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How to improve the irradiation conditions for the International Fusion Materials Irradiation Facility

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Abstract

The accelerator-based intense D-Li neutron source International Fusion Materials Irradiation Facility (IFMIF) provides very suitable irradiation conditions for fusion materials development with the attractive option of accelerated irradiations. Investigations show that a neutron moderator made of tungsten and placed in the IFMIF test cell can further improve the irradiation conditions. The moderator softens the IFMIF neutron spectrum by enhancing the fraction of low energy neutrons. For displacement damage, the ratio of point defects to cascades is more DEMO relevant and for tritium production in Li-based breeding ceramic materials it leads to a preferred production via the ^{6}Li(n,t)^{4}He channel as it occurs in a DEMO breeding blanket. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

For the future fusion materials development program it is necessary to have a dedicated high intensity neutron source available. Such a facility was requested many times by high ranking panels [1,2] and the fusion materials community. Under the promotion of the International Energy Agency (IEA) a D-Li neutron source concept was proposed in San Diego in 1989 and subsequent meetings [3–5] as the only concept which is technically feasible within a reasonable temporal frame. Under the auspices of the IEA the International Fusion Materials Irradiation Facility (IFMIF) entered the concept design stage (CDA) in 1994 [6–15] and the concept design evaluation (CDE) phase in 1997 [16–25]. At present, the activities of the IEA study group concentrates on key technological issues and possibilities for cost reduction and a staged construction approach.

IFMIF is an accelerator-based intense D-Li neutron source that produces neutrons with a suitable energy spectrum at high intensity and sufficient irradiation volume. It is a near term feasible concept, which fulfills all essential requirements of the fusion materials development program defined by the users community. IFMIF performs all necessary kinds of material tests with high flexibility in the materials test matrix and the very attractive capability of accelerated irradiations up to about 55 dpa per full power year.

The irradiation characteristics in the IFMIF test cell are well investigated [26–34] and for iron-based alloys the conditions are excellent, especially in the high flux region. This paper has its focus on some ongoing work in the neutronics field with the goal to further improve the irradiation conditions.

2. IFMIF overview

2.1. IFMIF design

IFMIF, a high intensity neutron source for fusion materials testing, is being designed under coordination of the IEA by an international team to be built within the next decade and to be operated with the objective to develop a database for a variety of materials to full lifetime of anticipated use in a fusion reactor, e.g., DEMO. The present CDA reference design of IFMIF [9] is based on conservative linac technology and two parallel operating 125 mA, 40 MeV deuteron beams that are bombarding a common liquid lithium target. The neutrons, generated with a total yield of $> 10^{17}$ n/s, are focused in the test cell which is subdivided into a high,

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medium and low flux test region following the material test guidelines provided by the user community [35,36]. A wide variety of materials like f/m-steels, vanadium alloys, SiC/SiC composites, ceramic breeders, ceramic insulators and superconductors are under consideration in the materials test matrix. This is possible by use of a set of seven miniaturized specimens [9]. The requested damage doses range from 0.001 to 150 dpa and the temperature ranges from cryogenic temperatures to 1000°C. The irradiation experiments are conducted under controlled temperature conditions by making use of helium gas cooled irradiation rigs with secondary heaters for beam off cases [23].

2.2. IFMIF irradiation characteristics

The neutronics in the IFMIF test cell are well investigated and are discussed in detail in [26–34]. The irradiation conditions in the IFMIF test cell are characterized by hydrogen and helium gas production and by the primary knock-on atom distribution and displacement damage production. For iron, a comparison of H, He and dpa production rates between DEMO first wall and IFMIF high flux test region is given in Table 1. With respect to materials development, IFMIF meets all DEMO first wall requirements, and especially the gas to dpa ratios are bracketed quite well. Furthermore, IFMIF allows accelerated irradiations up to 55 dpa per full power year (dpa/fpy).

DEMO relevant damage doses for first wall materials can be achieved in the high flux test region. IFMIF provides over half a liter for displacement damage rates above 20 dpa/fpy for iron, more than a quarter liter above 30 dpa/fpy and more than a tenth of a liter above 40 dpa/fpy.

3. Irradiation conditions improvements

Since the H, He and dpa production calculated for IFMIF compare quite well with DEMO, it is not easy to understand why further improvements in the irradiation capabilities are necessary. However, characterizing displacement damage also includes the spectral distribution of the primary knock-on atoms (pka-atoms). This distribution depends strongly on the neutron spectral distribution. The important point is the defect morphology generated under neutron irradiation. Low-energetic neutrons preferably produce Frenkel defects while higher energetic neutrons are more likely to produce large defect cascades that lead finally to different changes in material properties. For this reason it is really necessary to achieve good agreement between IFMIF and DEMO pka-spectra.

Table 1
Irradiation parameters in iron for DEMO first wall [28] and IFMIF

	IFMIF high flux (min/max)	DEMO	IFMIF high flux (typical)		IFMIF medium flux (typical)		IFMIF low flux (typical)	
Moderator	No	–	Yes	No	Yes	No	Yes	No
Flux (n/(s cm^2))	4×10^{14}–10^{15}	7.1×10^{14}	8.0×10^{14}	6.7×10^{14}	3.1×10^{14}	1.5×10^{14}	2.5×10^{13}	4.4×10^{13}
Hydrogen (appm/fpy)	1000–2500	780	1631	1621	381	597	30.3	123
Helium (appm/fpy)	250–600	198	421	419	97.8	153	7.8	31.5
Damage (dpa/fpy)	20–55	19	35.9	33.9	9.2	9.7	0.7	2.3
H/dpa (appm/dpa)	35–50	41	45.4	47.7	41.4	61.4	42.0	53.6
He/dpa (appm/dpa)	9.5–12.5	10.4	11.7	12.3	10.6	15.7	10.8	13.7

The displacement damage is calculated by use of the standard NRT-model. As discussed in [26] the function *W*(*T*) gives the fraction of displacement damage as a function of pka-energy. This function permits estimation of the ratio of point defects versus displacement cascades. The objective is to adjust the IFMIF neutron spectra in such a manner that the IFMIF and DEMO *W*(*T*) function fit best. A comparison of the IFMIF and DEMO neutron spectra, based on Monte Carlo MCNP-4B [37] calculations, is shown in Fig. 1. It indicates a deficiency of low energy neutrons for IFMIF relative to DEMO.

A sensitivity study was performed to determine the sensitivity of the neutron spectrum to the *W*(*T*) function. The *W*(*T*) functions were calculated for a DEMO first wall spectrum and for cases in which the neutron flux was set to zero below a certain neutron energy threshold. The result is shown in Fig. 2. Neutrons are not shown for a threshold below 0.1 MeV which have almost no effect on the *W*(*T*) function. For a 0.4 MeV threshold, DEMO is quite close to IFMIF and for a 1 MeV threshold DEMO drops significantly below IFMIF. This means, that the IFMIF neutron spectrum suffers most from missing neutrons in the energy range between 0.1 and 0.4 MeV. In order to generate neutrons in this energy range a neutron moderator/reflector component placed in the IFMIF test cell has been studied.

3.1. The moderator concept

The IFMIF test cell is designed to house three test modules for the high, medium and low flux regions. To also put a neutron moderator in the test cell is not simple. Due to the high loads, the moderator material must have a high melting point, a good thermal conductivity and such good neutronic properties as high back scattering, good neutron multiplication and low neutron absorption. Tungsten was selected because it is a material that combines these properties. An advanced test module design for the medium flux test region foresees in-beam fatigue irradiation experiments with a universal testing machine (UTM). A 3D-construction drawing of the UTM can be found in [23]. The UTM is placed at the front part of the medium flux region and the moderator with its two 3 cm thick, 30 cm wide and 20 cm high tungsten moderator plates is put within the frame of the universal testing machine. The nuclear and gamma heating peak load at this location is about 1.5 W/g. With an active He-gas cooling system mounted to the He-cooling loop of the UTM, the W-moderator can be operated safely at 400°C.

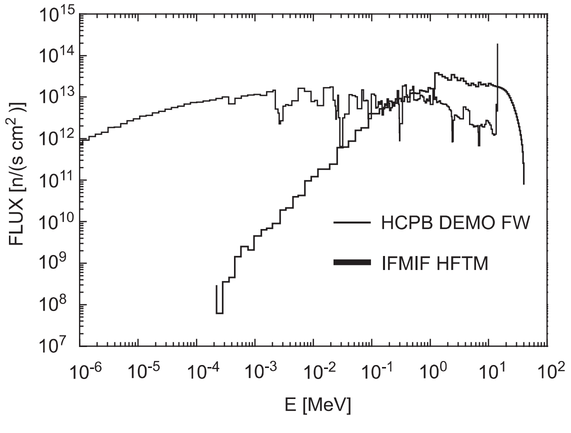

Fig. 1. Neutron spectra for the HCPB DEMO first wall and the IFMIF high flux region.

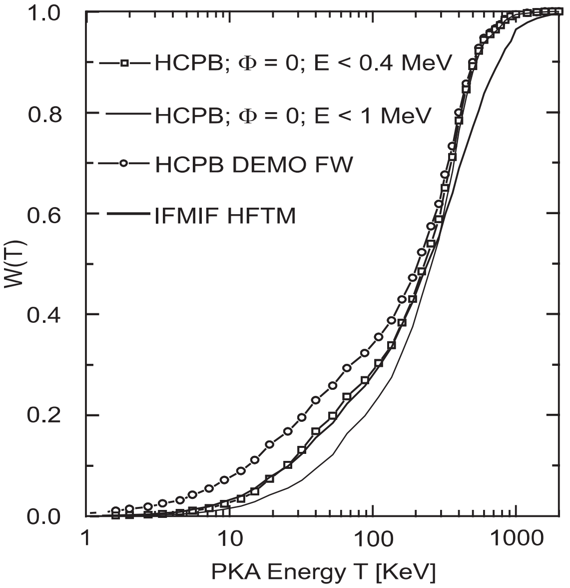

Fig. 2. *W*(*T*) functions for the helium cooled pebble bed (HCPB) DEMO blanket and the IFMIF high flux region.

3.2. Impact on the test regions

The main objective is to improve the neutronic conditions in the high flux test region. However, the moderator does not solely change the neutron spectrum in the high flux region. The neutron field is altered due to neutron scattering and (n,2n) reactions in the moderator everywhere in the IFMIF test cell with a more pronounced effect in the downstream direction. Fig. 3 shows that for the high flux region only a moderate change of the neutron spectrum occurs which results in a small shift of the *W*(*T*) function. However, for the medium flux position, the IFMIF *W*(*T*) function shifts significantly towards DEMO and slightly surpasses the curve in the intermediate energy range. This shows clearly,

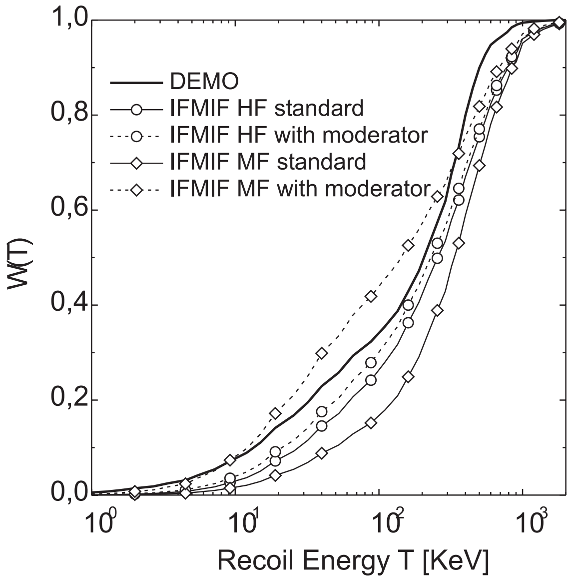

Fig. 3. $W(T)$ functions for DEMO and IFMIF's high flux region (HF) and medium flux region (MF).

that the IFMIF $W(T)$ function can be improved and therefore the ratio on point defects to cascades in IFMIF irradiated samples can be adjusted to meet DEMO requirements with the use of a neutron moderator of the proposed design.

Furthermore, in the medium flux region, irradiations of ceramic breeding materials like Li_2O, Li_4SiO_4 etc. are also planned. Lithium consists of the two stable isotopes ^6Li and ^7Li. Tritium breeding in fusion reactors is dominated by the $^6Li(n,t)^4He$ reaction because of its very high thermal neutron capture cross section. The tritium reaction in ^7Li has a threshold of about 3 MeV. Comparing the tritium breeding capabilities of IFMIF without a moderator and DEMO shows that in the IFMIF medium flux region about half of the tritium production is governed by the ^7Li reaction because of the high energy neutrons in this region. The neutron moderator, however, softens the spectrum which results in much less tritium production via the ^7Li reaction and thus also improves the irradiation conditions for breeding ceramics. This topic is still under investigation and further results are expected soon.

The results in Table 1 show that the use of a W neutron moderator component improves the gas to displacement damage ratios for iron relative to DEMO which requires for structural materials H/dpa ~ 40 appm/dpa and He/dpa ~ 10 appm/dpa. Especially in the medium and low flux regions a significant drop of the gas to dpa ratios occurs. The only drawback of the moderator is that the total production rates in the medium and low flux regions decrease somewhat.

4. Conclusions

The excellent irradiation conditions of IFMIF for fusion materials development can further be improved by applying a neutron moderator to the IFMIF test cell. As demonstrated, beside the H, He and dpa data, the defect morphology and the tritium breeding process can be adjusted quite well to DEMO first wall and DEMO breeding blanket conditions. The neutron moderator for IFMIF is expected to become a major device for future investigations on further improving the irradiation characteristics of IFMIF.

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