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Neutronic assessments towards a comprehensive design of DEMO with DCLL Breeding Blanket

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On the way towards a comprehensive design of DEMO, step by step all the systems and components must be introduced as their definition or refinement progresses, in order to demonstrate the viability of a design on larger scale, i.e. leaving fewer margins to undetermined questions.

Among the EUROfusion Programme, new aspects have been recently fixed or furtherly developed as the Divertor, the First Wall (FW) and the Flow Channel Inserts (FCI) designs. Furthermore, the integration of Heating and Current Drive (H&CD) systems, as the Neutral Beam Injector (NBI), has started.

The introduction or modification of these systems and components could seriously jeopardize the nuclear behaviour of an initially validated Breeding Blanket (BB) DEMO concept, since many neutronics criteria - among others - could be no more fulfilled. Since the design of DEMO is a continuous upgrade under iterative process, as the advances push on, most of the studies have to be repeated to demonstrate that criteria are still respected in a fully integrated design. The consequences of these upgrades over the neutronic responses are addressed in this paper. Among others, the influence on Tritium Breeding Ratio (TBR) of a new design of detached FW protecting BB from high heat fluxes is investigated. The impact of different typologies of FCIs is assessed also according to the degree of detail in the neutronic description. The divertor composition also reveals to have strong impact on responses apparently not related with its design, as the tritium production in the BB. Besides, the integration of NBI minimizing its invasiveness in the BB is verified by neutronic analyses concerning the main BB functions: fuel breeding and heat generation. Accordingly, TBR and Nuclear Heating (NH) are assessed.

The study is performed for a Dual Coolant Lead Lithium (DCLL) BB DEMO although can be extrapolated to other BB concepts.

Keywords: Neutronics, DCLL, FW, FCI, Divertor, NBI, TBR

1. Introduction

In order to progress towards a comprehensive DEMO design, as much as the definition of the components advances, also their combined integration inside the machine has to be analysed and tested, to prove that the requirements are still fulfilled under different scale or they have to be updated to answer the progresses. For instance, in the initial phase of the Breeding Blanket (BB) design for the future European DEMOnstration fusion reactor a Tritium Breeding Ratio (TBR) >1.1 [1] was required to take into account (among others) a 5% of uncertainty due to the equatorial port penetrations trough which H&CD system would pass. When the design of such system will be ready and they will be introduced inside the reactor, the re-analysis of the TBR would be required, and the preliminary hypothesis would be substituted by a value given on the basis of a realistic calculation.

Among the EUROfusion Programme new aspects have been recently fixed or furtherly developed as the Divertor and First Wall (FW) designs; novel activities are being performed as the development of Flow Channel Inserts (FCIs); and, the integration of H&CD systems, as the NBI are, has started.

The paper here presented focuses on the neutronic analysis of the Dual-Coolant Lithium Lead (DCLL) BB System [2], one of the 4 BB options conceived for DEMO [3], and the integration of newly developed components to refine the initial design.

Different DCLL BB designs have been developed in the period 2014-2018 in the frame of such Programme. The evolution of such design and their neutronic analyses is widely described in [4][5][6][7][8][9][10]. The last version of the DCLL, called v3.1 based on the plasma parameters of DEMO2015 [11][12] (i.e. 2037 MW and pulsed scenario [13]), is here briefly described and the main neutronic results referred to the BB are summarized in section 2. Section 3 is devoted to the description of those BB components recently developed more in detail which could compromise the performances of an initially validated DCLL DEMO design. BB components such as the FW and the FCIs are analysed in section 3.1 and 3.2, respectively. Other elements outside the BB components that could seriously compromise the nuclear behaviour of an initially validated BB design are analysed in section 4. Here the divertor design and its composition are shown to be related to the achieved TBR. Finally in section 5 the integration of a preliminary model of NBI is described and the impact of such ex-vessel component on the BB nuclear performances is highlighted.

2. DCLL BB DEMO features and main neutronic responses

The last version of the DCLL neutronic design has been developed on the way towards a higher refinement of

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the BB and its Back Supporting Structure (BSS). The novelties of such v3.1 version respect to the previous v3.0 [6] are summarized in the following:

1. Introduction of attachments between each BB module and the BSS.
2. Separation of 2 cm among BB and BSS.
3. All the stiffening plates included.
4. Their cooled areas are separated from the plates' areas that are not required to be cooled, using different compositions for them.
5. A similar separation is adopted for Top and Bottom walls (only the front area requires to be cooled with He).
6. The FCI (sandwich concept) are included in all the modules.

The only simplification adopted in the neutronic model and which could have an effect on the results is that the helium channels inside the FW and stiffening plates (where present) are simulated as homogenized composition. For the rest it is a completely heterogenized neutronic design. The main geometric parameters of the DCLL at the equatorial plane (Z=0) in the radial direction are:

- FW: tungsten coating of 2 mm + 25 mm of Eurofer + helium;
- BB + BSS: 39.8 cm + 36 cm in the IB side; 63 cm + 63.7 cm in the OB side.

The overall neutronic model for the DCLL is presented in Figure 1, where different parts have been highlighted for clarity using for them the same nomenclature assumed in text and tables. The neutronic design has been developed through the CAD/MC interface software SuperMC [14] while the particle transport calculations have been performed with MCNP5 Monte Carlo code [15] and JEFF 3.2 nuclear data library [16]. Direct simulation results have been normalized to $7.232x10^{20}$ neutrons per second [n/s] source, corresponding to a fusion power of 2037 MW.

Results strictly related to the blanket design such as the TBR and the nuclear heating (NH) are here briefly discussed. The results of tritium production are presented in Table 1, in which local values are shown for each module position (from 1 to 16) giving values for the entire 360º reactor. The values in the BSS are also provided. The total TBR in the BB modules is 1.085. Adding up the contribution of the BSS PbLi channels the final value reaches 1.196. This very high amount of T produced, much higher than the target of 1.1, would imply high margins for further design improvements and new components integration. Concerning the assessments on nuclear heating, assuming the fusion power of 2037 MW and having obtained a total power of 1971 MW, the obtained Energy Multiplication Factor M_E is 1.21, being M_E the ratio of the total nuclear power and the fusion neutron power (80% of 2037 MW). In Table 2 the breakdown of the nuclear power deposited in the different structures of the reactor is shown giving the relative contribution (%) to the total.

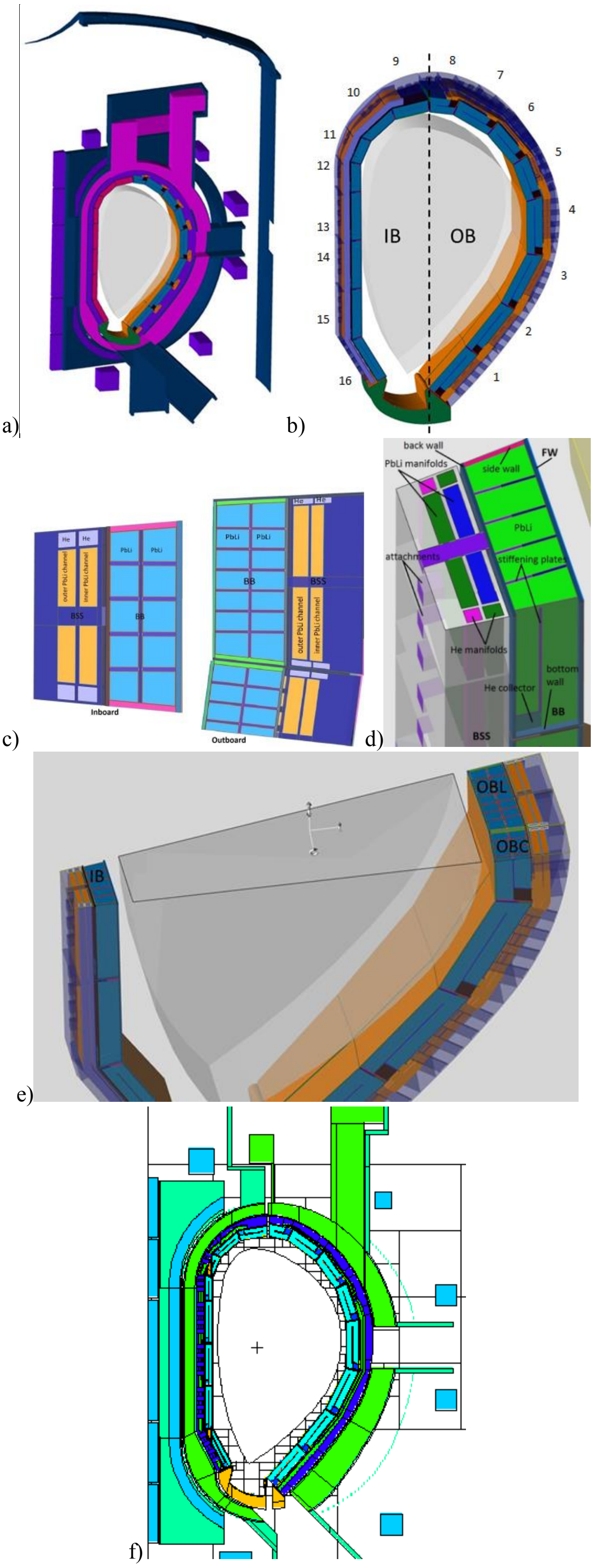

Figure 1: DCLL DEMO neutronic model: a) generic DEMO model with DCLL BB; b) BB + BSS IB and OB segments; c) IB and OB horizontal cross-section; d) IB equatorial BB and BSS; e) horizontal section of a 10º sector; f) MCNP plot of DEMO DCLL model.

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Table 1. Tritium production in the BB modules (nº position in figure 1b) and in BSS cells in terms of local and total TBR.

BB	IB	OBL	OBC	total v3.1
1		4.70E-02	3.20E-02	7.90E-02
2		7.41E-02	4.03E-02	1.14E-01
3		9.38E-02	4.35E-02	1.37E-01
4		1.00E-01	4.34E-02	1.43E-01
5		7.15E-02	3.16E-02	1.03E-01
6		6.15E-02	3.05E-02	9.20E-02
7		4.88E-02	2.94E-02	7.82E-02
8		2.37E-02	1.74E-02	4.11E-02
9	4.44E-02			4.44E-02
10	3.32E-02			3.32E-02
11	2.22E-02			2.22E-02
12	2.38E-02			2.38E-02
13	4.54E-02			4.54E-02
14	4.58E-02			4.58E-02
15	4.05E-02			4.05E-02
16	4.10E-02			4.10E-02
			TBR BB	**1.085**
BSS	IB	OBL	OBC	total v3.1
out ch.	1.98E-02			1.98E-02
in ch.	2.83E-02			2.83E-02
out ch.		1.93E-02	8.80E-03	2.81E-02
in ch.		2.27E-02	9.81E-03	3.25E-02
			TBR BSS	**1.09E-01**
BW			**TBR BW**	**2.59E-03**
		Total TBR		**1.196**

Table 2. Breakdown of the nuclear power deposited in the different reactor main components and M_E.

	MW in 360º	**% on TOT**
IB BB+BSS	506.03	25.67%
OBL BB+BSS	805.55	40.86%
OBC BB+BSS	435.32	22.08%
VV+Ports+Shell+Coils+Tshield	50.95	2.58%
Divertor	173.70	8.81%
Tot Power	**1971.6**	
M_E	**1.21**	

Further partitions have been analysed in order to show the contribution of fluids and structures, to evaluate the actual amount of power recoverable from the PbLi as coolant.

Considering the relative contribution of IB, OBL and OBC BB+BSS segments to the total (respectively a 25.67%, 40.86% and 22.08%, see Table 2) and the PbLi contributions to each segment (71.52% for IB and 75.08% for OBL and OBC) it is obtained an absolute contribution to the total of 18.36% for IB PbLi, 30.68% for OBL PbLi and 16.58% for OBC PbLi, and a comprehensive contribution of this fluid of 65.61% (1293 MW) on the total (1971 MW) recoverable with thermal cycles. The water cooling of Vacuum Vessel (VV) and Divertor is not summed up to this calculation.

Mesh tallies 3D map distributions of both the TBR (as atoms of T per cm^3) and NH (as W/cm^3) for Eurofer and PbLi materials are shown in figures 2 and 3, respectively, to have a fast idea of the most efficient zones.

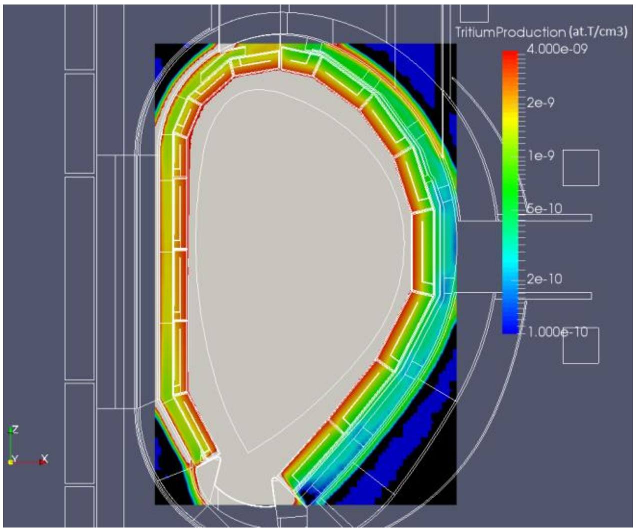
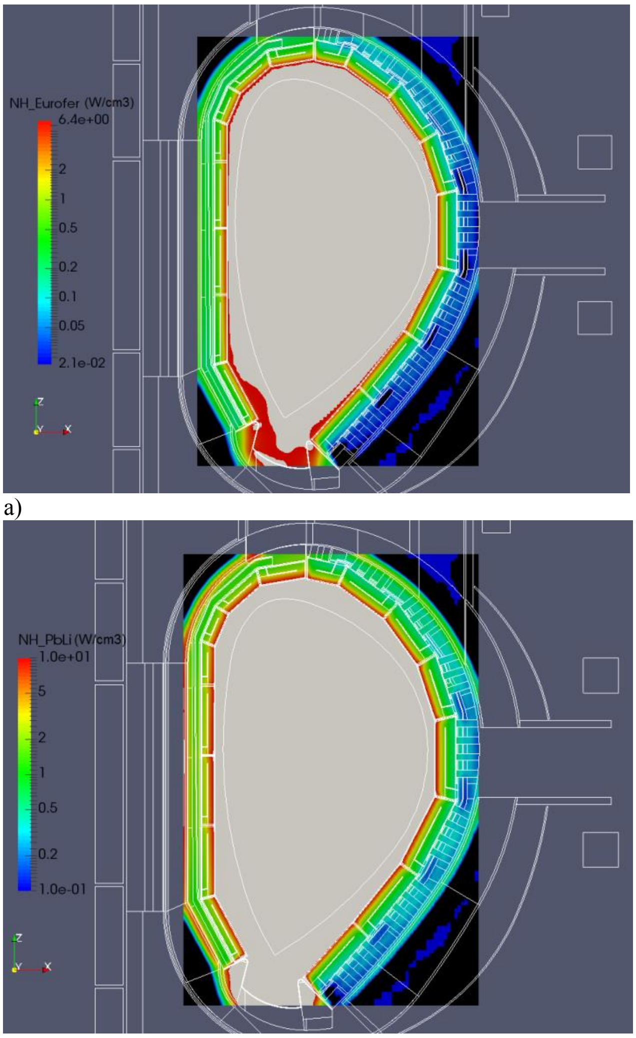


Figure 2. Mesh tally radial-poloidal distribution of the tritium generated in the DCLL DEMO model (as at. T per cm^3)



a)

b)

Figure 3. Mesh tally radial-poloidal distribution of the nuclear heating (W/cm^3) generated in the whole DCLL DEMO BB and BSS sector for: a) Eurofer and b) PbLi components.

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3. Development of BB components and their impact on nuclear performances: FW and FCIs selection

Beyond the neutronic analyses of the baseline version of the DCLL BB DEMO model (v3.1) other assessments have been performed with special emphasis on the choice of some components essential for the design of the BB, as the FCIs and the FW are. In section 3.1 the impact of different FW designs is analyzed from the neutronic point of view. In section 3.2 the effect on nuclear responses of different FCI designs and the degree of detail of their description in the neutronic design is assessed.

3.1 Influence of FW design on TBR and Nuclear Heating

The design of the FW determines the nuclear performances of a reactor. The radial thickness and compositions of both the W coating and the Eurofer wall have been recently studied [17][18] showing a big impact of such parameters on the TBR and shielding results.

Recently a new design of FW has been proposed [19] consisting in a detached wall made by stacking fingers covering totally or partially the BB modules to protect them from very high heat fluxes. The separation is structural but can be also hydraulic since the cooling fluid which passes throughout the wall can be decoupled from the cooling circuit of the BB module. For this reason different cooling options are proposed studying their benefits or disadvantages. In this paper two different fluids have been considered as coolants of the FW: water and helium.

Thus, the integrability of such detached first wall has been preliminarily assessed in terms of impact on nuclear responses: the TBR would be in fact highly conditioned by the kind of cooling fluid and by the % amount of fluid vs. steel in the mixed composition. The nuclear heating in the Eurofer structure is also briefly analysed.

In a first attempt to give representative results on simplified geometries (to have the possibility of changing easily the composition of the detached FW) a new DCLL v3.1 neutronic model with simplified FW fingers has been developed, modifying one by one each BB module. The modifications (Figure 4) consist in introducing a covering panel (representing the stacking fingers) made of 2 mm of W coating and 1.8 cm of finger wall (the "new" FW of Eurofer mixed to the coolant option) and adding a separation gap of 2 cm (void) between this and the "old" 2.5 cm FW (made by Eurofer + He at the same composition than the baseline).

The modules remain unaltered in their essence but, as the Scrape-Off-Layer cannot be occupied by the new FW, all the BB structures have to retrocede 4 cm to leave space to the 2 cm new FW + 2 cm gap. Such reduction of 4 cm in the BB module radial size has been basically applied to the breeder channels (2cm of radial reduction per each of the 2 PbLi poloidal channels). Furthermore, in order to maintain the same distribution of the available radial space among the 2 PbLi channels, the stiffening plate which separates the 2 channels has been moved back 2 cm. All the other structures have been also moved to keep the previous geometry (FCIs, He collectors).

Three different FW finger compositions have been preliminary chosen to analyze the effect of such new component on the TBR results:

- Composition 1: 44.04% He, 55.96% Eurofer (extrapolated from the finger CAD design).
- Composition 2: 44.04% H_2O, 55.96% Eurofer (substitution of helium by water).
- Composition 3: 13.91% H_2O, 86.09% Eurofer (composition of the FW of the 2016 WCLL neutronic model developed by ENEA [20]).

The FW composition of the baseline model (now 'Second Wall') is kept. The results of TBR in the 3 different cases are given in tables 3 and 4. As it is possible to observe, the use of entire panels cooled by helium and covering the whole blanket segments implies a TBR loss of about 5%. Considering that both the BB and the BSS have not been optimized for this new configuration, the result is quite promising.

On the other side, a strong reduction of the global breeding performances is produced by the use of water as coolant since the loss is of 24% and 13% respectively from the initial value (1.196), when a 44% and a 13% of water are mixed with the Eurofer inside the detached FW. Both options would have an invalidating effect on the breeding capability of the DCLL blanket. Accordingly, such hypothesis of detached FW cooled by water has been discarded for this version of DCLL.

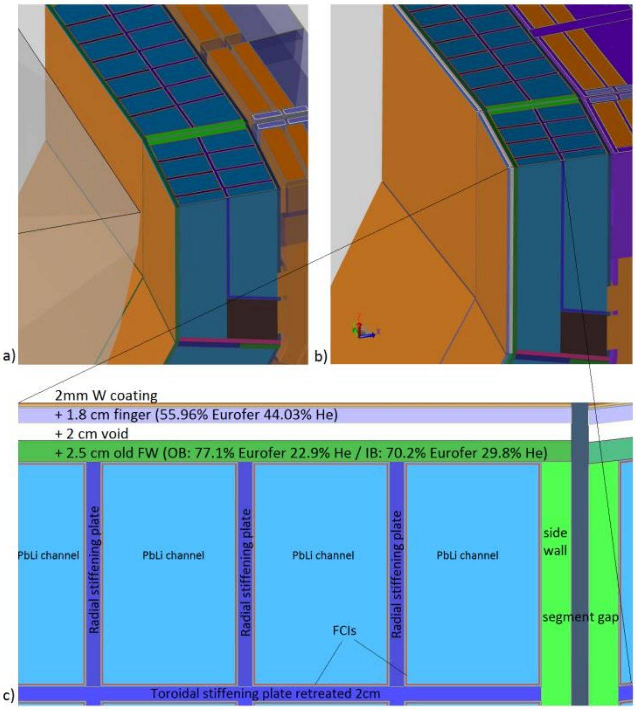

Figure 4. a) Original DCLL design v3.1 with the FW integrated structure (green); b) new DCLL design with a detached FW (light violet) covering the old "Second Wall" (green); c) detailed structure of the modified BB modules with a detached FW made by an initial finger composition of helium and steel.

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Table 3. TBR % variation inside the DCLL main structures between the baseline v3.1 and the version with detached FW cooled by helium.

Comparison He cooled detached – No detached FW			
	Integrated FW (baseline)	Detached FW (Comp.1)	% ΔTBR
Breeding zone (BZ)	1.085	1.013	-6.64%
Back wall (BW)	2.59E-3	2.76E-3	+6.56%
Back Supporting Structure (BSS)	1.09E-1	1.16E-1	+6.42%
Total	1.196	1.132	-5.35%

Table 4. TBR % variation between the baseline DCLL v3.1 and the 2 DCLL versions with detached FW cooled by water.

Comparison Water cooled detached – No detached FW		
	Total TBR	% ΔTBR
Integrated FW	1.196	
Detached FW Comp. 2	0.909	-24%
Detached FW Comp. 3	1.039	-13.13%

Nuclear heating radial profiles for an IB segment (figure 5), calculated for Eurofer and comparing the baseline and the detached helium-cooled FW model, are given at positions Y=0-2 cm and Y=60-62 cm (respectively, on the side wall and in the middle of the module where also PbLi is present, implying some deviation from actual Eurofer values). From these it is possible to observe that the IB detached FW is slightly more heated by nuclear reactions than the baseline FW and some increase in the NH values is also observed along the entire radial domain.

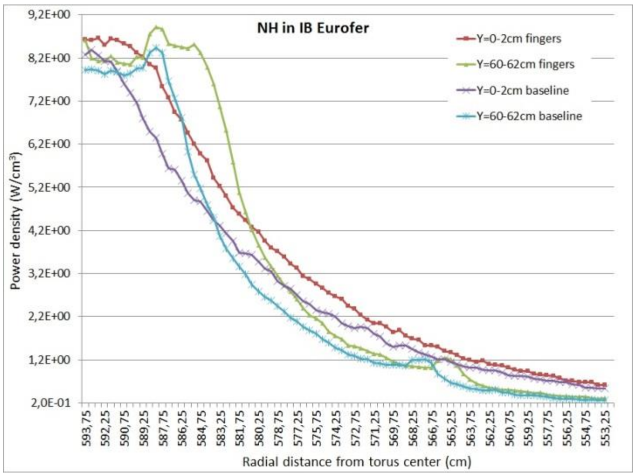

Figure 5. Power distribution (W/cm^3) on pure Eurofer for the IB side equatorial zone of the DCLL model comparing the baseline and the detached helium-cooled FW model. Radial profiles taken from mesh tallies of 332.100 voxels of 0.5x2x5 cm^3 at positions: Y=0-2 cm (side wall) and Y=60-62 cm (inside module) at constant z=50-55 cm and in 5 mm radial bins.

3.2 Effect of FCIs design on TBR

Different kinds of flow channel inserts to mitigate magnetohydrodynamic (MHD) effects are under consideration for the DCLL blanket [21].

In order to give a preliminary estimation of the FCI impact on the TBR according to the kind of FCI adopted and the level of realism in the description of such component in the neutronic design, an initial assessment has been performed considering three possible situations:

1. The FCI is not included in the BB.
2. The FCI 'naked' type (5 mm Al_2O_3) is included in the BB description as homogenized mixture (90.51% PbLi and 9.49% Al_2O_3), taking into account the volumetric percentage inside the breeder material and an adjusted density.
3. The sandwich-like (Eurofer-Al_2O_3-Eurofer) FCI concept [22] (95% Eurofer and 5% Al_2O_3) of 1.1 mm is realistically included in the BB neutronic design as a separate component with its actual geometry (baseline DCLL version v3.1).

The three possibilities are schematized in Figure 6.

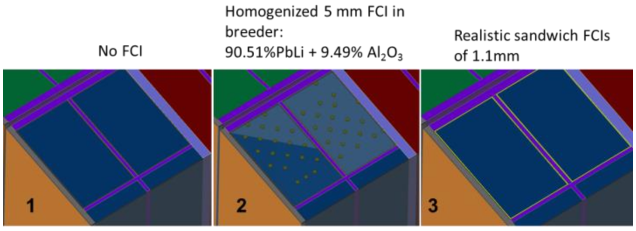

Figure 6. Different kinds of representation of the FCI under consideration in a DCLL blanket: 1) FCI not included in the BB; 2) 5 mm Al_2O_3 FCI included as homogenized mixture; 3) 1.1 mm sandwich-like (Eurofer-Al_2O_3-Eurofer) FCI included as a separate component (baseline).

Table 5. Local and global TBR values for the three FCI descriptions and % variation of cases II and III respect to the case without FCI (I).

BB		No FCI (I)	5mm naked alumina FCI (II)	1.1mm sandwich FCI (III) **baseline**	% ΔTBR (I-II)	% ΔTBR (I-III)
OB	1	8.03E-02	7.95E-02	7.90E-02	-0.96	-1.60
	2	1.16E-01	1.15E-01	1.14E-01	-0.95	-1.50
	3	1.39E-01	1.38E-01	1.37E-01	-0.70	-1.43
	4	1.46E-01	1.46E-01	1.43E-01	-0.12	-1.58
	5	1.05E-01	1.04E-01	1.03E-01	-0.62	-1.48
	6	9.35E-02	9.26E-02	9.20E-02	-0.94	-1.65
	7	7.94E-02	7.86E-02	7.82E-02	-1.02	-1.47
	8	4.18E-02	4.12E-02	4.11E-02	-1.43	-1.56
IB	9	4.51E-02	4.51E-02	4.44E-02	-0.08	-1.68
	10	3.37E-02	3.39E-02	3.32E-02	0.60	-1.43
	11	2.25E-02	2.27E-02	2.22E-02	0.76	-1.20
	12	2.42E-02	2.43E-02	2.38E-02	0.74	-1.31
	13	4.61E-02	4.67E-02	4.54E-02	1.32	-1.60
	14	4.65E-02	4.72E-02	4.58E-02	1.42	-1.57
	15	4.12E-02	4.17E-02	4.05E-02	1.04	-1.64
	16	4.18E-02	4.21E-02	4.10E-02	0.79	-1.81
total BB		**1.102**	**1.098**	**1.085**	**-0.31**	**-1.54**
BSS	IB out	2.00E-02	1.59E-02	1.98E-02	-20.46	-1.26
	IB in	2.86E-02	2.34E-02	2.83E-02	-17.93	-0.83
	OB out	2.88E-02	1.91E-02	2.81E-02	-33.64	-2.48
	OB in	3.30E-02	2.36E-02	3.25E-02	-28.44	-1.41
total BSS		1.10E-01	8.21E-02	1.09E-01	**-25.63**	**-1.51**
BW		2.59E-03	2.16E-03	2.59E-03	**-16.60**	**0.07**
total TBR		**1.215**	**1.183**	**1.196**	**-2.65**	**-1.53**

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The total and local TBR values for the BB system, the BSS and the Back Wall (BW) connections are given in table 5 for the three cases and their respective variation.

Calculations show that the use of a homogenized 5 mm alumina FCI reduces the TBR in a 2.65% and the use of a detailed 1.1 mm sandwich in a 1.53% in comparison with the case without FCI, respectively. When the homogenized 5mm FCI is used the TBR is almost constant or slightly higher in the breeding zones nearer to the plasma. In these regions, in which fast neutrons can produce 27Al(n,n') and 27Al(n,2n)26Al reactions, moderation and multiplication of neutrons occur, being absorbed more easily through 6Li(n,t) reactions. The effect is more pronounced in the inboard side modules, at a radial distance less than 50 cm from plasma. On the contrary the local TBR is strongly reduced in those zones further away from the plasma (the BW and BSS) where the neutron spectrum is already slowed down and the neutron flux is reduced (BW has ~16% and BSS ~25% of TBR loss).

With the realistic 1 mm sandwich the TBR loss is almost constant in all the structure, IB/OB and BB/BSS, being around a 1.5% if comparing with the case without FCI. The difference with the 5 mm homogenized FCI resides also in the different material used as main element of the FCI that in the sandwich case is basically Eurofer. The steel in fact inhibits that multiplication and moderation occurs and no enhancement of (n,T) reaction with Li6 is possible in zones near to the plasma.

To separate the effect of the FCI typology (naked vs. sandwich) and the FCI neutronic description (homogenized vs. detailed) the data of a previous analysis [10] are provided in support. In such study it was possible to observe that the introduction of a realistically described FCI (sandwich-like case of 2 mm) in only one PbLi channel of one BB module implied a loss of the local TBR of 2.3% (slightly higher than the loss of breeder volume which was 2.18%). When the component was taken into account in the homogenized composition, the TBR dropped a 1.29% more than the previous 2.3%, for a total of 3.59% of loss. This analysis evidenced that the homogenization has a conservative effect on the TBR performance of the BB. Appling such conclusion to the situation above, it would mean that the use of 5 mm naked alumina FCI could imply a TBR reduction lower when a realistic detailed design is implemented and more similar to that caused by the Eurofer-alumina-Eurofer 1.1 mm FCI.

4. Influence of other in-vessel components design on the TBR: the case of the divertor

Similarly to the studies performed for previous versions of the DCLL model [23] the impact on the TBR performance caused by the selection of the divertor design and its coolant amount for the current version of DCLL DEMO is here discussed.

The DEMO DCLL model v3.1 described in section 2 (the baseline for which TBR results are given in table 1) used a neutronic model of divertor based on the 2015 water cooled divertor cassette design developed within the WPDIV project. The assumed composition of the cassette is 28.3%vol Eurofer, 24%vol water and rest (47.7%vol) void [24] (also equivalent to 54% Eurofer and 46% water at the reduced density of 2.43 g/cm^3).

On the other side, the divertor design used in previous phases of the WPBB neutronic studies [25] was a solid steel body of Eurofer97 except two layers facing the plasma of 5 mm thick tungsten armour, with in between a 15 mm thick tube layer filled with a homogenized mixture of 39.5% W, 17% CuCrZr, 13% Cu and 30% water. Almost 17.3 tons of Eurofer were assumed in one divertor cassette of 2.21 m^3.

The total TBR and its poloidal distribution among the BB modules and the BSS are reported in table 1 for the baseline model with water cooled divertor, and in table 6 for the previous steel cassette divertor. In there the % variation of TBR respect to the baseline is also given.

Table 6. TBR poloidal distribution in BB modules and in BSS for the DCLL DEMO 2015 v3.1 using a full steel divertor composition.

v3.1 Steel divertor					% ΔTBR using baseline
BB	IB	OBL	OBC	TBR	
1		5.21E-02	3.57E-02	8.78E-02	
2		7.71E-02	4.20E-02	1.19E-01	
3		9.74E-02	4.51E-02	1.42E-01	
4		1.04E-01	4.52E-02	1.50E-01	
5		7.48E-02	3.31E-02	1.08E-01	
6		6.45E-02	3.20E-02	9.65E-02	
7		5.14E-02	3.09E-02	8.22E-02	
8		2.50E-02	1.84E-02	4.34E-02	
9	4.68E-02			4.68E-02	
10	3.49E-02			3.49E-02	
11	2.33E-02			2.33E-02	
12	2.48E-02			2.48E-02	
13	4.71E-02			4.71E-02	
14	4.77E-02			4.77E-02	
15	4.29E-02			4.29E-02	
16	4.51E-02			4.51E-02	
total BB				**1.141**	-4.96%
BSS	IB	OBL	OBC		
out ch.	2.09E-02	2.00E-02	9.21E-03		
in ch.	2.92E-02	2.32E-02	1.01E-02		
total BBS				**1.13E-01**	-3.41%
BW				2.69E-03	
total TBR				**1.257**	-4.81%

Comparing the tritium production between the previous full-steel divertor model and the "water cooled divertor" a general reduction of the breeding capabilities of the blanket modules is observed when the water content increases inside the cassette. In fact, when the new water cooled divertor composition is used, the loss of TBR is between ~3% and ~5%, in the BSS and the BB modules. Furthermore, the total TBR loss (~5%) is higher than the margin of 3% suggested to account for unknown uncertainties in design elements [26][1]. This would suggest revising the target TBR (1.10) representing the self-sufficiency, at this status of the DEMO project, by increasing the design related uncertainties due to in-vessel components.

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5. Integration of ex-vessel components and their influence on BB nuclear performance: the consequences of NBI integration on TBR and Nuclear Heating

The integration of the Neutral Beam Injector (NBI) system [27] into the BB is under investigation by the Dual Coolant Lithium-Lead (DCLL) design team [28][29][30]. Choosing the lowest beam injection angle (30º), which compromise the minor number of segments, and focusing the beam at the middle of the BB modules instead than at the tangential point of the plasma it is possible to minimize the invasiveness of this system on the general performances (not only nuclear) of the BB+BSS complex.

In a first approach [28][29], the impact on the TBR was evaluated by subtracting the contribution of the removed breeding material. This was a conservative calculation, since it is equivalent to annul the neutron flux in the affected zone and therefore the possibility for neutrons to be scattered towards the surrounding breeder. A 0.769% of TBR loss was achieved. If the breeder volume inside the BSS is also suppressed, a total loss less than 1% could be conservatively assumed.

A more comprehensive neutronic analysis for a better characterization of the BB DCLL design adapted to the NBI system is here discussed.

In figure 7 it is possible to note that the breeding channels (blue) of OBL module #4 have been substituted by a homogenized Eurofer dummy module (violet) and one breeding channel of the OBC module #4 has been also replaced by an Eurofer block with shielding function. The neutrals beam crosses the blanket segments through a rectangular duct which consist of 2 mm thickness tungsten coating (orange) covering a Eurofer + helium mixed composition wall (dark green colour). It is used also as containment structure for the PbLi BSS channels (bottle green colour). Such BSS channels have to be preserved the most in order to not jeopardize the continuity of the PbLi manifolds along the total BSS poloidal distribution. The rest of the NBI duct from the Eurofer structure of the BSS to the equatorial port is a completely voided component which goes through the port.

Since the DEMO neutronic model comprises only 10º and an half equatorial port, when using reflecting surfaces at the boundaries of 0º and 10º it implies that the 360º are virtually modelled in the same way that the 10º half-sector. This means that when an NBI is introduced in a 10º model it corresponds to a full 360º model with 36 NBI. Although a real configuration is not possible to be considered in a 10º model, more realistic scenarios have been studied (Table 7), considering a mix of half-sectors with and without NBI (although no cross-talk between a half-sector with NBI and another without NBI can be taken into account since the two options cannot be integrated together in the same DEMO model).

Table 7. TBR variation with the number of NBI systems (BB configuration: suppression of breeder in complete OBL #4 and in one channel of OBC #4).

Local TBR in half-sector of 10º		nº of NBI in 36 sectors				
		0 baseline	**3**	**6**	**9**	**18**
With NBI	0.0303	0	0.0910	0.1819	0.2729	0.5457
No NBI	0.0332	1.1962	1.0965	0.9968	0.8972	0.5981
Final TBR		**1.1962**	**1.1875**	**1.1787**	**1.1700**	**1.1438**
ΔTBR to Baseline		0%	-0.73%	-1.46%	-2.19%	-4.38%

According to the results for the selected cases of Table 7 and considering that the most probable configuration in a real tokamak would have 3 NBI systems [27], such hypotheses would suppose a reduction of TBR of 0.73% being the absolute value 1.187.

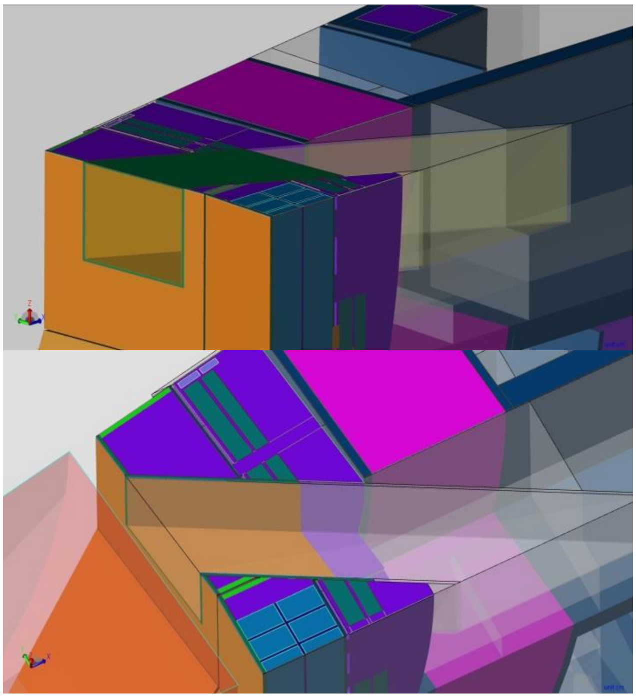

Figure 7. Views of the NBI duct which shows the two layers composing the duct panels (tungsten coating -in orange- and Eurofer wall cooled by helium -in dark green colours) and the inside structures of the OBL #4 and OBC #4 with the Eurofer blocks (violet) instead of PbLi channels (blue).

Hence, the prediction done in the past was not far from the current calculation made by analysing the transport in a realistic modified model.

The target criterion of TBR=1.1 would be still fulfilled for the DCLL even with 1 NBI per sector (18 in total). Although, since other H&CD systems and diagnostics would also impact on the original breeder performances, a more comprehensive analysis with all the systems integrated will be essential. Nonetheless, the most probable assumption of 3 NBI systems is demonstrated to have a not invaliding impact over the tritium self-sufficiency (at least for the DCLL DEMO 2015 v3.1, which has an initial TBR of 1.196). This justifies the decision of suppressing the breeding capability of OBL #4 and reducing it from OBC #4. Although the model of BB

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and the design of DEMO change in the future, new estimations can be obtained based on the approximate value achieved here of 0.243% of TBR loss per NBI system (with 1 OB equatorial module suppressed and 1 slightly modified).

Regarding the NH assessment, the results of power density in the DEMO DCLL model with the integrated NBI are compared with the DEMO DCLL baseline ones (Figure 8). A strong streaming toward the duct is observed in figure 8b implying higher heating of the duct walls itself and of the dummy EUROFER modules. The BSS structure appears to be also subjected to higher power densities and an effective shielding system has to be designed to protect the VV and toroidal field coils behind it.

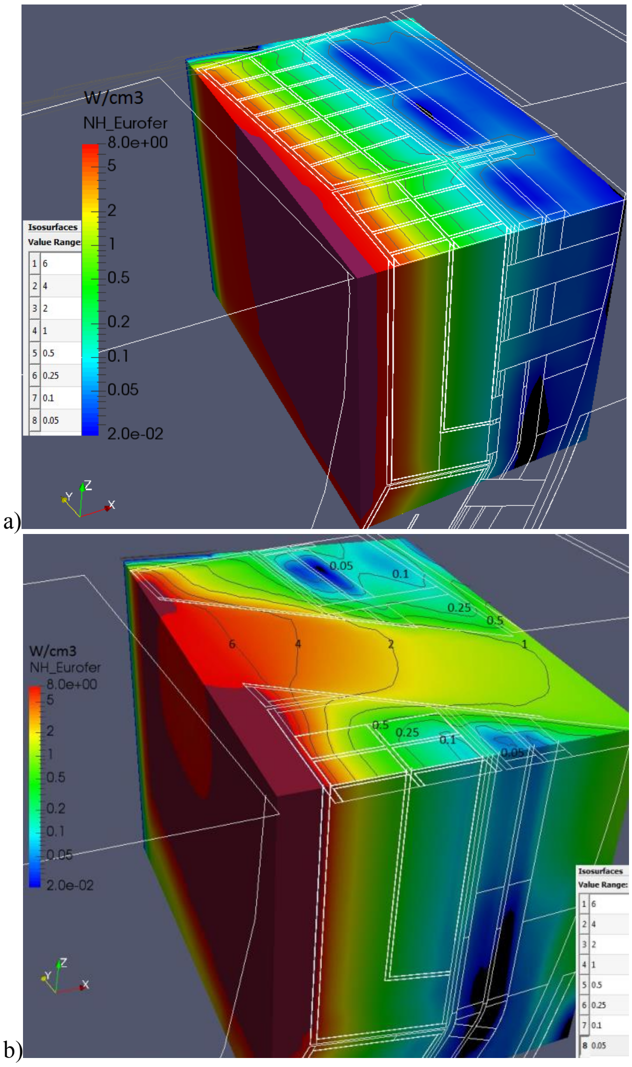

Figure. 8. Mesh tally radial-poloidal distribution of the nuclear heating (W/cm^3) deposited in the BB and BSS at equatorial OB level, for Eurofer material in DCLL v3.1 (a) without NBI and for b) NBI integrated model.

6. Conclusions

Neutronic analyses have been performed to support an improved design of a DCLL breeding blanket concept for the pulsed European DEMO reactor. For such design the impact on nuclear responses of the introduction of new details and reactor components has been investigated.

The influence on TBR and NH of a new design of detached FW protecting BB from extremely high heat fluxes is studied. Depending on the cooling fluid and its amount inside the wall the impact of a 2 cm FW panel covering the previous BB structure varies between 5, 13 and 24% of TBR loss when helium at 44%$_{vol}$, water at 13%$_{vol}$ or water at 44%$_{vol}$ is employed to cool such wall. Thus, the water cooled options would be discarded for a detached FW design since the target TBR of 1.1 would be seriously jeopardized. Furthermore, the helium-cooled detached FW implies a slight increase of the NH in the entire IB module due to the helium/void zones replacing Eurofer/PbLi ones in the front part of the module.

The impact of different typologies of FCIs is assessed also according to the degree of detail in the neutronic description. Calculations show that the use of a 5 mm alumina FCI reduces the TBR in a 2.65% and the use of a 1.1 mm sandwich in a 1.53% in comparison with the case without FCI.

The divertor composition also reveals to have strong impact on responses apparently not related with its design, as the tritium production in the BB. In fact, when a water cooled divertor composition is used in comparison with a massive steel divertor, the loss of TBR is between 3 and 5%, in the BSS and the BB modules. Moreover, the total TBR loss (5%) is higher than the margin of 3% suggested accounting for unknown uncertainties in design elements.

Besides, the integration of NBI minimizing its invasiveness in the BB is verified by neutronic analyses concerning the main BB functions: fuel breeding and heat recovery. The presence of the duct leads to a very high streaming which increases the power deposited in the surrounding components (dummy Eurofer modules, BSS and PbLi channels) and will entail the development of an efficient shielding system for the VV and toroidal field coils. Furthermore, according to the results and considering that the most probable configuration in a real tokamak would be with 3 NBI systems, it would suppose a reduction of TBR of 0.73%, being the absolute value 1.187, still higher than the target. This justifies the decision of suppressing the breeding capability of OBL #4 and reducing it from OBC #4. Although the model of BB and the design of DEMO change in the future, new estimations can be obtained based on the approximate value achieved here of 0.243% of TBR loss per NBI system (with 1 OB equatorial module suppressed and 1 slightly modified).

Summarizing, selecting the options of:

- Water cooled divertor (TBR from 1.257 to 1.196)
- 5mm pure alumina naked FCI (TBR from 1.196 to 1.183)
- Helium cooled detached FW (TBR from 1.183 to 1.12)

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- 3 NBI systems integrated suppressing 1 full OBL eq. module an 1 channel of the OBC eq. module, (TBR from 1.12 to 1.11)

the sum of their negative contributions to the TBR would have a total impact of almost a 12% of lost from an initial favorable value of 1.26 to a most accurate value of 1.11.

The study is performed for a DCLL BB DEMO although can be extrapolated to other BB concepts. It is worth to mention that the BB designs based on the brand new features of the DEMO2017 Baseline [31], which implies a radial reduction of 30 cm in the OB side with a consequent TBR reduction between 0.04 [32] and 0.09 [33], the starting TBR would be around 1.11-1.07 depending on the BB concept. If the effect of a detached FW would be summed up, these values would drop very near to the limit of 1 and the inclusion of H&CD systems could seriously invalidate the tritium breeding capability of such BB designs. Hence, for the future, important modifications are expected to be implemented to cope with the tritium breeding challenge, as the substitution of the Multi-Module Segment BB system to a Single-Module one, among others.

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