EUROFUSION WPBB-CP(16) 15569

jcj Jaboulay et al.

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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.

Nuclear Analysis of the HCLL blanket for the European DEMO

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This paper presents the nuclear analysis of the European DEMO baseline 2015 with HCLL blanket carried out with the TRIPOLI-4® Monte Carlo code and the JEFF-3.2 nuclear data library. The TRIPOLI-4® model was imported from CAD using the McCad tool. A procedure that generates the detailed 3D model describing all the HCLL blanket internal structures was developed. This procedure allows to parametrize the blanket internal structures such as the number of cooling plates, manifolds, etc. and the thickness of the stiffening grid for instance. Different design variants were studied to improve the tritium production. From this previous study a complete nuclear analysis was carried out on a promising design which is a compromise between tritium production and mechanical robustness. All criteria (TBR, nuclear heating in coils and displacement damage in vacuum vessel) are met using this new reference design.

Keywords: DEMO, neutronics, blanket, HCLL, tritium breeding, nuclear heating, TRIPOLI-4®

1. Introduction

The EUROfusion Consortium [1] develops a conceptual design of a fusion power demonstrator (DEMO) in the framework of the European "Horizon 2020" innovation and research programme [2]. Key issues for DEMO are tritium self-sufficiency and heat removal for conversion into electricity. These functions are fulfilled by the breeding blankets surrounding the plasma chamber.

Within the Breeder Blanket project (WPBB) of EUROfusion's Power Plant Physics and Technology (PPPT) programme [3], CEA is in charge of the design of the helium cooled lithium lead (HCLL) blanket [4] for DEMO including the nuclear analyses. In WPBB's framework three other blanket concepts are respectively studied by KIT, ENEA and CIEMAT: the helium cooled pebble bed (HCPB), the water cooled lithium lead (WCLL) and the dual coolant lithium lead (DCLL).

CEA's nuclear analysis approach is based on the TRIPOLI-4® Monte Carlo code [5] and the JEFF-3.2 [6] nuclear data library. This was validated in previous HCLL nuclear analysis [7]. The TBR evaluated in this analysis, based on the DEMO 2014 baseline, is equal to 1.07, below the target value of 1.1 [8]. To improve the tritium production, design modifications have been investigated. The reduction of the steel amount and the optimisation of the manifolds scheme (to increase to breeding zone) were the main options.

To model the different breeding blanket design variants an automated procedure was developed to generate the internal structures in an empty segmentation. Three designs with TBR $\geq$ 1.1 (with DEMO 2014 baseline) have been identified: one called optimized-conservative (beer box concept,with internal horizontal and vertical stiffening plates, is kept) the second called advanced (vertical stiffening plates are removed) and the last called advanced+ (with horizontal stiffening plates only and no cooling plates).

Finally, these three design variants have been implemented in the new DEMO baseline called "EU DEMO1 2015" [9]. This paper present the nuclear analysis performed to evaluate the different HCLL design option.

2. HCLL blanket design

The HCLL breeding blanket layout is a multi-module segment design. Modules are welded in a stiff poloidal back plate in order to form a banana-shaped segmentation that can be removed from the upper port. The back supporting structure (BSS) also works as a manifold, collecting and distributing lithium-lead and helium in the different blanket modules.

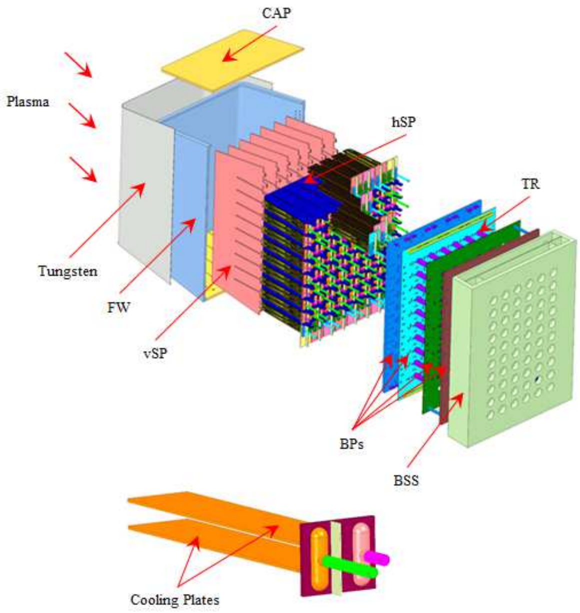

Fig. 1 HCLL DEMO equatorial outboard blanket module

The design of outboard equatorial HCLL module is shown in Fig. 1 [10]. Each HCLL blanket module consists of an Eurofer [11] steel box formed by an U-shaped plate

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composing the First and side walls FW (coated with a 2 mm tungsten layer), closed by two caps on the top and bottom and on the back by a set of Back Plates (BP) and tie rods TR (for BSS attachments).

The blanket module structure is reinforced by an inner grid of vertical and horizontal Stiffening Plates (vSP, hSP). The Stiffening Plates defines an array of internal cells where the Breeder Units (BU) are located. The eutectic Pb-Li (enriched 90% in ^{6}Li) flows around parallel horizontal Cooling Plates (CP). An inlet and an outlet chamber on the Breeder Unit back plate ensure the helium distribution and collection for the Cooling Plates (bottom part of Fig. 1). All the plates, except the back plates constituting the manifolds, have internal cooling channels with a rectangular section.

The reference design used in previous analysis [7] (called ref. 2014) has three cooling plates per breeding unit and three helium manifolds: one for the first wall, one for the stiffening plates and one for the cooling plates; the TBR obtained is 1.08 (this higher value compared to results of [7], 1.07, is due to geometrical error corrections). Three design variants to improve the TBR have been defined. Firstly, the optimised-conservative that keeps the beer box concept (i.e. hSP and vSP grid) but reduces the number of CP (2) and helium manifolds (2, FW is feed directly from the BSS). The advanced concept has the same number of CP and manifolds but the vSP are removed. The third called advanced+ has only one manifold; CP and hSP function are merged in a thin hSP (8 mm instead of 14 mm). With the DEMO 2014 baseline the TBR achieved are respectively 1.11, 1.14, 1.15. The two advanced concepts are very promising for tritium production but thermal, hydraulical and mechanical analyses [10] show some drawbacks in case of LOCA (lose of stiffness in caps area) and pressure drops increase. Design developments are needed to solve these problems. The optimized-conservative design offers a robust solution to meet all the criteria and it is considered as the reference design 2016 (ref. 2016).

3. HCLL DEMO model

The TRIPOLI-4® EU DEMO1 2015 HCLL model is based on a generic CAD model with empty blanket developed at KIT [12]. The parameters of the studied tokamak are presented in Table 1. Compared to the previous baseline more space for breeding blanket is available (minor radius is higher and divertor is smaller).

Table 1. Main parameters of the DEMO reactor.

Major radius, (m)	9.072
Minor radius, (m)	2.927
Plasma elongation	1.59
Plasma triangularity	0.33
Fusion power, (MW)	2037.
Net electric power, (MW)	500.0

The segmentation CAD model developed by the HCLL design team has been implemented in the generic model using the SALOME platform [13]. The TRIPOLI-4® model was generated using the CAD import tool McCad [14]. To ease CAD import only empty modules are considered. An automated procedure, written in python, fills the empty blanket cells with the internal structures (FW, Caps, BPs, CPs, hSP, vSP, manifolds). This automated procedure allows to parametrize the BU to study different design. Fig. 3 shows a radial-poloidal cut of the tokamak with HCLL blanket. Fig. 4 shows the internal structure: stiffening grids, cooling plates, back plates and manifolds of the 2014 reference HCLL design.

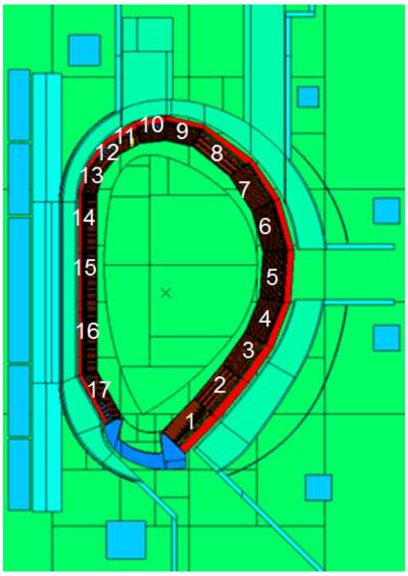

Fig. 3. TRIPOLI-4® plot of the EU DEMO1 2015 HCLL model

Fig. 4 poloidal-radial cut of a breeding unit design ref. 2014 with 3 CP and 3 helium manifolds

4. Results

In this section neutron wall loading, tritium breeding ratio, nuclear heating and neutron flux distribution obtained is presented.

4.1 Neutron Wall loading

First of all, the NWL was calculated. It is defined by the neutron current (normalised to the fusion power) crossing the first wall surface divided by the first wall area; NWL is expressed in MW/m². To avoid the back scattering of neutrons in the current tallying (due to reflective surface) the neutrons must be killed after passing through the first wall. Leakage conditions at first wall surfaces are used in TRIPOLI-4®.

Fig. 5 shows the obtained poloidal NWL. It was estimated on each BBM first wall surfaces numbered 1 to 15 (see Fig. 3). The maximum value 1.4 MW/m² is obtained in the outboard equatorial module, NWL at Inboard equatorial module is around 1.2 MW/m². Averaged breeding blanket NWL is 1.01 MW/m².

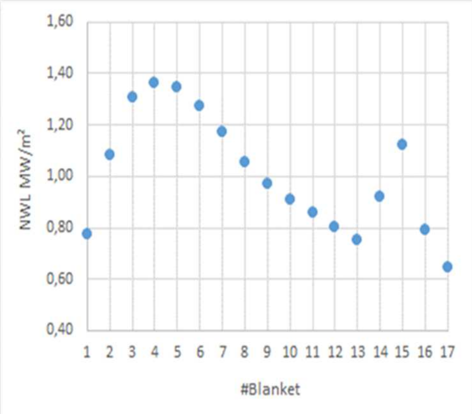

Fig. 5. NWL poloidal distribution

4.2 Tritium breeding ratio

The TBR was evaluated for the different HCLL design variants and different DEMO baselines, results are presented in Table 2. The new baseline has a strong impact on TBR, using the same BU design with 3 CPs and 3 manifolds (MF) the TBR increase by +0.07. This is due to a smaller divertor and higher minor radius that increase the space for breeding blanket. Nevertheless this TBR margin will be consumed considering future probable modifications (high heat flux panel, second divertor, etc.). HCLL ref. design 2014 and 2016 are not directly comparable (see * below table 2). Advanced designs have good TBR performance but thicker caps must be considered to draw a conclusion.

Table 2. TBR for different design options

HCLL BB design	#CP	#MF	vSP	DEMO baseline	TBR
Ref. 2014	3	3	yes	2014	1.08
Ref. 2014	3	3	yes	2015	1.15
Ref. 2016*	2	2	yes	2015	1.17
Adv.*	2	2	no	2015	1.21
Adv.+*	-	1	no	2015	1.20

*In these cases BZ thickness was reduced by 31 mm to increase BSS thickness, MF thickness is divided by 2 and stiffening plates thickness are increased from 11 mm to 14 mm

Back supporting structure CFD analysis showed too much pressure drop in the inboard. A study was carried out to increase inboard BSS thickness with the objective to keep the same TBR value. The strategy employed is to reduce the inboard BZ and counterbalance the TBR loss by outboard BZ thickness increase (outboard BSS decrease). It have been shown that TBR can be kept reducing inboard BZ thickness by X mm and increasing outboard BZ thickness by X mm with $X < 60$ mm.

4.3 Nuclear Heating

Nuclear heating in EU DEMO1 2015 HCLL components are reported in Table 3. The energy multiplication factor (M_E) is 1.2. Only results obtained with the ref. 2016 HCLL design are reported, there are very slight difference with the other designs.

Table 3. Nuclear heating breakdown

Components	BBMs	BSS	VV	Div.	Tot.
NH in MW	1725	42	70	115	1960

The poloidal NH distribution within each BBM range from 0.8 MW to 3.5 MW (the maximum value is obtained in the outboard equatorial module).

4.4 Inboard shielding analysis

In this part only the HCLL ref. 2016 design was studied (no significant impact in the rear part of the machine of the BB design is expected since the neutron flux in the BSS is quite similar). The neutron flux (Fig. 7), nuclear heating (Fig. 6), displacement damage rate (Fig. 8) and helium production (Fig. 9) have been calculated along the inboard mid-plane. For a proper calculation mesh tally function was not used (to avoid quantity averaging over different materials in a mesh), the geometrical cells were discretised (5 cm thickness). The nuclear quantity is averaged on a poloidal height of 50 cm (from z=10 to z=60 mm). Variance reduction techniques were used in TRIPOLI-4® simulation to obtain results with reasonably low statistical errors up to the toroidal field coil region (lower than 5%). Functionality presented in [15], addressed to coupled neutron photon transport biasing, was very useful to set the variance reduction options. Only neutron transport was biased, but this functionality, which is a diagnostic tool, shows the area where neutrons collisions generate photon that contribute to the tally. This area of interest is located in the front of the Toroidal Field Coil (TFC) casing along a large poloidal height (several meters). A surface attractor (an infinite cylinder centred in the tokamak axis with a radius corresponding to the TFC location) was used to improve the neutron transport in this region.

The table 4 shows the main quantity obtained and criteria defined in [8], the HCLL ref. 2016 design met all the criteria.

Table 4. Main quantity in the first 5 cm and **criteria**

	FW[1]	BZ	MF	VV	TFC
$\Phi_{(E>1MeV)}$ n.cm^{-2}.s^{-1}	5.8 10^{14}	5.3 10^{14}	7.2 10^{13}	3.1 10^{13}	3.6 10^{8} **1. 10^{9}**
NH W/cm^{3}	20	6.9	0.3	1.26	1.8 10^{-5} **5. 10^{-5}**
DPA dpa/fpy	11.2	9.3	0.5	8. 10^{-2} **0.46**[2]	6.8 10^{-6}
He prod. appm/fpy	110	77	0.5 **0.64**[3]	1.5	3.3 10^{-5}

[1] in the tungsten armor
[2] criteria is 2.75 dpa for 6 full power year (fpy)
[3] criteria is 1 appm for 1.57 fpy

A simulation was done with a thicker BSS (+ 35mm of helium to reduce pressure drop in the inboard BSS cf. 4.2) to evaluate the impact on NH in coils. This thicker BSS increase by +6W/m^3 the NH in coils i.e. 22 W/m^3 still below the limit. The other criteria are also met with this geometry.

In this study BSS cells are homogeneous. Future works will focus on a better modelling of the BSS to verify the shielding requirement in the inboard mid-plane.

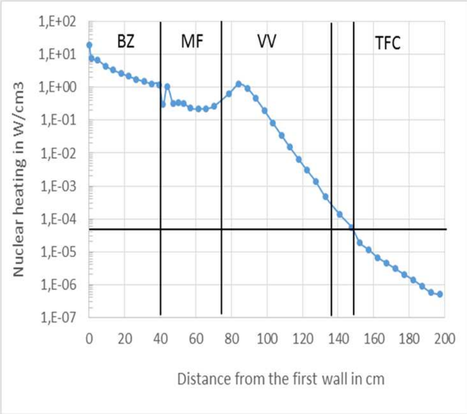

Fig. 6. Nuclear power density radial profile across inboard mid-plane

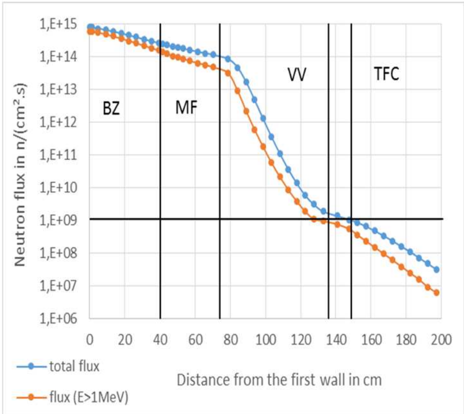

Fig. 7. Inboard radial neutron flux profile

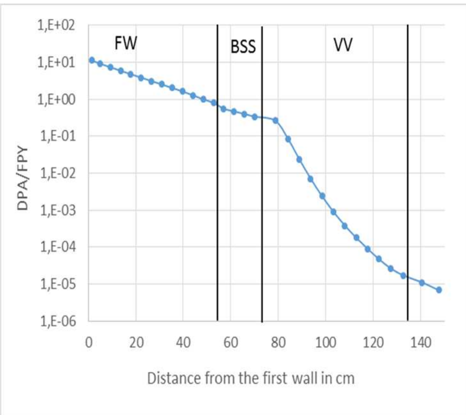

Fig. 8. Inboard radial displacement damage rate profile

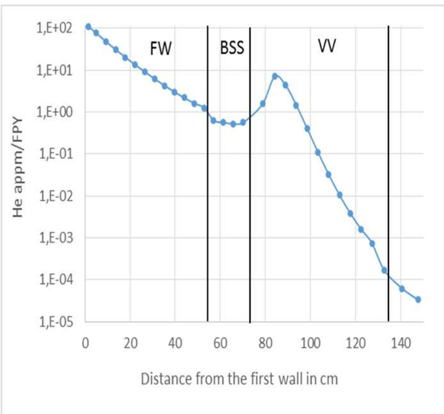

Fig. 9. Inboard radial helium production profile

Conclusions

This paper presents the nuclear analysis of the HCLL blanket with the new DEMO baseline. Several breeding blanket design variants were studied to improve the tritium production. A reference design which is a compromise between TBR performance and mechanical robustness was completely analysed. This design met all the neutronic requirements. Future works will focus on the advanced designs precisely the impact of thicker caps (that withstand LOCA loading) on TBR. A better modelling of the BSS is underway to verify its impact on inboard shielding.

Acknowledgments

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