ARTICLE IN PRESS
JID: NME [m5G;May 7, 2016;17:37]
Nuclear Materials and Energy 000 (2016) 1–9
Contents lists available at ScienceDirect
Nuclear Materials and Energy
journal homepage: www.elsevier.com/locate/nme

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

J. Knaster[a,*], F. Arbeiter[b], P. Cara[c], S. Chel[d], A. Facco[e], R. Heidinger[c], A. Ibarra[f], A. Kasugai[g], H. Kondo[h], G. Micciche[i], K. Ochiai[g], S. O'hira[g], Y. Okumura[a], K. Sakamoto[g], E. Wakai[j]

[a] IFMIF/EVEDA Project Team, Rokkasho, Japan
[b] KIT, Karlsruhe, Germany
[c] F4E, Garching, Germany
[d] CEA, Saclay, France
[e] INFN, Legnaro, Italy
[f] CIEMAT, Madrid, Spain
[g] QST, Rokkasho, Japan
[h] QST, Naka, Japan
[i] ENEA, Brasimone, Italy
[j] JAEA, Tokai, Japan

ARTICLE INFO

Article history:
Received 19 November 2015
Revised 29 March 2016
Accepted 21 April 2016
Available online xxx

Keywords:
IFMIF
Lithium
Deuterons
Liquid target
Fusion materials
DONES
A-FNS

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.

© 2016 Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

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

* Corresponding author.
E-mail address: juan.knaster@ifmif.org (J. Knaster).

http://dx.doi.org/10.1016/j.nme.2016.04.012
2352-1791/© 2016 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Please cite this article as: J. Knaster et al., IFMIF, the European–Japanese efforts under the Broader Approach agreement towards a Li(d,xn) neutron source: Current status and future options, Nuclear Materials and Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.04.012

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

Please cite this article as: J. Knaster et al., IFMIF, the European–Japanese efforts under the Broader Approach agreement towards a Li(d,xn) neutron source: Current status and future options, Nuclear Materials and Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.04.012

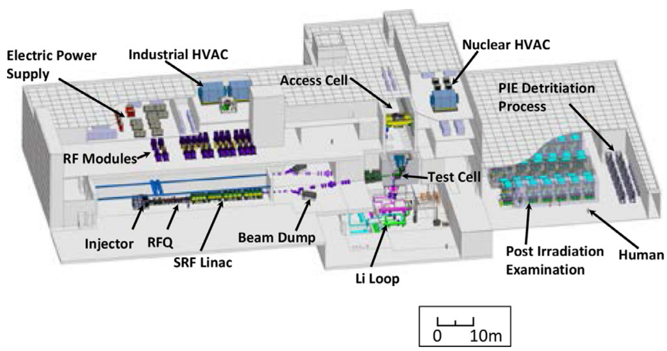

Fig. 1. Artistic bird's eye view of the IFMIF [REF].

(this % refers to Kelvin units). The neutron flux provided and the design of its High Flux Test Module containing the 12 capsules directly irradiated allows > 20 dpa per year of operation at fusion relevant conditions. The Test Cell is designed to also house a Middle and a Low Flux test Module for higher volumes but lower dpa capabilities. IFMIF is conceived for 30 years of operation [19].

The IFMIF plant is composed of 5 specific facilities grouped into the Accelerator Facility (AF), the Lithium Target Facility (LF), the Test Facility (TF), the Post Irradiation Examination Facility (PIEF) and the Conventional Facilities (CF). The latter group of systems ensure power, cooling, ventilation, rooms and services to the other facilities and itself [15]. An artistic view of IFMIF plant is shown in Fig. 1.

The IIEDR is composed by five major elements: (a) an Executive Summary that explains the status of the project at the time of the accomplishment of the EDA phase; (b) the IFMIF Plant Design Description (PDD), that summarizes the content of the full IIEDR consisting of more than 100 technical reports; (c) a careful cost and schedule report, based on the experience gained with the construction of prototypes during the EVA phase and the analysis of recognised Japanese and European engineering companies; (d) Annexes to the PDD; and (e) 34 Detailed Design Description documents of all the sub-systems supporting the PDD.

An improvement in the design from former phases has been developed during EVEDA Phase [20], being the most relevant ones: (a) the Alvarez-type Drift Tube Linac (DTL) in the Accelerator Facility has been replaced by a Superconducting Radio-Frequency (RF) Linac following the demonstration of feasibility of superconducting cavities for low-β protons, presenting a simplification of the RF system and significant reduction of operational power consumption; (b) the configuration of the Test Cell evolved as in the present design, where the irradiation modules have no more a shielding function and are thus detached from the shielding block, improving the irradiation flexibility and reliability of the remote handling equipment and cost reducing; (c) the Quench Tank of the Lithium loop, previously inside the Test Cell, has been re-located outside reducing the tritium production rate and simplifying the maintenance processes; (d) the maintenance strategy together with the management of the irradiated samples has been modified to allow a shorter yearly stop of the irradiation operations.

3.2. The Engineering Validation Activities (EVA) phase of IFMIF

The validation activities focused on the three most technologically challenging equipment, namely, the accelerator, the lithium loop and the test modules addressing all possible aspects to allow a rapid construction, with no technological challenges remaining open whenever the decision for its construction arrived, and allowing the continuous and stable operation of each IFMIF subsystem. The activities were substantially wider that what is here reported, details of the full scope are provided elsewhere [17]. All the Target Facility validation activities (with the exception of on-going corrosion/erosion tests in LIFUS6 lithium loop in operation in Brasimone [21]) have been accomplished [22]. All the Test facility validation activities have been accomplished [23]. Only the prototype accelerator under installation and commissioning in the International Fusion Energy Research Center (IFERC) of Rokkasho remains to be validated [24].

3.2.1. LIPAc, the Linear IFMIF Prototype Accelerator

LIPAc, the Linear IFMIF Prototype Accelerator, designed and constructed in Europe and under installation and commission in the IFERC site of Rokkasho will operate in CW 125 mA deuteron beam at 9 MeV [24]. LIPAc implements most modern and reliable available accelerator technologies to demonstrate feasibility of its nominal operational performance. The breakdown of its contribution is shown in Fig. 2. It implements the 2.45 GHz and the 875 Gauss Electro-cyclotron resonance concept of Chalk River [25] (and successfully operated in SILHI [26] since the 90s) at 140 mA and 100 kV with a 5 electrode beam extraction system. The extracted beam is matched to the RFQ entrance thanks to a dual solenoid focusing scheme; in turn, the transverse emittance values at the output of the LEBT < 0.3 π mm·mrad and 95% D^+ fraction will allow a transmission > 90% at the 5 MeV output of the RFQ [27] as per simulations performed. The RFQ follows the four vanes design [28] of LEDA, successfully operated in Europe in TRASCO [29] to accelerate the beam to 5 MeV along its 9.8 m length. The validation of the tuning and stabilization procedures were established following low power tests on an aluminum real-scale RFQ [30], which determined the mode spectra and the electric field distribution with the bead pulling technique applying a novel perturbation theory developed in INFN [31]. The 125 mA beam commissioning with low duty cycles through the RFQ is scheduled during 2016. The 5 MeV beam at the output of the RFQ will be matched and bunched in the MEBT before its injection in the superconducting SRF linac to be accelerated up to 9 MeV.

IFMIF accelerators will take the beam up to full nominal energy in three ensuing stages of 14, 26 and 40 MeV in three corresponding superconducting cryomodules of design similar to LIPAc's. The validation of IFMIF accelerators is achieved by succeeding in operating at 9 MeV at its 1st cryomodule as explained in Section 4.1 'About feasibility of IFMIF accelerators'.

3.2.2. ELTL, the EVEDA Lithium Test Loop

ELTL, the EVEDA Lithium Test Loop was designed and constructed by JAEA in collaboration with Japanese industries [32]. Unfortunately, the Great East Japan Earthquake of March 2011 damaged the ELTL just few days after its successful commissioning; the operation was suspended for 16 months to allow for a careful inspection and repair. The validation phase could only start in September 2012 limiting the operational time and available budget. With its 5 m^3 of lithium, the ELTL is the largest world lithium loop to date; it has been operating in Oarai until October 2014. The main loop consists of 304 L AISI stainless steel 6-inch circulation pipes, a quench tank, an electromagnetic pump, an electromagnetic flow meter, a heat exchanger, cold traps and suitable liquid metal valves. The tanks are connected to an argon gas system and vacuum pumps in order to control pressure and to evacuate and expose the lithium jet to IFMIF operational vacuum values (10^{-3} Pa). Capable to operate at 250–350 °C range at up to 20 m/s flow rate, the validating target assembly comprised the flow straightener, the double contraction nozzle, and the R250 mm backplate as per Nitti shape [33]. Lithium flows into the double reducer nozzle, and the 25 mm thick Li target is formed with a reduced width (100 mm compared with the 260 mm of IFMIF) along the concave

Please cite this article as: J. Knaster et al., IFMIF, the European–Japanese efforts under the Broader Approach agreement towards a Li(d,xn) neutron source: Current status and future options, Nuclear Materials and Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.04.012

backplate. A window allowed the observation and measurement of the lithium flow in the validating target.

The validation of the operational flow conditions of IFMIF was achieved in the ELTL as explained in Section 4.2 'About long term stability of lithium flow at IFMIF nominal conditions'.

3.2.3. HFTM-DC, the High Flux Test Module Double Compartment

HFTM-DC, the High Flux Test Module Double Compartment designed and constructed in KIT is a full scale prototype of the HFTM of IFMIF, where only 2 compartments will be available (compared with the 4 directly irradiated compartments of the HFTM of IFMIF with three rigs each capable of housing a total ~1000 small specimens) [34]. Small specimens filled the capsules, thermalized with NaK, and with Thermocoax heaters, were instrumented with 17 thermocouples to observe the specified feasibility of the $\Delta T <$ +/−3% of 80% of specimen stack. The HFTM-DC was installed in the HELOKA-LP, the Helium Loop Karlsruhe – Low Pressure design to provide coolant at IFMIF's HFTM operational conditions (mass flow 12–120 g/s, inlet pressure 0.3–0.6 MPa, inlet temperature RT–250 °C) [35].

The validation of the temperature uniformity in small specimens inserted in the irradiated capsules during operation of IFMIF HFTM was achieved in the HFTM-DC installed in the HELOKA-LP as explained in Section 4.4 'About the uniformity of temperature in specimens during irradiation' and 4.5 'About the validity of data provided with small specimens'.

4. About the five major historical concerns of feasibility of IFMIF

The technological challenges of IFMIF have been overcome thanks to the research efforts that with continuity have been in place since the late 70 s. We have selected what can be considered the five major historical ones.

4.1. About feasibility of IFMIF accelerators

The operation of proton or deuteron accelerators at high currents in CW has been subject of intense developments efforts driven by its enormous technological interest due to the number of possible applications, among which fusion materials research has been one of the drivers of these endeavours since the 80s. The first attempt was framed by FMIT and it was unsuccessful; its 100 mA 2 MeV H_2^+ beam basically burnt its RFQ when ramping up the duty cycle [36]. The quality of the beam injected with a hot cathode approach was very poor demanding above double beam current to reach the H_2^+ wished input current (species fraction was below 50%). The understanding of beam physics under high space charge phenomena was insufficient to properly steer the beam.

The accelerator know-how has matured in all possible aspects since the times of FMIT conception in the 70s; today operating 125 mA deuteron beam at 40 MeV in CW with high availabilities seems feasible thanks to three main technological breakthroughs in accelerator technology [37]: (1) the ECR ion source for light ions developed in Chalk River Laboratories in the early 90s [25], (2) the RFQ operation of H^+ in CW with 100 mA demonstrated by LEDA in LANL in the late 90s [38], and (3) the growing maturity of superconducting resonators for light hadrons and low-β beams achieved in recent years [39].

The main difficulty to overcome in high current accelerators is related with space charge phenomena induced by non-gaussian interparticle repulsive forces leading to beam emittance growth, that vanishes in relativistic domain; this effect being stronger the lower the energy, the successful demonstration of 125 mA in CW at 9 MeV will validate the 40 MeV operational specified values of IFMIF [40]. LIPAc matches the design of IFMIF accelerators up to its 1st superconducting cryomodule (see Fig. 2).

The accelerating cavities chosen, 175 MHz Half-Wave Resonators (HWR), are suitable for high current applications with low-β beams, keeping most of the more widely used Quarter-Wave Resonators (QWR) virtues without their main drawback (the asymmetry of its shape, might cause an undesired beam steering). Experience with HWR with light hadrons is limited and difficulties related with microphonics or ponderomotive instabilities might be encountered [41], but should not become a showstopper.

4.2. About long term stability of lithium flow at IFMIF nominal conditions

The lithium screen serving as beam target presents two main functions: (1) react with the deuterons to generate a stable neutron flux in the forward direction and (2) dissipate the beam power in a continuous manner [42]. The impossibility for any known material to be directly bombarded by the deuteron flux for long periods constrains the lithium jet to operate with a free surface matching the beam footprint exposed to the vacuum conditions present in the beam line. Furthermore, the jet must also be thick enough to completely absorb the deuteron beam, but also to maximize the neutron flux and available high flux tested volume, thus the jet and its guiding structural back wall must be kept as thin as possible. The distance of the High Flux Test Module to the backplate wall has a strong influence on the neutron flux available for material testing; actually calculations show around 1% reduction per mm increased distance [43].

The long term operational conditions of the lithium target to ensure the absorption of the 2×5 MW deuteron beam are severe. The 25 mm thick lithium screen must flow at 15 m/s at a temperature of 250 °C exposed to beam vacuum (pressure specified on the lithium surface is 10^{-3} Pa) with thickness variation driven by potential waves in the surface within +/1 mm. These are considered safe operational conditions given that the range in lithium of deuterons at 40 MeV is of ~20 mm.

In September 2014, during 25 consecutive days the ELTL (see Fig. 3) was operating 24 h/day at 15 m/s flow speed and 250 °C [22]. The overlap of 12 measurements of the thickness spanned during this period showed the fulfilment of this challenging requirement (see Fig. 5) disregarding edge effects. Surface was measured with special developed contact and interferometric tools [44].

It is relevant to note that the feasibility of the yearly remote removal of the backplate wall without welding thanks to the bayonet concept developed in ENEA [45] will allow the achievement of the required tight operational tolerances between the backplate and the main irradiation modules (see Fig. 4).

4.3. About potential instabilities in the lithium screen induced by the 2 × 5 MW colliding deuteron beam

The beam – target interaction was subject of careful theoretical study for FMIT reaching analytical expressions for the maximum possible perturbances induced by beam momentum transfer or density gradients [46]. It is to be noted that beam power density in FMIT was x10 higher than the 1 GW/m^2 of IFMIF, and the perturbances depend strongly on this parameter [47]. In IFMIF, the heat is evacuated with the 15 m/s flowing liquid lithium exposed to the accelerator high vacuum in the target area. The average temperature rise in the liquid is ~50 °C due to the fast cross flow allowing a short exposure of 3.3 ms to the two concurrent 5 MW deuteron beams and high heat capacity of lithium. The heat removal system of the main lithium loop circulates the 97.5 l/s lithium flow from the exit of the beam target to a 1.2 m^3 quench

ARTICLE IN PRESS

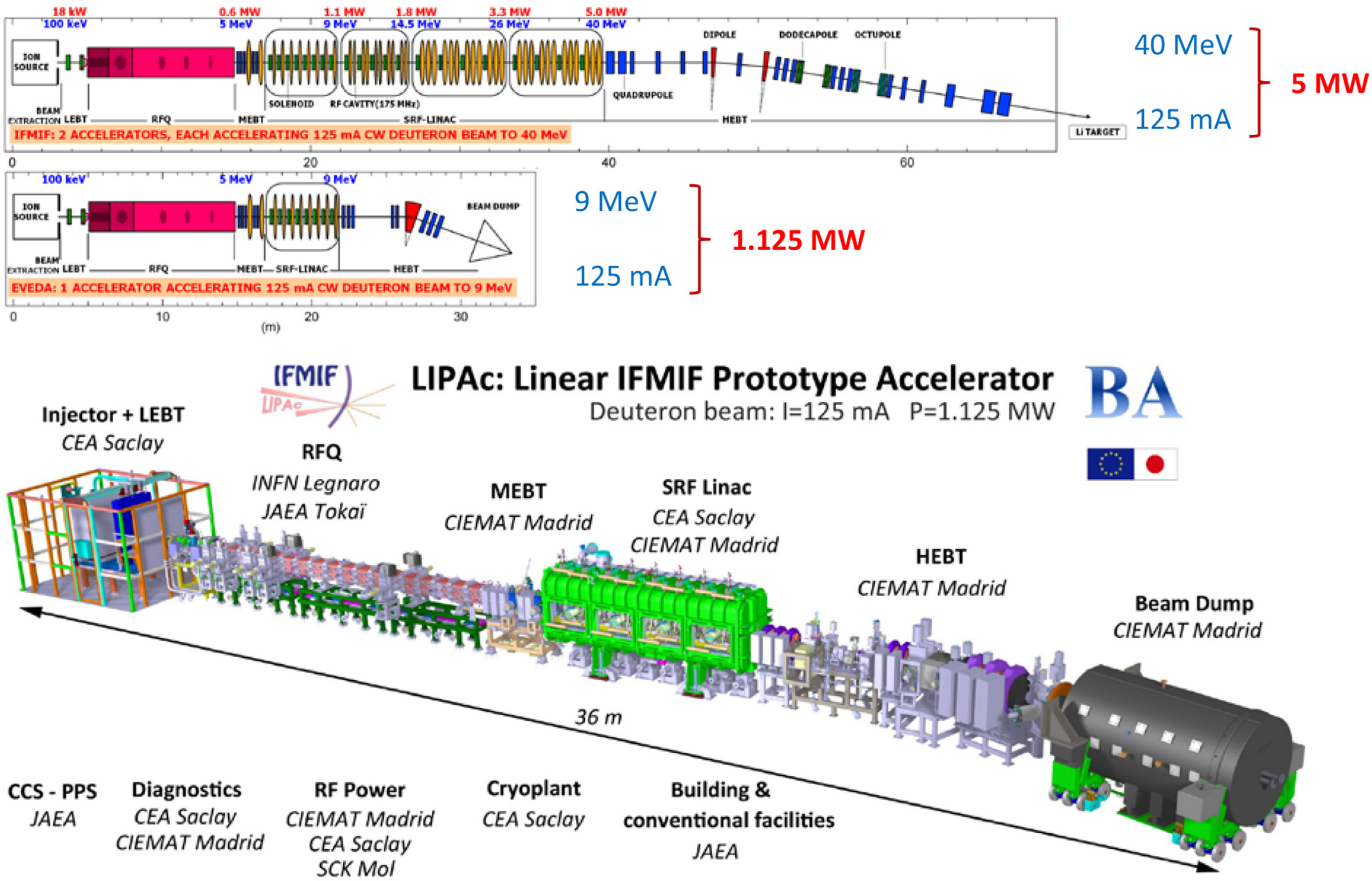

Fig. 2. Comparison of IFMIF accelerators and LIPAc, matched up to the 1st accelerator stage at 9 MeV and breakdown of the contribution for LIPAc, presently under installation and commissioning in the International Fusion Energy Research Center (IFERC) in Rokkasho (Japan), by European and Japanese laboratories.

Fig. 3. The ELTL upon its construction on November 2010 with the team involved [17].

tank, where it is slowed down and thermally homogenized before it flows to the electromagnetic pump. The lithium is then cooled to 250 250 °C by a serial of heat exchangers [48]. The temperature reached during operation in the lithium surface exposed to accelerator deuteron beam vacuum is 301 °C [42].

The flowing lithium is shaped and accelerated in proximity of the beam interaction region by the validated two-stage reducer nozzle to form the concave jet of 25 mm thickness channeled by the backplate wall. This last exhibits a radius of curvature of 250 mm in the beam footprint area, that builds a centrifugal acceleration of 90 g. This compression raises the boiling point of the flowing lithium guaranteeing stable liquid phase in Bragg's maximum heat absorption regions where the peak temperature reaches 687.5 K [42], in a region where the pressure induced by the concave shape of the backplate takes the saturation temperature T_s, i.e., the boiling temperature > 1000 °C (see Fig. 6). In turn, pressure waves amplitudes are damped down by centrifugal pressures (32 Pa maximum pressure driven by beam momentum transfer compared with the centrifugal pressures induced by the concave backwall plate in the order of kPa) [42].

Theoretically, a situation with lithium temperatures beyond saturation ones could cause dramatic instabilities in the lithium surface induced by boiling. Despite the design efforts in IFMIF not to enter into over-saturation scenarios, recent experiments framed by the Facility for Rare Isotope Beams (FRIB) with a 4.6 mA proton beam at 65 kV, with a beam Gaussian size $\sigma = 0.7$ mm colliding on a lithium jet confirmed the severe super saturation conditions that lithium can hold without nucleation due to its high surface tension [27]. The proton beam collided in a 14 mm wide and 10 μm thick lithium screen flowing at 50 m/s; the range being of < 2 μm thick released a power density of $> 10^3$ times higher than the 150 kW/cm^3 power densities of IFMIF in Bragg's peak regions [49].

4.4. About the uniformity of temperature in specimens during irradiation

The ΔT measured in the stack of small specimens instrumented in the HFTM prototype rigs assembled in the HFTM-DC tested in

Please cite this article as: J. Knaster et al., IFMIF, the European–Japanese efforts under the Broader Approach agreement towards a Li(d,xn) neutron source: Current status and future options, Nuclear Materials and Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.04.012

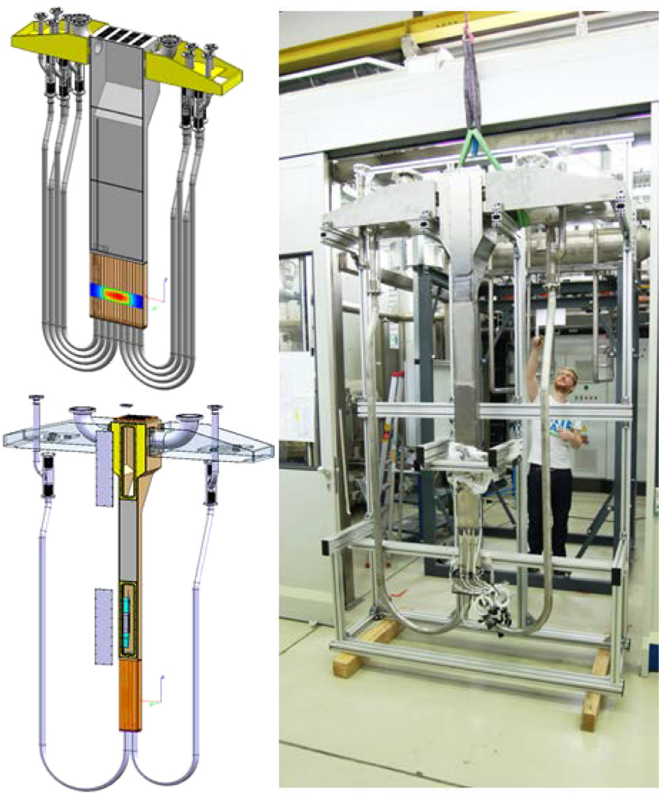

Fig. 4. Top left: 3D model of the HFTM of IFMIF with the beam footprint indicated. Bottom left: 3D model of the HFTM-DC, with two compartments instead of the 4 that IFMIF will have. Right: the full scale prototype of the HFTM-DC during its installation in the HELOKA-LP.

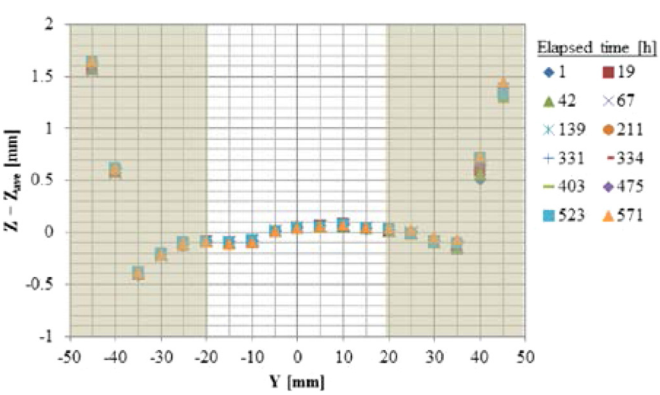

Fig. 5. Measurements of surface wave amplitudes along the target width of the ELTL where a stable shape within +/−0.5 mm, disregarding edge effects, can be observed during 25 days continuous operation.

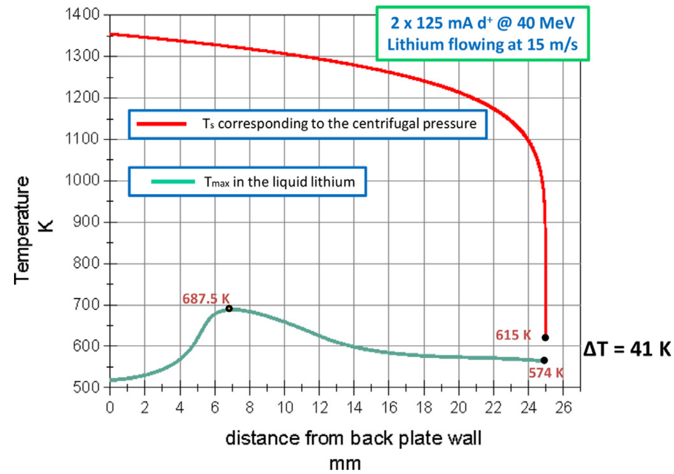

Fig. 6. Tmax envelope in the beam footprint under nominal conditions at different depths (in green) vs Ts corresponding to the centrifugal pressure in the flowing lithium (in red). 615 K corresponds to the beam line pressure of 0.001 Pa [42]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

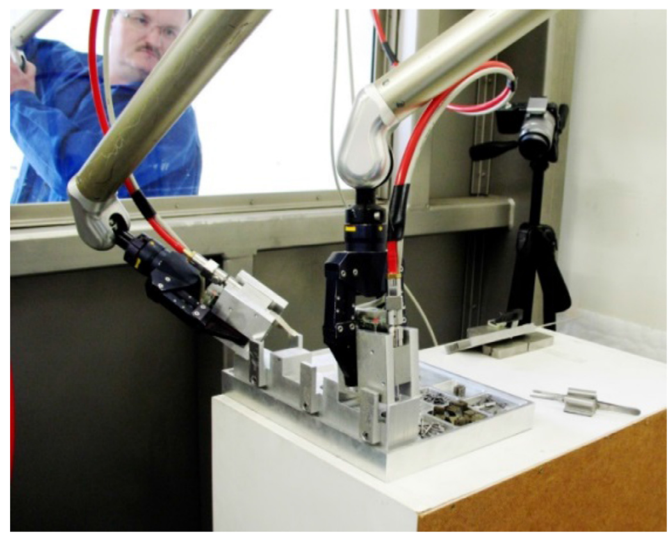

Fig. 7. Remote handling of specimens in hot cell environment with a special developed manipulator.

the HELOKA-LP (see Fig. 4) was within the target 3% in 97% of the capsule volume and successfully tested in the temperature range 250 °C<T <550°C [23]. In addition, three capsules filled with small specimens and thermalized with NaK were irradiated in the experimental reactor of SCK-CEN in Mol providing essential information towards an enhancement of the reliability of the design. The irradiation tests showed some hints of possible degradation of thermocouples and capsule heaters, but the appearance of a wetting leak of NaK from one capsule did not allow obtaining conclusive results. Reaching the wished reliability of the irradiated capsules during one future testing campaign needs further studies. The feasibility of the capsules remote NaK filling and specimens handling in a hot cell environment was also demonstrated (see Fig. 7). The potential corrosion suffered by RAFM steels exposed to NaK was also assessed thanks to the exposure of the specimens immersed in NaK up to 6 months at around 500 °C with no relevant impact beyond few μm depth measured traces of NaK and no observable degradation of mechanical properties.

4.5. About the validity of data provided with small specimens

The developments of small size specimens for fusion materials mechanical characterization started with FMIT in the early 80 s, framed by the US fusion program [50], and have continued uninterruptedly since then [51]. It is a technique widely used for many decades in fission materials research with typically 1 in. in major dimensions; though the availability of fission neutrons is not compromised, volumes are also to be optimized. Despite its obvious success in characterizing fission materials, an overall normalization is missing and suitable standards for small specimens are only available for Charpy [52] and fracture toughness estimation through the Master Curve method for ferritic steels [53]. Mechanical properties are intensive, thus they do not depend on the size of the test specimen if a sufficient number of grains across its dimensions is present.

Please cite this article as: J. Knaster et al., IFMIF, the European–Japanese efforts under the Broader Approach agreement towards a Li(d,xn) neutron source: Current status and future options, Nuclear Materials and Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.04.012

Under the EVEDA phase, JAEA, in collaboration with Japanese universities and NIFS, studied the small specimens for fracture toughness (in particular ductile to brittle transition temperature), fatigue at the relevant number of cycles of DEMO and ensuing fusion power plants, and fatigue crack growth. These were the properties considered to require further development, that in addition to tensile data, impact properties, creep and fatigue crack growth [54] would accomplish the mechanical characterization of a given material at the desired temperature following the irradiation > 20 dpa/y expected in IFMIF (with two sets of ~40 small specimens per capsule) (see Fig. 8).

Fatigue: The tests with round-bar type specimens having diameters between 1 and 10 mm showed no size effects (the hourglass flat specimens showed some shortening of life compared with full size standard specimens due to stress concentrations enhancing crack initiation) [55].

Fracture toughness: specimens ¼ Compact Tension (CT) specimens were tested. The master curve defined in ASTM E1921 developed for ferritic steels pressure vessels of fission reactors $K_{Jc}=30+70e^{0.019(T-To)}$, where K_{Jc} is the average fracture toughness and To the test reference temperature at which the median of the K_{Jc} distribution from 1″ size specimens will equal 100 MPa(m)$^{0.5}$, did not work for the fusion reactors ferritic martensitic steel F82H. However, a modified version $K_{Jc}=20+70e^{0.05(T-To)}$ worked [56].

Crack growth rate: Tests using H^+ charging technique were performed to examine the effect of hydrogen on crack growth in F82H steel. A small-size specimen ¼ CT with wedge opening load steel was developed. The estimated crack growth rate at 30 MPa(m)$^{0.5}$ in water at 288 °C provided suitable data that successful validated the method [57]. However, slight differences in the results from 1 CT standard size (in particular 0.4 CT and 0.6 CT) were obtained from previous results.

The shape defined for the three properties selected showed conclusive results [54]. No further iterations on this respect are needed, however a Round-Robin exercise between various laboratories will be still required towards a standardization. The mechanical properties provided by IFMIF will be undoubtedly accepted by the design engineers for the accomplishment of the design of DEMO reactor; however the corresponding licensing bodies will inquire about their validity. Fission power plants are in operation without standards backing their 1″ small specimens used, but fusion neutrons are significantly more degrading and IFMIF will be the only fusion relevant source available. An efficient use of its operational time is essential, standards or IAEA guidelines for all the small specimens of the Test Matrix designed and defined to fit in IFMIF irradiation capsules must be timely accomplished before the start of operation of any Li(d,xn) fusion relevant neutron source.

5. Perspectives for a Li(d,xn) fusion relevant neutron source

The conceptual design of IFMIF suited the irradiation needs framed by the construction of DEMO, which has evolved towards a lower fusion power since the 90s when IFMIF performance was conceived. Therefore, IFMIF's original specified irradiation levels > 20 dpa/year on the structural materials specimens can be reduced accordingly. Finding suitable parameters of the facility to reach needed neutron fluxes and spectrum is straightforward given the excellent understanding of the d-Li nuclear reactions cross sections up to 50 MeV [58], the design of IFMIF proposed [15] and the validated activities under EVEDA phase [17]. An optimal use of the accelerators design as per the IFMIF design would imply deuteron energies at either 9, 14, 26 or 40 MeV. The neutron spectrum broad peak, the Bragg peak and the relative α-particle generation for such deuteron energies are shown in Table 1.

A careful assessment of the optimal choice of parameters have been carried out [43]. Furthermore, the shallower the range is,

Table 1
Neutron spectrum broad peak, Bragg peak of deuterons in lithium and relative cross section for α-particle generation for potential available deuteron beam energies.

Deuteron energy MeV	n spectrum broad peak MeV	Bragg peak mm	Relative cross section $^{56}Fe(n,\alpha)^{53}Cr$
9	~4	1	2.5×10^{-3}
14	~6	3	9×10^{-3}
26	~10	7	0.5
40	~15	19	1

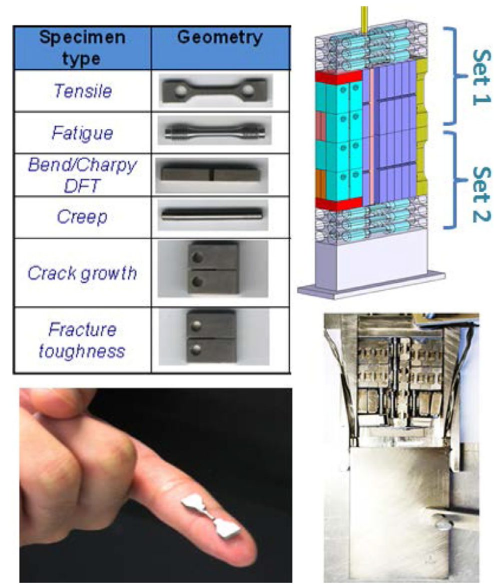

Fig. 8. Small specimens defined for the Test Matrix of IFMIF that fit in a number of ~80 in each irradiation capsule (2 sets of needed specimens for the full characterization of a given material at the chosen irradiation temperature) [17,19,23,54].

the higher volumetric power density deposition of the deuteron beam in the lithium screen becomes, which would induce a severe impact on the design of the lithium loop and beam target specifications. Therefore, the optimal choice to adapt to the reduced fusion power of DEMO is to consider a Li(d,xn) fusion relevant neutron source with one only accelerator at IFMIF's specifications, i.e., 125 mA in CW at 40 MeV. These beam characteristics would maximize the neutron flux and the validated hardware during this EVEDA phase (in particular the accelerator and lithium loop) would be directly usable.

World fusion roadmaps foresee the start of the construction of DEMO in the 30 s, therefore data on structural materials degradation is needed the 2nd half of next decade. Following the achievements of this EVEDA phase, ideas towards the construction of the simplified version of IFMIF with one only accelerator line are maturing in Japan with A-FNS [59] and Europe with DONES [60] (see Fig. 9). The cost of construction, operation and decommissioning of IFMIF has been carefully assessed, backed with the known cost of prototypes and support of engineering companies in Japan and Europe coinciding consistently with all previous estimations of former phases. Within less than 10 years from the project approval and around 1 billion euros, 14 MeV neutrons with suitable fluxes would be available for fusion materials testing. Thanks to the successful validation activities during this on-going EVEDA phase, no technical showstoppers are present that could jeopardize this program. Details on construction schedule and cost have been published [15]. The decision of constructing the simplified version of IFMIF, would have a significant impact on cost reduction and faster schedule (around 1 year anticipation). In particular, A-FNS will

Please cite this article as: J. Knaster et al., IFMIF, the European–Japanese efforts under the Broader Approach agreement towards a Li(d,xn) neutron source: Current status and future options, Nuclear Materials and Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.04.012

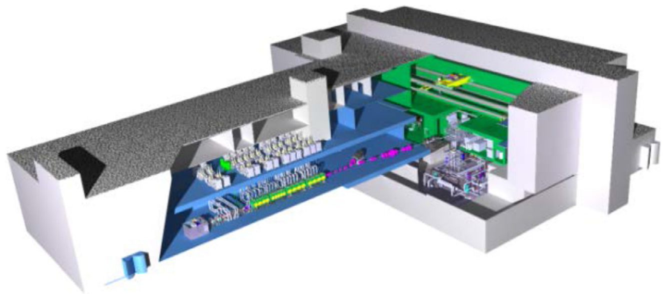

Fig. 9. Artistic bird's eye view of the DONES [60].

profit from LIPAc facilities already available in the IFERC site of Rokkasho.

5. Conclusions

Forty years of worldwide research endeavors towards the demonstration of the technological feasibility of a fusion relevant neutron source are coming to an end [8,15]. The EVEDA phase of IFMIF has accomplished successfully the Target and Test facility validation activities. Main challenges have been overcome and doubts about the technical feasibility are vanishing. The efforts of FMIT in the 80s have been essential for this success; the lessons learnt were crucial, not only for fusion materials research present maturity, but also for modern Accelerator Driven Systems (ADS) and liquid metals technologies.

The ELTL of Oarai has demonstrated the feasibility of the long term stability of the 250 °C lithium flow along the R250 mm concave backplate with the two staged Nitti profile [33] and the liquid target thickness of 25 mm within +/−1 mm at the required 15 m/s [22]. It is also worth mentioning that the yearly easy replacement of the backplate in the absence of welds has been successfully demonstrated in Brasimone with a full scale prototype [45].

The HFTM-DC full scale prototype tested in the HELOKA-LP of KIT has demonstrated the feasibility to reach the uniformity of the small specimens, capable to characterize a given material at the wished temperature within 250 °C < T < 550 °C, within +/−3% during irradiation [23]. In turn, the shape of small specimens to be housed in the irradiation rigs is defined [50,54], though further international efforts would be required, including Round Robin exercises, towards their standardization.

The 125 mA CW deuteron beam at 40 MeV will be validated with the 125 mA CW deuteron beam at 9 MeV designed and constructed in Europe and under installation and commissioning in the IFERC site of Rokkasho [24,40]. This activity remains as the only pending one to overcome all historical doubts about the feasibility of a Li(d,xn) source. The challenges of running in CW such a high current beam are not underestimated, but accelerator technologies are today mature for such operational characteristics [37]. The expected performance of LIPAc aims at unique performances of accelerator technologies, difficulties might still appear during the on-going validation activities of IFMIF's accelerators, but solutions to potential problems arisen could be found timely for a Li(d,xn) neutron source. It is to be noted that IFMIF's accelerator features are equivalent to other ADS planned around the world for next decade [61].

The times for a Li(d,xn) fusion relevant neutron source have arrived. Other technical ideas under study, either accelerator driven based on rotatable solid targets [62] or based on fusion reactions [63,64], are less mature, and would demand intensive developments to demonstrate their feasibility. Furthermore, they would face serious structural materials degradation to reach the needed fluences; a difficulty that IFMIF will overcome thanks to its modular design and remote maintenance careful studies accomplished under this EVEDA phase [15,17].

Fusion research devices up to now, including a fusion reactor like ITER, could be designed and licensed with the available materials database obtained without neutrons at suitable energy and fluxes; unfortunately this will not be the case for next generation of fusion reactors. Our technology is mature to construct a Li(d,xn) fusion relevant neutron source after four decades of international endeavours. The cost is marginal compared to that of a fusion reactor. The schedule breakdown is clearly developed, with no technical showstopper that could jeopardize its fulfillment. The necessity of a fusion relevant neutron source is indisputable. Thanks to the successful validation prototypes constructed in the EVEDA phase [17,22,23,24] and the released engineering design of IFMIF [15], that is being easily adapted to A-FNS [59,65] and DONES [43,60], we trust to count with 14 MeV neutrons next decade for fusion materials testing.

References

[1] M.R. Gilbert, et al., Nucl. Fusion (2012) 52.
[2] M.I. Norgett, et al., Nucl. Eng. Des. 33 (1975) 50–54.
[3] M.R. Gilbert, et al., J. Nucl. Mater. 442 (2013) S755–S760.
[4] P. Vladimirov, A. Moeslang, J. Nucl. Mater. 329–333 (2004) 233–237.
[5] S. Zinkle, A. Moeslang, Fusion Eng. Des. 88 (2013) 472–482 Issues 6–8.
[6] R. Serber, Phys. Rev. 72 (11) (1947) 1008–1016.
[7] A.N. Goland, et al., IEEE Trans. Nucl. Sci. (3) (June 1975).
[8] P. Grand, et al., Nucl. Technol. 29 (1976) 327.
[9] E.W. Pottmeyer Jr., J. Nucl. Mater. (1979) 463–465.
[10] J.E. Leis et al., (Ed.), Report on the international Fusion Irradiation Facility, IEA Workshop at San Diego, Calf., USA., February, 1989
[11] T. Kondo, et al., J. Fusion Energy 8 (1989) 229–235.
[12] G.L. Varsamis, et al., Nucl. Sci. Eng. 106 (1990) 160.
[13] M. Martone, (Ed.), IFMIF - Conceptual Design Activity Final Report, IFMIF-CDA-Team, ENEA-RT/ERG/FUS/9611-Report, December 1996.
[14] IFMIF International Team, "IFMIF Comprehensive Design Report", IEA on-line publication, (2004) (also available on electronic format upon request at ifmif@ifmif.org).
[15] J. Knaster, et al., Nucl. Fusion 55 (2015) 086003.
[16] J. Knaster, et al., J. Nucl. Mater. 453 (2014) 115–119.
[17] J. Knaster, et al., Nucl. Fusion 53 (2013) 116001.
[18] R. Heidinger, et al., Fusion Eng. Des. 88 (2013) 631–634.
[19] P. Garin, et al., Fusion Eng. Des. 86 (2011) 611–614 6-8.
[20] M. Perez, et al., Fusion Eng. Des. 96–97 (2015) 325–328.
[21] A. Aiello, et al., Fusion Eng. Des. 88 (2013) 769–773 6-8.
[22] H. Kondo, et al., Fusion Eng. Des. 96–97 (2015) 117–122.
[23] F. Arbeiter, et al., Nucl. Mater. Energy (2016).
[24] P. Cara et al., The linear IFMIF prototype accelerator (LIPAc) design development under the European-Japanese collaboration, Proceedings of IPAC 2016 Busan, www.jacow.org.
[25] G.M. Arbique et al., Multi-beamlet injection to the RFQ1 accelerator - a comparison of ECR and Duopigatron proton sources, PAC 1991, San Francisco, www.jacow.org.
[26] R. Gobin et al., Saclay high intensity light ion source status, Proceedings of EPAC 2002, Paris, www.jacow.org.
[27] M. Comunian et al., Beam dynamics redesign of IFMIF/EVEDA RFQ for a larger input beam acceptance, Proceedings of IPAC 2011, San Sebastian, www.jacow.org.
[28] A. Pisent et al., "IFMIF-EVEDA RFQ design", Proceedings of EPAC 2008, Genova, www.jacow.org.
[29] A. Pisent et al., The TRASCO-SPES RFQ, Proceedings of LINAC 2004, Lübeck, www.jacow.org.
[30] A. Palmieri et al., The IFMIF RFQ real scale aluminium model: RF measurements and tuning, Proceedings of IPAC 2010, Kyoto, www.jacow.org.
[31] A. Palmieri, Preserving beam quality in long RFQs on the RF side: voltage stabilization and tuning, 54th ICFA Advanced Beam Dynamics Workshop on High-Intensity, High Brightness and High Power Hadron Beams, Lansing, www.jacow.org.
[32] H. Kondo, et al., Fusion Eng. Des. 87 (2012) 418.
[33] S. Nitti, Termofluidodinamica di un getto di litio (Ph.D. Thesis), Università di Bologna, Modena, Parma e Trieste, 2014 http://amsdottorato.cib.unibo.it/2793/.
[34] F. Arbeiter et al., Fusion Eng. Des. (2012) 87 1506.
[35] G. Schlindwein, et al., Fusion Eng. Des. 87 (2012) 737–741.
[36] W.D. Cornelius, Nucl. Instrum. Methods Phys. Res. B10/l1 (1985) 859–863.
[37] J. Knaster, Y. Okumura, Rev. Accelerator Sci. Technol. 8 (2015) 115–142.
[38] L.M. Young et al., High power operations of LEDA, LINAC 2000, Monterey, www.jacow.org.
[39] M. Kelly, Rev. Accel. Sci. Technol. 5 (2012) 185.
[40] F. Scantamburlo, et al., in: Proceedings of IPAC, Dresden, 2014.
[41] Z. Gao, et al., Nucl. Instrum. Methods Phys. Res. A 767 (2014) 212–217.
[42] J. Knaster, et al., Fusion Eng. Des. 89 (2014) 1709–1716.

Please cite this article as: J. Knaster et al., IFMIF, the European–Japanese efforts under the Broader Approach agreement towards a Li(d,xn) neutron source: Current status and future options, Nuclear Materials and Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.04.012

ARTICLE IN PRESS

[43] F. Mota, et al., Nucl. Fusion 55 (12) (2015) article id. 123024.
[44] T. Kanemura, et al., Fusion Eng. Des. 89 (2014) 1688–1693.
[45] G. Micchiche et al., Design, manufacturing and testing of a fast disconnecting system for the European target assembly concept of IFMIF, 25th Symposium on Fusion Engineering (2013) San Francisco.
[46] J.A. Hassberger, Preliminary Assessment of Interactions Between the FMIT Deuteron Beam and Liquid Lithium Target, HEDL-TME 82--28, Hanford Engineering Development Laboratory Richland, WA, 1983, March
[47] A. Hassanein, J. Nucl. Mater. 233--237 (1996) 1547–1551.
[48] F. Nitti, et al., Fusion Eng. Des. 100 (2015) 425–430.
[49] Y. Momozaki, et al., J. Radioanal. Nucl. Chem. 305 (3) (2015) 843–849.
[50] G.E. Lucas, J. Nucl. Mater. 117 (1983) 327–339.
[51] G.E. Lucas, et al., J. Nucl. Mater. 367–370 (2007) 1549–1556.
[52] ASTM E2248, Standard Test Method for Impact Testing of Miniaturized Charpy V-Notch Specimens.
[53] ASTM E. 1921, Standard Test Method for Determination of Reference Temperature, To, for Ferritic Steels in the Transition Range.
[54] E. Wakai, et al., Fusion Eng. Des. 98–99 (2015) 2089–2093.
[55] S. Nogami, et al., J. Nucl. Mater. 441 (2013) 125–132.
[56] B.J. Kim, et al., J. Nucl. Mater 442 (2013) S38–S42.
[57] Y. Ito, J. Plasma Fusion Res. 11 (2015).
[58] U. Fischer, et al., J. Nucl. Mater 367--370 (2007) 1531–1536.
[59] T. Nishitani et al., DEMO activities in the broader approach and beyond, Fusion Sci. Technol. 66 July/Aug 2014.
[60] A. Ibarra et al., A stepped approach from IFMIF/EVEDA toward IFMIF, Fusion Sci. Technol. 66 July/Aug 2014.
[61] J. Wei, The very high intensity future, Proceedings of IPAC 2014, Dresde, www.jacow.org.
[62] E. Surrey, et al., Fusion Eng. Des. 89 (2014) 2108–2113.
[63] M.A. Abdou, Fusion Eng. Des. 27 (1995) 111–153.
[64] G.M. Voss, et al., Fusion Eng. Des. 83 (2008) 1648–1653.
[65] T. Yamanishi, et al., Fusion Eng. Des. (2016).

Please cite this article as: J. Knaster et al., IFMIF, the European–Japanese efforts under the Broader Approach agreement towards a Li(d,xn) neutron source: Current status and future options, Nuclear Materials and Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.04.012