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Characterization of the irradiation parameters in the IFMIF high flux test region

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Abstract

The purpose of the international fusion materials irradiation facility (IFMIF) is to provide typical D–T fusion irradiation conditions for future material testing and material development. In order to demonstrate the suitability of IFMIF for irradiation experiments a comprehensive characterization of the neutronics of the high flux test region (HFTR) has been carried out. For Fe, the neutron flux density was found to range between 4×10^{14} and 10^{15} n/s cm^2 which corresponds to 20–55 DPA/FPY in a maximum volume of 550 ± 180 cm^3. Gas production rates were calculated and a H/DPA ratio of 35–50 appm/DPA and a He/DPA ratio of 10–12 appm/DPA were found, which are very similar to those of a DEMO D–T fusion reactor. Additionally, an analysis of the primary knock-on spectra has been performed and a displacement damage characteristic in IFMIF almost ideal to the first wall of DEMO was found. IFMIF therefore provides an adequate environment for the simulation of D–T fusion reactor irradiation conditions.

1. Introduction

The International Fusion Materials Irradiation Facility (IFMIF) is designed to provide typical D–T fusion irradiation conditions for use in the fusion materials testing and materials development program. IFMIF is a high intensity neutron source driven by two 40 MeV deuteron CW linear accelerators with 125 mA beam current each striking a single thick flowing lithium target under 20° impinging angle producing neutrons up to 55 MeV. The materials testing volume is subdivided into four regions: The high flux test region (HFTR) (>20 DPA/FPY), the medium flux test region (1–20 DPA/FPY), the low flux test region (0.1–1 DPA/FPY) and the very low flux test region (<0.1 DPA/FPY). This paper focuses primarily on the characterization of the neutron flux and engineering responses and on the qualification of the displacement damage in the HFTR.

During the IFMIF conceptual design activity (CDA) phase (1995–1996) and the early conceptual design evaluation (CDE) phase (started January 1997) significant progress has been achieved in the neutronics [1,2]. The previously existing neutron transport and engineering response data (H-, He-, damage production and nuclear heating) in the ENDF-B VI data file were limited to 20 MeV neutron energy. For IFMIF neutronic calculations, data up to 50 MeV were provided in a comprehensive data evaluation program for ^{56}Fe, ^{23}Na, ^{39}K, ^{52}Cr, ^{51}V, ^{28}Si and ^{12}C [3]. For detailed three-dimensional Monte Carlo calculations a neutron source model based on the Li(d,xn) nuclear reaction was developed [4] and applied with the Monte Carlo neutron and photon transport code (MCNP) [5]. For the different flux regions irradiation modules have been designed [6]. In particular, for the high flux test module (HFTM), a He-cooled and a NaK-cooled design have been set up. On this basis detailed investigations of the irradiation parameters by extensive MCNP calculations of all test regions have been performed. This paper, however, is confined only to the HFTR.

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2. Description of the calculations

For the analysis of the HFTM the conditions of 20° angle between the impinging deuteron beams, the test region filled with 50% ^{56}Fe, 50% void and a non-uniform beam profile were assumed for the MCNP calculations. The results are volume averaged over 0.5 cm^3 cells. The HFTM in the present design has the dimensions (x, y, z) of (5, 20 and 5 cm).

The results of these three dimensional calculations are presented in a special manner as explained in Fig. 1. The deuteron beam direction goes along the x-axis. The planes A, B and C allow the understanding of the general three dimensional behavior in the HFTR. Plane A represents the results along the centerplane of the test region, viewed from the side. Plane B represents the results from the backplate of the target, and plane C show the results on the horizontal centerplane, viewed from the top. The plot style used is shown on the right side of Fig. 1.

3. Neutron flux characteristics

Results are shown for the neutron flux (Fig. 2), fraction of neutron flux above 14.6 MeV (Fig. 3) and neutron flux gradient (Fig. 4). The neutron flux throughout most of the HFTR is greater than 4×10^{14} n/s cm^2. Close to the target the flux is greater than 10^{15} n/s cm^2. The peaked edges effect of the non-uniform beam profile can be seen in the Z-Y-plane.

The total neutron flux gradient is between 20%/cm and 30%/cm in a large portion of the proposed HFTR. One of the IFMIF HFTR requirements is a limit on the flux gradient of less than 10%/cm over specimen width (which was assumed to be 1 cm). This means, that miniaturized specimen are required and, additionally, the HFTM design needs to allow the orientation of the samples in direction with minimized gradients. It is valuable to note, that the DPA gradients behave very similarly to the flux gradients.

The high energy fraction of the neutron flux (E_n > 14.6 MeV) is between 15% and 20% of the total neutron flux throughout the HFTR. This high energy fraction increases the displacement and gas production responses significantly and allows IFMIF to provide accelerated material irradiations compared to fusion reactors.

4. Characteristic of the engineering responses

Results are shown for the displacement damage production (Fig. 5), the H/DPA ratio (Fig. 6), the He/DPA ratio (Fig. 7) and the nuclear heating (Fig. 8). In particular, the gas to DPA ratios are important parameters for materials embrittlement.

The H-production throughout the HFTR varies between 1000 and 2500 appm/FPY, the He-production between 250 and 600 appm/FPY and the damage production between 20 and 55 DPA/FPY. The gas to damage ratios allow the consideration of how well IFMIF simulates a D–T fusion environment. The H/DPA ratio throughout the HFTR is between 35 and 50 appm/DPA and the He/DPA ratio is between 10 and 12 appm/DPA. This is very similar to the first wall values of DEMO and ITER, see Table 1. The nuclear heating is a very important engineering value because the High Flux Test Module needs to have an external cooling loop. The nuclear heating production throughout the HFTR varies between 30 and 55 W/cm^3.

5. Irradiation volume characteristics

One of the primary design requirements for IFMIF is an available irradiation volume of at least 0.5 l with a

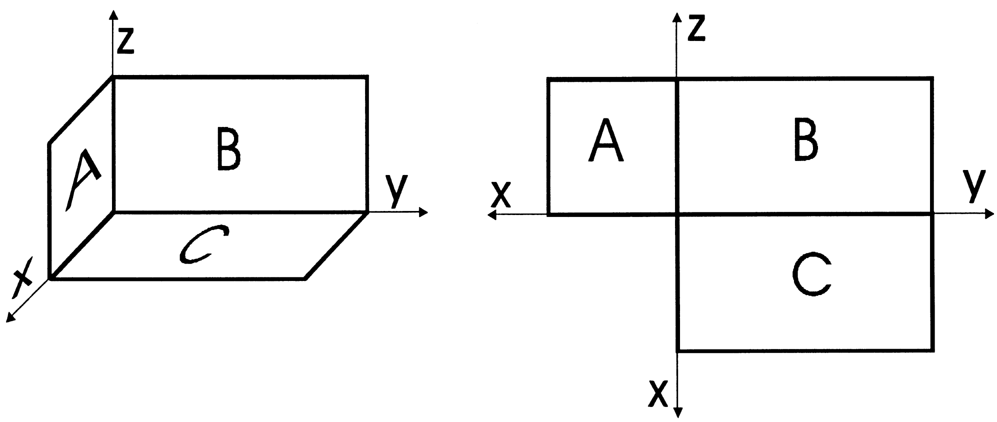

Fig. 1. Explanation of the data representation. The deuteron beam goes along the x-axis. The planes A, B and C show the general three dimensional behavior.

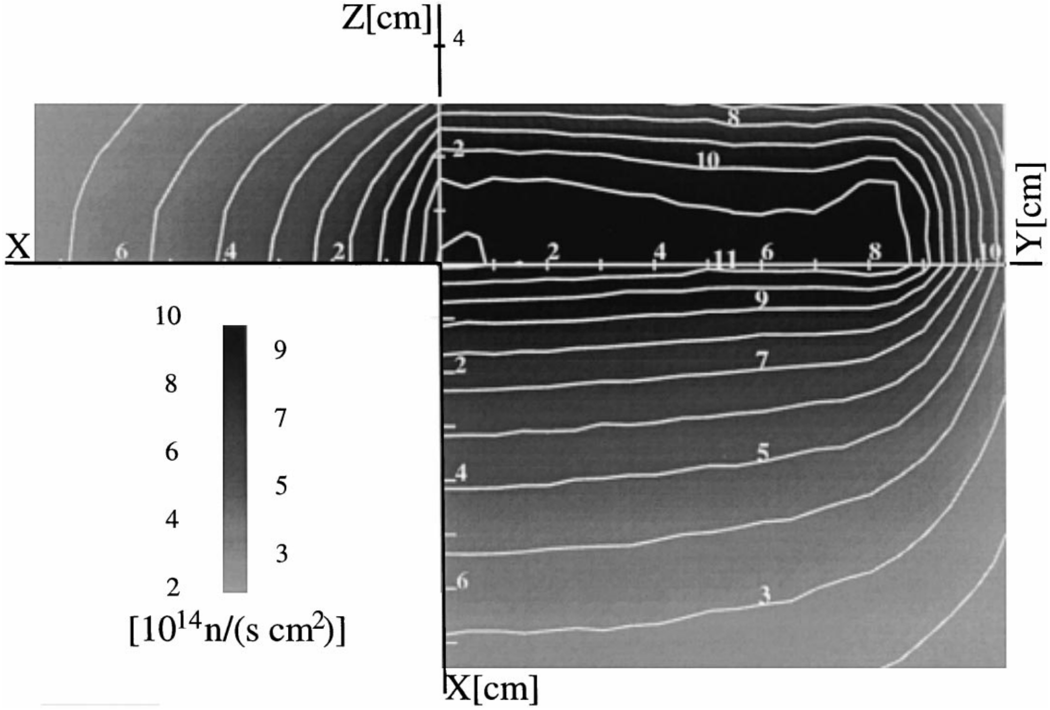

Fig. 2. Neutron flux distribution in units of 10^{14} n/s cm^2 at selected planes in the HFTR.

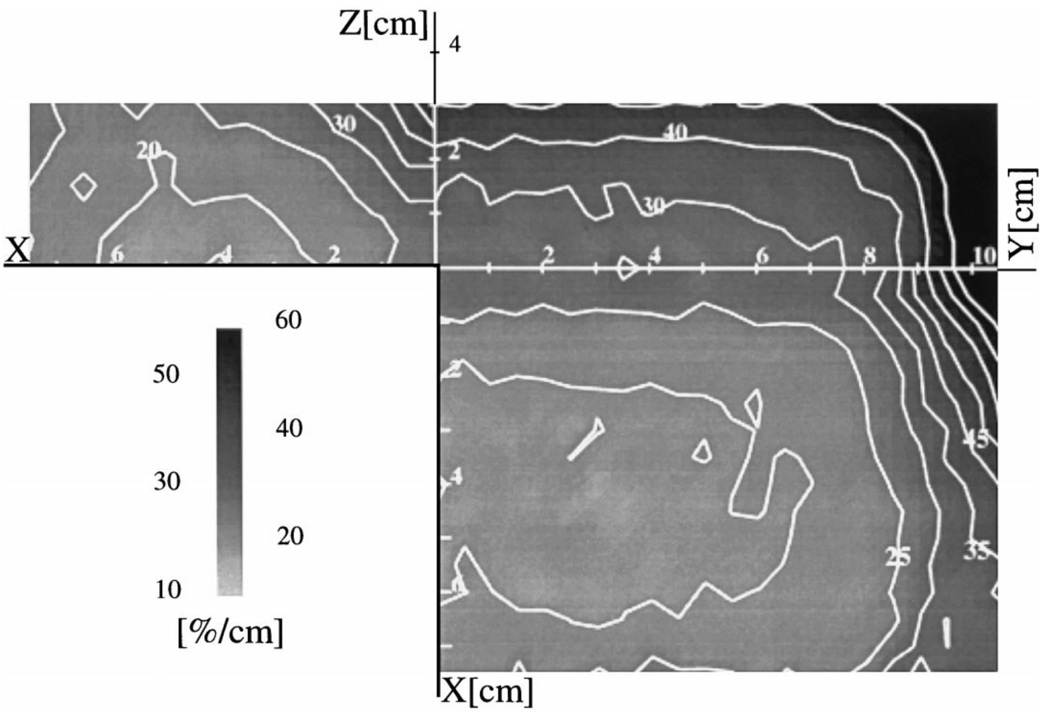

Fig. 3. Normalized neutron flux gradient in units of %/cm at selected planes in the HFTR.

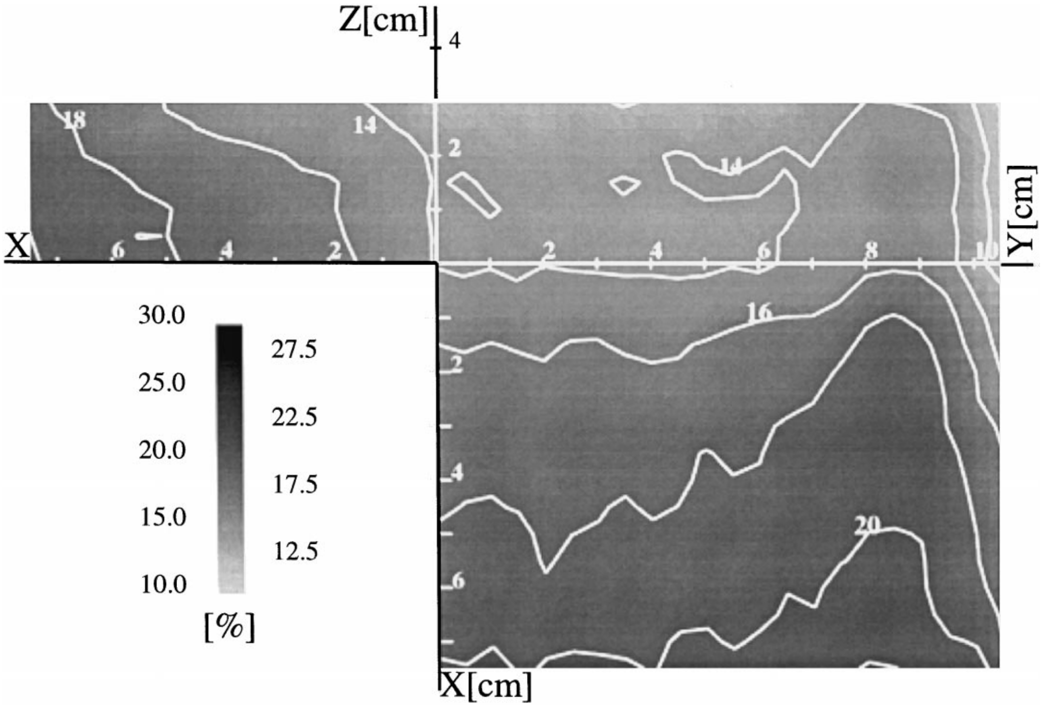

Fig. 4. Fraction of neutron flux with E_n > 14.6 MeV in units of % at selected planes in the HFTR.

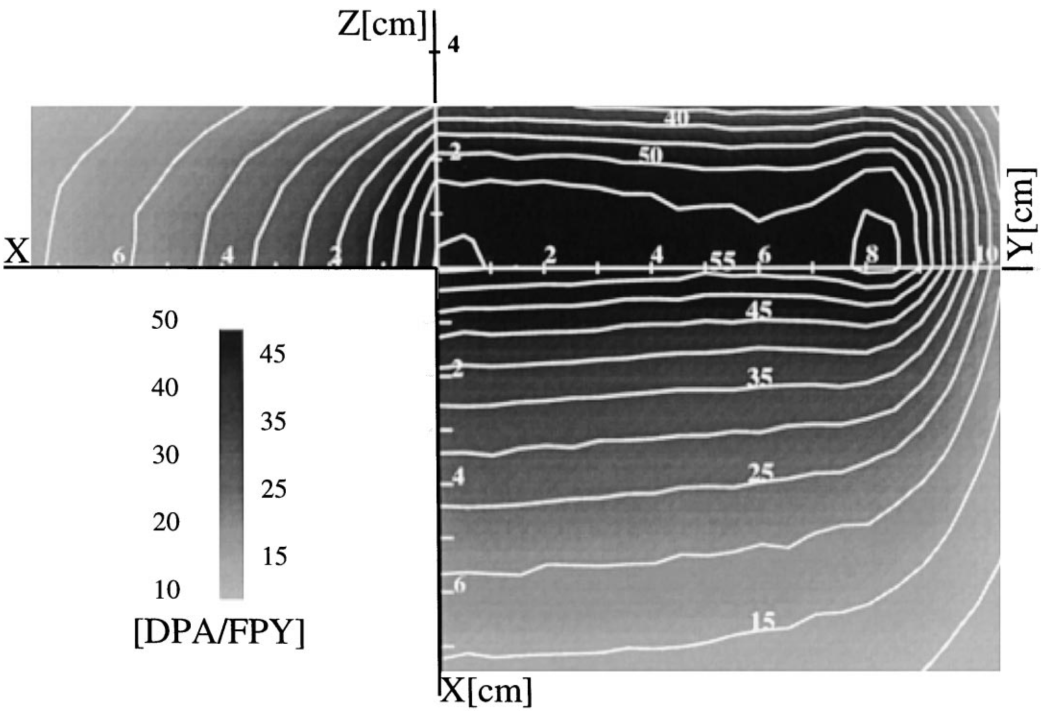

Fig. 5. Displacement Damage Production Rate in units of DPA/FPY at selected planes in the HFTR.

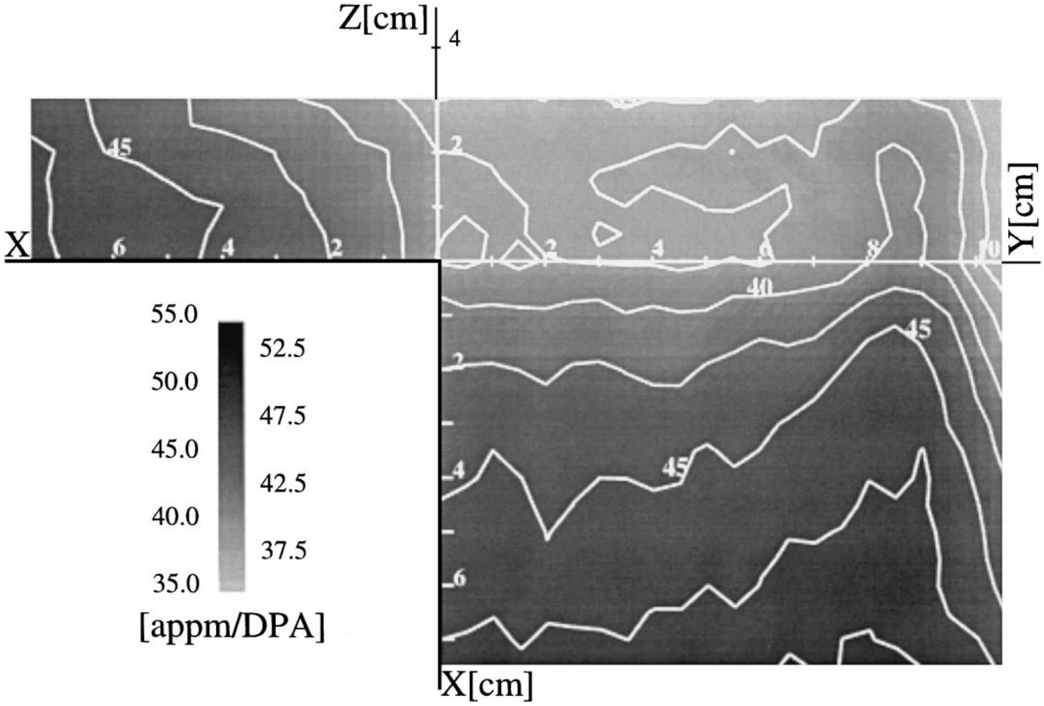

Fig. 6. Ratio of hydrogen to damage production in units of appm/DPA at selected planes in the HFTR.

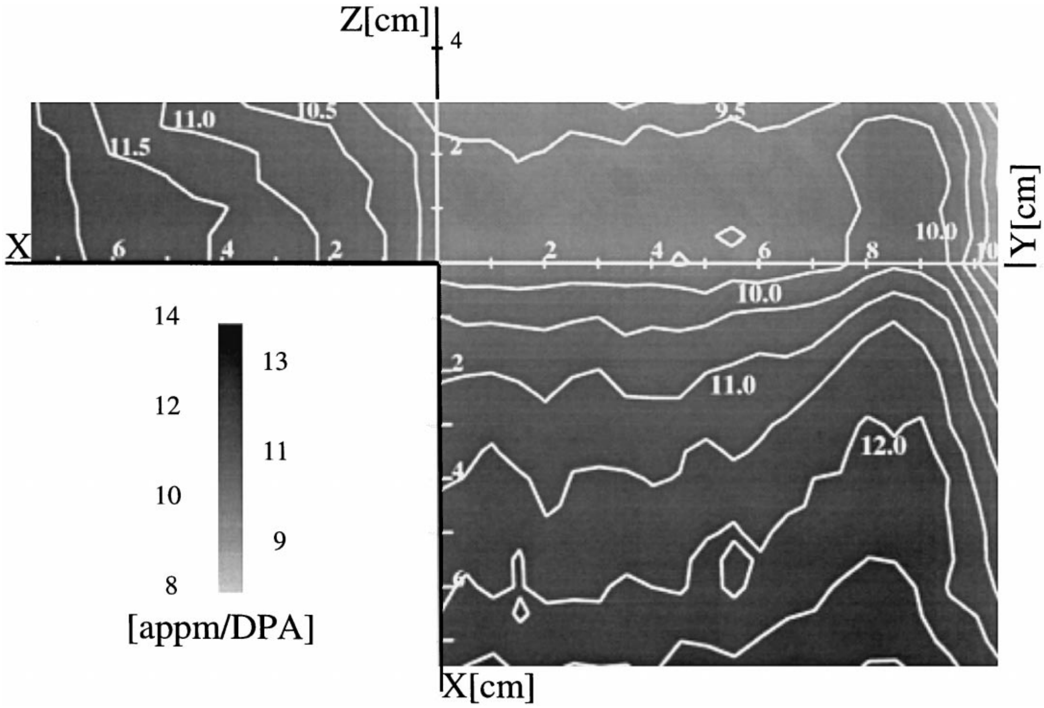

Fig. 7. Ratio of helium to damage production in units of appm/DPA at selected planes in the HFTR.

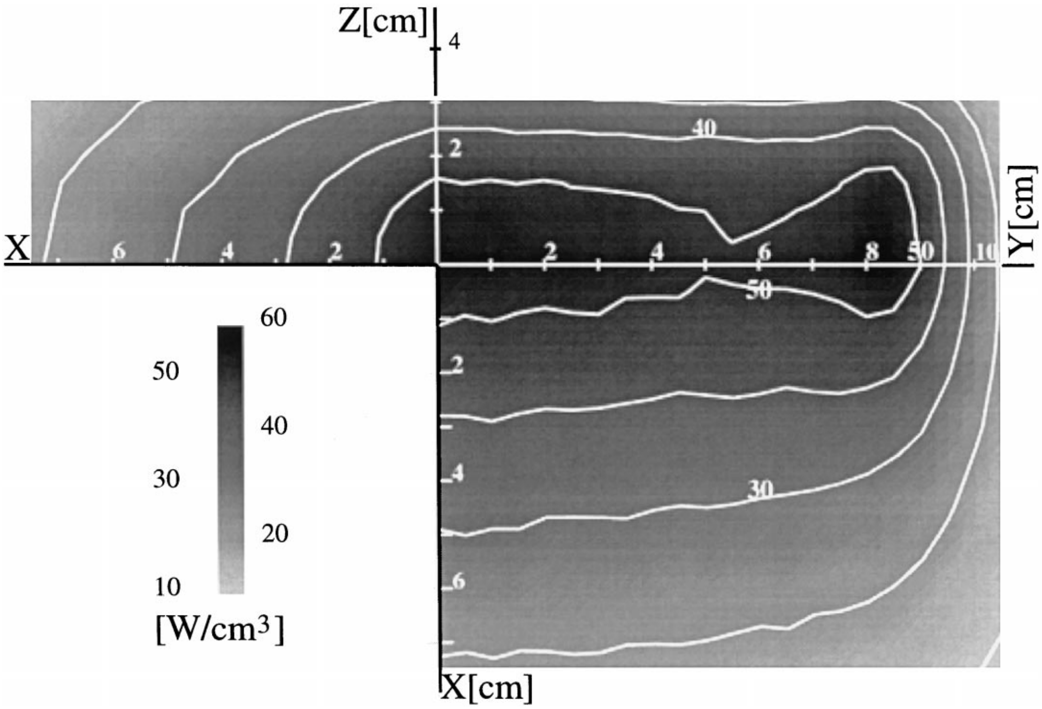

Fig. 8. Nuclear heating production in units of W/cm^3 at selected planes in the HFTR.

damage rate greater than 20 DPA/FPY. The maximum available volume is 550 ± 180 cm^3 and the volume inside the proposed HFTM amounts to 420 ± 60 cm^3. The volume uncertainty is mainly due to the total neutron yield uncertainty. This is described in detail in [7].

6. More detailed analysis of the displacement damage

As was shown above, IFMIF is very well suited to a fusion reactor environment if the gas to DPA ratios are considered. However, these values are generated only on a gross DPA scale. For a more quantitative evaluation of the effects of displacements on different radiation damage phenomena, the analysis of the transferred damage energy as a function of the primary knock-on atom (PKA) energy is important. Low energy PKA's produce primarily Frenkel pairs. For high energy PKA's two aspects have to be considered. First, the instantaneous recombination of single defects is larger in defect cascades and therefore the concentration of mobile Frenkel defects is reduced. This leads favorably to a reduced supersaturation of single defects and hence suppresses point defect agglomeration phenomena like void formation. Secondly, the formation of cascades and subcascades becomes more probable, which can lead e.g. to a more intense irradiation hardening. As shown by many experimental and computational studies, the effect on mechanical properties for the low-energy PKA's is different from that of high energy PKA's, because of the varying

Table 1
Comparison of irradiation parameters in the High Flux Test Region of IFMIF and the first wall data in ITER and DEMO [2]

Irradiation parameter	IFMIF	ITER	DEMO
Total neutron flux (n/s cm^2)	4×10^{14}–10^{15}	4×10^{14}	7.1×10^{14}
Neutron flux, E_n > 14.6 MeV (n/s cm^2)	4×10^{13}–2×10^{14}	0	0
Hydrogen production (appm/FPY)	1000–2500	445	780
Helium production (appm/FPY)	250–600	114	198
Displacement production (DPA/FPY)	20–55	10	19
H/DPA ratio (appm/DPA)	35–50	44.5	41
He/DPA ratio (appm/DPA)	9.5–12.5	11.4	10.4
Nuclear heating (W/cm^3)	30–55	10	22
Wall load (MW/m^2)	3–8	1.0	2.2

defect morphology. This explains that irradiation damage not only depends on the DPA scale but also on the PKA spectrum and thus on the neutron spectrum in a nontrivial way. In order to assess relevant spectrum effects, the normalized energy transfer function $W(T)$ can be used. $W(T)$ describes the fraction of damage energy produced by PKA's as a function of their kinetic energy.

$$W(T) = \frac{\int \sigma_{\text{dam}}(E_n, T)\,\frac{\phi_n(E_n)}{dE_n}\,dE_n}{\int \sigma_{\text{dam}}(E_n, T_{\max})\,\frac{\phi_n(E_n)}{dE_n}\,dE_n},$$

$$\sigma_{\text{dam}}(E_n, T) = \int^{T} \frac{d\sigma_{\text{PKA}}(E_n, T)}{dT}\,T_{\text{dam}}(T)\,dT,$$

where E_n = Neutron energy, T = PKA energy, $T_{\text{dam}}(T)$ Damage energy, $\sigma_{\text{dam}}(E_n, T)$ = Damage energy cross section, $d\sigma_{\text{PKA}}(E_n, T)/dT$ = PKA spectrum, $d\phi_n(E_n)/dE_n$ = Differential neutron flux.

The $W(T)$-function comparison in Fig. 9 shows that IFMIF very well suits the first wall DEMO and ITER function. The IFMIF $W(T)$-function fits much better to the first wall DEMO and ITER functions than the $W(T)$-functions of fission reactor HFR Petten [8], a 800 MeV proton spallation source [9] and a pure 14 MeV neutron peak.

In general it is clear, that the physics on defect reaction kinetics including specific features of e.g. defect accumulations, dissociation, migration and annihilation needs to be further developed in order to quantify more precisely relationships between the mechanical properties and the neutron spectrum.

7. IFMIF and fusion reactors

Table 1 shows how IFMIF covers the fusion irradiation conditions, giving a collection of all important values to be compared. The IFMIF values chosen for the irradiation parameter comparison are based on detailed MCNP calculations for the helium-cooled HFTM design described in more detail in [7].

8. Summary and recommendations

The presented information demonstrates the performance of IFMIF and shows that IFMIF is very valuable in simulating a fusion irradiation environment. All important characterization parameters are in good agreement with a typical DEMO fusion reactor environment. In particular, the detailed comparison of the displacement damage impressively demonstrates the quality of IFMIF irradiations. The neutron flux gradients in the IFMIF HFTR lead to the conclusion that the

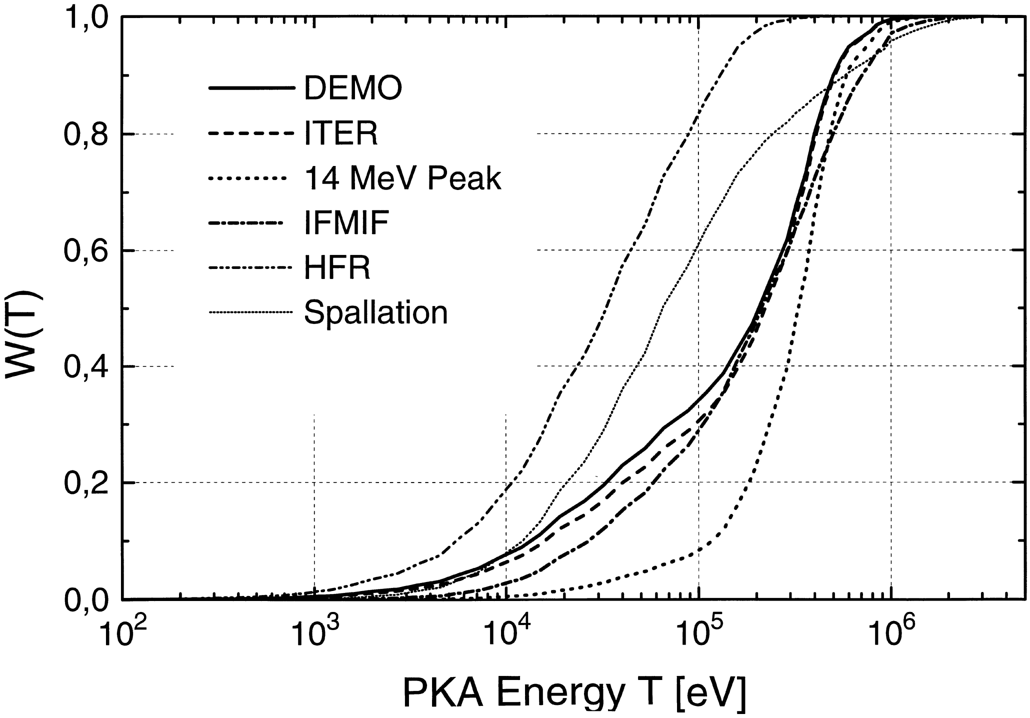

Fig. 9. Comparison of the fraction of damage energy as a function of PKA-energy ($W(T)$-function) for various irradiation facilities.

development of miniaturized specimen is urgently required.

Although much progress has been made further evaluation of nuclear data (e.g. activation data) and further development of the computational tools for the analysis of IFMIF are required. In particular, the uncertainty of the total neutron yield needs to be improved in order to get more accurate results in future.

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