EUROFUSION WPBB-CP(16) 15579

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Preprint of Paper to be submitted for publication in
Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Neutronic analyses for the optimization of the advanced HCPB breeder blanket design for DEMO

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This work gives an overview of the neutronic analyses to support and optimize the advanced HCPB blanket concept for DEMO. Full scale 3D Monte Carlo particle transport simulations were performed to this end with the MCNP5 code employing a very detailed HCPB DEMO torus sector model. The HCPB blanket was optimized to fulfil the design requirements on tritium breeding, thermal stress stability and shielding performance.

Keywords: neutronics, HCPB DEMO, breeder blanket

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1. Introduction

Within the Power Plant Physics and Technology (PPPT) programme of EUROfusion, a major development effort is devoted to the conceptual design of a fusion power demonstration reactor (DEMO) which has the capability to breed Tritium for self-sufficiency [1]. Several design concepts, such as the HCPB, HCLL, WCLL and the DCLL, are considered as viable options for a breeding blanket in the considered DEMO. This DEMO is assumed to be suitable for the accommodation of any blanket type out of the four concepts. For the neutronics analyses, a generic DEMO model is thus set-up which serves as common basis for the integration of blankets of the considered four concepts.

The objective of the present work was to support with neutronic analyses the systematic design development of the HCPB blanket [2]. To this end the tritium breeding performance of the HCPB blanket was successively studied depending on the design modifications applied. The power generation was finally assessed and several options of the new HCPB blanket shield were studied. Special attention was paid to the application of different materials that could serve as alternative neutron multiplier.

2. Design and model generation

2.1 HCPB basic blanket model

1/4th of the new CAD HCPB blanket model (cut in poloidal and toroidal directions) is shown in Fig. 1. The blanket casing is built by a 25 thick U-shaped first wall (FW), 25 mm caps and a back wall, the FW is being covered with a 2 mm W armor. The total radial depth of the breeder zone from the FW up to back plate is 45 and 82 cm on the inboard and outboard sides, respectively. The thickness of the back supporting structure with feeding pipes (BSS) is 43 cm. The breeder zone (BZ) is filled with cooling plates of 5mm thick arranged parallel in poloidal direction. The Li_4SiO_4 breeder ceramic pebbles with 0.64 package factor are arranged between two cooling plates forming an 11 mm breeder bed. The neighboring breeder beds are separated with 33 mm thick Be pebbles layer. Being repeated this structure fills the blanket breeder zone. All structural elements of the blanket are assumed to be manufactured from Eurofer steel. The material composition in the BZ The module is assumed to be maintained with a He cooling flow of ~80 bar pressure.

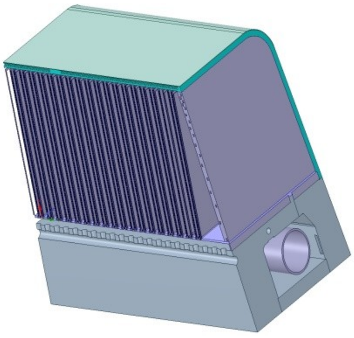

Fig. 1. CAD model of the HCPB blanket.

2.2 HCPB DEMO geometry model

A generic CAD model of the DEMO reactor without blankets was developed at the PPPT department in Garching. The main parameters of this reactor are listed in the Table 1.

Table 1. Main parameters of the DEMO reactor.

Major radius, (m)	9.072
Minor radius, (m)	2.927
Plasma elongation	1.590
Plasma triangularity	0.333
Fusion power, (MW)	2037.0
Net electric power, (MW)	500.0

The CAD geometry model of the HCPB DEMO was developed in two steps. First, from the generic DEMO model a 10 degree toroidal segment was extracted accounting for the symmetry of the model. This segment represents a half of the 18 repeated toroidal DEMO sectors. Before further manipulations the 10° segment CAD model was properly modified to avoid spline surfaces and complex geometry bodies. Second, empty HCPB blanket casings with BSS were arranged in the breeder blanket space of the generic CAD model assuming gaps around the modules as follows: 10 mm in poloidal and 20 mm in toroidal directions. In this way 7 full inboard modules, 7 full and 7 half outboard modules were arranged around a plasma forming a plasma chamber. Additional adjustments regarding the angle between the parallel plates of the U-shaped FW and the radial length were applied to fill the breeder blanket volume.

In the next step a semi-finished HCPB DEMO CAD model was converted into the MCNP geometry model using the McCad conversion tool [3]. The generation of the final HCPB DEMO geometry model was performed already on the MCNP platform. To this end the detailed structure of the single HCPB blanket was manually replicated in all modules using an MCNP inbuilt repeated structure function and proper geometry transformation cards. Shown in the Fig. 2 is the final MCNP HCPB DEMO geometry model as used in the following simulations.

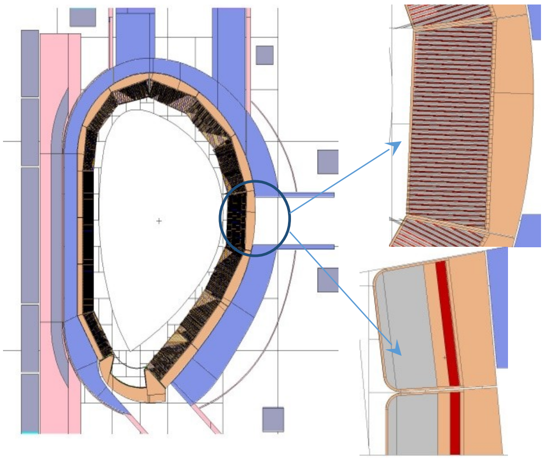

Fig. 2. MCNP geometry model of the HCPB DEMO.

3. Simulation results

3.1 MCNP results for the basic configuration

The neutronics analyses comprised the assessment of main nuclear responses of the newly developed HCPB DEMO reactor including the nuclear power generation, the tritium breeding capability and the shielding performances. The calculations were carried out making use of the geometry model discussed above and the MCNP5-1.60 code [4] with nuclear data from the JEFF-3.2 library. The toroidal fusion neutron plasma source was simulated making use of the specially developed source subroutine [5] linked to the MCNP executable. For heavy duty MCNP5 runs such as shielding calculations, the mesh based weight window variance reduction technique was applied. Such an approach results in a good statistics of the final results that usually do not exceed ~3% for the cells outside vacuum vessel and <0.1% for the plasma facing components.

The neutron wall loading distribution calculated with MCNP for the 10° HCPB DEMO model is presented in the Fig. 3. The numeration of the blanket modules is clockwise starting from the lowest blanket module on the inboard side. The maximum neutron first wall load on the inboard side is 1.08 MW/m^2 (blanket 3) and on the outboard side is 1.34 MW/m^2 (blanket 12). The average neutron wall load for the current HCPB DEMO design is ~1.0 MW/m^2.

The tritium breeding analyses for the HCPB DEMO were performed by a comparison of the tritium breeding ratio (TBR) for different design options with the target of TBR>1.10. For the assumed 60% ^{6}Li enrichment in the basic configuration the TBR is as high as 1.37. This value of the TBR is unrealistically high but it demonstrates the very high potential of the current HCPB blanket design. The excess of this TBR compared to the target comes from: 1) a large radial depth of the breeder zone in the outboard and inboard blanket modules and 2) the relatively low steel content (11.8%) in the breeder zone (BZ) that is much lower compared to 18.6% in the previous design [6].

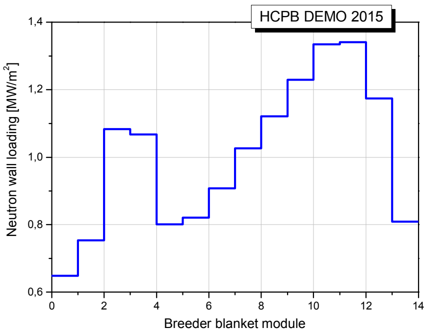

Fig. 3. FW neutron wall loading in the HCPB DEMO.

The stress analyses performed for the basic HCPB blanket design for the unlikely event of an in-box LOCA have shown a very weak performance of the blanket caps. In order to improve the structural integrity of the modules against this type of accident the caps were replaced with two 2 cm thick He-cooled plates separated by the 4.3 cm thick stiffening structure (the so-called "double caps", see [2] for a more detailed description of this component). The HCPB blanket module design (Fig. 1) assumes that the BZ space close to the blanket caps is not filled with cooling plates and breeder ceramic. This modification was also consequently implemented in the MCNP geometry model. The TBR was reduced down to 1.33 and 1.30, respectively, for these modifications. These results indicate that the BZ should be further reduced.

The usage of Be in the HCPB breeder blanket raises some concerns due to the T production and inventory, its cost and scarcity, its toxicity and the reactivity with water . An additional study was performed to compare various alternative materials that could potentially replace Be as neutron multipliers for solid breeding blankets like the HCPB. The design discussed above provides a sufficient space for that. The choice of the alternative neutron multipliers can be made on a comparison of the (n,2n) and (n,γ) reaction rates (RR) in the HCPB blanket. To this end the RRs were calculated for all elements with atomic numbers $4 \leq Z \leq 83$ using JEFF-3.2 data and a typical neutron spectrum for HCLL reactor [7]. This spectrum is harder compared to that in the HCPB blanket and it is assumed to be representative for the RR calculations with alternative to Be metal neutron multipliers. Shown in the Fig. 4 are the RR over RR$_{max}$ for the (n,2n) and (n,γ) reactions respectively. In case of the (n,2n) RR$_{max}$ was found for Bi and for Eu in case of the (n,γ) reaction.

The results show an approximate tendency of the relations between (n,2n) and (n,γ) reactions in the DEMO with hard neutron spectrum. These results enable a first preliminary choice of the possible alternative neutron multipliers for the HCPB DEMO. The (n,2n) RR for Pb is close to the RR$_{max}$ for Bi(n,2n) and the (n,γ) RR for it is very low. Therefore the Pb is the most suitable alternative neutron multiplier for DEMO but due to a low melting point it cannot be used as a solid material. Possible solutions here are the Pb based alloys with another element that increases its melting temperature. These elements must have high enough (n,2n) and low (n,γ) RRs and the potential for industrial scale production of these alloys should be feasible. To keep advantages of the high neutron multiplication by Pb, the alloys should have as high as possible its mass fraction. The results presented in the Fig. 4 give some indications for the possible elements with the atomic numbers around Z=25, 40 and 58. The MCNP transport simulations were performed for the blanket configuration discussed above, Be being replaced with solid compounds. To assess the maximum TBR the ^{6}Li enrichment in lithium was set to 90% at. The results of the calculations for some possible Pb-based compounds are presented in the Table 2. The data in brackets refer to the TBR obtained with the neutron multiplier made with pebbles with a packing factor of 0.64.

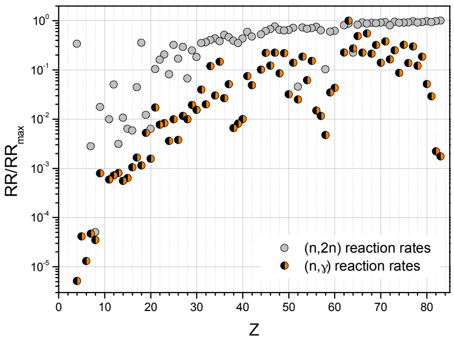

Fig. 4. Relative RRs for (n,2n) and (n,γ) reactions.

Table 2. TBR for various neutron multipliers.

Compound	Melting point [°C]	TBR
$MnPb_3$	320	1.18(1.13)
YPb_2	940	1.17 (1.12)
Zr_5Pb_4	1500	1.13(1.11)
$LaPb_3$	1160	1.19(1.14)
$CePb_3$	1170	1.15(1.11)

The TBR found for the alternative neutron multipliers show their certain potential to be used in the DEMO, also in form of pebble beds. In particular, a sufficient TBR can be obtained for the $LaPb_3$, YPb_2 and probably for $CePb_3$ and Zr_5Pb_4 alloys. Additional increase of the TBR can be obtained by a further optimization of the breeder to multiplier volumes relations. Fig 5 demonstrates the results of the optimization simulations for the blanket with YPb_2. Due to such optimization of the blanket design the TBR can be increased from 1.12 to ~1.15. These results are to be cross-checked with thermo-hydraulic simulations in order to evaluate the temperature distribution in the functional materials so as to assess that the design temperatures for these materials are met.

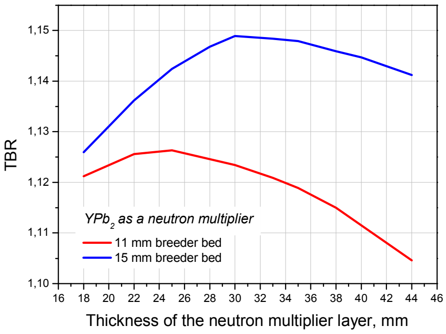

Fig. 5. TBR as a function of the YPb_2 layer thickness.

3.2 MCNP results for the advanced configuration

As it was shown above, the TBR in the basic HCPB blanket configuration is 1.30 due to unreasonably large BZ. The proper BZ reduction was estimated using results of the parametric study. For the fixed ^6Li enrichment of 60% the radial thickness of the BZ was varied separately for all blankets either only in the inboard or only in the outboard sides. The results of the MCNP simulations for TBR are presented in the Fig. 6.

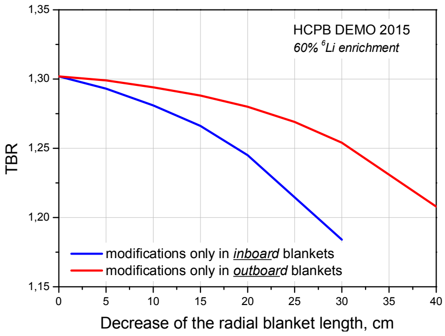

Fig. 6. Effect of the BZ thickness decrease on the TBR.

Appling the results shown in the Fig. 6 the breeder zone in all blankets in the inboard side was reduced by 23 cm and by 31 cm in the outboard side. This results in the BZ radial thickness of 22 cm in the inboard and of 51 cm in the outboard side modules respectively. With such modifications the blanket supporting structure can accommodate an additional ~20 cm massive steel block behind the feeding pipes, Fig. 7. This steel block serves as an additional shield to protect the vacuum vessel and toroidal field coil (TFC) from the neutron irradiation. If required the shielding performances of the blanket can be enhanced by the arrangement of other materials, for instance, tungsten carbide.

For the design modified in such a way, the tritium breeding is TBR=1.19 that is fully consistent with the results of the parametric study (Fig.6). The excess above the design limit TBR=1.10 provides a comfortable design margin for the further HCPB DEMO development. The TBR contributions from ^7Li was found to be 0.005 and it is accounted for in the TBR.

The relation between Be and breeder ceramic volumes can be used for the further enhancement of the tritium breeding performances of the HCPB blanket. The simulations were performed for two cases of the breeder ceramic layer thicknesses: 11 mm and 15 mm. The Be layer poloidal thickness was varied from 33 to 60 mm. In all cases the thickness of the cooling plates remained constant (5 mm). The results of the TBR calculations are presented in the Fig. 8. The present blanket demonstrates a potential for further increasing of the TBR.

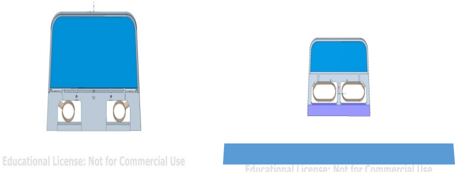

Fig. 7. HCPB blanket geometry: from basic to advanced

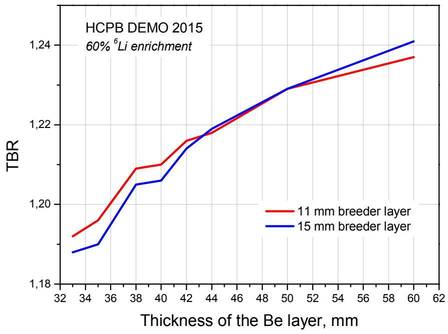

Fig. 8. TBR as function of the Be layer thickness.

The breakdown of the nuclear power generation in the new HCPB DEMO reactor is given in the Table 3.

Table 3. Nuclear energy generation of the HCPB DEMO

	Nuclear power [MW]
Blankets	2031
Vacuum vessel	46
Divertor	112
Ports	4
Total	2193
Global energy multiplication	1.35

The newly designed BSS of the blanket has inbuilt shielding functions thanks to the massive block behind the manifold. In the present study radial profiles of the nuclear power density in the steel in the inboard side were assessed in the reactor mid plane for several shielding options in the BSS. The results of the calculations are presented in the Fig. 9. The power density and high energy neutron flux in the winding pack of the TFC were found to be below the design limits.

4. Conclusions

In the framework of the EUROfusion PPPT program, a new HCPB DEMO reactor model was elaborated and dedicated neutronic analyses were carried out. Numerous parametric studies were performed for the optimization of the blanket design. Two HCPB blanket options were investigated: basic and advanced. In the basic configuration the tritium breeding performances appeared to be excessive. This option can be used for the integration of alternative neutron multipliers such as $LaPb_3$, $MnPb_3$ and YPb_2 alloys. For these materials the HCPB DEMO design with sufficient TBR seems to be technically feasible.

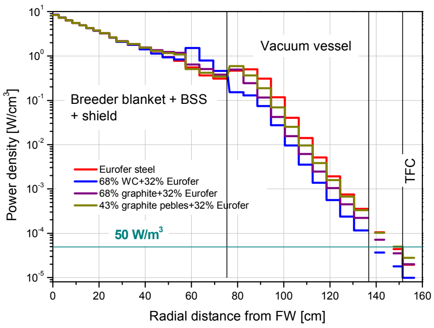

Fig. 9. Radial power density profile at inboard mid-plane

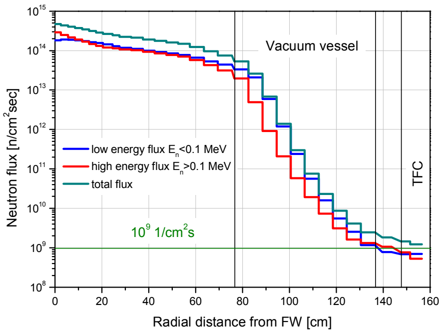

Fig. 10. Radial neutron fluxes profiles at inboard mid-plane.

The advanced option of the HCPB DEMO is based on shorter blanket modules compared to the basic configuration. This option shows a high enough tritium breeding capability as well as an inherent shielding performance sufficient for the protection of the TFC from the particle irradiation.

Acknowledgments

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