WPBB-CPR(17) 17620

J.-C. Jaboulay et al.

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Preprint of Paper to be submitted for publication in Proceeding of
13th International Symposium on Fusion Nuclear Technology
(ISFNT)

Nuclear Analysis of the HCLL "Advanced-Plus" Breeding Blanket

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In the frame of the European R&D effort to develop a fusion demonstrator (DEMO) a new concept of Helium Cooled Lithium Lead breeding blanket is studied to improve the tritium breeding. The aim of this paper is to present the nuclear analysis of this new HCLL design called "Advanced-Plus". Neutrons transport is simulated using the TRIPOLI-4® Monte Carlo code and the Joint European Fission and Fusion nuclear data version 3.2 (JEFF-3.2). Nuclear quantities such as: neutron flux, tritium breeding ratio, nuclear heating, displacement damage and helium production are reported. Sensitivity analysis is also carried out to investigate the impact, in tritium breeding, of the next DEMO baseline with reduced outboard thickness and the advantage, in tritium production point of view, of the single module segment against the current multi-module segment option.

Keywords: European DEMO, Neutronics, Blanket, HCLL, Tritium breeding, TRIPOLI-4

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1. Introduction

The European R&D effort to develop a conceptual design of a fusion power plant demonstrator (DEMO) is organized through the EUROfusion Consortium [1]. In this framework CEA, with the support of Wigner-RCP and IPP-CR is responsible of developing the Helium Cooled Lithium Lead (HCLL) Breeding Blanket (BB) concept. BB is a key component of DEMO. It must handle severe heat load from the plasma and ensure tritium self-sufficiency, heat removal and shielding functions. HCLL uses Eurofer as structural material, liquid lithium lead eutectic as tritium breeder and neutron multiplier and helium gas as coolant.

The HCLL BB design called “Optimized Conservative” is a robust solution in terms of nuclear performance [2] and thermal and mechanical behavior Error: Reference source not found. This design is derived from the ITER HCLL Test Blanket Module (TBM) [4]. Nevertheless, it offers very slight margin in term of tritium breeding [2]. In addition, more and more constraints tend to reduce the tritium breeding. For instance: the water cooled divertor and BB size reduction. For this reason, a new HCLL design called “Advanced-Plus” has been investigated to improve tritium breeding. The first structural analysis is encouraging but some improvements are necessary to fulfil all criteria [5].

The aim of this paper is to present the nuclear analysis of this new “Advanced-Plus” concept, which is now considered as the reference HCLL BB and compared for TBR and shielding requirements to the “Optimized Conservative” concept which is now considered as the HCLL BB backup solution [6]. HCLL BB nuclear analysis is based on the TRIPOLI-4® Monte Carlo code [7] and the Joint European Fission and Fusion nuclear data version 3.2 (JEFF-3.2) [8][8]. Nuclear quantities such as: neutron flux, tritium breeding ratio, nuclear heating, displacement damage and helium production are reported in part 4. Part 5 is dedicated to sensitivity analysis that investigates the impact, in tritium breeding, of the future DEMO baseline and the single module segment (SMS) against the current Multi-Module Segment (MMS) option.

2. HCLL “Advanced-Plus” Breeding Blanket description

The HCLL breeding blanket general layout is a MMS design. The current DEMO baseline called “EU DEMO1 2015” [9] is divided in 18 sectors (corresponding to the number of toroidal field coils). A sector (Fig. 1) is made of two inboard segments and 3 outboard segments. Inboard segment is divided into 8 modules and outboard segment is divided into 9 modules. Modules are attached to the Back Supporting Structure (BSS) with Tie Rods (TR) in order to form a segment which can be easily 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.

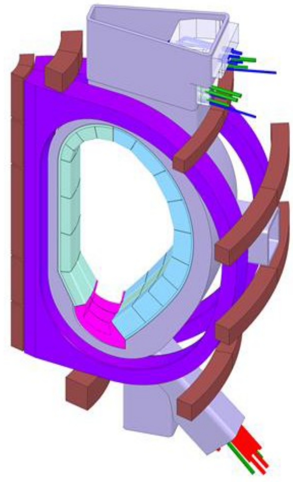

Fig. 1. One sector of the EU DEMO 2015

Each module consists in a steel box made of a U-shaped plate, two cover plates (CAP) and a set of Back Plates (BP) with tie rods TR (for BSS attachments). The First Wall (FW) is coated with a 2 mm tungsten layer.

Compared to the backup “Optimized Conservative” design Error: Reference source not found the “Advanced-Plus” concept is characterized by the suppression of the vertical Stiffening Plates (vSPs) and the Cooling Plates (CPs). The functions of stiffening and cooling are merged in a thin horizontal Stiffening Plates (hSP) of 5 mm instead of 14 mm. To keep a sufficient cooling the distance between two hSPs has been decreased (35.4 mm instead of 167.8 mm). These modifications permit to reduce the number of helium manifold (only one) and could simplify manufacturing. CAP have been reinforced (thickness was increased from 25 mm to 75 mm) to withstand the pressure in case of in-box Loss Of Coolant Accident (LOCA). Fig. 2 presents a fourth of HCLL “Advanced-Plus” equatorial module.

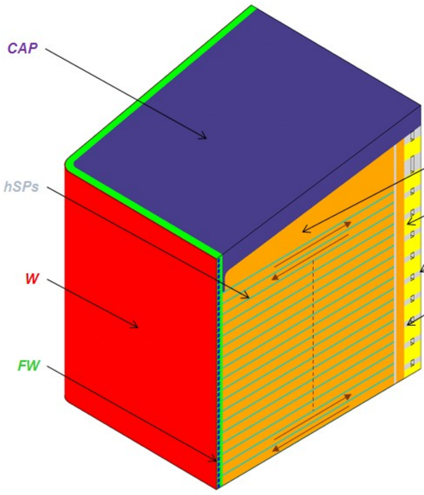

Fig. 2. Isomeric scheme of HCLL “Advanced-Plus” BB

3. DEMO HCLL “Advanced-Plus” model

The TRIPOLI-4® DEMO HCLL model is described in [2]Error: Reference source not found. It is based on a generic CAD model with empty blanket developed at KIT [10]. The parameters of the studied tokamak are presented in Table 1.

Table 1. Main “EU DEMO1 2015” *parameters.*

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.

The TRIPOLI-4® model was generated using the CAD import tool McCad [11]. 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, CAP, BP, hSP, manifolds, BSS, etc.). Fig. 3 shows a radial-poloidal cut of the tokamak with HCLL "Advanced-Plus" blanket. Fig. 4 shows the internal structure of the BB and the BSS.

Fig. 3. TRIPOLI-4® plot of the DEMO HCLL "Advanced-Plus" model

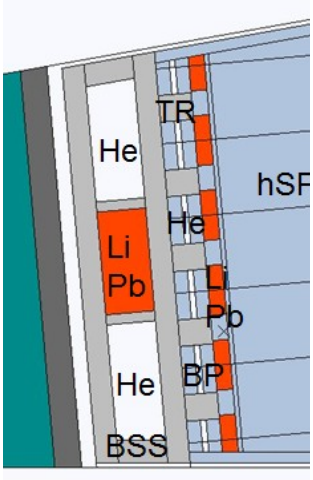

Fig. 4. Toroidal-radial plot of a HCLL "Advanced-Plus" module

4. Results

In this section the main nuclear quantities are presented: tritium breeding ratio, nuclear heating and neutron flux distribution obtained. Differences between the "Advanced-Plus" design and "Optimised Conservative" (TBM-like) design are reported.

4.1 Tritium breeding ratio

TBR obtained in previous studies Error: Reference source not found for the "Optimised Conservative" and the "Advanced-Plus" designs are respectively 1.17 and 1.20. Since this analysis was carried out several modifications were implemented. Firstly, the water cooled divertor was considered, it has a serious impact in TBR (around -0.04). Thicker CAP were implemented in "Advanced-Plus" design (to withstand LOCA pressure loading), it reduces TBR of -0.05. "Advanced-Plus" hSP were optimized, regarding thermal and mechanical consideration their thickness were reduced from 8 mm to 5 mm, TBR was increased by +0.04. Finally, in both case (Optimised Conservative and Advanced-Plus) a heterogeneous model of the BSS was developed (Fig. 3), it does not change the TBR. Table 2 presents the TBR obtained from the last studies to the current state of the design. Both HCLL BB design met TBR requirement (> 1.10), nevertheless Advanced-Plus BB presents more margin (1.15 TBR) and is even more promising if SMS is considered since the thicker CAP impact is reduced (see part 5.).

Table 2. TBR evolution with design options modifications (TBR contribution of manifolds and BSS is taken into account)

HCLL BB design	2016 Error: Reference source not found	Water cooled divertor
Opt.-Cons.	1.17	1.13
Adv.+	1.20	1.16

4.2 Nuclear Heating

Table 3 reports the Nuclear Heating (NH) breakdown in DEMO HCLL "Advanced-Plus". The energy multiplication factor (M_E) is 1.2. 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). The outboard nuclear heating profiles are given in the equatorial module in Fig. 5. NH Nuclear heating maximum value is located in tungsten armour (21.6 W/cm3), in the FW NH is 8.2 W/cm3. NH in coils is reported in the next part.

Table 3. Nuclear heating breakdown

Components	BBMs	BSS
NH in MW	1700	37

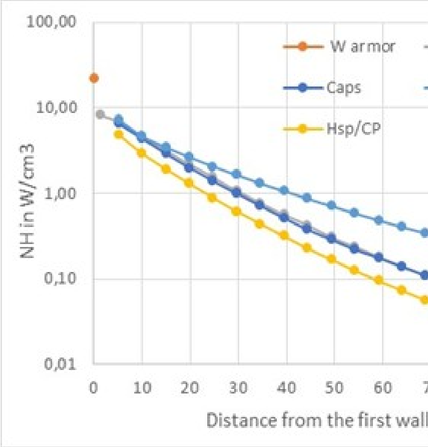

Fig. 5. Outboard equatorial module radial nuclear heating profile in the different part of the HCLL BB "Advanced-Plus" design

4.3 Inboard Profiles

Severe irradiation condition occurs at inboard mid-plane, Neutron Wall Loading (NWL) is important (1.2 MW/m²) and shielding material thickness is reduced. Neutron fluence and NH in Toroidal Field Coils (TFC) must be assessed and criteria [12] fulfilled: fast neutron flux (E>1MeV) lower than 10^9 n/(cm².s) and NH in TFC below 50 W/m^3. Other criteria are also defined for displacement damage in vacuum vessel (<2.75 dpa for 6 full power years) and helium production in the rear part of the BSS (< 1 appm for 1.57 full power years). Table 4 shows that all criteria are met considering "Optimised Conservative" or "Advanced-Plus" designs. The main difference between "Opt.-Cons. 2016" and "Opt.-Cons. 2017" is the BSS description (2016: homogeneous, 2017: heterogeneous). BSS homogeneous description over estimates fast neutron flux in coils by 20%, impact in nuclear heating in coils is negligible compared to statistical error, displacement damage in Vacuum Vessel (VV) is also overestimated on the contrary helium production is underestimated. This shows the importance of BSS modelling for shielding analysis. Slight differences between “Opt.-Cons. 2017” and “Adv.+” are observed.

Radial profiles are given for the Advanced-Plus” design. Fig. 6 and 7 show the inboard radial profile of respectively the neutron flux (fast and total) and the nuclear heating. Fig. 8 and 9 show the inboard radial profile of respectively the displacement damage in steel (FW + BSS: Eurofer, VV + coils casing: stainless steel 316L) and the helium production in steel.

Table 4. Nuclear quantities and criteria at inboard mid-plane

HCLL BB design	Fast n. flux n.cm^{-2}.s^{-1}	NH in TFC W/m
Opt.-Cons. 2016	3.60 10^8	18.0
Opt.-Cons. 2017	2.99 10^8	17.6
Adv.+	2.83 10^8	16.5
Stat. err.	1%	5%
Criteria	10^9	50

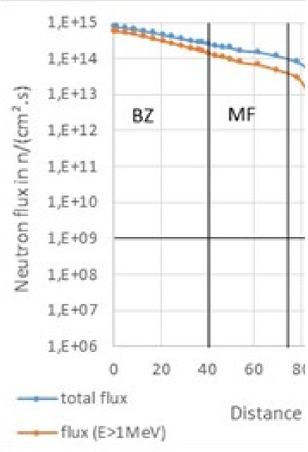

Fig. 6. Inboard radial neutron flux profile (BZ: breeding Zone, MF: in-box manifold region + BSS, VV: vacuum vessel)

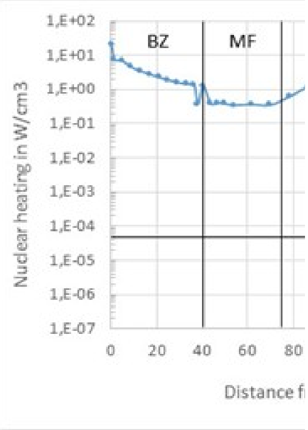

Fig. 7. Inboard radial nuclear heating profile (NH in BZ is given for the W armor, FW and then the LiPb in MF NH in the back plates is around 0.3 W/cm^3 and 1 W/cm3 for the LiPb manifold)

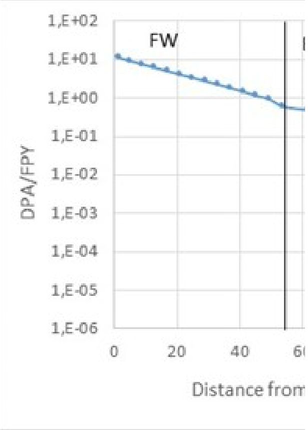

Fig. 8. Inboard radial displacement damage profile in steel (FW include Side Wall SW)

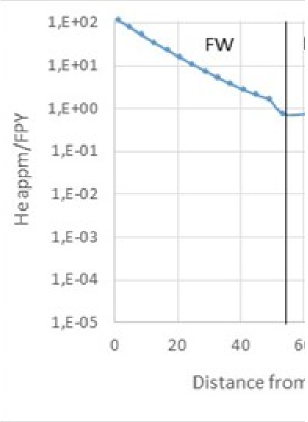

Fig. 9. Inboard radial helium production profile in steel

5. Future DEMO baseline and SMS option

The aim of this part is to investigate the impact, in terms of tritium breeding, of the future DEMO 2017 baseline [13]. To ensure a better plasma vertical stability the outboard BB radial thickness of the next DEMO baseline is reduced by 30 cm. This reduction has a strong impact on TBR. Fig. 10 shows that TBR of DEMO HCLL “Advanced-Plus” MMS is reduced by -0.03 with a -15 cm outboard BB radial thickness reduction and -0.06 with an extra -15 cm reduction i.e. -0.09 in TBR for a total -30 cm outboard BB radial thickness reduction.

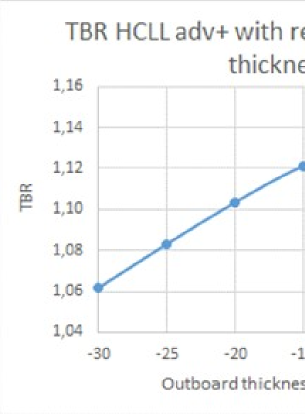

Fig. 10. DEMO HCLL “Advanced-Plus” MMS TBR against outboard BB radial thickness reduction

The next baseline presents also a modest inboard BB radial thickness increase (+6 cm). TBR obtained in these conditions (outboard BB radial thickness -30 cm and inboard BB radial thickness +6 cm) is 1.07. To fulfil TBR requirement SMS option must be considered. But SMS feasibility must be demonstrated with dedicated studies, so another option based on MMS with a reduced number of modules is also investigated.

The SMS model showed in Fig. 12 is based on the “Advanced-Plus” DEMO HCLL, described in part 3 with the 2017 baseline characteristics (inboard BB radial thickness: +6cm and outboard BB radial thickness: -30 cm). Only 2 CAPs (at inboard and outboard) were kept to close the SMS (the gaps between the previous modules in poloidal direction were closed). TBR achieved is 1.14.

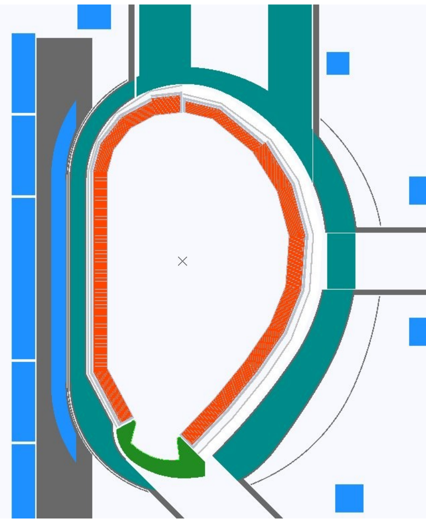

Fig. 12. DEMO baseline 2017-like HCLL “Advanced-Plus” SMS model plot

The intermediate solution between SMS and the current MMS to reduce the number of the modules. This was tried to estimate the gain in term of tritium breeding. The bigger module DEMO baseline 2017-like HCLL is shown on Fig. 13, three modules at inboard and outboard are considered. TBR obtained is 1.12.

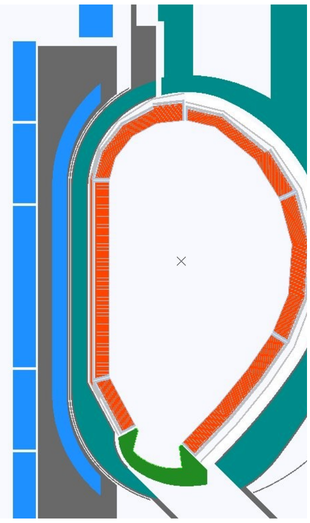

Fig. 13. DEMO baseline 2017-like HCLL "Advanced-plus" MMS with reduced number of modules model plot

TBR evaluations for the SMS and MMS with a reduced number of modules were carried out also with the current DEMO 2015 baseline. Table 5 shows the need for a HCLL "Advanced-Plus" BB segmentation evolution in a near future (the next DEMO baseline). TBR requirement is not fulfilled using the current MMS. Nevertheless, these results must be verified using the "real" DEMO 2017 baseline.

Table 5. TBR of the DEMO HCLL "Advanced-Plus" BB for different segmentation options and DEMO baseline

Segmentation	Baseline 2015	Baseline 2017*
MMS	1.15	1.07
MMS with Bigger Module	1.20	1.12
SMS	1.22	1.14

*evaluation based on the DEMO baseline 2015 with modified BB radial thickness corresponding to the DEMO baseline 2017

Conclusions

From nuclear performance point of view the new HCLL "Advanced-Plus" design is very promising. The obtained tritium breeding ratio presents comfortable margin (1.15) and it could be increased using SMS approach. Regarding the inboard shielding, this new concept fulfil all criteria (fast neutron flux and nuclear heating in coils, displacement damage in vacuum vessel and helium production in the rear part of the BSS). This new concept is still underdevelopment, and the first structural analysis are encouraging but some improvement are necessary regarding the cover plates cooling and corner area design in case of LOCA [5].

This year a new 2017 DEMO baseline was proposed. Preliminary calculations based on the current DEMO model have shown a strong negative impact on tritium breeding in HCLL case (-0.09). This is due to the reduction by 30 cm of the outboard radial breeding blanket thickness. The plasma vertical stability was compromised with the previous outboard blanket size. To achieve the tritium breeding requirement with HCLL blanket in the next DEMO baseline SMS option or MMS with a reduced number of modules must be considered. In a near future nuclear analysis based on the DEMO 2017 baseline will confirm this first evaluation. This new outboard blanket size constraint demonstrates the importance of the HCLL "Advanced-Plus" design development, using the previous HCLL "Optimized Conservative" design, tritium breeding requirement is unreachable.

Acknowledgments

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.

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