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Tungsten spectral shifter: neutronics analysis (dpa evaluation, H, He and other impurities generation, recoil spectrum, etc) of different positions and geometries

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For the comparative tungsten irradiation conditions analyses the nuclear responses in the W tiles covering the divertor of 4000 MW fusion power reactor with helium cooled lithium lead blanket were calculated.
In the case of IFMIF they were calculated at several locations around Li target using McDeLicious code and latest deuteron-lithium and neutron evaluated cross sections files. It was found that in the neutron downstream direction (High Flux Test Module, its lateral neutron reflector, Universal Test Machine) the displacement damage rate (dpa) and the gas-to-dpa production ratios for tungsten exceeds that of the fusion power reactor divertor several times. In backward direction (inside deuteron beam tube) the gas-to-dpa ratio is comparable whereas atom displacement rate is much less than in the fusion rector divertor. It means that a compromise could be found in the flange of lithium target located in perpendicular direction to the deuteron beam.
The optimization of the location and thickness of tungsten neutron spectral shifter near Creep Fatigue and Tritium Release Modules was performed, considering as a criterion the damage rates, neutron and nuclei recoil spectra. It was found that the variant with half-width (3.2 cm) tungsten plate located behind CFTM would be the most preferable one. It provides similar damage level at CFTM as the previous variant with full-width (6.4 cm) plates and the highest damage rate in beryllium irradiated at TRM.</td></tr>
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Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Tungsten spectral shifter: neutronics analysis (dpa evaluation, H, He and other impurities generation, recoil spectrum, etc) of different positions and geometries

Final report on the EFDA task TW5-TTMI-003, Deliverable 8

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October 2006

1. Introduction

The IFMIF facility is projected to reproduce irradiation conditions of fusion power reactors and to study the radiation properties of the fusion structural materials [1, 2]. So far many efforts have been undertaken for developing the computational tools and data and predicting the nuclear responses mainly in the low activated steel and tritium breeder materials [3 - 7]. It was shown that IFMIF irradiation conditions can perfectly meet helium, hydrogen and displacement production rates relevant for fusion reactor.

The objective of this task is the optimization of (i) the tungsten irradiation conditions in IFMIF to closer represent those in the divertor of the power fusion reactors and (ii) the tungsten spectral shifter plates position in front and behind the creep-fatigue testing machine (CFTM) to adjust the primary knock-on atom spectrum in the in situ creep-fatigue samples.

2. Tungsten nuclear response parameters in power fusion reactor divertor

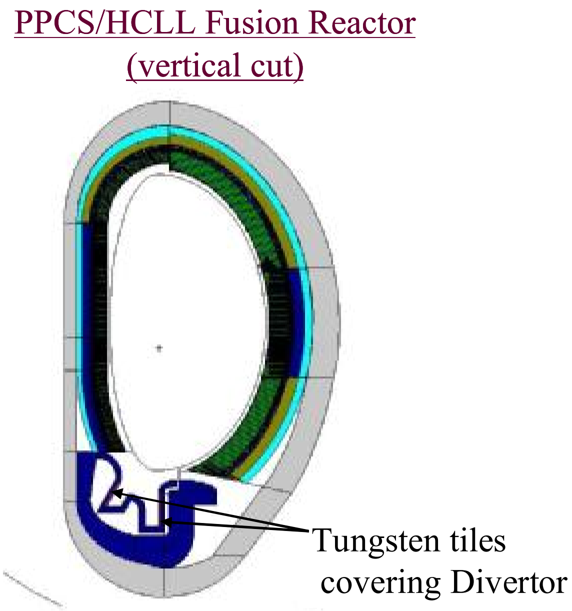


Fig.1. Vertical cut of the PPCS fusion power reactor with HCLL blanket

For the comparative tungsten irradiation conditions analyses the nuclear responses in the W tiles covering the diverter of fusion power reactor (Fig. 1) were calculated. This was done for a 4000 MW power reactor with helium cooled lithium lead blanket (HCLL) investigated in the Power Plant Conceptual Study (PPCS) [8]. The tungsten nuclear responses were calculated by the MCNP4C Monte Carlo code using a three-dimensional 20 degrees torus sector model and FENDL-2 cross section data for the neutron transport.

The results presented in Table 1 show that each tungsten atoms will be displaced 2.4 times from its lattice node during 1 full power operation of fusion reactor. The gas generation in tungsten will be dominated by hydrogen and helium production caused by neutrons at the levels of 2.3 appm and helium 0.7 appm, that give the gas to dpa ratios 1.0 and 0.3, correspondingly.

3. Tungsten irradiation parameters in IFMIF

The aim of this subtask is a search of location for the tungsten specimens in the IFMIF test modules or close to them, where the atom displacement rate and gas production ratio will optimally reproduce the ones expected in fusion power reactor.

3.1. Optimization of the tungsten specimens location

In the IFMIF facility the High, Medium and Low Flux Test Modules (HFTM, MFTM, LFTM) are located just behind Li-jet target to house the specimens for long term irradiations.

As a first step we have estimated nuclear responses in the tungsten specimens located there, supposing that they will partly replace the steel samples in the HFTM or can be easily allocated between pull-push rods of Universal Test Machine (UTM), which is a front part of MFTM (see Fig. 2). To perform such neutronics calculations the McDeLicious code [5] with recently updated and validated d-Li cross sections data (task TW4-TTMI-003, Deliverable D9) [6] were employed. For the representation of current IFMIF test cell design the global MCNP model developed in the frame of task TW4-TTMI-003, Deliverable D5a (TEKES, Finland) was used.

IFMIF: HFTM, Reflector, UTM (plan view)

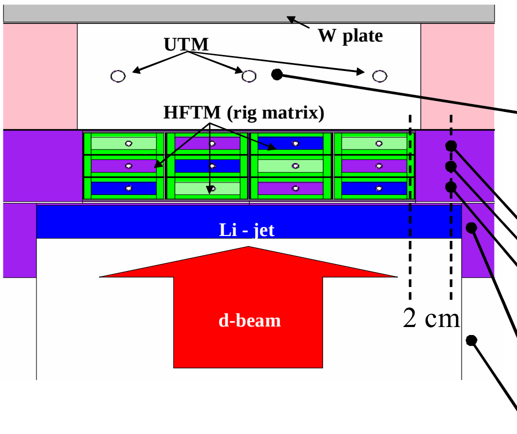
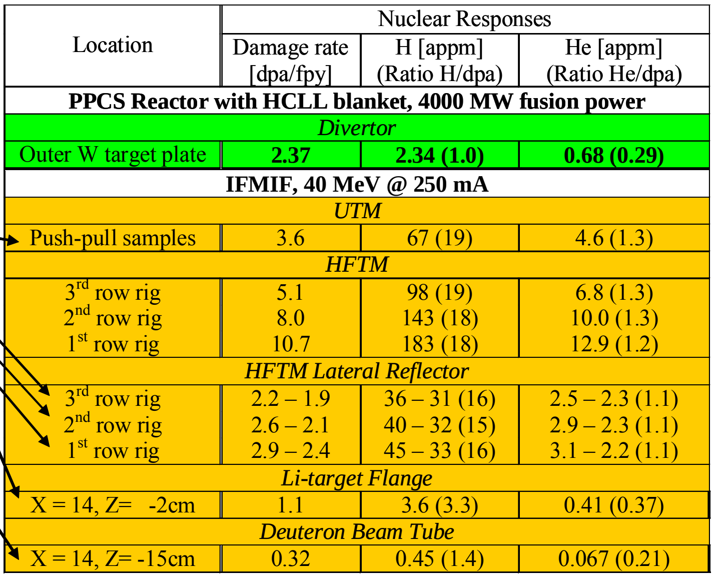


Fig. 2. Horizontal cut of the IFMIF test cell fragment: Li-jet, HFTM, neutron reflector, UTM and W plate.

Nuclear Responses: IFMIF vs. Fusion Reactor



Location	Nuclear Responses		
	Damage rate [dpa/fpy]	H [appm] (Ratio H/dpa)	He [appm] (Ratio He/dpa)
PPCS Reactor with HCLL blanket, 4000 MW fusion power			
Divertor			
Outer W target plate	**2.37**	**2.34 (1.0)**	**0.68 (0.29)**
IFMIF, 40 MeV @ 250 mA			
UTM			
Push-pull samples	3.6	67 (19)	4.6 (1.3)
HFTM			
3rd row rig	5.1	98 (19)	6.8 (1.3)
2nd row rig	8.0	143 (18)	10.0 (1.3)
1st row rig	10.7	183 (18)	12.9 (1.2)
HFTM Lateral Reflector			
3rd row rig	2.2 – 1.9	36 – 31 (16)	2.5 – 2.3 (1.1)
2nd row rig	2.6 – 2.1	40 – 32 (15)	2.9 – 2.3 (1.1)
1st row rig	2.9 – 2.4	45 – 33 (16)	3.1 – 2.2 (1.1)
Li-target Flange			
X = 14, Z= -2cm	1.1	3.6 (3.3)	0.41 (0.37)
Deuteron Beam Tube			
X = 14, Z= -15cm	0.32	0.45 (1.4)	0.067 (0.21)

Table 1. Tungsten nuclear responses in the divertor of fusion power reactor and at different locations inside IFMIF as indicated in Fig. 2.

The results listed the Table 1 show that atom displacement rate 3.6 dpa/fpy in tungsten could be achieved in UTM, if the specimens will be located between the push-pull rods. This already exceeds the dpa rate in the fusion power divertor. On other hand for the proper representation of the fusion reactor radiation conditions one needs to have the gas production to dpa ratios 1.0 for hydrogen and 0.3 for helium. As Table 1 shows during irradiation near UTM rods these ratios will amount 20 and 1.3, hence 20 - 4 times exceeding the fusion levels.

In the HFTM, even higher tungsten atom displacement rates (5 to 11 dpa/fpy) could be reached depending on the rig and row housing the specimens. But the gas-to-dpa ratios will also exceed fusion level by same large factor as in UTM.

The reasons of that are the difference of energy neutron spectra inside the fusion and IFMIF facilities and sensitivity of gas production reactions to the high energy neutrons. The fusion neutron spectra cut off at 15 MeV, whereas IFMIF ones produced by d-Li reaction extends up to 55 MeV (Fig. 3). The gas productions cross sections on tungsten such as (n,xp) and (n,xα) have thresholds around 10 MeV and increases one-two orders of magnitude as neutron energy goes up from 14 to 55 MeV (Fig. 4). The dpa cross section increases only two times in this energy range, being the same time non threshold reactions.

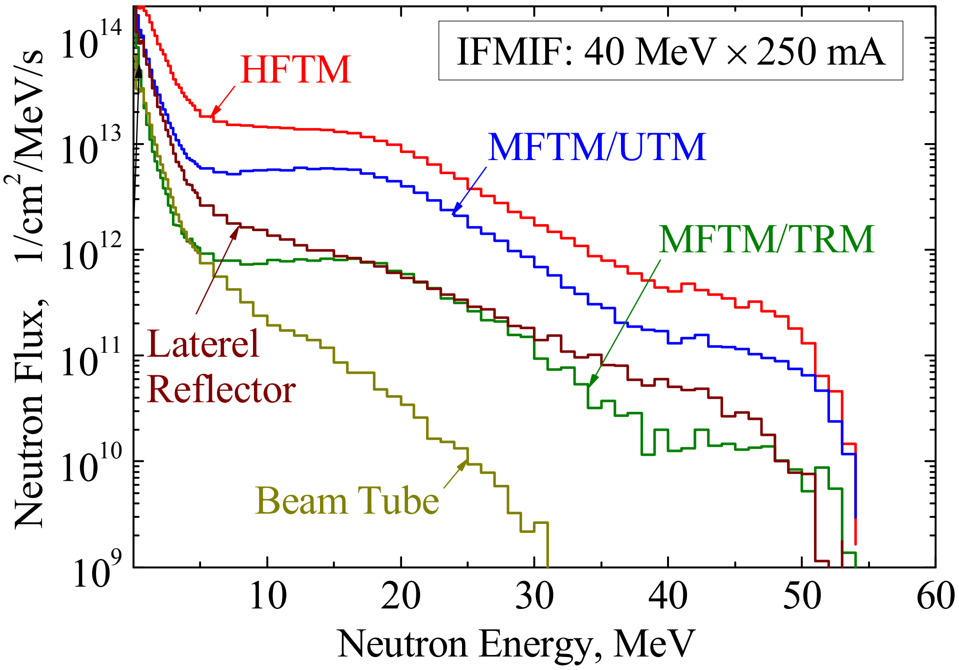


Figure 3. Energy differential neutron flux in the HFTM, MFTM, HFTM Lateral reflector and deuteron beam tube.

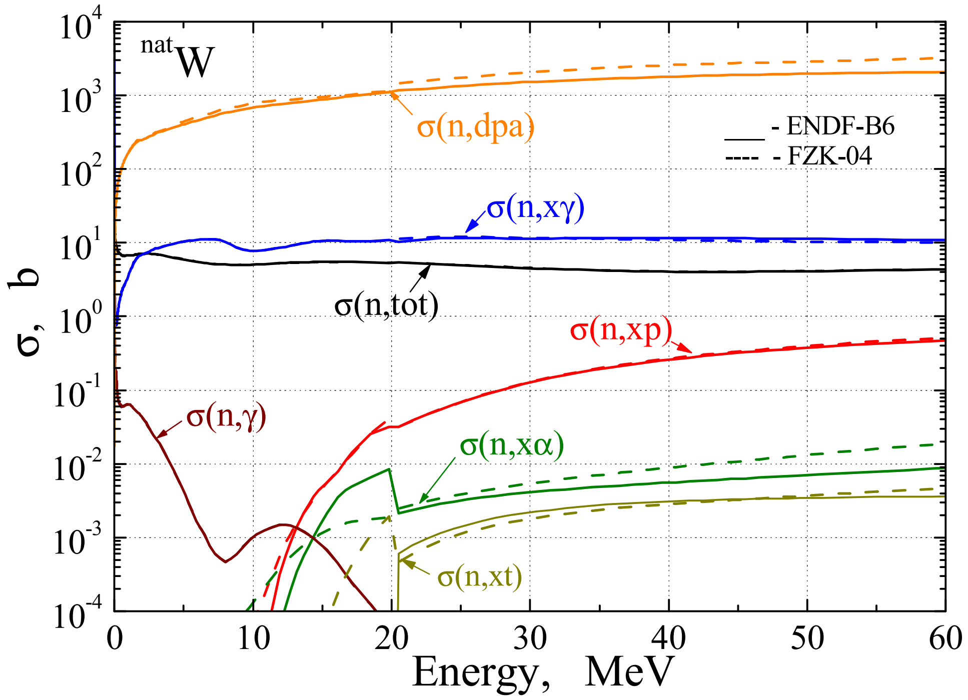


Figure 4. Neutron reactions cross sections for natural tungsten from ENDF/B-VI (solid curves) and FZK-04 (dash curves) libraries.

Principally, for the reproduction the fusion gas-to-dpa ratios in the IFMIF the tungsten specimens should be shifted in sideward or even backward directions relative to the deuteron beam direction, where the fraction of neutrons with energy more than 15 MeV essentially decreases (Fig. 3). We considered following geometrically possible spots for the samples as indicated in Fig. 2: the HFTM lateral reflector, lithium target flange and deuteron beam tube (inside the vacuum system).

Results of calculations are summarized in Table 1:

- location of the tungsten specimens inside the HFTM lateral reflector gives the acceptable dpa rate but the gas-to-dpa ratio as large as in HFTM and UTM;
- practically the same gas-to-dpa ratios as in the fusion reactor divertor could be achieved inside the deuteron beam tube, but at 0.3 dpa/fpy displacement rate which is 10 times less than fusion one;
- location of the W specimens in the flange of Li-target exhibits the intermediated option with dpa rate half of fusion one and gas-to-dpa ratios 3-2 times larger.

Further study is needed to clarify the possibility of the housing the tungsten specimens there regarding all engineering issues.

3.2. Dependence of results of calculations on nuclear data base

The results of estimation of nuclear responses in the tungsten depend on the neutron induced reactions cross section used in the calculations. As Fig. 4 shows, the agreement between ENDF/B-VI library and recent new evaluation FZK'04 [9] are quit reasonable up to 60 MeV. Nevertheless the differences for some specific reactions are visible and reach in the case of helium production even a factor of 5.

Table 2. Dependence of tungsten nuclear responses on nuclear data used in calculations.

Location	**Nuclear Responses**			**Neutron cross section Data**
	Damage rate [dpa/fpy]	**H [appm]**	**He [appm]**	
PPCS Reactor with HCLL blanket, 4000 MW fusion power ***Diverter***				
Outer W target plate	**2.37**	**2.34**	**0.68**	**ENDF-B6**
	2.45	**2.26**	**0.72**	**FZK-04**
	3.3%	**3.5%**	**5.7%**	**Difference**
IFMIF, 40 MeV @ 250 mA ***HFTM***				
3rd row rig	**5.1**	**98**	**6.8**	**ENDF-B6**
	5.8	**105**	**5.7**	**FZK-04**
	13%	**6.7%**	**18%**	**Difference**
2nd row rig	**8.0**	**143**	**10.0**	**ENDF-B6**
	9.0	**150**	**8.3**	**FZK-04**
	12%	**4.7%**	**19%**	**Difference**
1st row rig	**10.7**	**183**	**12.9**	**ENDF-B6**
	9.0	**150**	**8.3**	**FZK-04**
	17%	**20%**	**43%**	**Difference**

To estimate the influence of nuclear data base on final results we calculated tungsten nuclear responses with these two evaluations. The results listed in the Table 2. show that dependence of W nuclear responses on nuclear data amounts 3 to 6% for the case of fusion reactor calculations and 5 to 40% for IFMIF. The largest difference appears for gas production in tungsten, that emphasizing the necessity for experimental validation of the relevant cross sections in the IFMIF energy range.

4. Optimization of the Tungsten spectral shifter for reproduction fusion irradiation conditions in Medium Flux Test Module

Previous Monte Carlo simulations has shown that for the properly selected geometry IFMIF irradiation conditions can perfectly meet helium, hydrogen and displacement production rates relevant for DEMO reactor. Additional spectral shifter allows also fitting primary recoil spectrum so that the fraction of damage produced by recoils with the energy greater than given is very close to that of DEMO reactor.

Spectral shifter materials should withstand significant radiation and thermal loads being able to effectively modify neutron spectrum. Tungsten was selected as a spectral shifter material due to its high melting temperature, good thermal conductivity as well as good neutronics properties such as high scattering ability. The further sections describe the selection of the optimal geometry of spectral shifter plates (position, width) with the aim to reproduce DEMO irradiation conditions at creep-fatigue testing machine and tritium release module as close as possible (details are available in [10]).

4.1. Various positions of spectral shifter plates

Two tungsten spectral shifter plates positioned in front and behind the creep-fatigue testing machine (CFTM) were proposed for the adjusting of the primary knock-on atom spectrum at in situ creep-fatigue samples. Previous neutronics calculations showed that an adjusted spectrum perfectly matches that of the DEMO reactor at the first wall position.

Later during preliminary engineering design it was recognized that two plates would require too much design efforts and space for their cooling and temperature monitoring. Therefore designers suggested placing one plate of double width behind the CFTM. This part of the task is aimed at the study of consequences of such disposition for the change of irradiation conditions at CFTM and tritium release module (TRM).

Several geometry variants differing by the width and placement of tungsten spectral shifter plates were considered (see Figs. 5 - 9 and Table 3).

Table 3. Description of geometry variants.

Variant	Position relative to CFTM	Width, cm	Figure
md39	behind	6.4	5
md40a	in front	6.4	6
md40b	in front	3.2	7
md40c	behind	3.2	8
md40d	in front & behind	3.2	9

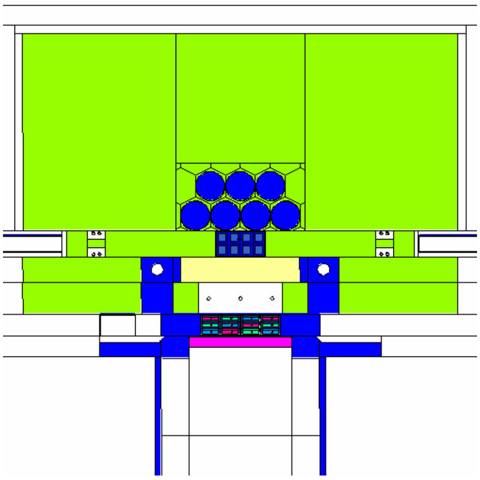


Figure 5. Double width plate (6.4 cm) behind CFTM: md39

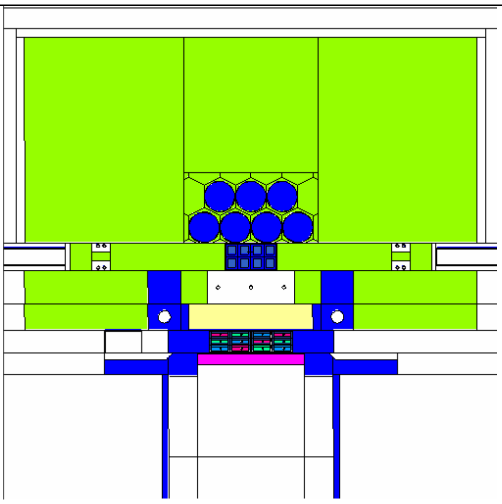


Figure 6. Double width plate (6.4 cm) before CFTM: md40a

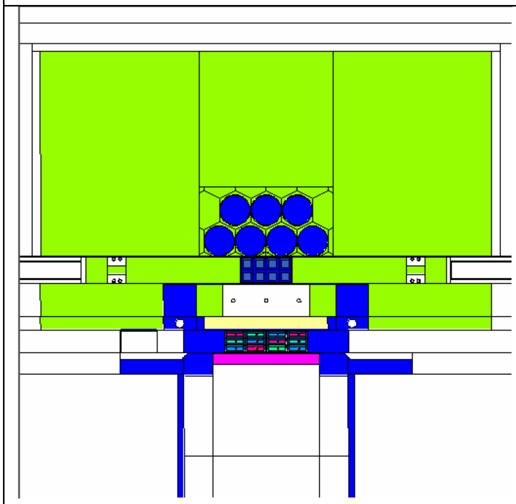


Figure 7. Half width plate (3.2 cm) before CFTM: md40b

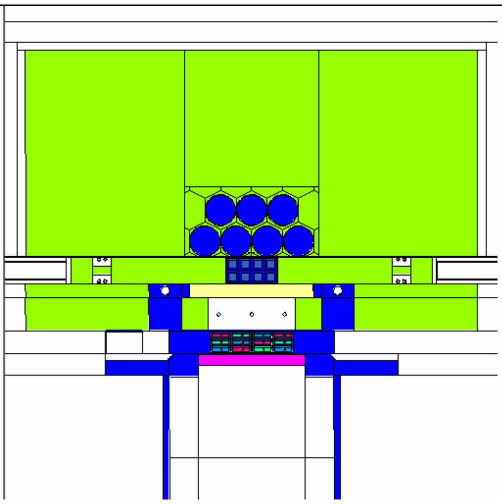


Figure 8. Half width plate (3.2 cm) behind CFTM: md40c

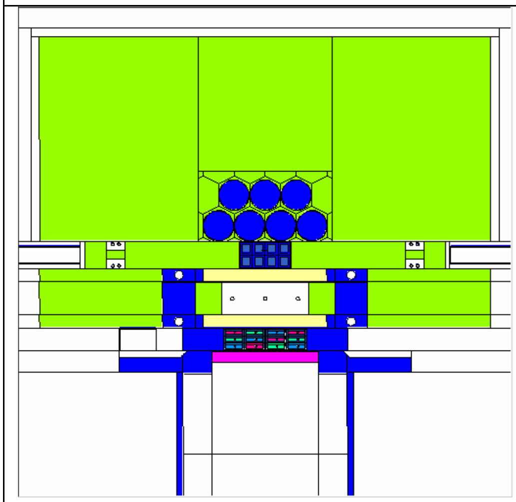


Figure 9. Two half width plates (3.2 cm) before and behind CFTM: md40d

Comments to Figures 5 - 9:
plot origin (0, 0, 24.5 cm)
plot scale (60, 60 cm).

4.2. Neutron spectra, damage and gas production at CFTM

Neutron transport calculations were performed using McDeLicious-05 code with an updated version of the evaluated d-Li reaction cross sections. The obtained neutron spectra for the discussed above IFMIF geometry variants and DEMO reactor are presented in Figure 10. The effect of the width of the spectral shifter plate positioned in front of CFTM is clearly visible as a change of the shoulder height in the range 1 - 20 MeV. This part of the neutron spectrum is effectively shifted to the low neutron energy by the tungsten plate.

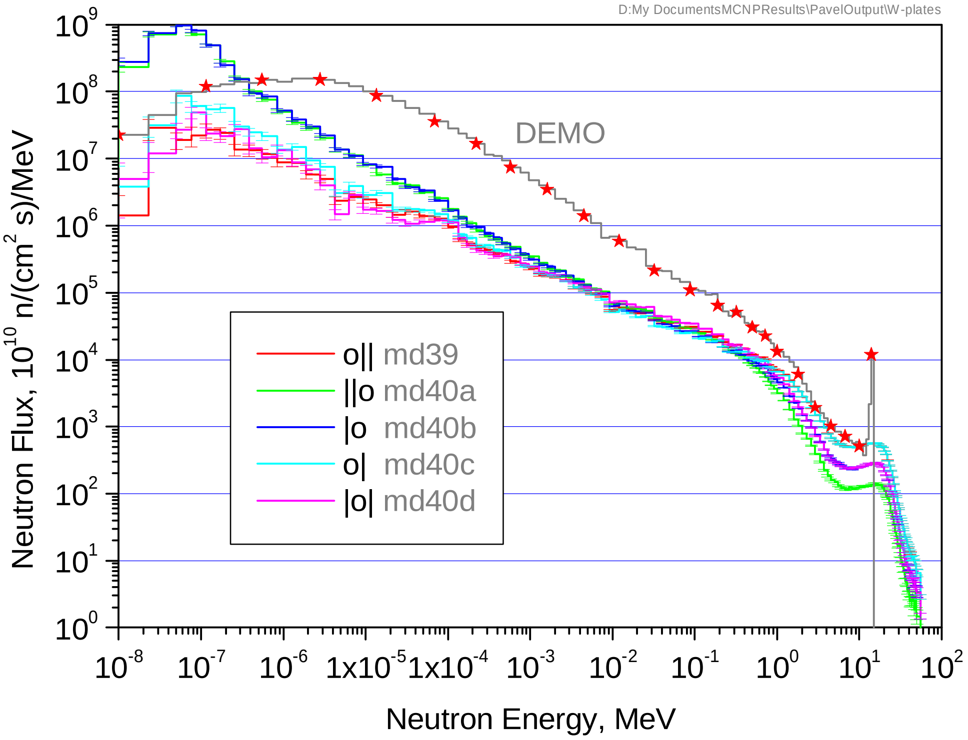


Figure 10. Differential neutron spectra at CFTM position in comparison with the DEMO First Wall spectrum.

The plate placed behind the CFTM reflects neutrons back further decreasing neutron flux available at TRM. The efficiency of thermal neutron absorption slightly increases with the plate thickness (cf. md39 and md40c). Damage and gas production rates in iron located inside the central creep-fatigue specimen are collected in Table 4.

Table 4. Iron irradiation conditions for the central creep-fatigue specimen (cell 5021) at CFTM.

Variant	Flux, 10^{14} n/cm^2/s	Damage, dpa/fpy	He appm/fpy	H, appm/fpy
md39	3.33	11.76	75.4	215.2
md40a	1.81	3.50	18.4	52.3
md40b	2.30	6.26	37.2	106.0
md40c	3.16	11.64	75.4	215.1
md40d	2.53	6.48	37.2	105.9

As could be expected very similar results were obtained for the variants with full (md39) and half-width (md40c) W-plates behind CFTM. The plates placed in front of the CFTM gradually degrease damage and gas production rates with increasing plate thickness. Qualitatively similar results were obtained during preliminary study performed before the availability of the global geometry IFMIF model [Report TW0-TTMI-003-D10, 2002]. The results of damage rate in beryllium placed at TRM are presented in Table 5.

Table 5. Beryllium irradiation conditions at the first row of TRM.

Variant	Flux, $n/cm^2/s$	Damage, dpa/fpy
md39	$9.73x10^{13}$	3.23
md40a	$1.33x10^{14}$	2.76
md40b	$1.69x10^{14}$	3.74
md40c	$1.81x10^{14}$	4.22
md40d	$1.32x10^{14}$	2.91

Differential primary recoil spectra are qualitatively similar to that for DEMO First Wall (see Fig. 11). Considerable difference is observed only at energies lower than 300 eV.

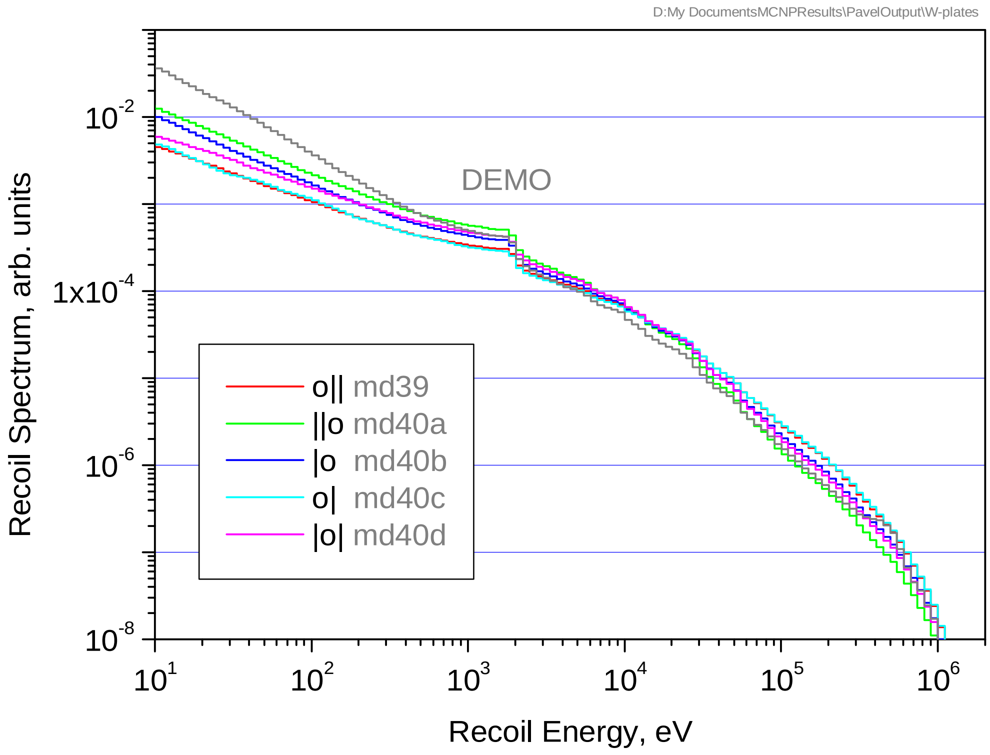


Figure 11. Differential recoil spectra at CFTM position for various geometry configurations versus DEMO First Wall recoil spectrum.

However, even a small difference in the high-energy portion of the spectrum could result in substantial change of radiation damage rates. For example, damage produced at the central creep-fatigue sample varies in the range from 3.5 up to 11.8 dpa/fpy. It can be seen from

Table 3 that maximum damage rate at CFTM is obtained for the variants (md39, md40c) where tungsten plates are placed behind CFTM. For the plate of full-width the damage rate is slightly larger than that for the half-width due to the more effective neutron backscattering from the thicker plate.

It is expected that damage at TRM decrease with the width of W-plates placed in front of TRM. Indeed, thick tungsten plate noticeably reduces damage rate at TRM (cf. 3.50 dpa/fpy for the full-width plate (md40a), 6.26 dpa/fpy for the half-width plate (md40b) and 11.64 dpa/fpy for the half-width plate placed behind CFTM (md40c)). In contrary, damage rate for the variant with half-width plate behind CFTM (md40.c) is even slightly higher than for the variant without W-plates (fw21.6) from our previous study. It might be related to the presence of the extended carbon reflector in variants considered in the present report.

Fraction of damage produced by recoils with an energy greater than given energy T, so called W(T) function, is plotted in Figure 12. It can be seen from the Figure that good approximation to the DEMO curve is provided by the variants md39, md40c and md40b.

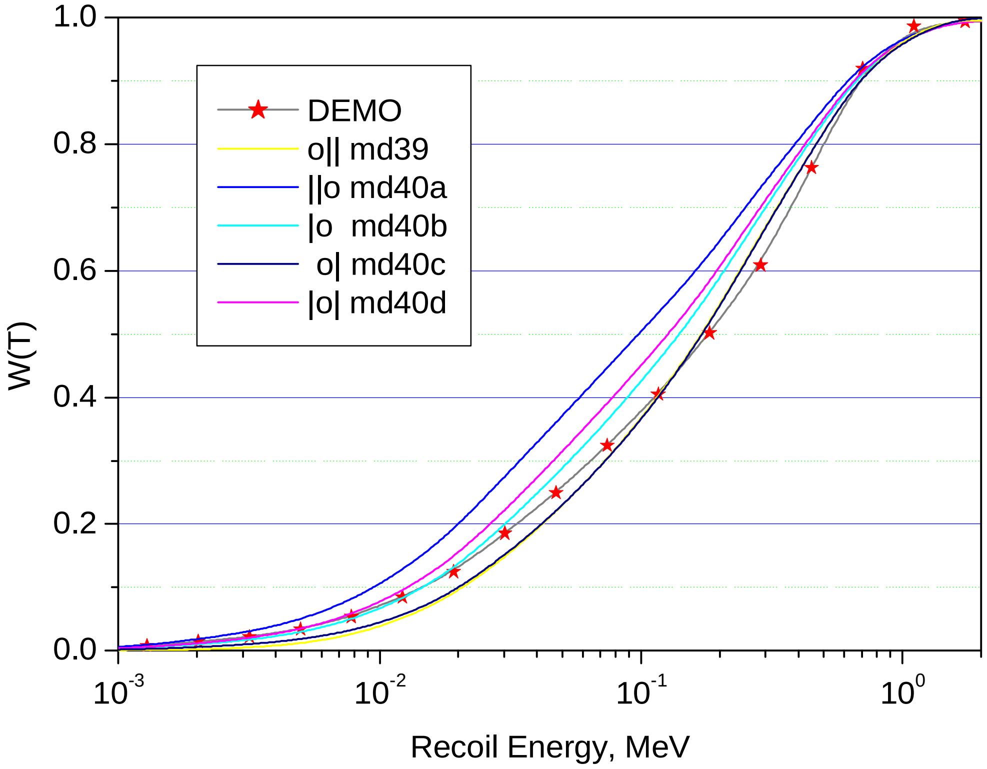


Figure 12. Fraction of damage produced by recoil with energy greater than given for various geometry configurations.

Conclusions

The nuclear responses in the tungsten under irradiation parameters for 4000 MW power reactor with helium cooled lithium lead blanket have been calculated. To reproduce them in the IFMIF facility the relevant calculations have been performed at several locations: inside the High Flux Test Module (HFTM) and its lateral neutron reflector, between the pull-push rods of the Universal Test Machine (UTM), in the lithium target flange and inside deuteron beam vacuum tube. The calculations have been performed by the McDeLicious code using a detailed 3-d geometrical model of the entire IFMIF test cell. In this approach the recently updated d-Li evaluated cross section data and high energy neutron transport cross sections from LA-150, ENDF/B-VI and FZK/INPE-50 libraries were employed.

The comparison of the tungsten nuclear responses has shown that the atom displacement damage rate (dpa) inside UTM and HFTM is 1.5 - 4.5 times higher than for the fusion power reactor divertor and is comparable in the cases of the HFTM lateral reflector. The gas-to-dpa production ratio for tungsten irradiated there, however, exceeds that of the fusion power reactor divertor by several times due to the IFMIF neutron spectrum which extends above 14 MeV. Desirable ratio could be obtained in deuteron beam tube, but dpa rate there drops by one order of magnitude below fusion one. Some kind of compromise could be reached in the lithium target flange, where dpa under- whereas gas-to-dpa ratio over-rate the fusion levels by factor of 2-3.

The comparison of the nuclear responses calculated with different evaluated cross sections files (ENDF-B6 and FZK-04) reveals the spread of 3 - 40%.

If a degree of approximation of W(T) is considered to be the major criterion for recoil spectra optimization together with the damage rates at CFTM and TRM, than the variant with half-width tungsten plate located behind CFTM (md40c) seems to be the most preferable one. It provides similar damage level at CFTM as the variant with full-width plates and the highest damage rate in beryllium irradiated at TRM.

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