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IFMIF, the European–Japanese efforts under the Broader Approach agreement towards a Li(d,xn) neutron source: Current status and future options

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ABSTRACT

The necessity of a neutron source for fusion materials research was identified already in the 70s. Though neutrons induced degradation present similarities on a mechanistic approach, thresholds energies for crucial transmutations are typically above fission neutrons spectrum. The generation of He via ^{56}Fe (n,α) ^{53}Cr in future fusion reactors with around 12 appm/dpa will lead to swelling and structural materials embrittlement. Existing neutron sources, namely fission reactors or spallation sources lead to different degradation, attempts for extrapolation are unsuccessful given the absence of experimental observations in the operational ranges of a fusion reactor. Neutrons with a broad peak at 14 MeV can be generated with Li(d,xn) reactions; the technological efforts that started with FMIT in the early 80s have finally matured with the success of IFMIF/EVEDA under the Broader Approach Agreement. The status today of five technological challenges, perceived in the past as most critical, are addressed. These are: 1. the feasibility of IFMIF accelerators, 2. the long term stability of lithium flow at IFMIF nominal conditions, 3. the potential instabilities in the lithium screen induced by the 2×5 MW impacting deuteron beam, 4. the uniformity of temperature in the specimens during irradiation, and 5. the validity of data provided with small specimens. Other ideas for fusion material testing have been considered, but they possibly are either not technologically feasible if fixed targets are considered or would require the results of a Li(d,xn) facility to be reliably designed. In addition, today we know beyond reasonable doubt that the cost of IFMIF, consistently estimated throughout decades, is marginal compared with the cost of a fusion reactor. The less ambitious DEMO reactor performance being considered correlates with a lower need of fusion neutrons flux; thus IFMIF with its two accelerators is possibly not needed since with only one accelerator as the European DONES or the Japanese A-FNS propose, the present needs > 10 dpa/fpy would be fulfilled. World fusion roadmaps stipulate a fusion relevant neutron source by the middle of next decade, the success of IFMIF/EVEDA phase is materializing this four decades old dream.

1. Introduction

The endeavours towards making a fusion relevant neutron source available for fusion materials qualification (and development), a decades old pending essential step of world nuclear fusion community, is coming to an end. In future fusion power plants, the

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reactor vessel's first wall will be exposed to neutron fluxes in the order of 10^{18} $m^{-2}s^{-1}$ with an energy of 14.1 MeV causing potentially > 15 dpa per year of operation [1,2]. The plasma facing components shall withstand the severe irradiation conditions without significant degradation for a period long enough to make a power plant viable and economically interesting. ITER, with its estimated maximum of 3 dpa of irradiation exposure at the end of its operational life, does not need the results from a fusion relevant neutron source for its licensing. However, an understanding of the mechanical properties of the structural materials exposed to high fluences of fusion neutrons will be soon indispensable to design next generation of fusion reactors with guarantees of obtaining the facility license and its reliable operation.

The accumulation of gas in the materials microstructure is intimately related with the impacting neutron energy; in steels $^{54}Fe(n,\alpha)^{51}Cr$ and $^{54}Fe(n,p)^{54}Mn$ reactions are responsible for most of the α-particles and protons produced with incident neutron energy thresholds at around 3 MeV and 1 MeV respectively. Thus fission neutron sources, which show an average energy around < 2 MeV as per Watt's distribution spectrum, cannot adequately suit the testing requirements for fusion materials since the transmuted helium production rates are far from fusion reactor's (actually around 0.3 appm He/dpa compared with around 11 appm He/dpa for 14 MeV neutrons) [3]. In turn, spallation sources presents a pulsed neutron spectrum with long tails reaching the typically GeV order of the incident particle energy, compared with the mono-energetic continuous spectrum of fusion neutrons, that might induce thermal effects in irradiated materials (that can be small, but are unavoidable) and generates light ions as transmutation products [4]). Attempts to overcome the absence of a fusion relevant neutron source and simulate the impact of the accumulation of helium follow the bombarding of suitable materials in cyclotron facilities, with α-particles at energies ranging from 20 to 100 MeV, that leads to He/dpa ratios of 10,000 appm/dpa and Bragg peaks typically in the μm range difficult to characterize [5].

All efforts to overcome the absence of a fusion relevant neutron source are not capable to reach the required maturity of the understanding of the behaviour of the structural materials exposed to the high fluxes of monoenergetic 14.1 MeV fusion neutrons in future reactors.

2. Four decades of efforts towards a fusion relevant neutron source

The seminal idea to use Li(d,xn) nuclear stripping reactions [6] towards a fusion relevant neutron was proposed in 1975 [7], with a prompt reaction [8] that ended within few years with the proposal of the Fusion Materials Irradiation Testing (FMIT) facility [9] in the US. FMIT 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 continuous wave (CW) and an energy of 35 MeV colliding on a flowing lithium jet exposed to the bean vacuum. The project started with enthusiasm; validating prototypes of the Accelerator, Target and Test facility were constructed. However, the combination of the technical difficulties faced with the prototype accelerator and the lack of urgency of such a facility without fusion power in the horizon led to the cancellation of the project in 1984.

The International Energy Agency (IEA) fostered a series of regional meetings the ensuing years in the US, Europe, and Japan, which culminated early 1989 in an international workshop concluding that a Li(d,xn) facility was the most promising candidate [10] for a fusion relevant neutron source. In line with this conclusion, JAERI proposed in 1988 the Energy Selective Neutron Irradiation Test (ESNIT) facility with 50 mA CW, 40 MeV deuteron beam and a 125 cm^3 testing volume with a neutron flux of 3×10^{18} $m^{-2}s^{-1}$ [11], in parallel with other initiatives in the US [12].

In 1994, the International Fusion Materials Irradiation Facility (IFMIF) became the reference concept within the Fusion community. Since this time, the project has successfully passed through its Conceptual Design Activity (CDA) phase in 1996 [13] as a joint effort of the EU, Japan, the RF, and the US within the framework of the Fusion Materials Implementing Agreement of the IEA. The release of its Conceptual Design Report (CDR) co-authored by a team from the four aforementioned in 2004 [14]; and in 2007, the Broader Approach Agreement signed between EU and Japan (entered into force in June 2007), in support of the ITER project towards an early realisation of fusion energy for peaceful purposes, which included the IFMIF/EVEDA project (where EVEDA stands for Engineering Validation and Engineering Design Activities). IFMIF/EVEDA received the mandate to produce an integrated engineering design of IFMIF, and to validate continuous and stable operation of each IFMIF subsystem.

A careful account of the genealogy of IFMIF up to the present moment has been reported [15].

3. The on-going success of the EVEDA phase of IFMIF

The technological challenges of a Li(d,xn) neutron source have been overcome through the intense four decades of continuous worldwide research efforts. Its present maturity [16] has enjoyed the previous stages before this definitive EVEDA phase. Difficulties appeared on the road have been eventually overcome; only pending technical challenge is the demonstration of the feasibility of the CW operation of a deuteron beam at 125 mA for long periods and at the high availabilities needed.

The mandate of EVEDA and the maturity of its validation activities will be explained. The validation work carried out has been substantially broader than what will be detailed, where only the most significant achievements will be addressed. An overview of the full scope of the validation activities has been detailed elsewhere [17].

3.1. The accomplished Engineering Design Activities (EDA) phase of IFMIF

The initial allocated time for IFMIF/EVEDA under the BA Agreement was six years; insufficient time to achieve the full validation scope expected; thus the validation activities were not fully completed when the Engineering Design Activities (EDA) phase ended on schedule in June 2013. However, the maturity of the on-going validation activities in 2013, backed by the previous decades of development work, allowed the release of the IFMIF Intermediate Engineering Design Report (IIEDR) [15]. The status of the project and of the Engineering Validation Activities (EVA) phase at the time of the accomplishment of the EDA phase has been reported elsewhere [16,17,18].

IFMIF will generate a neutron flux with a broad peak at 14 MeV thanks to two parallel 125 mA CW deuteron accelerators at 40 MeV colliding with a footprint of 200 mm × 50 mm in a liquid lithium screen. The lithium target will be flowing at 15 m/s with a stable thickness of 25 +/−1 mm to fully absorb and evacuate the 2 × 5 MW beam power. The 40 MeV energy of the beam and the 2 × 125 mA current of the parallel accelerators have been tuned to reach a comparable neutron flux (10^{18} $m^{-2}s^{-1}$) to the one expected in the most exposed structural materials of a fusion power reactor. An irradiation volume of 500 cm^3 will contain 12 independently cooled capsules housing each around 2 × 40 small specimens for a total of around 1000 specimens. Each capsule can be independently cooled at a target temperature ranging 250 °C < T < 550 °C with the specimens presenting a ΔT < 3% during irradiation