam in CW) to be operational in June 2017 [3]; 2) a Lithium Test Loop (ELTL) at Oarai [4], integrating all elements of the IFMIF lithium target facility, complemented by corrosion experiments performed at the LIFUS6 lithium loop at Brasimone; and 3) the High Flux Test Module (Japanese and European designs) and its internals to be irradiated in a fission reactor and tested in the purposed constructed helium loop HELOKA in KIT. The technological excellence of the validation activities is best represented by LIPAc in Rokkasho and with ELTL in Oarai. LIPAc will become the leading world Linac in average beam power with its 1.125 MW; the challenge of running a deuteron beam in CW at 40 MeV will be overcome by succeeding at 9 MeV since space charge issues are enhanced at lower energies. In turn, ELTL is the world largest liquid lithium facility; it has been conceived to overcome the most relevant operational aspects required for IFMIF (flow characteristics, free surface stability, purification and diagnoses); the design of the beam target implements the lessons learnt since FMIT times with various different studies worldwide throughout the years presenting a 25 mm thick flowing lithium screen at 15 m/s flowing speed with a concave shape that increases through centrifugal acceleration the saturation pressure in the bulk of the liquid lithium dissipating efficiently the 2 x 5 MW deuteron beam power and providing safe operational margins without nucleation or constructive interferences [5]. The successful accomplishment of the validation activities will allow a safe construction anticipating cost and schedule of a neutron source based on Li(d,xn) nuclear reactions timely with fusion roadmaps.

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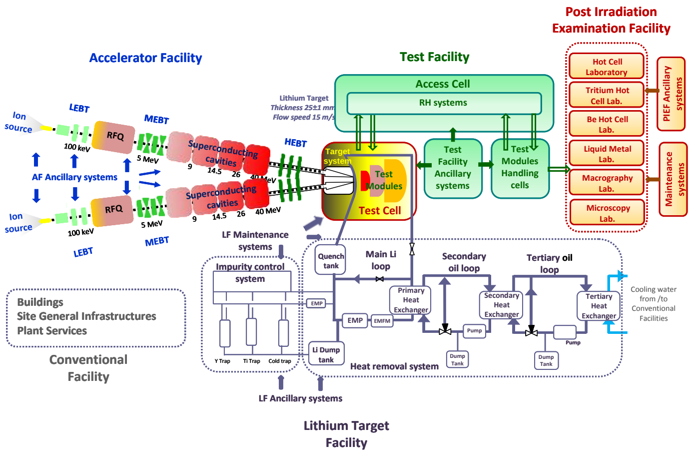

Fig 1: Schematic of IFMIF plant including its 5 facilities

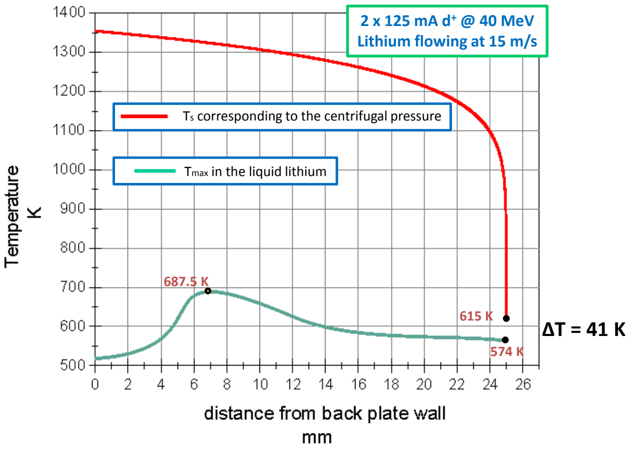

Fig 2: T_{max} envelope in the beam footprint under nominal conditions at different depths vs T_s