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Tritium production assessment for the DCLL EUROfusion DEMO

Iole Palermo*, David Rapisarda, Iván Fernández-Berceruelo, Angel Ibarra

*CIEMAT, Fusion Technology Division, Avda. Complutense 40, 28040-Madrid, SPAIN, *iole.palermo@ciemat.es*

The viability of a fusion reactor is preeminently conditioned by the tritium self-sufficiency. An assessment of different parameters representing the tritium production, as the Tritium Breeding Ratio (TBR), the Tritium Production Rate (TPR) density and their poloidal and radial variations along the PbLi breeder zones has been performed for the last DCLL DEMO designs developed in the frame of the EUROfusion Programme. The final overall value of 1.104 obtained allows accomplishing the fuel self-sufficiency requirement. This TBR value includes not only the contribution of the Breeding Blanket (BB) modules but also of the Back Supporting Structure (BSS). The BSS design resulted fundamental to reach the 1.1 criterion. Lastly, the influence of the integration in the reactor of the heating and current drive (H&CD) systems that will penetrate the breeder volume has been evaluated. Assuming different configurations for them, the TBR loss has been determined. All the calculations have entailed the use of the particle transport Monte Carlo code MCNP5.

Keywords: DCLL, Tritium Breeding, H&CD, DEMO

1. INTRODUCTION

The existing tritium resource available for the future fusion power plant D-T operation is severely limited. As no external tritium sources are foreseen, all fusion power plants must demonstrate their fuel self-sufficiency and have to breed their own tritium to maintain the continuous consumption in the D-T plasma.

The Tritium Breeding Ratio (TBR) requirement, which is the measure for the self-sufficiency, is design and breeder-dependent and evolves with time. At present, for the fusion power demonstration reactor DEMO developed among the EU fusion roadmap “Horizon 2020”, the requirement for the overall TBR of PbLi systems is 1.1[1]. In fact, due to the various uncertainties and plant-internal losses occurring during DEMO operation that made difficult to predict exactly the produced tritium, a margin of 10% (for a final net TBR $\geq$ 1.0) is required.

This primary nuclear requirement and other related nuclear responses have been addressed in this paper to demonstrate a reliable operation of the DEMO conceptual design based on a Dual-Coolant Lithium Lead (DCLL) Breeding Blanket (BB) System, one of the 4 BB options conceived for the future European Demonstration Power Plant [2].

The DCLL concept is basically characterised by the use of eutectic PbLi as neutron multiplier, tritium breeder and carrier. The self-cooled liquid metal is also the primary coolant for extracting most of the heat generated by fusion energy. The secondary coolant is helium, mainly used to cool the first wall (FW) of the BB. A DCLL novel design [3][4] has been developed during 2014 for the DEMO 2014 design assumptions [5][6] (i.e. 1572 MW and pulsed scenario). This paper describes how the design improvements adopted during 2015 have affected the tritium production and the progress done to attain the TBR target. The preliminary design and its evolutions are described in section 2; the resultant tritium responses are presented in section 3.1; and a specific assessment of the influence on the TBR of the integration in the reactor of the heating and current drive (H&CD) systems that will penetrate the breeder is addressed in section 3.2.

2. FEATURES AND EVOLUTION OF THE NEUTRONIC DESIGN

The basic DEMO design used in the present study and known as “EU DEMO1 Baseline 2014” [5] has 1572 MW fusion power, a plasma major radius of 9 m, an aspect ratio of 4 and a plasma elongation of 1.56 [6]. The torus is divided into 16 sectors of 22.5º (given by the number of toroidal field coils), each sector having 3 outboard (OB) and 2 inboard (IB) BB segments. For the neutronic purposes, an 11.25º half-sector has been studied exploiting the toroidal symmetry of the tokamaks. Thus each 11.25º sector is composed by 1 IB blanket segment and 1 and half OB segments. The BB design is based on a Multi-Module Segmentation (MMS), that is, a certain number of modules are attached to a common Back Supporting Structure (BSS). The modules distribution in both OB and IB segments has been made in such a way that the functional volume is optimized, resulting in 7 and 8 modules for the IB and OB segments, respectively. Each segment is supported by one BSS.

A specific DCLL OB equatorial module has been firstly developed [3] and then repeated to the rest of modules adapting it to the specific features (i.e. dimensions, available space, shape, etc.) of each one. The modules in their specific DCLL segmentation have been then introduced into the generic DEMO 2014 [5] to create a complete DCLL DEMO neutronic model.

In the preliminary design (Fig.1a) the initial IB/OB breeder radial thickness is 30/64cm. The thickness and the materials compositions for all the components of the equatorial OB module and the corresponding BSS are summarized in table 1. In the 3D detailed neutronic model, built with the MCAM software tools [7], the blankets are fully-described (the homogenization concerns only the helium channels inside the walls, the helium collector and the BSS). The homogenized composition for the BSS is very dense, because the actual design has no empty areas, being therefore an efficient shielding system [3][4]. Furthermore, having a high PbLi content, a benefit in the TBR was produced due to the tritium generated in this region.

In a second phase of the design process (Fig.1b), the optimization of structural and safety aspects has been pursued implying new design specifications to be analyzed under the nuclear point of view. In fact, during 2015 the DCLL BB design has evolved to safely accommodate the consequences of an accidental overpressure inside the module (in-box LOCA) and has been adapted to manufacturing requirements.

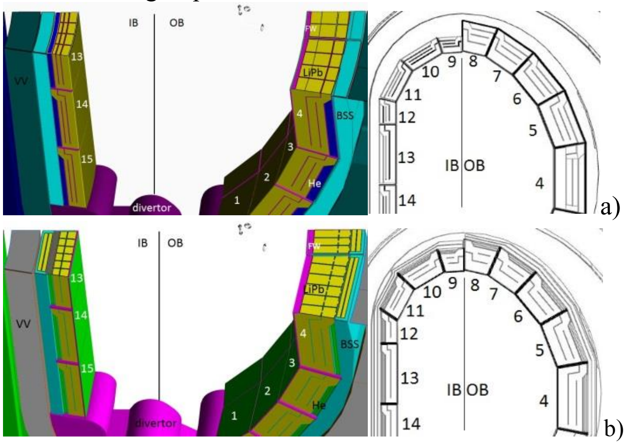


Fig. 1.: DCLL DEMO design evolution: horizontal cut and upper modules vertical section of the a) previous and b) new version

Table 1. Thickness and composition of the equatorial OB module and BSS components for the first/second version of the DCLL

equatorial OB module		Thickness (cm)	Sub-total (cm)	Composition (% vol)			
	Total BB	=	**91**	Eurofer	He	PbLi	W
FW	FW coating	0.2	2.2/ 2.7				100
	FW	2/ 2.5		85.54/ 70.7	14.46/ 29.3		
Breeder zone	stiffening plates	2 each/ 1.7, 1.7, 2	6/ 5.4	91.33/ 100	8.67/ 0		
	1st PbLi channel	30/ 30	64/ 69.2			100	
	2nd PbLi channel	18.5/ 22.2				100	
	3rd PbLi channel	15.5/ 17				100	
Helium collector	He plena	- / 4.4 each	17*/ 11.7**		47/ 100		
	Eurofer walls	- / 1, 0.9, 1		53/ 100			
walls	Side walls	2/ 3	-	85.54/ 100	14.46/ 0		
	Top wall	4/ 2	-	85.54/ 70.7	14.46/ 29.3		
	Bottom wall	4/ 2	-	85.54/ 70.7	14.46/ 29.3		
	Back wall	2	2	85.54/ 100	14.46/ 0		
BSS previous	variable thickness homogenized			51.29	4.35	44.36	
BSS new	variable thickness, separated Eurofer and PbLi channels			100			
						100	

*17 cm homogenized representing 4 He collectors inside the Eurofer channels (53%Eurofer+47%He),
**11.7 cm heterogenized: 2 He collectors in the Eurofer channels

Some of the new design features relevant for the reactor neutronic behaviour are summarized as follows:

1. FW thickness changed from 20 to 25 mm.
2. Helium fraction in FW passed from ~14 to 30%.
3. Toroidal breeding channels increased from 4 to 6.
4. Helium manifolds reduced from 4 to 2.
5. Helium collector reduced from 17 to 11.7 cm.
6. Radial thickness of the 3 radial OB breeding channels passed from 30+18.5+15.5=64 cm to 30+22.2+17=69.2 cm.
7. Radial thickness of the IB upper modules #11/10/9 increased from 50 cm to 65/70/70cm, respectively (observe that the OB upper modules are 91 cm thick).
8. 1 stiffening toroidal plate suppressed from IB #12-15.

With the exception of points 1 and 3 that would have a strong negative impact on the TBR, the other modifications could balance and have positive influence on it. It is important to mention that the new DCLL design use parallel walls for the central OB segment (i.e. the central segment and the lateral are not exactly one the half of the other, as shown in Fig.1b) and has fully described BSS and helium collector (thus the homogenization concerns only the helium channels inside the FW, top and bottom walls which are part of the same cooling circuit).

The new radial build for the OB equatorial BB and BSS is presented in table 1. The total radial thickness for the OB BB is maintained to 91 cm, plus 38 cm for the BSS in the mid-plane (variable along the poloidal direction according to the available space left in the generic DEMO design). The equivalent thicknesses for the IB are 32.3 cm for the breeder zone, 9.3 cm for the helium collector (for a total of 50 cm BB) and 24.4 cm for the BSS in the mid-plane.

Particle transport calculation has been then performed to evaluate such design evolutions using the MCNP5 Monte Carlo code [8] and JEFF 3.1.1 nuclear data library [9]. Parallel computations have been carried-out in CIEMAT EULER cluster.

3. RESULTS

3.1 Tritium production assessment

The tritium production has been primarily evaluated because it represents the essential condition for the reactor viability. Thus, different responses regarding tritium production have been evaluated for the versions of the DCLL DEMO with detailed breeding zones of 64/30 and 69/32 cm (OB/IB) respectively.

A first comparison between the previous DCLL model [3] and the new one shows some improvements of the breeding capabilities for the IB modules #9-12, as it may be observed in Fig. 2, where the module 'DCLL64' stands for the previous model and 'DCLL69' for the new one. Normalizing to the module volume (Fig. 3) the tritium production rate (TPR) density allows showing tritium efficiency improvements in IB modules #10-15 with respect to the previous 2014 model.

Nevertheless, the overall TBR (table 2) compared to the previous result of 1.13 is now reduced to 1.104, even though still higher than the self-sufficiency criterion. In table 2 contributions for the total TBR are specified giving values for each poloidal position inside the 360º tokamak including local breakdowns, and normalizing to the volumes and the 5.581×10^{20} n/s plasma source to provide the TPR density.

It is noteworthy that the design of the BSS (Fig. 1c) is fundamental to reach the 1.1 target being in fact its contribution to the TBR 0.0626 T/n. An improvement in the IB modules' TBR is also shown. That was expected due to the increase of the radial thickness of the upper modules and the suppression of the intermediate stiffening toroidal wall in the lower modules. On the other side the OB suffers a reduction of the TBR due principally to the increase of the number of the radial stiffening walls and FW thickness.

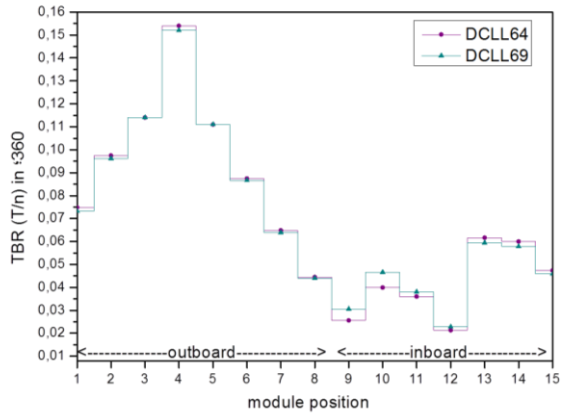


Fig. 2. Local TBR in the 15 poloidal positions of the DCLL DEMO model. The new design (69/32cm OB/IB breeder) is compared with the previous one (64/30 cm).

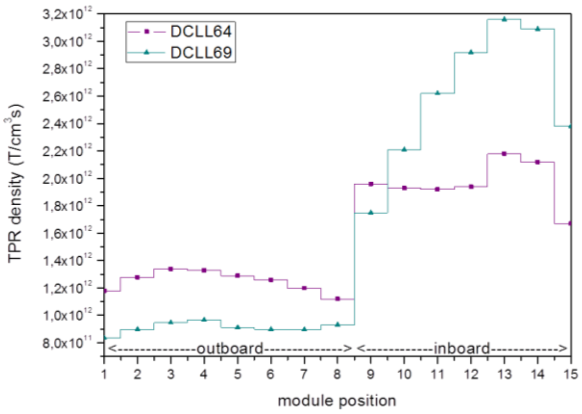


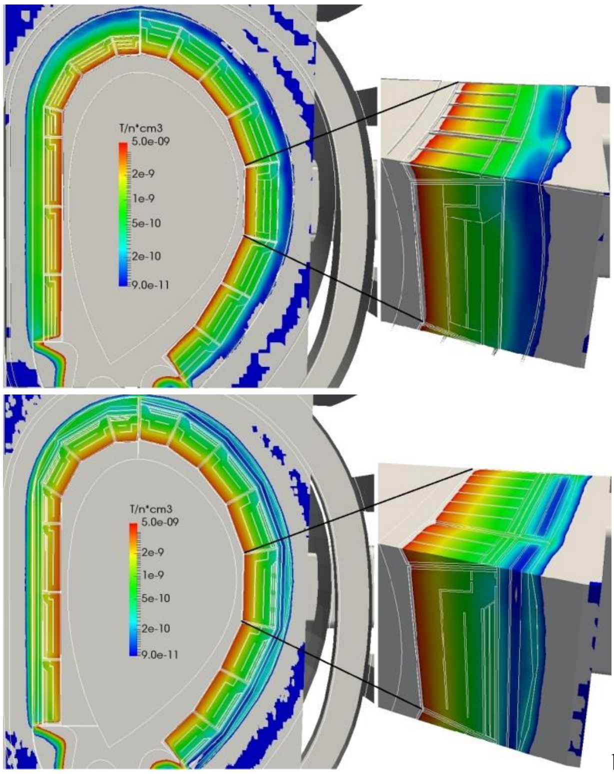
Fig. 3. Local TPR density in the 15 poloidal positions of the DCLL DEMO model for the new and previous designs.

Table 2. Tritium production in the new DCLL design of 69/32 cm of breeder thickness (OB/IB) vs. the previous one of 64/30 cm in terms of local TBR, TPR density and total TBR.

	nº	T/n in 360º		T/cm^{3}s	
		prev.	new	prev.	new
OB	1	7.49E-02	7.32E-02	8.81E+11	8.35E+11
	2	9.74E-02	9.62E-02	9.53E+11	8.98E+11
	3	1.14E-01	1.14E-01	9.94E+11	9.47E+11
	4	1.54E-01	1.52E-01	9.92E+11	9.69E+11
	5	1.11E-01	1.11E-01	9.59E+11	9.12E+11
	6	8.74E-02	8.66E-02	9.37E+11	8.99E+11
	7	6.48E-02	6.39E-02	8.95E+11	8.98E+11
	8	4.45E-02	4.39E-02	8.37E+11	9.31E+11
IB	9	2.56E-02	3.06E-02	1.46E+12	1.75E+12
	10	3.99E-02	4.66E-02	1.44E+12	2.21E+12
	11	3.60E-02	3.80E-02	1.43E+12	2.62E+12
	12	2.13E-02	2.28E-02	1.45E+12	2.92E+12
	13	6.16E-02	5.94E-02	1.62E+12	3.16E+12
	14	6.00E-02	5.78E-02	1.58E+12	3.09E+12
	15	4.73E-02	4.58E-02	1.24E+12	2.38E+12
BB	OB	0.7490	0.7408		
	IB	0.2920	0.3009		
	total	1.0410	1.0418		
BSS	OB	3.30E-02	2.50E-02		
	IB	5.73E-02	3.76E-02		
	total	9.02E-02	6.26E-02		
	TBR	**1.131**	**1.104**		

Considering the specific contribution of the BSS, the IB contributes a 60% (63.46% in the previous design) and the OB a 40% (36.64%). This makes evident the relevance of the IB BSS because the less space occupied in this side by the BB allows high tritium breeding potential behind the breeder, as shown in Fig. 4. However a reduction of the TBR throughout the BSS PbLi channels is observed both due to the novel BSS heterogenized design and to the increase of the BB thickness in the new DCLL version.

In Fig. 4 MCNP "mesh tally" 3D maps (as T/n per cm^3) have been represented to visualize how the T produced is distributing in the previous (a) and new (b) versions showing an increment of the local T density in the BB of the second one, due to the larger thickness of the breeder zone (mainly in the IB upper modules). Special interest has the lower tritium produced locally in the first breeder radial centimeters due to the larger FW thickness.



a)

b)

Fig. 4. Tritium production as "mesh tally" (in T/n per cm^3) for the a) previous and b) new DCLL versions

3.2 H&CD systems integration effect on the TBR

Different heating and current drive (H&CD) systems, such as Neutral Beam Injection (NBI), Electron Cyclotron Resonance Heating (ECRH) and Ion Cyclotron Resonance Heating (ICRH) systems, will be installed through the Equatorial and Upper Ports of the DEMO tokamak entering the BB modules that will be affected in their functionality (having implication on cooling and remote maintenance schemes, and shielding and tritium breeding, among other functions). In this paper the impact on the TBR of these systems which penetrate the breeder volume reducing the amount of material available for tritium production has been evaluated.

The number and position of these systems is still under investigation [10][11]. The NBI system will pass through the Equatorial Port and could affect 1 or 2 equatorial OB modules [12]. The ECRH could enter from the Upper port being not so invasive, affecting the modules in poloidal position nº 8 (Fig. 1) [11]. Since their exact dimensions are still unknown, a conservative assessment has been done by suppressing complete modules. The ICRH system consists in an array of antennas that could occupy the whole 360º torus affecting the position of module nº 6 [13]. They could invade only the first 6 cm of the module radial thickness (including the FW) with local extensions occupying up to 20 cm [13], thus 2 estimations have been done eliminating 5 and 10 cm of breeder zone instead of whole modules.

Table 3. TBR variation due to the H&CD system

NBI	TBR eq.#4	TBR BSS #4	new TBR
1	3.40E-03	1.16E-04	1.1008
4	1.36E-02	4.65E-04	1.0903
8	2.72E-02	9.31E-04	1.0762
16	5.43E-02	1.86E-03	1.0481
ECRH	TBR #8	TBR BSS #8	new TBR
1	8.56E-04	2.93E-05	1.1035
4	3.42E-03	1.17E-04	1.1008
8	6.85E-03	2.35E-04	1.0973
16	1.37E-02	4.69E-04	1.0902
ICRH	TBR #6	ΔTBR x360º	new TBR
5cm	1.86E-03	(-14.3%)* 1.24E-02	1.092
10cm	1.86E-03	(-26.5%)* 2.30E-02	1.081

*percentages established according to the TBR radial profile of BB#4

Hence, assuming different configurations for each system, the TBR loss has been determined. For the NBI have been eliminated 4, 8 or 16 modules (and the corresponding rear BSS). The results (table 3) show that the TBR target of 1.1 is almost observed if up to 4 BB modules and BSS are eliminated. The same has been done for the ECRH system. In this case up to 16 modules could be affected by the ECRH with no major problems for the tritium self-sufficiency. For the ICRH system the result of eliminating the first 10 or 5 cm of modules nº 6 in the whole torus is that in both cases no major problems for the tritium self-sufficiency will be caused.

Nevertheless considering:

1. the 3 systems together, and
2. that the 1.1 target includes a 6% of margin due to the non-breeding blanket ports and hence 1.05 is the expected target when the related reduction of blanket coverage ("loss of breeder area") of about a 3% is considered [1],

some possible combinations and the corresponding TBR variations have been studied as shown in table 4.

With up to 4 NBI, 8 ECRH (or *viceversa*) and ICRH occupying 10 cm, a TBR higher than 1.05 it is still obtained.

Table 4. H&CD systems combinations and resultant TBR

nº of Heating systems	**TBR**
1NBI, 1ECH, 5cm ICRH	1.088
2NBI, 2ECH, 5cm ICRH	1.083
2NBI, 2ECH, 10cm ICRH	1.073
4NBI, 4ECH, 10cm ICRH	1.064
4NBI, 8ECH, 10cm ICRH	1.060
8NBI, 4ECH, 10cm ICRH	1.050

4. CONCLUSIONS

Tritium breeding assessments have been performed to support the design of a new DCLL breeding blanket concept, for the development of the newly established pulsed European DEMO reactor. As general results, the preliminary TBR of 1.13 achieved in the 2014 DCLL model has resulted reduced by the new design choices for the 2015 DCLL, being currently 1.104, but still higher than the target of 1.1 and specially thanks to the BSS design, with high PbLi content. Other results have been also obtained as the radial/poloidal profiles of the tritium production for both the two version of the DCLL model in order to see specifics effects of the design choices (FW thickness and composition, number of breeder channels, IB upper modules thickness, etc.). The impact on the TBR due to the introduction in the reactor of H&CD systems occupying different BB areas has been also assessed.

Further analyses in different fields are ongoing to demonstrate the design viability and the next step will be the adaptation of the current DCLL design to the features of the new generic EU DEMO1 baseline 2015 [13].

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