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ORIGINAL RESEARCH

Neutronics assessment for Detailed Helium-Cooled And Water-Cooled DEMO Breeder Blanket Concepts

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Abstract

The Water-Cooled Lithium–Lead Breeding Blanket (WCLL) and Helium-Cooled Pebble Bed (HCPB) are two leading breeding blanket concept candidates to become the driver blanket for the EU-DEMO reactor. As a breeding material, WCLL uses Lithium–Lead alloy, HCPB uses lithium orthosilicate, and all breeding units have tubes for cooling purposes. The same concepts, as neutrons multiplier, use Li–Pb alloy and Be. The estimation of neutron fluxes, nuclear heating and dose rates are essential to assess the nuclear performance of the breeding blankets. It is a necessary calculation that supports the design of the two breeder blanket concepts of the DEMO nuclear fusion reactor. Two widely used codes, MCNP6 with FENDL-3.2 nuclear data library and ADVANTG, which employs the FW-Cadis method to reduce the variance of Monte Carlo simulation results, were used in this paper.

Keywords MCNP · DEMO · Neutron flux · Dose rate

Introduction

A fusion demonstration reactor (DEMO) is assumed to be a near-term reactor facility that can generate electricity and operate in a self-sufficient tritium fuel cycle [1]. The development of a breeding blanket is one of the most important and challenging issues in the DEMO project due to its novelty and numerous technical and safety problems to be solved. There are two breeding blanket concept candidates that might be used as the driving blanket for the EU-DEMO reactor: the Water-Cooled Lithium–Lead Breeding Blanket (WCLL) and the Helium-Cooled Pebble Bed (HCPB).

Neutronics analysis is a crucial part of the fusion reactor design process, traditionally using MCNP [2]. While the geometry of fusion reactors such as the European Fusion Demonstration Reactor (EU DEMO) becomes increasingly complex, the corresponding MCNP constructive solid geometry (CSG) model requires many material and void cells, surfaces, and universes, thus complicating and prolonging the modelling process.

Over the past few years, several analyses were performed relevant to the activities of this paper. It should be noted that the neutron flux estimation was made by U. Fisher [3] in 2016. In Ref.3 paper, there were evaluated four blanket modules not considering detailed structure. In addition to the flux estimation, DPA (displacement damage per atom), power density, TBR (tritium breeding rate) and neutron flux were included in the calculations. Another example is where a more detailed model was estimated as described in Hernandez A. [4] paper. The author made neutronics calculations for the HCPB breeding blanket, and the evaluated neutron flux was reported in just one fuel–breeder pin. Finally, F. Moro [5] did a neutronics analysis to support WCLL as the better candidate to be the breeding blanket in the EU DEMO fusion reactor.

This paper presents the estimated neutron fluxes, nuclear heating, and dose rates at the breeding blanket area when heterogenized HCPB and WCLL concepts are used.

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Computational Tools, Data and Geometry

Model Description

Neutron transport calculations were performed using 3D Monte Carlo particle transport simulations using the proposed MCNP code, widely evaluated and validated in neutron fusion applications. Therefore, the 11.25° DEMO Base Line 2017 [6] with the heterogeneous breeding blanket module was used for calculations in this paper. One can see employed models in Fig. 1, where Helium Cooled Pebble Bed (HCPB) [7] and Water-cooled Lithium Lead (WCLL) [8] are represented in more detail.

HCPB

HCPB breeding blanket for DEMO has 7 segments in the inboard part and 7 at the outboard and is based on a multi-module segment configuration. Each component can be subdivided into three radial zones:

- The First Wall (FW)—its primary purpose is to protect the further reactor from neutrons and provide a suitable heat transfer area for the plasma heat. FW's first layer is made of Tungsten and the rest of Eurofer.
- The Breeding Zone (BZ) main purpose is to breed Tritium. The BZ comprises layers with pebble beds of Li_4SiO_4 (breeder material) with a diameter from 0.25 to 0.63 mm and Be (neutron multiplier) with a diameter of 1 mm. These layers also include cooling plates/pipes.

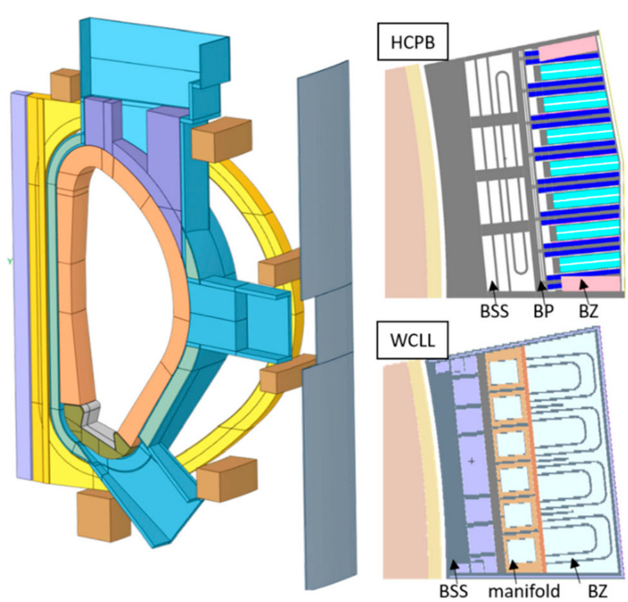

Fig. 1 Envelop the blanket design of DEMO (***left***), the MCNP model of HCPB (***top right***) and the WCLL fully heterogeneous breeder blanket design (***bottom right***). [9]

- The Back Supporting Structure (BSS) primary purpose is to hold the segments in their positions [10].

The graphical representation of the MCNP model plot is shown in Fig. 2, where the locations of FW, BZ and BSS are outlined in the general view of BB.

WCLL

In the DEMO CAD model, the WCLL blanket design is based on a single module segmentation (SMS), and all structural elements are made of Eurofer. The 25-thick mm U-shape housing is attached to the 100 mm thickness back supporting system (BSS). Ahead the BSS, water manifolds are located, and mainly used to cool down FW and BZ, where water temperature varies between 295 and 325 °C and pressure reaches 155 bar.

The breeding zone is filled with cooling pipes and breeding elements: pipe water is used as a coolant, and PbLi (90% enriched with Li6) is used as breeding material and a neutron multiplier. Square steel pipes separate breeding inner and outer materials, and BZ is divided into

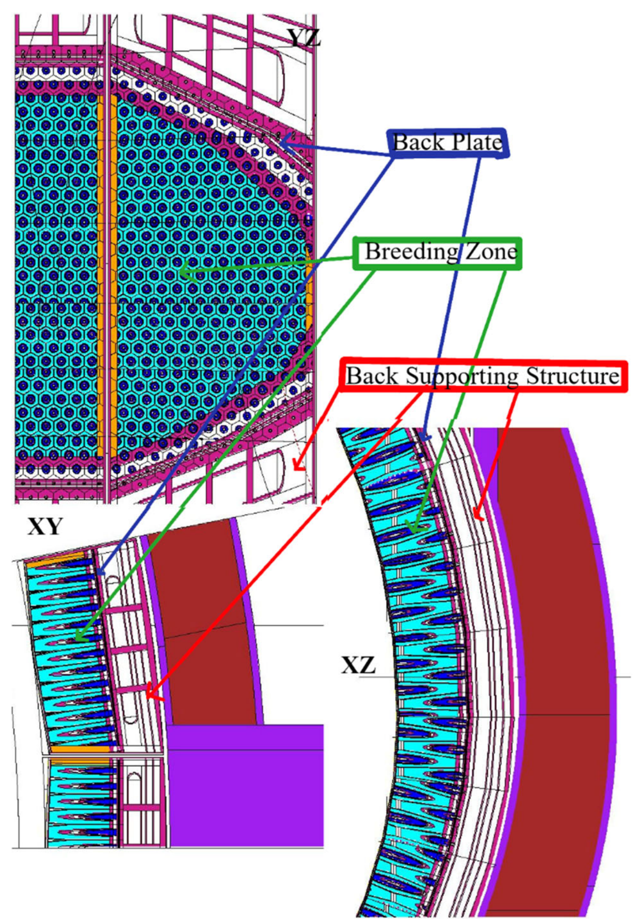

Fig. 2 The MCNP model of HCPB fully heterogeneous breeder blanket design, view from different planes[11].

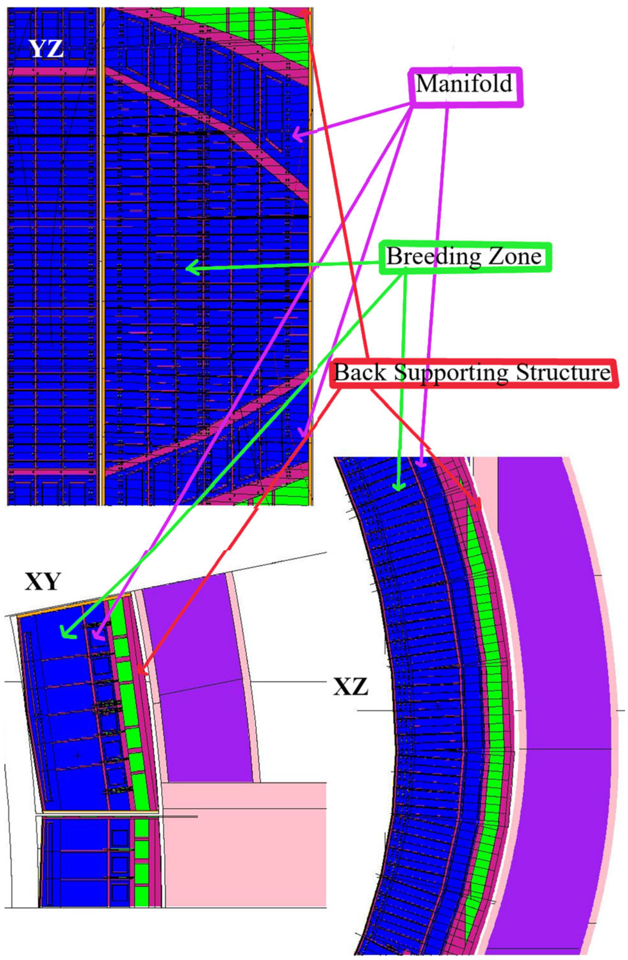

Fig. 3 The MCNP model of WCLL fully heterogeneous breeder blanket design, view from different planes [11].

small squares with stiffening plates that confine the PbLi flow [12]. For the general view of the BB MCNP model with the outlined locations of FW, BZ, and BSS, see Fig. 3. In addition, one should note that the geometrical cross-sections of the BB models correspond to the ones in Fig. 2, and the calculation results are displayed along the same planes as well (adress to Ref. [11] for more detailed description of the simulation model).

Methodology

MCNP 6.2 code is widely recognized for neutron transport calculations and used for fusion neutronics applications [13]. The neutron decay data were taken from Fusion Evaluated Nuclear Data Library—FENDL-3.2 [14], where fission yields, DPA, and activation data are also included.

For variance reduction purposes, the ADVANTG [15] code with FW-CADIS (Forward-Weighted Consistent Adjoint Driven Importance Sampling) method was used. The outcome of ADVANTG is weight windows bounds. Weight windows are based on space-specific and energy-dependent meshes and create the three-dimensional discrete ordinate outputs determined with the Denovo code [15]. One of the outcomes of using weight windows is the reduced statistical error and computation time when dealing with the geometry is as complicated as the EU DEMO MCNP model with heterogeneous components. The generated weight windows plotted over the geometry can be seen in Fig. 4.

In order to evaluate the safety aspects, which were identified in the introductory section of this paper, several quantities were calculated in this work. As mentioned before, the neutron flux plays an important role in neutronics, thus, the standard F4 MCNP mesh tally was used, and the estimated flux was normalized to 7.09×10^{20} n/s, which is equivalent to the DEMO 1998 MW fusion power.

In addition, the dose rate equivalent H was calculated from neutron flux $\phi(V)$ using the formula [13]:

$$H = \sum \phi(V) * h \quad (1)$$

where h—fluence-to-dose conversion coefficient. In this work, isotropic factors were taken from ICRP publication 116 [16].

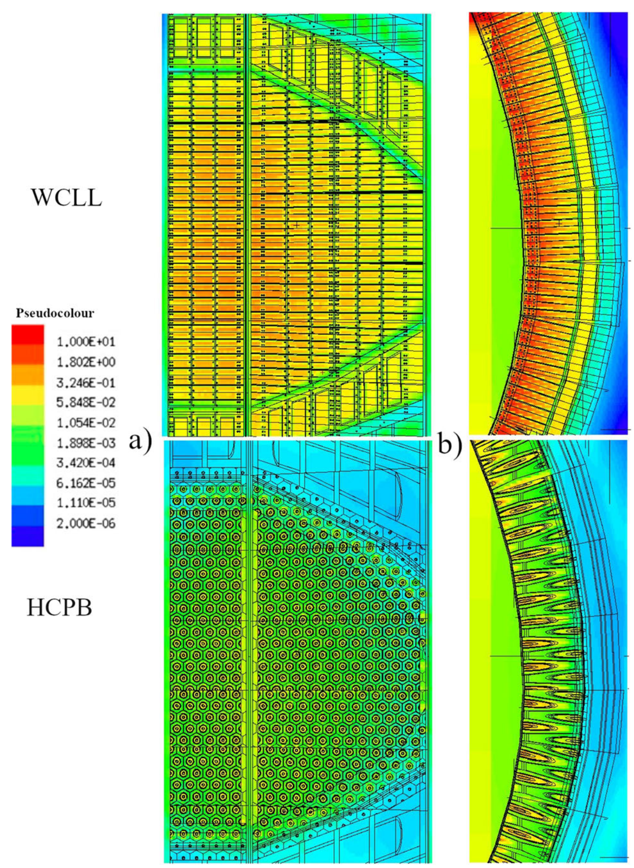

Fig. 4 WW for DEMO breeding blanket generated using ADVANTG code. Planes **a** *YZ* **b** *XZ*

Finally, the nuclear heating was evaluated using a TYPE 1 mesh tally with the keyword PEDEP, which makes it analogous to standard F6 computation [13]. F6 is used for track-length heating for any particle or combination of particles in Monte Carlo calculations for neutrons and photons using MCNP code.

Table 1 Coordinates of the selected cases (cm)

	X	*Y*	*Z*
Case 1	1170–1300	122	35
Case 2	1235	− 6–265	35
Case 3	1235	122	− 230–300

Results

Although there are areas where the statistical error oversteps the 10% limit, the averaged error values in locations of breeding units, back support systems and manifolds are much lower than 10%. For instance, at the *YZ* base (with *X* = 1235 cm.) in the HCPB model, the average error is 1.42%, and similarly, in the case of *XY* (where *Z* = 35), the average error is 2.19%, while in-plane *XZ*—2.32% was reached. WCLL statistical errors are 1.6%, 2.8% and 2.7%, respectively, on the same geometry planes. One can see more details in the statistical error maps represented in Fig. 5.

The results of neutron flux and dose rate equivalent calculations are displayed and discussed further in the paper, where three cases with the following cross-section planes of the model were considered as outlined in Table 1. The motivation for this selection of the cases is mainly based on the tally location, which is in the middle of BB and should accurately reflect the calculations and is the driving factor in the selection of the examined cases.

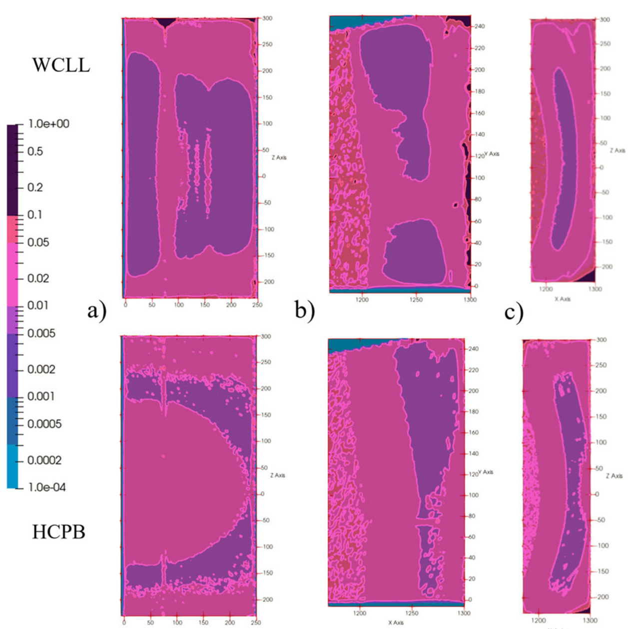

Fig. 5 Statistical error (in %) maps at different cross-section planes **a** *YZ* (*X* = 1235 cm), **b** *XY* (Z = 35 cm), **c** XZ (*Y* = 122 cm)

Case 1 Results

The breeding area's inner part of WCLL has the highest value along the *x*-axis (*X* = 1200 cm), whereas the highest value for the HCPB breeding area is about 20 mm deeper (*X* = 1202 cm). The calculated difference between WCLL's and HCPB's highest values along the *X*-axis is 18% for the neutron flux and 16% for the dose rate.

Moreover, it was observed that from the first wall of the breeding unit to the BSS of WCLL, the neutron flux values decreased approximately 900 times (i.e. from 5.35e14 n/cm^3 to 6.09e11 n/cm^3), while in the case of dose rate—more than 3000 times (namely from 5.2e4 Sv/h to 16 Sv/h). The same estimation was performed for HCPB, where neutron flux and dose rate values decreased by 56 times (from 4.52e14 n/cm^3 to 8.13e12n/cm^3) and more than 200 (from 4.49e4 Sv/h to 2.44e2 Sv/h) accordingly. The larger decrease in results values employing the WCLL concept might be attributed to the difference in breeding material density and the fact that in WCLL water serves as the coolant, whereas helium serves for HCPB.

The following general outcomes could be observed from the Case 1 analysis. Firstly, when comparing WCLL BB concept to HCPB, data from the breeding zone (BZ) region show neutron flux and dose rates to be roughly 1.24 and 1.13 times higher. Secondly, in the Back Supporting structure (BSS) of HCPB, obtained values are more intense than the WCLL design by a factor of 5.34 and 8.55, respectively, for the flux and the dose. And finally, in part, between BZ and BSS, then WCLL concept is used, the neutron flux values are higher by 2.43 times, and dose rate values increase by a factor of 2 compared with HCPB analysis results (see Figs. 6, 7 and 8 for more details).

Case 2 Results

As clearly seen from Figs. 7, 8 and 9, the highest values along the *Y*-axis are at the gap between two modules of breeding units for both BB concepts, with the lowest values located on the edges of the mesh tally. The difference between the highest and the lowest values of HCPB and WCLL is approximately 6 times for both neutron flux and dose rate calculations. Moreover, the difference between

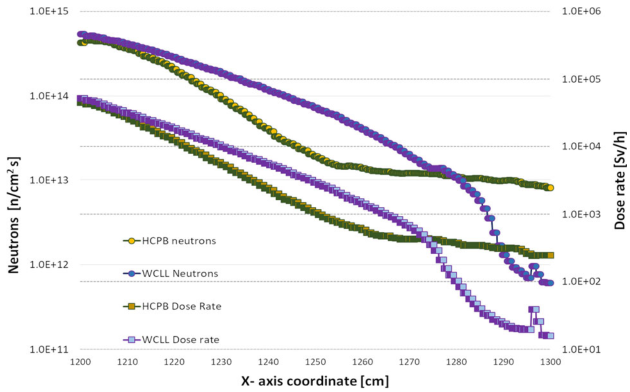

Fig. 6 The neutron flux and equivalent dose rate in HCPB and WCLL models (Case 1)

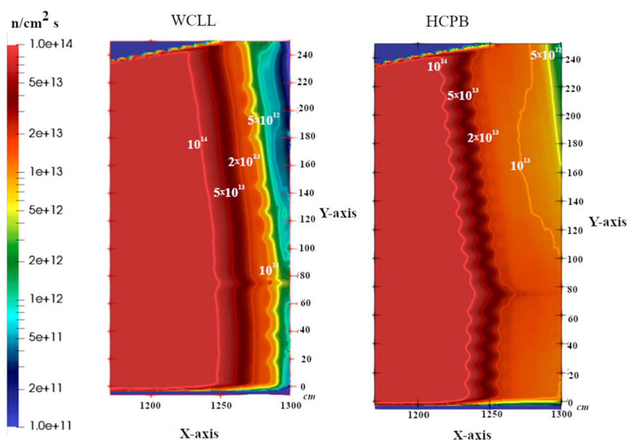

Fig. 7 The neutron flux maps of HCPB and WCLL (view of the *XY* plane)

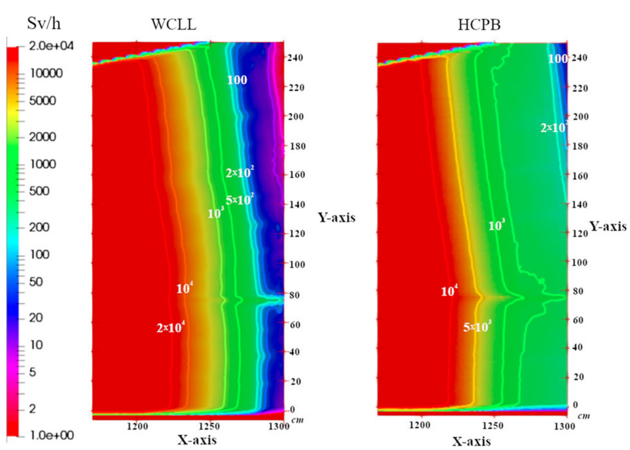

Fig. 8 The dose rate maps of HCPB and WCLL (view of the *XY* plane)

WCLL's and HCPB's highest values along *Y*-axis is 55% for neutron flux and 25% for dose rate results. In addition, Fig. 9 shows calculation values for Case 2, where it is seen

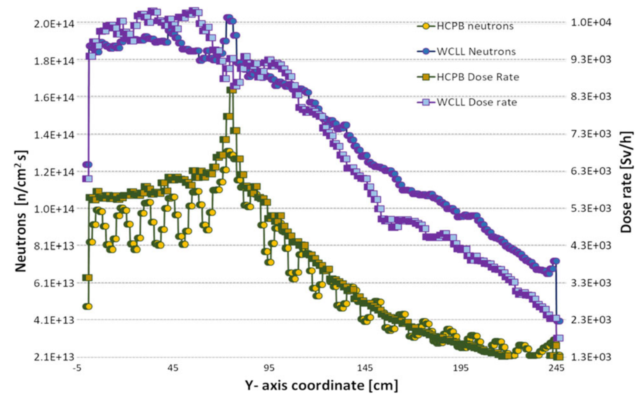

Fig. 9 The neutron flux and equivalent dose rate in HCPB and WCLL models (Case 2)

that WCLL values are higher by the factor of approximately 2.5 for the neutron flux and 2 for the dose rate.

Case 3 Results

The same analysis was performed for Case 3 (see Table 1 above in the paper), where the trend of value variation was investigated along the *Z*-axis (see Fig. 10). In this case, the difference between the highest and minimum HCPB neutron flux level is 30 times, compared to over 600 for WCLL, while for the dose rate, this ratio is 60 and 2100 accordingly. The highest values are at the location of BZ and the lowest in BSS. These differences between the highest and lowest values are highly influenced by the structure of the breeding blanket, cooling and breeding materials.

Furthermore, calculations of neutron flux and dose rate revealed the differences between the maximum values for HCPB and WCLL, which were 104% and 99%, respectively. Moreover, in the region from $Z = -177$ to 231 cm (i.e. breeding zone area), the neutron flux and the dose rate values are higher by 2.55 and 2.36 compared HCPB to the

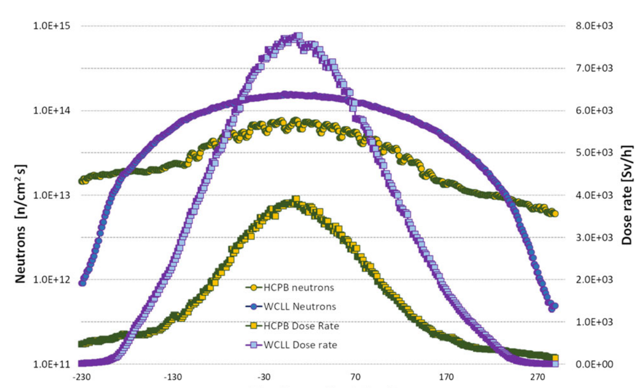

Fig. 10 The neutron and dose rate in HCPB and WCLL models (Case 3)

WCLL design. Also, considering HCPB structure, in other Z regions (i.e. $Z = -230$–-177 cm and $Z = 231$–335 cm), neutron flux values are higher by 5.62 times and the dose rate 8.5 times on average. For detailed information on the Case 3 simulation, see Figs. 10, 11 and 12. These calculations of neutron fluxes correspond to [3–5].

Nuclear Heating calculations

The track-length heating (as one of the key aspects in radiation transport analysis) of neutrons and photons was included in this paper. In the case where the HCPB model was used for neutron nuclear heating calculations, the highest value of 0.0702 kW/cm^3 at the coordinate 1206:80:34.5 (at the breeding blanket area) was observed, while photon heating was as low as 0.0057 kW/cm^3 at the coordinate at 1287:3.85:$-$ 3.61 (at the breeding blanket area). The lowest values were located both in BSS, which is 3.56 mW/cm^3 for neutrons and 0.0661 mW/cm^3 for photon heating (see Fig. 13).

A similar situation can be observed from WCLL calculation results. The highest values are 0.0068 kW/cm^3 and 0.0059 kW/cm^3, and the lowest is 5.3 mW/cm^3 and 0.051 mW/cm^3 for neutron and photon heating. See Fig. 14 for mapping nuclear heating results over the BB geometry.

Summary

The results of MCNP6.2 calculations using the FENDL-3.2 nuclear data library for neutron fluxes, nuclear heating, and dose rates are presented in this study. The analysis was performed for the outboard's part region of the outboard's WCLL and HCPB breeding blanket. The FW-CADIS approach was utilized in ADVANTG for the variance reduction. On the whole, except for the mesh edges, the computations' statistical error result is less than 10%. For neutron flux and equivalent dose rates estimations across the X axis, WCLL has higher values in comparison to HCPB by 24% and 13% in the breeding zone, respectively. However, throughout the blanket, the HCPB values don't decrease as much as WCLL, which leads to the fact that at the Back Supporting Structure, HCPB neutron flux values are higher 5 times and the equivalent dose rate 8 time in comparison to WCLL.

Additionally, HCPB has demonstrated greater values towards the mesh's ends along the Z-axis, where the

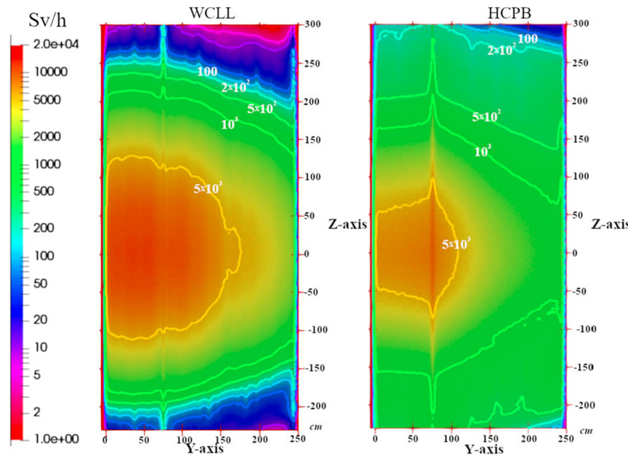

Fig. 12 The dose rate maps of HCPB and WCLL (view of the YZ plane)

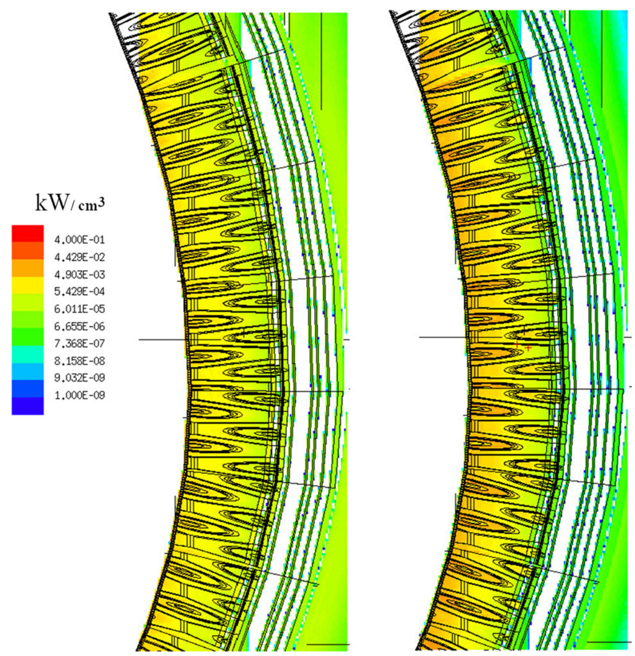

Fig. 13 The nuclear heating of HCPB breeding blanket concept for photons (***left***) and neutrons (***right***). View of ZX plane (at $Y = 122$)

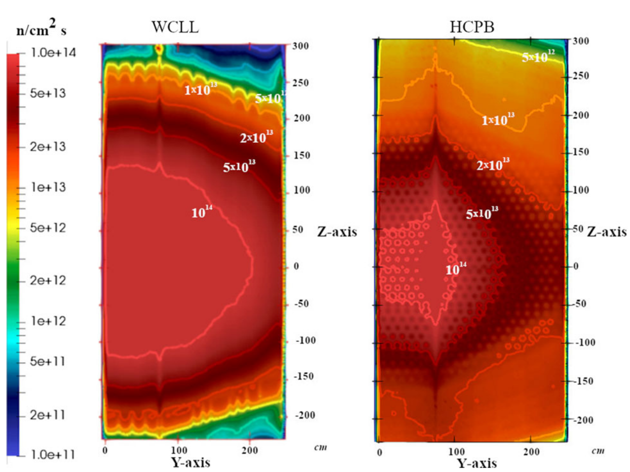

Fig. 11 The Neutron flux maps of HCPB and WCLL (view of the YZ plane)

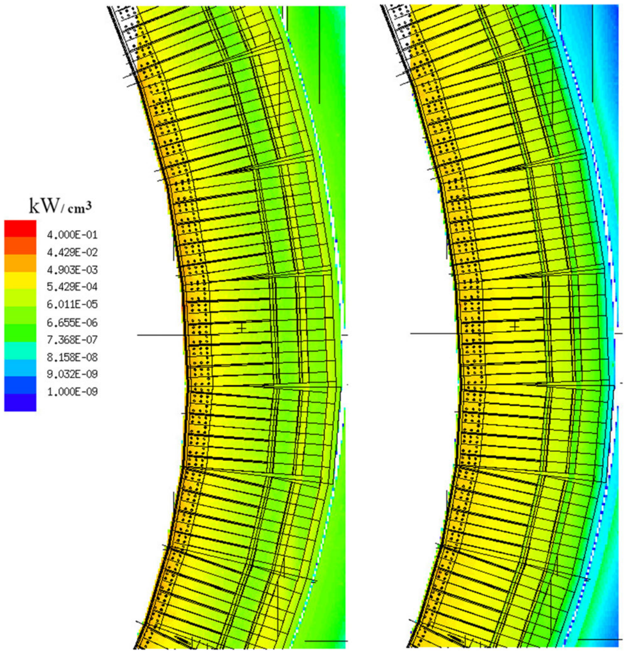

Fig. 14 The nuclear heating of WCLL breeding blanket concept for photons (***left***) and neutrons (***right***), View of *ZX* plane (at $Y = 122$)

computations of neutron flux, HCPB has around 5 times, while for those of dose rate—8 times when we compare to WCLL design case, while in breeding zone values are 2.5 and 2.3 times higher of WCLL concept. The calculated values along the *Y*-axis are the highest in the gap between the two modules. Still, WCLL provides values (across the whole line) around 2.5 times greater for neutron flux and 2 times higher for dose rate than HCPB. According to the calculations, nuclear heating produced comparable results for HCPB and WCLL, with the largest variance values between one and three percent. These distinctions, nevertheless, shouldn't affect the decision between these two design concepts. On the other hand, neutronics calculations revealed that the WCLL breeding blanket model is better suited for the DEMO design since it should produce less radiation load in the breeding zone, meaning that the radiation will potentially harm less EU DEMO components and additionally, it may provide a lower risk to both the environment and employees.

Authors' Contributions SB*:* Writing—original draft, Visualization, Formal analysis, Conceptualization. GS: Writing—review & editing, Software, Methodology.

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Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval (not applicable).

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