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Journal of Nuclear Materials 258–263 (1998) 421–426

journal of nuclear materials

Characterization of the volume for high dose irradiations with IFMIF

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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 materials testing and materials development. One of the major design criteria of IFMIF is to provide a volume of at least 0.5 l for high dose irradiations (>20 DPA/FPY). A comprehensive characterization of the irradiation volume of the High Flux Test Region (HFTR) has been carried out. For Fe, the damage rate was found to vary between 20–55 DPA/FPY in a maximum volume of (550 ± 180) cm^3 uncollided and (455 ± 145) cm^3 collided. The great volume uncertainty was found to be caused mainly by the total neutron yield uncertainty. In order to utilize the total high flux volume an improvement of the current helium cooled High Flux Test Module (HFTM) design is proposed. IFMIF is found to provide an adequate volume for high dose and accelerated material irradiations under D-T fusion reactor conditions.

1. Introduction

The International Fusion Materials Irradiation Facility (IFMIF) is designed to provide typical D-T fusion irradiation conditions for use in the future fusion materials testing and materials development program. IFMIF is a high intensity neutron source equipped with two 40 MeV deuteron CW linear accelerators operated at 125 mA beam current each striking 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 on the characterization of the irradiation volume of the HFTR.

During the IFMIF conceptual design activity (CDA) phase (1995–1996) significant progress has been achieved in the neutronics field [1–4]. The neutron transport and physical response data were extended up to 50 MeV [5]. A detailed neutron source model [3] based on the Li(d,xn) nuclear reaction was developed for use with the MCNP code [6]. Modules including materials loading for the four flux regions were determined. In particular, for the High Flux Test Module (HFTM), a He-cooled and a NaK-cooled irradiation rig concepts has been set up. On this basis, detailed investigations of the neutronic in the HFTM by extensive calculations with the analytical Intense Neutron Source Code INS [7] and the Monte Carlo Neutron and Photon Transport Code (MCNP) have been performed [2].

2. Description of the calculations

For the volume analysis of the HFTM different conditions were applied for the calculations with the INS and MCNP code. An overview is shown in Table 1. The main purpose of this analysis was to characterize the impact of the calculation parameters – beam profile, beam footprint, neutron source data, material loadings and engineering response data – on the HFTM irradiation volume.

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PII: S0022-3115(98)00233-5

Table 1
Comparison of the calculation parameters

Accelerator	*INS*	*MCNP*
D^+ energy	40 MeV	40 MeV
Beam current	250 mA	2 × 125 mA
Beam angle	0°	20°
Beam profile	Uniform, non-uniform	Uniform, non-uniform
Beam footprint	5 × 20 cm^2 (uniform), 7 × 22 cm^2 (non-uniform)	5 × 20 cm^2 (uniform), 7 × 22 cm^2 (non-uniform)
Target		
Li thickness	2.6 cm	2.6 cm
Li temperature	300°C, $\rho = 0.512$ g/cm^3	300°C, $\rho = 0.512$ g/cm^3
D^+ range	[16]	[16]
Backplate thickness	1.6 mm	1.6 mm
n-source model	BNL data [9], Cierjacks data [10]	Model description [3]
Test cell		
Type of calculation	Uncollided calculations	Uncollided and collided calculations
Loading parameters	none	50% Fe, 50% void
Nuclear response	[18]	[2,5]
Transport data	none	[2,5]
Kind of results	Point values	Volume averaged values over (0.5 cm)^3 cells

The reference definition of the beam parameters are a uniform beam density distribution striking the Li target at a footprint of 20 × 5 cm^2. However, a Monte Carlo beam transport analysis [8] has shown, that instead of these simplified beam characteristics the beam will exhibit a profiled beam density distribution, shown in Fig. 1, with a 22 × 7 cm^2 beam footprint. The neutron source function is of great importance. There a several data sets available which differ in total neutron yield and angular distribution. A first d-Li neutron source function was developed in the framework of the FMIT project [9]. Based on experimental thick target neutron yield data the double differential cross sections were calculated by nuclear model fitting [10]. This model has a total neutron yield of 6.7% at 40 MeV deuteron energy. In 1991 these double differential nuclear data were

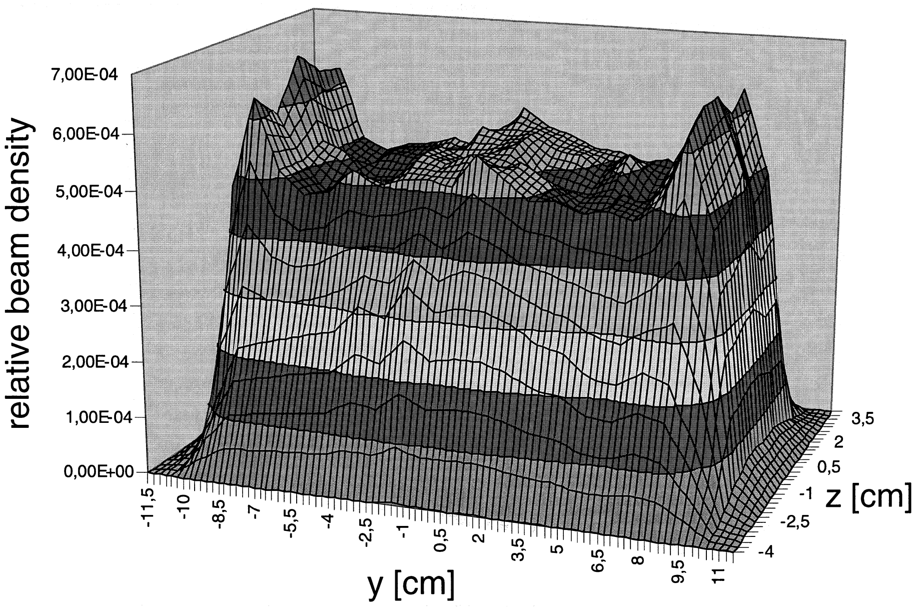

Fig. 1. Three-dimensional view of the non-uniform beam profile with the characteristic peaked edges.

Table 2
Irradiation volumes as a function of the minimum displacement damage calculated with MCNP, collided, non-uniform beam profile, 6.7% yield

Displacement damage (DPA/FPY)	Total volume (cm^3)	Volume inside the proposed HFTM (cm^3)
20	512	415
30	213	201
40	76	76
50	11	11

delivered by Mann to Cierjacks, FZK [11]. Cierjacks compared the data file with thick target neutron yield experiments [10] and found some differences in the angular distribution. Re-analysis of this data led to a second data set with a total yield of 5.5% at 40 MeV deuteron energy. Finally, in the framework of the Japanese ESNIT project [12] new experiments were made. A new set of double differential cross sections was carried out by Sugimoto [13] and a new neutron source function was suggested by Oyama [14]. Based on this data, a new Monte Carlo source function was developed by Wilson [15]. This neutron source function gives a total neutron yield of 7.3% at 40 MeV and is presently used by Wilson in the MCNP calculations shown in this paper. Due to three different total neutron yield values, the neutron yield uncertainty could only be estimated to (6.4 ± 0.9)%. It is obvious that this uncertainty will significantly affect the irradiation volume.

Since the neutrons interact with the material inside the test volume the neutron flux characteristics will change. Two cases were considered in discussing the material loading effect. Firstly an uncollided calculation (100% void) and secondly a collided calculation with 50% Fe and 50% void. The 50%/50% case is assumed to be realistic for future irradiation sample loadings.

The calculated irradiation volumes are based on displacement damage per full-power-year (DPA/FPY) data. For the INS and MCNP calculations displacement damage data from different origin were applied. The data used with the INS code are identically to those used in the SPECTER code [17] and were provided by Greenwood [18]. The data used with MCNP were evaluated up to 50 MeV recently [5] and are based on nuclear model theory and experiments. A comparison of these two damage cross section data sets shows their similarity [2].

3. The HFTM reference case

The HFTM reference case is defined by the 2 × 125 mA beam at 20° impinging angle, the non-uniform beam profile, the 7 × 22 cm^2 beam footprint, 6.7% neutron yield, the 50% Fe/50% void loading and all other target parameters listed in Table 1. The irradiation volumes for certain DPA/FPY levels under reference conditions are listed in Table 2. In the third column the volume portions inside the proposed HFTM, cutout of the total volume by HFTM design limits, are given. In Fig. 2 the volume shapes for different DPA/FPY levels are shown. The physical border of the present HFTM design is shown by the grid. Valuable high dose volume can be identified above and below the grid.

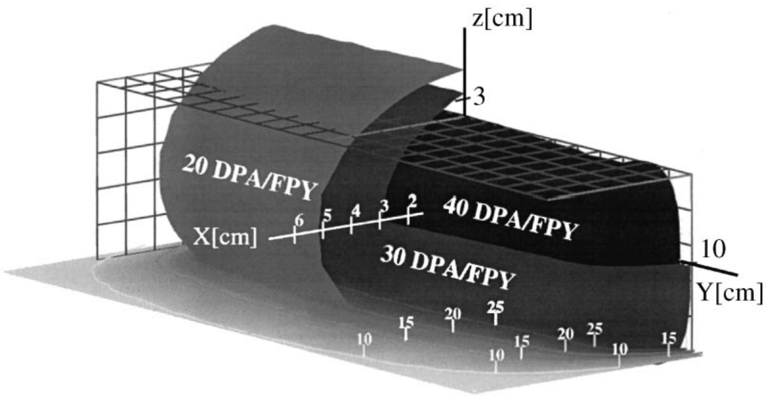

Fig. 2. Irradiation volumes in the HFTM based on minimum damage rates.

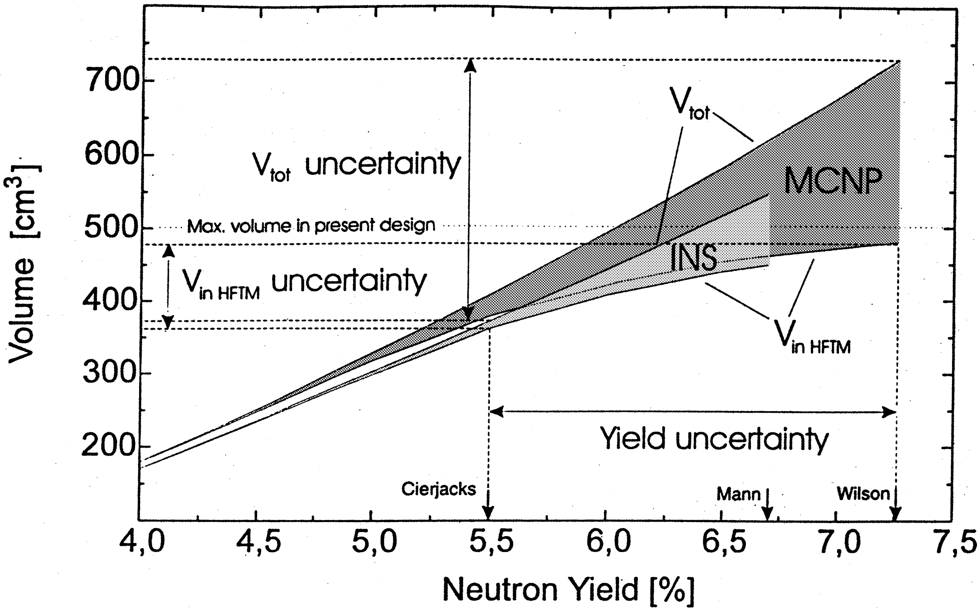

Fig. 3. Irradiation volumes in the HFTM with damage rates > 20 DPA/FPY as a function of the total neutron yield.

4. HFTM volume uncertainty considerations

4.1. The INS and MCNP method

The differences between the two calculation methods INS and MCNP were already pointed out in Table 1. The INS code was developed in 1991 when under IEA coordination different neutron source concepts were evaluated and the d-Li concept was selected. The INS code was very valuable in providing first uncollided approximate results and it is still used for quick calculations. Nowadays neutron transport codes are well developed. The MCNP code provides depending on the complexity of the geometry model accurate collided results. Using a total neutron yield of 6.7%, the uniform beam profile and the uncollided option, a comparison between INS and MCNP shows that INS underestimates the MCNP total volume by approx. 10–15% and the volume inside the HFTM by approx. <5%, see Fig. 3.

4.2. Beam profile/beam footprint effect

The beam footprint size depends on the beam profile chosen. Since the design of IFMIF is still under development, the beam footprint and beam profile may still improve in the future. Between the uniform and non-uniform beam profile the footprint varies from 5 × 20 cm^2 to 7 × 22 cm^2. This impacts a little on the available volume as the values in Table 3 show.

4.3. Material loading effect

MCNP calculations generate appropriate results if material is loaded in the test cell. The maximum volume is attained with no material (uncollided). The realistic loading parameters of 50% Fe/50% void (collided) cause a volume drop of about 20% as listed in Table 3.

4.4. Neutron yield effect

The uncertainty of the total neutron yield of (6.4 ± 0.9)% causes the greatest volume impact. Vol-

Table 3
Comparison of irradiation volumes for displacement damage > 20 DPA/FPY calculated with MCNP for 7.3% neutron yield

	Total volume (cm^3)	Volume inside HFTM (cm^3)
uniform, uncollided	732	478
non-uniform, uncollided	716	480
uniform, collided	594	460
non-uniform, collided	590	452

umes for INS/MCNP calculations (uncollided, uniform beam profile) are shown in Fig. 3 as a function of their total neutron yield. The neutron yield uncertainty domain between 5.5% and 7.3% causes an average total volume (uncollided) of 550 cm^3 with an uncertainty of ±180 cm^3 and an average total volume (collided) of 455 cm^3 with an uncertainty of ±145 The collided volume is evaluated by a plot similar to Fig. 3 which is not shown here. This large uncertainty in the volume indicates that a considerable effort is required to improve the neutron source function in future in order to get more accurate results.

5. Improved helium cooled HFTM design

In the present design, the HFTM simply covers a box-shaped volume of 0.5 l ($5 \times 5 \times 20$ cm^3). The MCNP calculations predict, however, a great portion of the available high dose volume to exist above and below the physical borders of the present HFTM design (see also Fig. 2). For the HFTM two versions have been designed: A helium gas cooled and a NaK cooled design. For both designs detailed geometry models were developed and detailed MCNP calculations were performed. As an example, future HFTM design improvements are discussed for the helium cooled design. A detailed insight gives the schematic layout of a part of the helium cooled HFTM (Fig. 4). The specimens to be irradiated are located in irradiation capsules which are placed in vertical rigs. The vertical rigs themselves fit into the rig vessel. In order to enlarge the utilized irradiation volume the irradiation capsules need only to be extended in vertical direction. This change in the design can be done without great effort but will make about 25–30% more volume usable above 20 DPA/FPY (see Table 3).

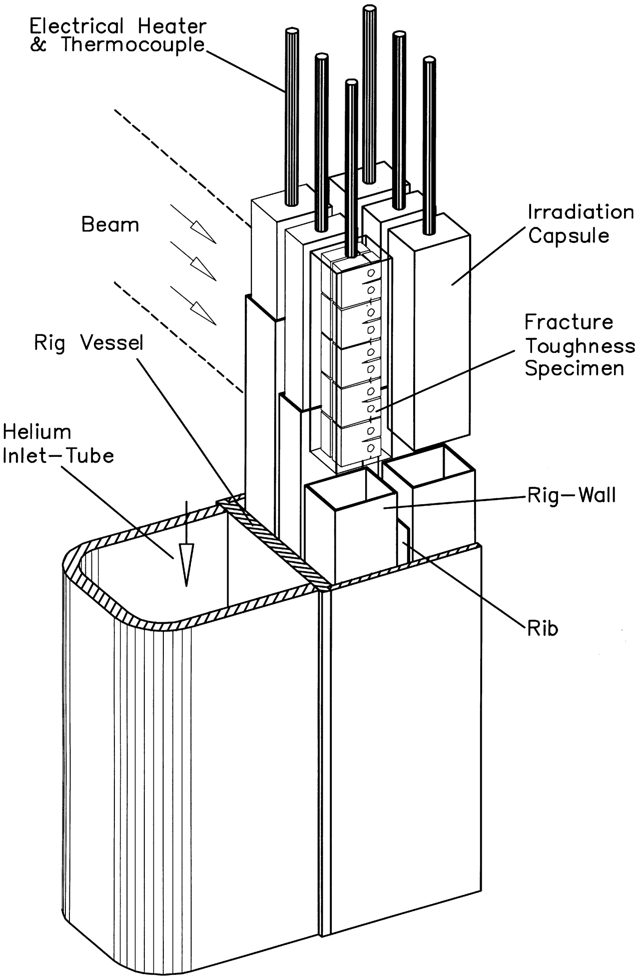

Fig. 4. Detailed three-dimensional schematic layout of a part of the helium cooled HFTM.

6. Summary and recommendations

The presented investigation shows that the irradiation volume calculated by different computer codes depends on several parameters. Quick and approximate results can be provided by INS while accurate and detailed results are provided by MCNP. Most of the calculation parameters show a small effect on the irradiation volume size. The neutron yield uncertainty, due to different neutron source data, however, needs to be urgently improved in order to reduce the irradiation volume uncertainty. The predicted high dose irradiation volume outside the present HFTM design can be made usable by straight forward design improvements as demonstrated with the helium cooled design. IFMIF provides an adequate volume of (455 ± 145) cm^3 for high dose and accelerated materials irradiations under D-T fusion reactor conditions.

Acknowledgements

The authors would like to express their appreciation to Dr. M. Sokcic-Kostic for her excellent work on MCNP calculations. This work has been performed in the framework of the Nuclear Fusion Project of Forschungszentrum Karlsruhe and is supported by the European Union within the European Fusion Technology Program.

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