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Materials subjected to fast neutron irradiation/Matériaux soumis à irradiation par neutrons rapides

# IFMIF: the intense neutron source to qualify materials for fusion reactors

Anton Möslang

*Forschungszentrum Karlsruhe, Institute of Materials Research I, P.O. Box 3640, 76021 Karlsruhe, Germany*

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**Abstract**

The International Fusion Materials Irradiation Facility, IFMIF, has become a major element in international road maps to fusion power and in the Japanese–European 'ITER Broader Approach' agreement. IFMIF is an intense neutron source driven by two 40 MeV deuteron beams striking a joint lithium target producing neutrons with a peak around 14 MeV. In the high flux test module (20–55 dpa/full power year) 12 rigs with individual temperatures allow the simultaneous irradiation of about 1000 qualified specimens. Analyses on the basis of advanced codes and nuclear data libraries have shown that IFMIF offers favorable conditions both for structural and functional materials. After a brief description of IFMIF, an overview on the irradiation conditions is given with special emphasis on users' attractiveness, neutronics, gas production to damage ratios, recoil energy spectra, and possible specimen test matrices. ***To cite this article: A. Möslang, C. R. Physique 9 (2008).***


**Résumé**

**L'IFMIF : source intense de neutrons pour la qualification des matériaux pour réacteur de fusion.** L'installation IFMIF (International Fusion Materials Irradiation Facility) est un élément majeur du développement international de la production d'énergie à partir de la fusion ainsi que de l'accord sur l'approche élargie entre L'Union Européenne et le Japon dans le cadre du projet ITER (International Thermonuclear Experimental Reactor). IFMIF est une source intense de neutrons qui sont produits, avec un pic de flux autour de 14 MeV, par deux faisceaux de deutons de 40 MeV bombardant une cible de lithium. Dans le module de tests à haut flux (20–55 dpa/an à pleine puissance) douze dispositifs à températures diférentes permettront d'irradier environ 1000 échantillons qualifiés. Les analyses sur la base des versions les plus récentes des codes et bibliothèques de données nucléaires ont montré qu'IFMIF offrira des conditions d'irradiation qui conviennent aux matériaux structuraux et fonctionnels. Après une brève description d'IFMIF, on donne une revue des conditions d'irradiation d'intérêt pour les utilisateurs : le spectre de neutrons, la production de gaz de transmutation en fonction du dommage, les spectres d'énergie des PKA (Primary Knocked-on Atoms) et la possibilité de différentes matrices de tests. ***Pour citer cet article : A. Möslang, C. R. Physique 9 (2008).***


*Keywords:* IFMIF; Neutron source; Irradiation damage; Helium embrittlement; Recoil energy spectra; Neutron spectra; Fusion materials

*Mots-clés :* IFMIF ; Source de neutrons ; Endommagement par rayonnement ; Spectres d'énergie de recul ; Spectres de neutrons ; Matériaux de fusion

*E-mail address:* anton.moeslang@imf.fzk.de.

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## 1. Introduction

In order to demonstrate the scientific and technical feasibility, as well as economic and environmental attractiveness of magnetic fusion energy within about 35 years, road maps to fusion power have been elaborated in Europe, Japan and US with many common features [1–3]. Major elements of the European 'reference' fusion development scenario include the essential facilities: the International Tokamak Experimental Reactor (ITER) for burning plasma physics, the d-Li accelerator based International Fusion Materials Irradiation Facility (IFMIF) for fusion specific materials testing, and a Fusion Demonstration Reactor (DEMO) for the qualification of components and processes as a basis for competitive electrical power generation. Fast track scenarios like the Fast Track Experts Meeting convened by the president of the EU Research council and chaired by Prof. D. King [4], or the FESAC Fusion Development Path Panel chaired by Prof. R. Hazeltine [5] confirmed again that material qualification and the related irradiations in IFMIF are on a critical path.

While for ITER or first generation fission reactor designs the maximum damage level achieved by core structural materials is of the order of a few displacements per atom (dpa), the structural materials of DEMO reactors will operate up to damage levels approaching 150–200 dpa. Such damage levels are achievable in some material test reactors available today. However, as fusion neutrons will generate, besides dpa damage, also high production rates of He and hydrogen isotopes, enhancing sensitively irradiation embrittlement, an intense neutron source with a fusion specific spectrum is needed to generate a reliable materials database. For this purpose, the International Fusion Material Irradiation Facility, IFMIF, has been tailor-designed. IFMIF is the world's most powerful accelerator-based neutron source project. IFMIF is also a major element of the 'Broader Approach' that has been signed by the European and Japanese governments. Within this Broader Approach, IFMIF entered in 2007 a 6 years 'Engineering Validation Engineering Design Activity' phase to allow a subsequent start of construction at the end of 2012.

After a justification of IFMIF, a description of its mission and its implementation in international road maps is presented. The major part of this chapter is dedicated to explaining the suitability of IFMIF and its indispensable role in establishing a fusion materials database for DEMO reactors. Major advances made during the past few years in test module design and irradiation performance are highlighted in the light of the users' attractiveness.

## 2. Strategies towards a fusion materials database

It is recognized worldwide that the effective development of materials for the first wall, blanket and divertor which are capable of withstanding the high neutron and heat fluxes for up to 10–15 $MWy/m^2$, corresponding to a component lifetime of several years, is a critical requirement on the path to fusion power. Testing of materials and blanket/divertor concepts in a fusion relevant environment is a necessary step in the design of DEMO. At present, there is no appropriate irradiation test facility which can adequately simulate the fusion environment, even though this need has been recognized for decades [6].

During the past years, the major elements of formally developed global fusion strategy scenarios have become very similar in the different parties. Fig. 1 shows an example of an updated related road map [3,7]. The criteria mentioned have led to a worldwide concentration of the R&D efforts towards a few material classes that are presently being developed in a largely coordinated manner under the umbrella of an IEA implementing agreement [8]. Materials for fusion DEMO reactors can roughly be subdivided into (i) structural materials and (ii) functional materials like neutron multipliers (e.g. Beryllium), tritium breeding ceramics (e.g. $Li_4SiO_4$, $Li_2TiO_3$) and diagnostics. Since the early 1990s, substantial progress has been made in combining computational science and code developments in the R&D fields of neutronics and nuclear activation libraries with the targeted and successful development of low or reduced activation materials. This very fruitful international enterprise resulted within Europe, Japan, US and Russia in a focussed development of four classes of structural materials. These are mainly the reduced activation ferritic martensitic (RAFM) steels, including nano-dispersion strengthened variants, the vanadium alloys, the SiC fibre reinforced ceramic SiC composites, and tungsten based alloys for divertors.

Worldwide efforts are presently underway to characterize and pre-qualify these materials mostly in existing fission reactors and charged particle accelerators including spallation sources. As neutrons have much higher ranges compared to charged particles of a similar energy, fission reactor irradiations lead to an almost range-independent damage morphology, and therefore are most suitable for the study of the impact of displacement damage on mechanical properties of macroscopic specimens.

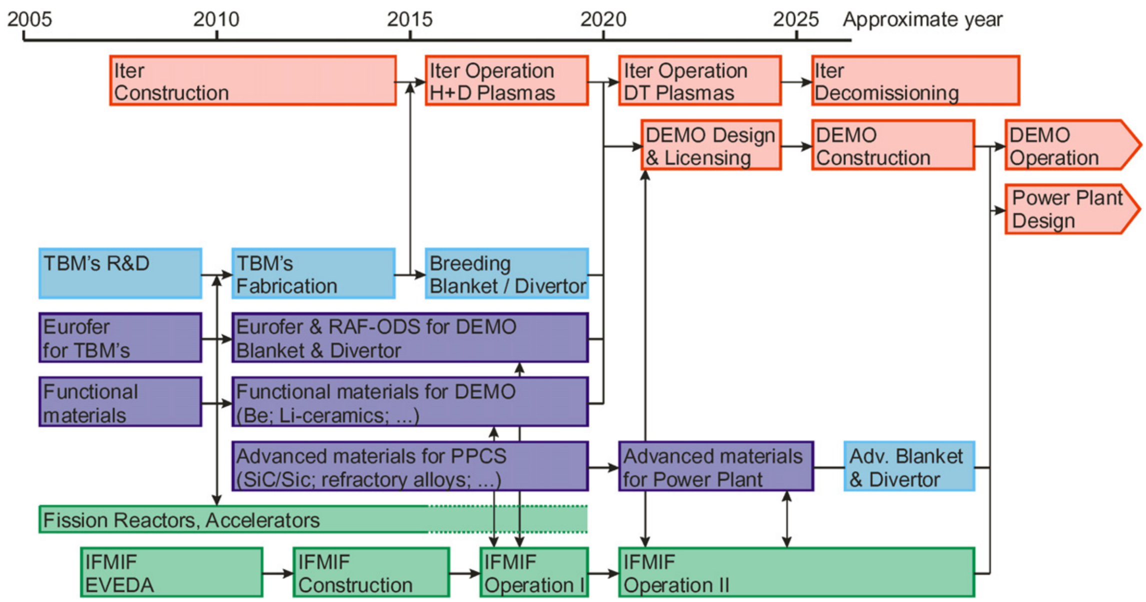


Fig. 1. Updated cross-linking between the materials development and the fusion road map according to [3] and [7].

Fig. 1. Calendriers actuels comparés du développement des matériaux et des étapes du développement d'un réacteur de fusion d'après [3] et [7].

On the other hand, particle accelerators are usually limited in range to a few microns but are very valuable and flexible tools to investigate certain aspects of irradiation damage on microstructure more systematically, like the helium and hydrogen interaction with defects, He/dpa ratio and implantation rate dependencies, or effects coming from different recoil energy spectra. Charged particle implantations or irradiations involve dual or triple ion beam facilities in which a heavy ion beam (e.g. Ni or Fe) is used to produce displacement damage while He and/or H are simultaneously implanted at the desired rate using the additional beam lines. Such irradiations are important to screen new material compositions, to pre-qualify candidate materials or to validate experimentally the modeling activities. Prominent examples for new European irradiation sources under construction are the high performance material testing reactor 'Jules Horowitz', and the accelerator based dual beam facility 'Jannus', as described in separate articles in this volume. Irradiation at spallation neutron sources provides an opportunity to investigate helium and hydrogen production at levels even higher than under DT fusion conditions. For example, the spallation neutron sources at the Los Alamos National Laboratory and the Paul Scherrer Institute in Switzerland have been used for this purpose. However, in addition to the excessively high He and H levels, the very-high energy spallation neutron spectrum leads to non-negligible production of a range of solid transmutation products that are quite different from DT fusion conditions.

Despite of the existing and forthcoming fission reactor and spallation neutron sources and accelerator based charged particle sources, an intense neutron source with a fusion relevant spectrum is, worldwide, considered to be indispensable. Otherwise, only certain aspects of the fusion specific irradiation behavior can be tested or simulated. However, even if IFMIF is available in due course, the neutron sources just described are needed to pre-qualify materials, as IFMIF has a limited irradiation volume, despite its ability to irradiate about 1000 qualified specimens simultaneously. IFMIF should start operation in the same time frame as ITER, to guarantee a timely implementation of its database into the DEMO design and licensing procedure. The interaction between major elements of the fusion road map in Fig. 1 is indicated with arrows.

## 3. Mission and users' requirements

To test and fully qualify candidate materials for high fluence service in DEMO, a high flux source of high energy neutrons has to be built and operated. No currently available facility can fill this need. The test facilities suitable for such purposes have been explored through a number of international studies and workshops over the past three decades. Under the assumption that such a facility should be available early this century, a neutron source based on the D-Li stripping reaction has been selected by high ranking international advisory boards as the basic concept for the International Fusion Materials Irradiation Facility (IFMIF) [12,9]. The technology of the accelerator-based D-Li neutron source concept was first developed by the Fusion Materials Irradiation Test (FMIT) Project (1978–1984) [10,11]. Major worldwide advances in accelerator technology over the past decade have further added to the credibility of this approach.

The primary mission which an IFMIF neutron source will play in fusion materials development and testing can be summarized as follows [12,13]:

(i) Generation of the major elements of a materials database for the design, construction, licensing and safe operation of a DEMO. This will be achieved through testing and verifying materials' performance under neutron irradiation that simulates fusion reactor service up to the full lifetime of anticipated service in DEMO. Medium fluence irradiation tests of high heat flux materials for divertors, ceramic materials for a variety of uses, and functional tests of small blanket elements (complementing the tests of blanket test modules in ITER), are also considered important uses of such a facility.
(ii) Calibration and validation of data generated by fission reactor irradiations and other simulation experiments with light or heavy ions.
(iii) Advanced material development for commercial reactors.
(iv) Functional testing of small blanket and divertor component elements or mock-ups.

The requirements for an intense neutron source and the resulting specifications have been discussed at international IEA workshops and re-examined before the final decision for a D-Li stripping source (IFMIF) has been made. These requirements include (i) neutron flux/volume relation equivalent to 2 $MW/m^2$ in 0.5 L volume (1 $MW/m^2$, $4.5 \times 10^{17}\ n/m^2\,s$; $E = 14$ MeV, $3 \times 10^{-7}$ dpa/s for Fe); (ii) close simulation of the first wall neutron spectrum with the quantitative criteria primary recoil spectrum (PKA) and transmutation reactions (He, H); (iii) DEMO-relevant fluences of 150 $dpa_{NRT}$ in a few years; (iv) neutron flux gradients below 10% over the gage volume; (v) a machine availability of at least 70%; (vi) a quasi continuous operation with respect to the time structure; and (vii) good accessibility of irradiation volume for experimentation and instrumentation. Further requirements include: (i) flexibility in the selection of materials, irradiation rigs and temperatures; (ii) the possibility for fully instrumented in situ experiments; and (iii) operational as well as maintenance requirements.

## 4. The International Fusion Materials Irradiation Facility – IFMIF

### *4.1. IFMIF overview*

Fusion material irradiation experiments require stable, continuous irradiation with high availability. IFMIF will achieve this using two 40 MeV deuteron steady state linear accelerators, each with 125 mA beam current striking a single thick, flowing Li target under a 20 degree impinging angle, thus providing an intense neutron flux of about $10^{18}\ n/m^2\,s$ with a broad peak near 14 MeV. As the neutrons produced within the common beam footprint of $5 \times 20\ cm^2$ are mainly collided in forward direction, the test modules housing the specimens to be irradiated are positioned immediately adjacent to the Li target. In the high flux test module 20–50 dpa/full power year will be achieved in about 1000 qualified specimens. These specimens are assembled in 12 individual capsules that are fully instrumented and independently temperature controlled. Long-time operation achieves a total facility availability of 70% or more to reach accumulated damage levels of 100 dpa within a few years of operation. IFMIF will be, with a beam power of 10 MW on a single target, the world's most powerful accelerator-driven neutron source.

In the framework of the Broader Approach Bilateral Agreement between European Union and Japan, a number of important projects of common interest for the rapid realization of fusion energy have been agreed. Among these projects, the Engineering Validation and Engineering Design Activities (EVEDA) phase of the International Fusion Materials Irradiation Facility (IFMIF) was included. The objective of the EVEDA phase of IFMIF is to perform reliability tests of key components and to provide a final system design to be able to start IFMIF component manufacture as soon as the construction decision is made.

A schematic, bird's-eye view of IFMIF is given in Fig. 2. IFMIF consists of three major systems: the Accelerator Facility; the Target Facility; and the Test Facilities, including the Post-Irradiation Examination (PIE) facilities. IFMIF

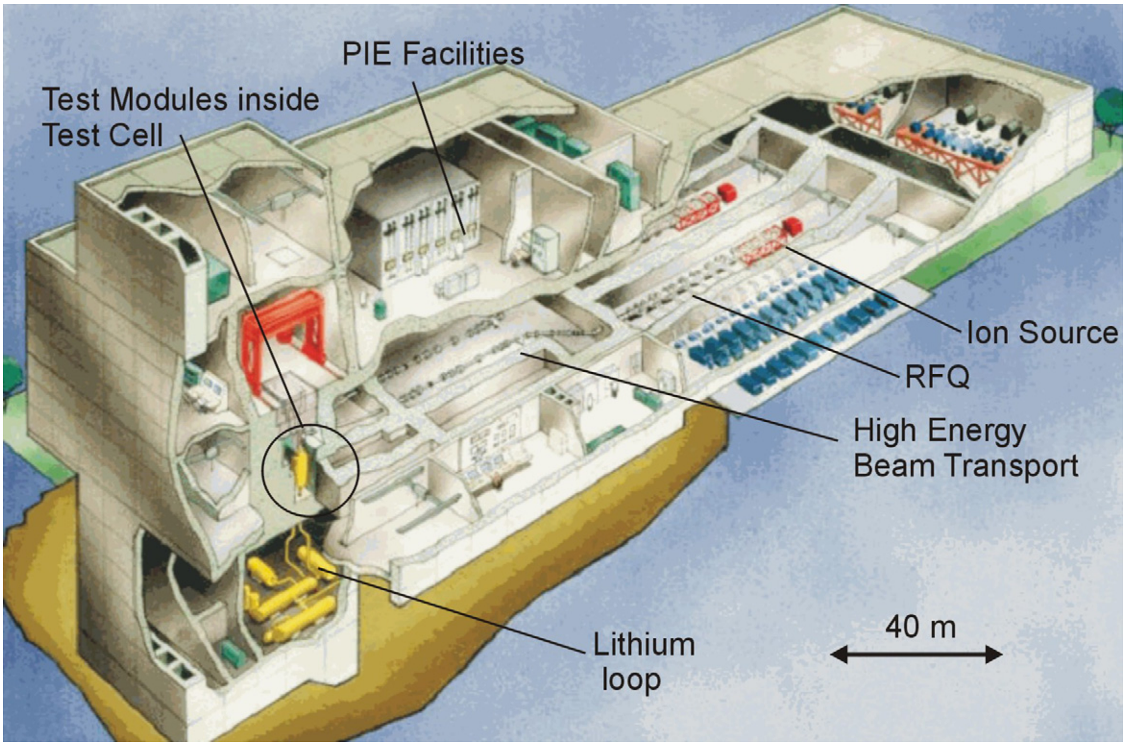


Fig. 2. Overview of the IFMIF design, with major subsystems identified. The lithium target and all test modules are located in a common test cell. Post-Irradiation Examination (PIE) facilities are provided to examine irradiated specimens on site. Maximum availability is achieved by using two independent accelerators.

Fig. 2. Vue générale de la conception d'IFMIF, avec les principaux sous-systèmes. La cible en lithium et tous les modules de tests sont dans une cellule commune. Les dispositifs pour les examens post-irradiatoires (EPI) seront disponibles pour permettre des examens sur place. Une disponibilité maximale de l'installation sera obtenue par la mise en oeuvre de deux accélérateurs indépendants.

also includes Conventional Facilities, mainly buildings and utilities, and the Central Control and Common Instrument Systems.

### *4.2. The IFMIF test cell*

As described in more detail in Refs. [13,14], the IFMIF target and test cell and specimen testing areas must be capable of accommodating the wide range of environments associated with fusion reactor materials. According to these materials testing needs, the irradiation volume downstream of the neutron-producing Li target has been partitioned into a high-flux region with a displacement damage accumulation of about 20–55 dpa/full power year (fpy) and an available volume of 0.5 L, a medium-flux region (1–20 dpa/fpy, 6 L), and a low-flux region ($<1$ dpa/fpy, $>100$ L). All test modules used for the different flux zones have to be instrumented and able to control the irradiation temperature that might vary from 250 to 1000 °C in the high-flux and medium-flux regions down to cryogenic temperatures in the low-flux zones. They are installed at the bottom of the Vertical Test Assemblies (VTA) through which heating power, coolant and signal transmissions are provided.

Hot cells will be necessary for periodic maintenance of activated devices and complete post-irradiation examination (PIE) of all irradiated specimens and mock-ups. Fig. 3 shows an outline of the present test cell design. The high-flux test module of the vertical test assembly 1 (VTA1) is devoted to high-fluence irradiation of candidate structural materials, the 2 medium-flux test modules of VTA2 are dedicated to more sophisticated in situ experiments like creep fatigue tests or T release tests on breeder ceramics, while the vertical irradiation tube system (VIT) allows the irradiation of special purpose materials in the low-flux region.

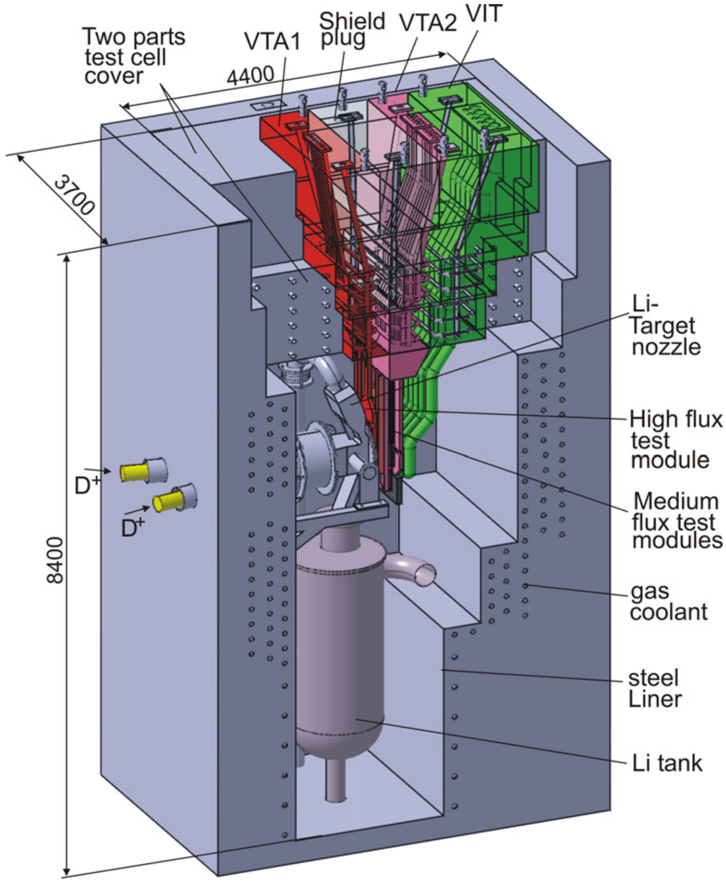


Fig. 3. Test cell with the deuterium beams from left striking the Li target, and with all assembled test modules. Dimensions are in mm.

Fig. 3. Cellule de tests avec les faisceaux de deuterium et vue de l'asssemblage des modules. Les dimensions sont en mm.

### 4.3. *High flux test module, small scale specimens and materials test matrix*

The high flux test module (HFTM) is basically a vessel with 12 irradiation rigs containing the encapsulated specimens at the desired irradiation temperature. Helium gas with only 0.3 MPa removes the heat very efficiently while flowing through narrow gaps of typically 1 mm width between the rig walls. Based on detailed neutronic analyses, in combination with thermal hydraulics and fluid dynamics calculations, the design outline of the HFTM has been significantly improved during the past few years. The performance gains include: (i) reproduction of fusion specific PKA spectra by the implementation of suitable neutron reflectors; (ii) enhancement of the high flux test volume by $\sim$20%; (iii) reduction of the flux gradients by $\sim$10%; (iv) increase of the available space for specimens by $\sim$30%; and (v) individual rig temperatures with a temperature uniformity of $\pm$1.7%, allowing practically homogeneous temperature profiles during irradiation and during beam-off periods. At the same time, the 12 rigs have become larger, thus providing a much higher flexibility in specimen test matrix arrangements.

Details of the rig design are shown in Fig. 4 [15]. Each rig has an outer cross section of $49 \times 16\ \text{mm}^2$ and is assembled with a capsule that contains a stack of specimens with optimized package density. That is, the irradiation rigs are carriers of the capsules that in turn contain the specimens, similar to rigs used in fission irradiation technology. This allows a rather dense arrangement of most of the envisaged specimens. Also in the style of many fission reactor irradiations, the space between the specimens is filled with a stagnant liquid metal like sodium or a potassium/sodium alloy in order to guarantee a well-defined heat transfer from the specimens to the capsule walls. In order to keep the temperature over the entire specimen volume inside each capsule within about $\pm$1.7%, three heaters are coiled up horizontally within the capsule wall and are operated and controlled individually by three thermocouples per capsule. While in the second and third rig row, a thermal insulating gap with stagnant helium gas acts as well defined isolation

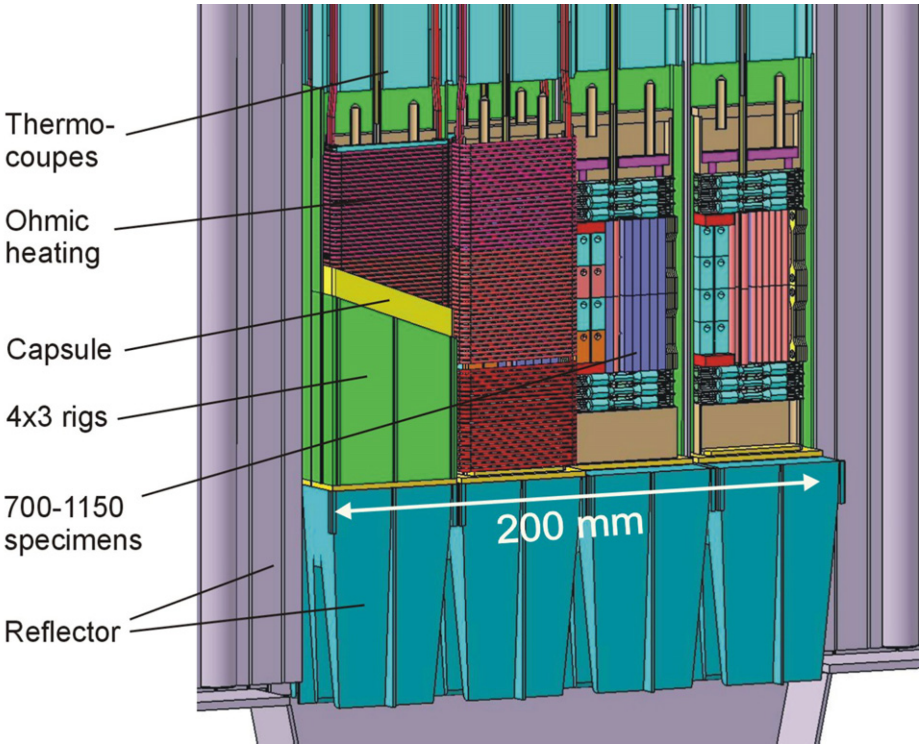


Fig. 4. Front view of the High flux test module. The temperature uniformity inside the individual capsules is despite flux gradients very homogeneous (±1.7%).

Fig. 4. Vue de face du module de tests à haut flux. Les températures à l'intérieur des différentes capsules sont uniformes : la variation est de ±1.7% en dépit des gradients de flux.

between capsule and rig wall, in the first rig row the capsule and rig wall might be brazed together to maximize the heat transfer, thus allowing specimen temperatures below 300 °C despite the very high damage rate of ⩾40 dpa/fpy. Each rig can be adapted in a straight forward manner for any other specimen material discussed in present power plant conceptual studies. More than 1000 specimens accommodated in 12 rigs can be irradiated in a well defined manner at the same time in the HFTM. The design of the HFTM is in its final stage and prototype fabrication of specimen capsules and rigs has started. In addition to the reference specimens and some remaining volume dedicated to experimental validation of computational modeling, each capsule is typically equipped with three thermocouples and one online subminiature fission chamber for a quantitative determination of local neutron/$\gamma$ spectra.

#### *4.3.1. Material test matrix*

Material loading strategies that are in line with international road maps to fusion power (Fig. 1) have to provide in time, for each material, complete database sets without losing flexibility in the choice of damage dose or irradiation temperature. With the above described rig and capsule geometries very flexible specimen loading matrixes have become possible. Although a multitude of different loading scenarios are in principle possible, the suggestions made in Ref. [16] are focused on two development stages: 80 dpa for DEMO pre-design and 150 dpa for final design within the shortest possible time, for two alloy classes. That is, if nominal IFMIF irradiation with one full beam on target (1 × 125 mA) will be available for users at the end of 2017, mid 2021 80 dpa will be achieved in two alloys, each covering about 1100 specimens with four different temperatures and six different damage doses. Other material test matrices for instance with more material classes but less specimens per test matrix are, of course, also possible.

#### *4.3.2. Small scale specimens*

The development and application of small specimen test technology (SSTT) has proceeded in parallel with the development of materials for fusion reactors. Today, we have an array of specimens and test techniques in hand, allowing the extraction of mechanical properties such as tensile data, fatigue, fracture toughness, impact properties, creep and fatigue crack growth from relatively small specimens [17,18]. Specific features of this set of specimens include, that major dimensions are typically of the order 25–27 mm, and that procedures for fabricating and testing these specimens have been largely derived from ASTM and DIN standards, allowing even qualified remote controlled testing in hot cells. It is important to note that within a wide parameter range the suggested tensile, fatigue, dynamic fracture toughness and in situ creep specimens show 'material intrinsic' behavior that hardly ever relies on specimen size or geometry. Such specimens have already been used in materials test reactor irradiations in a wide temperature range (250–500 °C) with damage doses up to 70 dpa. At least in Europe, material data bases today rely already largely on these small scale specimens, that is, the suggested set of specimens does not need further miniaturization.

### *4.4. Medium and low flux test modules*

In the medium flux position (Fig. 3) the present reference design concept includes (i) in situ creep-fatigue experiments on structural materials, and (ii) in situ tritium release experiments on ceramic breeders. In order to significantly improve the neutronics performance for functional materials like Be-alloys or ceramic breeders, two tungsten plates ($2 \times 30$ mm thickness) acting as a neutron spectral shifter and a carbon envelope (250–300 mm) serving as a neutron reflector were included during the past few years.

#### *4.4.1. Creep-fatigue test module*

The creep fatigue behavior of structural materials during irradiation in inert environments will be examined with a push-pull creep fatigue testing machine (Fig. 5) equipped with three independent drives. A suitable specimen design for such tests has been already developed [19]. For specimens with a cylindrical length of 10 mm, a diameter of 8 mm and 0.4 mm wall thickness, broad based thermal hydraulic analyses and related experimental validations have been performed very recently to implement a novel jet-array cooling concept inside the creep fatigue specimens that allows us to keep the specimen temperature variation within ±2.5% for any test conditions [20]. Three creep fatigue specimens may be tested independently at one time in this equipment. This universal testing device allows all major creep-fatigue modes: (i) push-pull, e.g. $R = -1$, (ii) stress or strain controlled, (iii) with or without dwell periods, (iv) thermal fatigue and beam cycling experiments.

#### *4.4.2. Tritium release test module*

Measurements of in situ tritium release and compatibility tests, for example, in neutron multipliers and ceramic breeders will be performed with this module. Eight independent rigs equipped with specimen capsules are foreseen that can be kept at individual temperatures typically between 400–900 °C with a coolant technology similar to the HFTM. Tritium released by the specimens in the capsules will be swept up by helium gas flowing through the capsules and will be carried through tubes in the VTA to the analyzing equipment located in the test cell control cell. Instead of ceramic breeders, the sub-test modules can also be equipped with any other instrumented PIE specimens.

### *4.5. IFMIF neutronics*

Since the beginning of the IFMIF development, broad based neutronics research activities have been one of the most important cornerstones for its scientific and technical performance. Substantial progress has been achieved in developing and processing nuclear data libraries above 20 MeV, and in the development and validation of various advanced codes describing the special distribution of the neutron–matter interaction [21]. Based on detailed 3D geometry models of the entire IFMIF test cell, extensive neutron transport calculations and activation analyses have been performed for the test cell, the test modules and other components, thus providing a sound basis for design improvements on properties like nuclear inventory, nuclear heat, displacement damage and recoil energy distribution and hydrogen and helium production rates.

#### *4.5.1. Neutron spectra*

The IFMIF neutron spectra have a flat top around 14–16 MeV and rapidly drop down above that energy. As for the displacement damage and the helium production in structural materials, only neutron energies beyond about 0.1 MeV and 2 MeV, respectively, are relevant, time-lapse irradiations up to 55 dpa/fpy are possible in the high flux volume

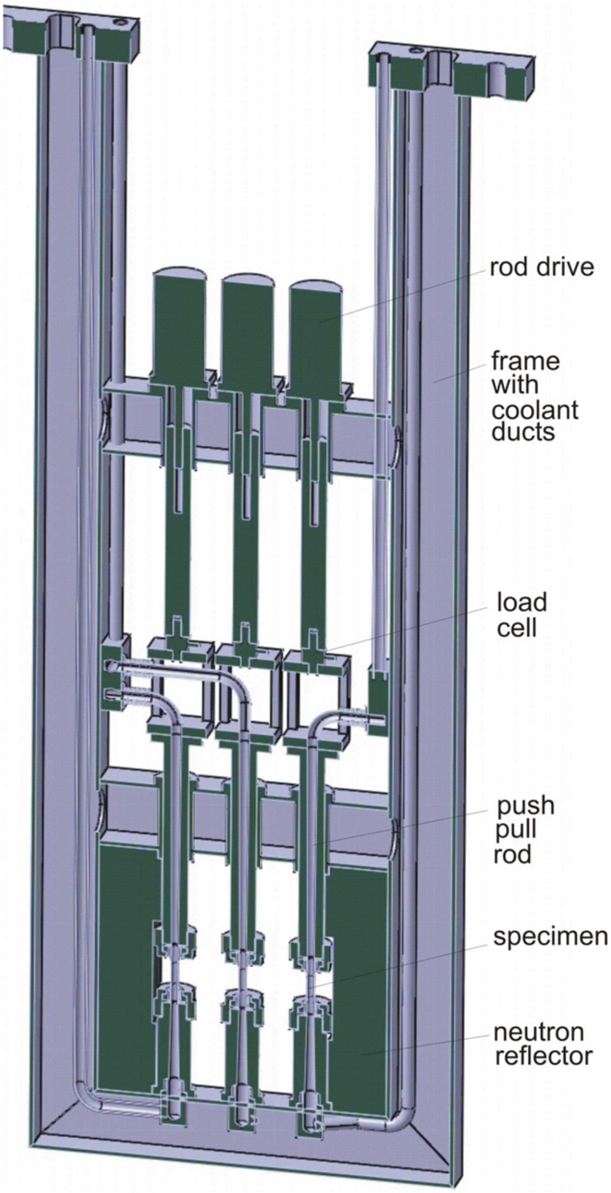


Fig. 5. Test module for 3 independent in situ creep fatigue experiments.

Fig. 5. Module de tests pour trois expériences de fatigue-fluage in-situ.

of IFMIF. It is important to note that, despite of the maximum neutron energy of 55 MeV, the He/dpa ratio and hydrogen/dpa ratio of IFMIF is exactly that one of a DEMO-reactor first wall, as Table 1 shows for Fe-based alloys.

In contrast to structural materials, tritium breeders like $Li_4SiO_4$ also require a high population at low neutron energies, as the tritium production is inversely proportional to the neutron energy. A major result of neutronics optimization of the medium flux test modules is that the shape of the IFMIF neutron spectrum follows that of a DEMO reactor breeding blanket over several orders of magnitude, if the test modules are surrounded with a proper combination of tungsten, graphite, and reduced-activation steel (Fig. 6). Tungsten acts mainly as a 'neutron spectral shifter' and graphite/steel as 'neutron reflector'. With respect to suitability criteria [22], IFMIF meets adequately DEMO reactor-relevant H, He, and dpa production rates as well as H/dpa and He/dpa ratios in structural materials like Fe-based alloys, and it can be considered a suitable test bed for ceramic breeder materials.

Table 1
Displacement damage and gas production in iron for several neutron irradiation environments; ‘fpy’ stands for ‘full power year’

Tableau 1
Dommage de déplacement et production de gaz dans le fer pour différents environnements d’irradiation. « fpy » signifie année à pleine puissance

| Irradiation parameter | | Demo FW 3 MW/m$^2$ | IFMIF HFTM | ESS irr. rigs reflector | XADS 1 MW window | HFR position F8 | BOR60 position D23 |
|---|---|---|---|---|---|---|---|
| Total flux, | n | $1.3 \times 10^{15}$ | $5.7 \times 10^{14}$ | $6.5 \times 10^{14}$ | $1.2 \times 10^{15}$ | $3.8 \times 10^{14}$ | $2.3 \times 10^{15}$ |
| 1/cm$^2$/s | p | 0 | 0 | $2.5 \times 10^{12}$ | $2.7 \times 10^{14}$ | 0 | 0 |
| Damage, dpa/fpy | | 30 | 20–55 | 5–10 | 38 | 2.5 | 20 |
| H, appm/fpy | | 1240 | 1000–2400 | 160–360 | 16250 | 1.9 | 14 |
| He,appm/fpy | | 320 | 250–600 | 25–60 | 1320 | 0.8 | 5.8 |
| H/dpa | | 41 | 35–54 | 33–36 | 430 | 0.8 | 0.70 |
| He/dpa | | 11 | 10–12 | 5–6 | 35 | 0.3 | 0.29 |

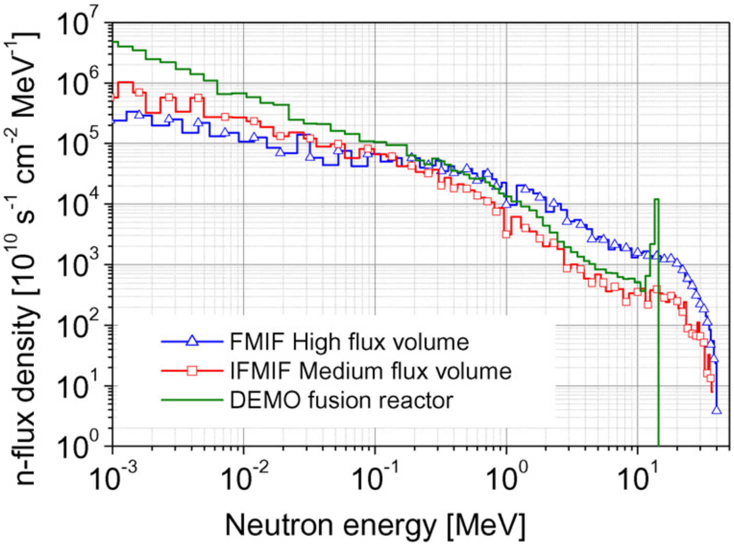


Fig. 6. Neutron spectra for a fusion DEMO-reactor, for the IFMIF high flux volume and for the in-situ tritium release test module of the medium flux position [22].

Fig. 6. Spectre de neutrons pour le réacteur de fusion DEMO, pour la partie haut-flux d’IFMIF et pour le module de test de dégagement de tritium in-situ dans la partie flux-moyen d’IFMIF [21].

### 4.5.2. *Recoil energy spectra*

Hard (high-energy neutron induced) and soft (e.g. electron irradiation induced) primary knock-on atom (PKA) spectra can produce very different damage morphologies. Low-energy recoils produce only Frenkel defects, that is, isolated pairs of vacancies and interstitials. A significant fraction of these defects survives recombination and can be involved in the further defect kinetics. On the other hand, high-energy recoils generate atomic collision cascades in which a high fraction of produced defects recombines during collision and cooling phases. For a PKA with energy higher than some critical value (about 50 keV for Fe), the formation of sub-cascades is more probable, which results in more intense radiation hardening. To characterize the entire PKA spectrum, we have used a cumulative damage production function $W(T)$, which represents the fractional damage energy created in all PKA recoils with energies between the threshold atom displacement energy $E_d$ (40 eV in Fe) and given recoil energy $T$.

The $W(T)$ function usually increases smoothly without steps in fusion structural materials. The filled area in Fig. 7 shows that the relevant test volume of IFMIF meets perfectly, over the entire PKA energy range, the DEMO reactor conditions in iron based alloys, as the shape of the $W(T)$ function can be adjusted by using an appropriate combination of W-moderator and graphite reflector. Obviously, only about 50% of PKA in the ESS and HFR, or even

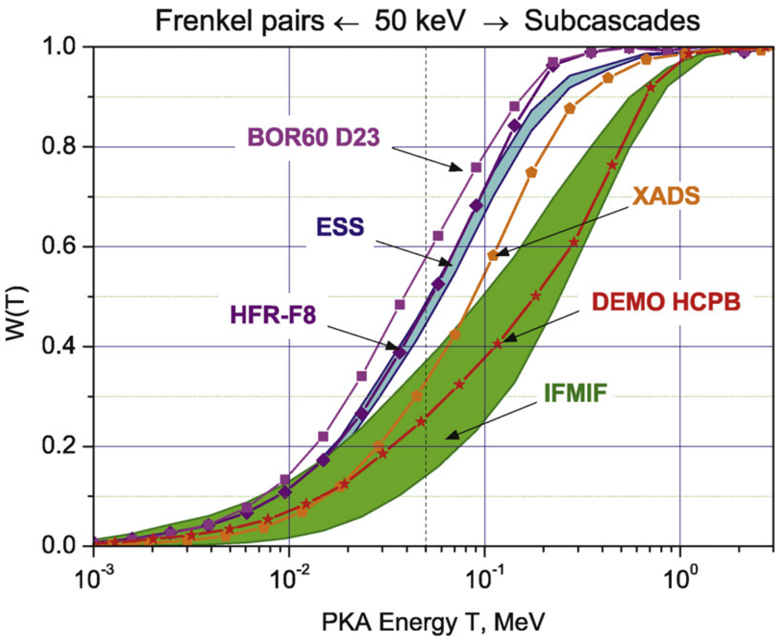


Fig. 7. Damage production function $W(T)$ in iron for HCPB blanket of DEMO reactor in comparison with IFMIF (colored area), neutron spallation sources ESS and XADS, and fission reactors HFR, Petten and BOR-60, Dimitrovgrad [22].

Fig. 7. Comparaison de la distribution cumulée $W(T)$ des PKA dans le fer irradié (i) dans une couverture tritigène de DEMO de type « pebble-bed » refroidie à l'hélium, (ii) dans IFMIF, (iii) dans les sources de neutrons de spallation ESS et XADS, et, (iv) dans les réacteurs de fission HFR de Petten et BOR-60 de Dimitrovgrad [22].

less for the BOR60, will produce sub-cascades, while in the case of DEMO or IFMIF, about 77% of PKA will result in sub-cascade formation.

## 5. Summary and future IFMIF plans

IFMIF is an essential facility in the pursuit of a low-risk path to the rapid development of commercially-viable fusion energy (DEMO). The present IFMIF design and irradiation performance is based on advanced design studies, thermo-hydraulics and neutronics calculations that also confirm the suitability of IFMIF with respect to all major users' requirements.

As the timely availability of a qualified material database is on a critical path of any approach towards fusion power, the International Fusion Materials Irradiation Facility, IFMIF, has become a major element in worldwide fusion strategy scenarios. In order to realize IFMIF in conjunction to ITER to best meet the recognized requirements, IFMIF has entered in 2007 within the European–Japanese 'Broader Approach' enterprise a 6-years EVEDA phase. This Engineering Validation and Engineering design activity (EVEDA) has the objectives: (i) to experimentally validate performance goals and reliable operation of the major subsystems; (ii) to develop the engineering design for the whole IFMIF plant to a level that will allow procurement; and (iii) to prepare on the basis of a central design team relevant activities for the IFMIF site approval and the start of the Construction, Operation, and Decommissioning Activities (CODA). In parallel, the IFMIF users group with representatives of the international fusion materials community is also needed in future to further improve the IFMIF irradiation performance or to continuously update irradiation test matrixes.

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## References

[1] K. Lackner, R. Andreani, D. Campbell, M. Gasparotto, D. Maisonnier, M.A. Pick, J. Nucl. Mater. 307–311 (2002) 10.
[2] T. Muroga, M. Gasparotto, S.J. Zinkle, Fusion Engrg. Design 61&62 (2002) 13.
[3] D. Maisonnier, J. Hayward, "Technological and engineering challenges of fusion" at 2nd IAEA Technical Meeting on First Generation of Fusion Power Plant, Vienna, 20–22 June 2007; Proceedings in press.
[4] D. King, Conclusions of the fast track experts meeting, November 2001, pp. 1–5, http://www.fusion.org.uk/research.html.
[5] R. Hazeltiner, A plan for the development of fusion energy, March 2003, pp. 1–82, http://fire.pppl.gov/fesac_dev_path_final_rpt.pdf.
[6] J.E. Leis, et al., Report on the international fusion irradiation facility, in: IEA Workshop, San Diego, 1989, vol. 1: Evaluation Panel Report.
[7] M. Gasparotto, et al., in: European Material Assessment Meeting, Report EFDA-T-RE-2.0, Garching, 2002, pp. 1–66.
[8] K. Ehrlich, E.E. Bloom, T. Kondo, J. Nucl. Mater. 283–287 (2000) 79–88.
[9] K. Ehrlich, et al. (Eds.), Proceedings of the IEA Workshop on Selection of Intense Neutron Sources, KfK Report 5296, May 1994.
[10] E.W. Pottmeyer Jr., The fusion materials irradiation facility at hanford, J. Nucl. Mater. 85&86 (1979) 463–465.
[11] A.L. Trego, et al., Fusion materials irradiation test facility – a facility for fusion materials qualification, Nuclear Technology/Fusion 4 (2) (1983) 695.
[12] T. Kondo, et al., Materials development and testing aspects of IFMIF in the conceptual design stage, J. Nucl. Mater. 233–237 (1996) 82.
[13] IFMIF International Team, IFMIF Comprehensive Design Report, IEA Report, December 2003, http://insdell.tokai-sc.jaea.go.jp/IFMIFHOME/ifmif_home_e.html#IFMIF.
[14] A. Möslang, V. Heinzel, H. Matsui, M. Sugimoto, The IFMIF test facilities design, Fusion Engrg. Design 81 (2006) 863.
[15] F. Arbeiter, V. Heinzel, B. Dolensky, U. Fischer, S. Gordeev, A. Möslang, K.-H. Lang, D. Leichtle, S.P. Simakov, E. Stratmanns, V. Slobodchuk, P. Vladimirov, IFMIF high flux test module design and design validation, in: 24th Symp. on Fusion Technology (SOFT 24), Warszawa, Poland, September 11–15, 2006, submitted for publication to Fusion Engineering and Design.
[16] A. Möslang, Development of a reference test matrix for IFMIF test modules, Final Report on the EFDA Task TW4-TTMI-003 D4, January 2006.
[17] P. Jung, A. Hishinuma, G.E. Lucas, H. Ullmaier, Recommendation of miniaturized techniques for mechanical testing of fusion materials in an intense neutron source, J. Nucl. Mater. 232 (1996) 186–205.
[18] G.E. Lucas, G.R. Odette, H. Matsui, A. Möslang, P. Spätig, J. Rensman, The role of small specimen test technology in fusion materials development, J. Nucl. Mater. 367–370 (2007) 1549–1556.
[19] A. Möslang, R. Lindau (Eds.), Proceedings of the IEA – Technical Workshop on the Target and Test Cell System for an International Fusion Materials Irradiation Facility, Karlsruhe, July 3–6, 1995, FZK Report, FZKA 5633, 1995.
[20] S. Gordeev, V. Heinzel, A. Möslang, V. Slobodschuk, New cooling concept for IFMIF medium flux test module. Validation of turbulence models and thermal hydraulic analyses, in: Annual Meeting on Nuclear Technology 2005, German Nuclear Society, May 10–12, 2005, Nürnberg, Germany; Proceedings, pp. 479-482.
[21] U. Fischer, Y. Chen, S.P. Simakov, P.P.H. Wilson, P. Vladimirov, F. Wasastjerna, Overview of recent progress in IFMIF neutronics, Fusion Engrg. Design 81 (2006) 1195–1202.
[22] P. Vladimirov, A. Möslang, Comparison of material irradiation conditions for fusion, spallation, stripping and fission neutron sources, J. Nucl. Mater. 329–333 (2004) 233–237.