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On the effects of the supporting frame on the radiation-induced damage of HCLL-TBM structural material

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Abstract

Within the European Fusion Technology Programme, research activities have been conducted on the Helium-Cooled Lithium Lead (HCLL) breeding blanket concept with the aim of manufacturing a Test Blanket Module (TBM) to be irradiated in ITER. HCLL-TBM is planned to be located in an ITER equatorial port, housed inside an AISI 316 stainless steel-supporting frame. Since that frame has been designed to provide two positions separated by a dividing plate and the HCLL-TBM is expected to fill one of them, its nuclear response could vary depending on the filling status of the other position and on the plate thickness. A parametric study has been carried out to investigate the potential effects on the radiation-induced damage of the HCLL-TBM structural material, due to the dividing plate thickness and to the presence of either a void, a water-cooled steel plug, or a Helium-Cooled Pebble Bed TBM in the adjacent frame position.

1. Introduction

Within the European Fusion Technology Programme, intense research and development activities have been conducted on the Helium-Cooled Lithium Lead (HCLL)-Test Blanket Module (TBM) to be irradiated in ITER [1]. In the framework of those activities, the Department of Nuclear Engineering of the University of Palermo (DIN) has been involved in the investigation of the TBM nuclear response in ITER, that is mandatory for the determination of its thermal-hydraulic and thermal-mechanical performances. In particular, a research campaign has been launched to determine the nuclear power deposited by neutrons and photons, tritium breeding and radiation-induced damage of the structural material, following a computational approach based on the Monte Carlo method.

Initially, attention has been focused on the module nuclear performance and the main results obtained have been reported in [2]. Later, the potential influence of the supporting frame configuration has been taken into account, since it could have a strong impact on the HCLL-TBM nuclear response. In fact, since HCLL-TBM is planned to be located in an ITER equatorial port inside a steel-supporting frame separated into two positions by a dividing plate and provided that it fills just one of them, its nuclear response could vary according to the filling status of the adjacent position as well as to the thickness of the dividing plate.

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Therefore, a parametric study has been launched at DIN to investigate the possible dependence of the HCLL-TBM nuclear response on the frame configuration, following the aforementioned numerical approach. In particular, thicknesses of the dividing plate ranging from 0 to the reference value (20 cm) and frame configurations with either a void, a water-cooled steel plug or a Helium-Cooled Pebble Bed (HCPB) TBM in the lower position have been taken into account.

Three-dimensional Monte Carlo neutronic and photonic analyses have been performed by means of MCNP-4C [3] code running on a cluster of four workstations through the implementation of a parallel virtual machine. A large number of histories (2×10^7) have been simulated so that the results obtained have statistical uncertainties lower than 1%. FENDL2 [4] transport cross section libraries have been used for the calculations.

The results on nuclear power distribution and tritium breeding can be found in [5], while the present paper is focused on the radiation-induced damage of the HCLL-TBM structural material.

2. The models

Three-dimensional models of both HCLL-TBM and the supporting frame have been set up for the various configurations considered and they have been input to an existing three-dimensional semi-heterogeneous model of ITER [6]. It represents 1/18 of the whole reactor toroidal extension (20°) and it is centred between two adjacent ports of the vacuum vessel. Two poloidal–radial reflecting planes limit its toroidal boundaries, simulating the reactor's continuity along that direction. A D–T plasma neutron source has been implemented in the model to be used for the calculations [6].

For the HCLL-TBM model, a toroidal lay-out has been assumed rather than the poloidal one outlined in [1] and adopted in the previous study [2]. The reason for that assumption is to be found in the particular configuration of the ITER model that includes two half equatorial ports limited, at their toroidal mid-planes, by reflecting surfaces. Therefore, the choice of the toroidal lay-out permitted simulating two distinct frame positions, allowing the option of modelling just one half of the whole supporting frame.

A three-dimensional heterogeneous model has been set up, located inside the upper position of the frame (Fig. 1). It realistically reproduces the main features of the HCLL-TBM structure [1], being mainly composed of a Segment Box (SB), a Breeder Zone (BZ) and a set of Cooling Plates (CPs).

The SB is a helium-cooled steel box that contains the Pb–Li eutectic alloy. It is mainly composed of a First Wall (FW), two Side Walls (SWs), a set of Stiffening Plates (SPs), a Top Cover (TC), a Bottom Cover (BC) and a Back-Plate (BP). Reduced-activation 9% Cr martensitic steel, named EUROFER, has been assumed as the structural material. The rectangular cooling channels inside FW and SWs have been realistically modelled, unlike the SPs and Covers where the channels and structure have been simulated by means of homogeneous slabs of a proper mixture of helium and EUROFER.

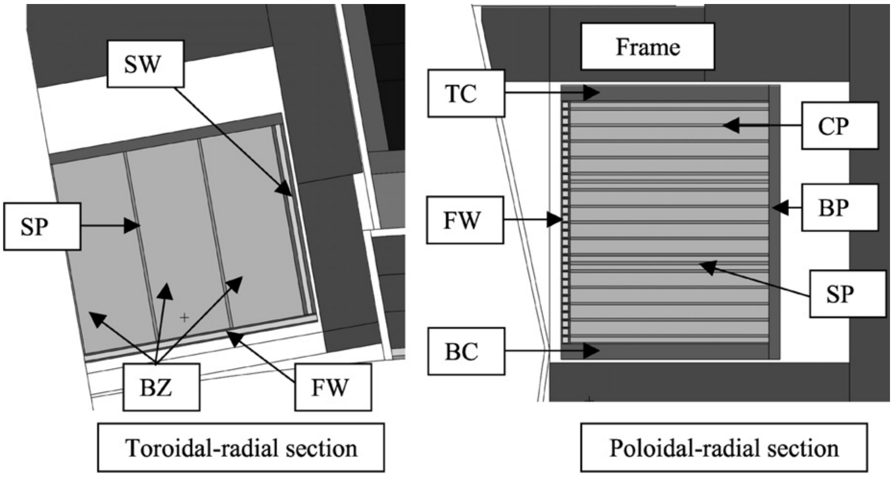

Fig. 1. Poloidal–radial and toroidal–radial sections of the HCLL-TBM model.

The BZ is subdivided in 24 breeder units, each mainly composed of Pb–Li liquid metal eutectic alloy (90% Li^6 enriched).

The purpose of CPs is to extract the thermal power deposited in each single breeder unit by neutrons and photons. According to [1] five of them cool each breeder unit. They have been modelled as homogeneous toroidal–radial slabs composed of a proper mixture of helium and EUROFER.

A homogeneous model has also been set up for the steel-supporting frame, assuming the frame to have the same composition of the typical ITER shielding blanket module in terms of water and AISI 316 stainless steel (20% and 80% in weight, respectively). In particular, three frame models have been developed, characterized by dividing plates that are 0, 10 and 20 cm thick. For each of these, three different filling statuses have been considered for the lower position, according to the presence of either a void, a steel plug, or a HCPB-TBM.

For the HCPB-TBM [7] a lay-out similar to the HCLL has been assumed, except for BZ. In fact, the typical breeder unit has been modelled as composed of toroidal–radial slabs of beryllium or lithium orthosilicate (Li_4SiO_4 – 90% Li^6 enriched) alternated along the poloidal direction and

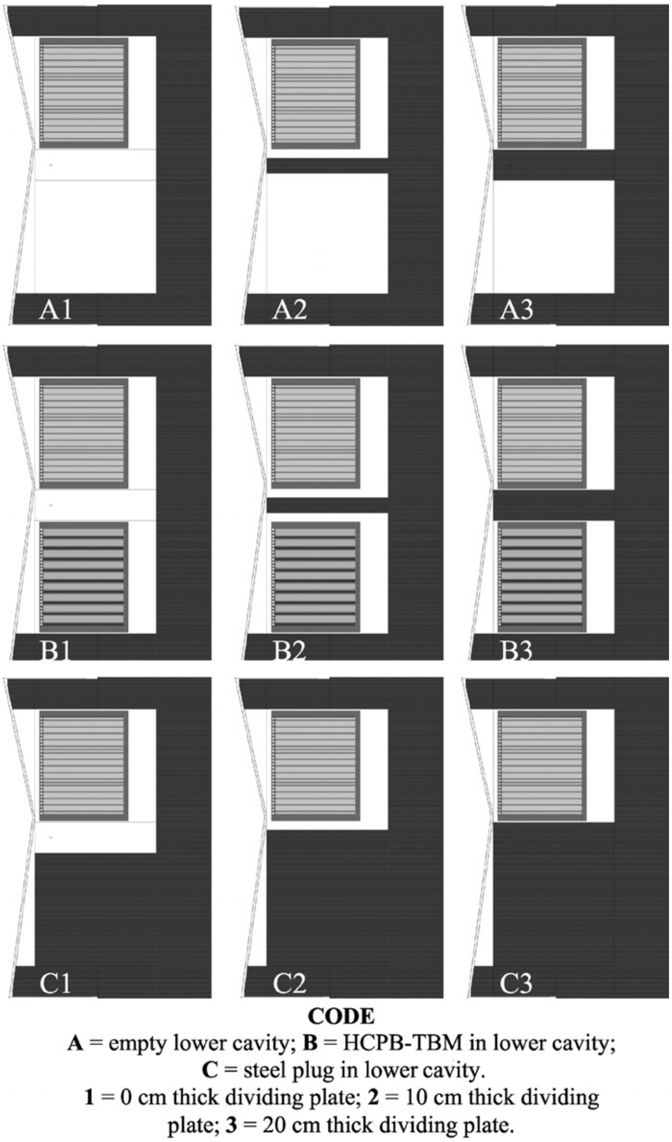

Fig. 2. Frame configurations investigated.

separated by CPs. Finally, the plug has been modelled as a homogeneous mixture of water and steel (20% and 80% in weight, respectively). In total, nine frame configurations have been taken into account. Details and labels are shown in Fig. 2.

3. The results

The potential impact of the frame configuration on radiation damage of the HCLL-TBM structural material has been investigated by carrying out a numerical analysis for each of the nine configurations considered. Attention has been paid to both the rates of Displacements Per Atom (DPA) and helium production within BC, where the influence of frame configuration is more important and not negligible as in the rest of the module.

Since the module nuclear response is expected to undergo small variations along the toroidal direction, they have not been investigated to reduce the time needed for calculations. Therefore, to investigate the influence of either the dividing plate or the filling status of the frame's lower position, the radial profiles relevant to both the different dividing plate thicknesses for each filling status and the different filling statuses for each dividing plate thickness have been reported.

Moreover, in the former case radial profiles have been normalized to that obtained in the absence of the dividing plate while, in the latter, the 'virtual' case of void has been chosen as reference.

Finally, calculations have been carried out by assuming an ITER duty cycle of 0.22 and by supposing a full power pulsed plant operation for a whole year.

Table 1 shows the maxima of the radial profiles used to normalize the results. All these maxima are obtained at the radial depth $r = 1.25$ cm, which is the centre of the first cell of the BC numerical grid.

Table 1
Maxima of the radial profiles used to normalize the results

	Models	Maxima
DPA rate (DPA yr^{-1})	B1	1.020
	C1	1.000
	A2	1.012
	A3	1.013
Helium production rate (appm yr^{-1})	B1	10.988
	C1	10.961
	A2	10.985
	A3	10.905

3.1. Displacements per atom

The radial profiles for the DPA rate along BC have been determined by adopting the displacement cross sections for iron taken from ASTM standards [8] and the most significant results obtained have been reported in Figs. 3 and 4. In particular, Fig. 3 shows the normalized radial profiles as a function of the dividing plate thicknesses considered for the most interesting filling statuses of the lower position (Cases B and C), while Fig. 4 shows similar profiles depending on the filling status analysed for 10 and 20 cm plate thicknesses (Cases 2 and 3).

From the analysis of the results, it can be concluded that DPA within BC is mainly determined by two classes of neutrons. The first includes neutrons from the plasma or those reflected within the gap between BC and the dividing plate. The second class comprises neutrons transmitted from the lower position through the dividing plate. It follows that

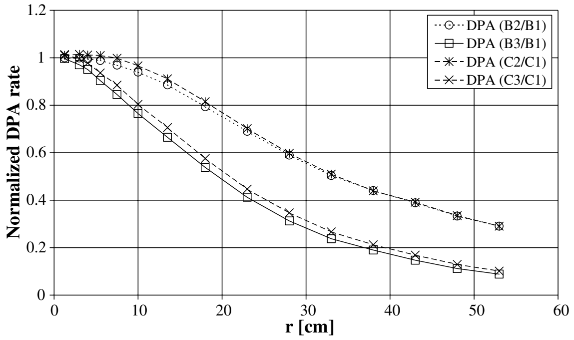

Fig. 3. Normalized radial profiles of the DPA rate within Bottom Cap obtained when the frame lower position houses an HCPB-TBM or a steel plug (Cases B and C).

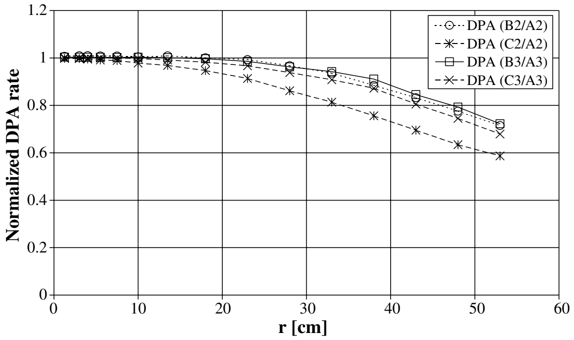

Fig. 4. Normalized radial profiles of the DPA rate within Bottom Cap obtained when the dividing plate is 10 or 20 cm thick (Cases 2 and 3).

for a given filling status, the thicker is the dividing plate and the lower is its gap with BC, the fewer are the neutrons reflected and transmitted, so inducing a local shielding effect as shown in Fig. 3. The progressive decrease of both neutron reflection and transmission along the BC radial depth explains the increase of the nuclear shielding effect in that direction, that can be observed in Fig. 3. Moreover, when the dividing plate thickness is 20 cm and the gap is negligible, the DPA radial profiles are quite independent on the filling status of the lower position (Fig. 4). Otherwise, when the dividing plate is thinner (10 cm) and the gap increases, the contribution within BC of both reflected and transmitted neutrons becomes significant, allowing the DPA rate radial profiles to differ according to the filling status of the lower position (Fig. 4). In particular, the presence of beryllium within HCPB-TBM enhances neutron multiplication and, consequently, increases the DPA with respect to the case of a steel plug (Fig. 4).

3.2. Helium production

In order to study the variation of the helium production rate, radial profiles have been evaluated along the BC structural material. The results reported in Figs. 5 and 6 allow separating the influence of the dividing plate and of the filling status of the frame's lower position.

As far as the dividing plate is concerned, from the analysis of Fig. 5, it can be argued that the plate behaves as a nuclear shield whose effect increases along the radial direction. In particular, the HCLL-TBM helium production rate appears to be a slightly decreasing function of the dividing plate thickness.

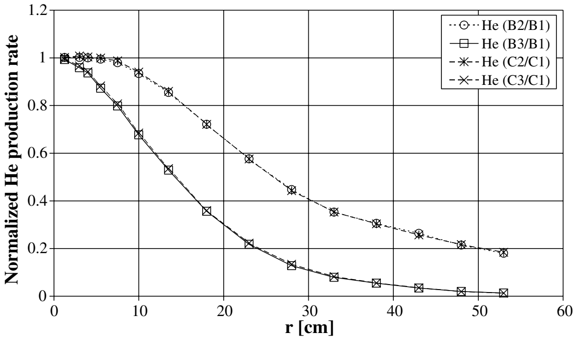

Fig. 5. Normalized radial profiles of the helium production rate within Bottom Cap obtained when the frame's lower position houses an HCPB-TBM or a steel plug (Cases B and C).

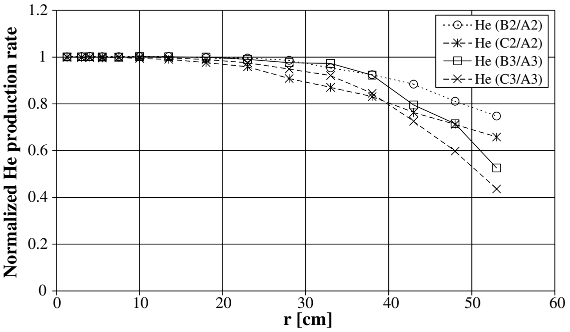

Fig. 6. Normalized radial profiles of the helium production rate within Bottom Cap obtained when the dividing plate is 10 or 20 cm thick (Cases 2 and 3).

As far as the filling status of the frame's lower position is concerned, the normalized radial profiles shown in Fig. 6 suggest that the helium production rate is higher in the presence of an HCPB-TBM than in the case of a plug. This is an effect of both neutron multiplications, higher in HCPB-TBM due to beryllium, and neutron absorption, more intense within the plug due to the presence of a homogeneous mixture of water and steel.

4. Conclusions

At DIN a research campaign has been launched to investigate the potential impact on the HCLL-TBM nuclear response of the possible configurations of the steel frame designed to house it inside an ITER equatorial port. In particular, attention has been focused on either the thickness of the frame dividing plate or the filling status of the frame's lower position. A computational approach based on the Monte Carlo method has been followed and a detailed parametric study has been carried out varying the thickness of the dividing plate from 0 to the reference value (20 cm) and assuming, for each case, the presence of either a void, a water-cooled steel plug, or a HCPB-TBM in the other frame position.

In this paper attention has been focused on radiation damage, evaluating DPA and helium production rates within the structural material of BC. The parametric analyses suggest that the dividing plate behaves mainly as a nuclear shield, the effect of which becomes significant towards the back of the module. As to the filling status of the frame's lower position, the study has indicated that the presence of a TBM induces within BC a higher level of radiation-induced damage, in terms of both DPA and helium production rates, if compared to the one obtained in the presence of a steel plug.

Finally, it should be pointed out that since the effects of the frame configurations on the HCLL-TBM nuclear response depend on neutron reflection, capture and inelastic scattering within the supporting frame and provided that those phenomena can be strongly affected by frame modelling, an appreciable impact on the HCLL-TBM nuclear response can be expected if a heterogeneous model is adopted. Therefore, the DIN research campaign continues to further investigate the effects of heterogeneous modelling of the whole supporting frame.

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