Parametric Study of the Influence of First Wall Coolant on the WCLL Breeding Blanket Nuclear Response

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In the framework of EUROfusion Work Package International Cooperation R&D activities, a close collaboration has been started among University of Palermo, ENEA Brasimone and ENEA Frascati for the development of the Water Cooled Lithium Lead (WCLL) Breeding Blanket (BB) concept. In this context, an intense research campaign has been carried out at the University of Palermo in order to investigate the influence of First Wall (FW) cooling water configuration on the nuclear response of the WCLL BB under irradiation in EU-DEMO, in order to gain useful indications for the WCLL BB pre-conceptual designs.

To this end, three-dimensional nuclear analyses have been performed by MCNP5 v. 1.6 Monte Carlo code. A semi-heterogeneous MCNP model of the WCLL BB "single module segment" concept has been used and its nuclear response has been assessed for different FW configurations, centring the attention, mainly, on global quantities as nuclear power deposition and tritium breeding ratio. The results obtained provided some information on the nuclear features of the WCLL BB concept, useful for its design optimisation. The outcomes of this parametric study are herein presented and critically discussed.

Keywords: DEMO reactor; WCLL Blanket; BSS.

1. Introduction

Within the framework of the Work Package International Collaboration of the EUROfusion action [1], a close collaboration among University of Palermo, ENEA Brasimone and ENEA Frascati been started. One of the key-points of this collaboration relies in the assessment of the influence of water coolant on the nuclear performances of the Water Cooled Lithium Lead (WCLL) Breeding Blanket (BB) concept [2 - 5].

In this context, the University of Palermo has launched a research campaign to investigate the nuclear behaviour of the WCLL BB, focusing the attention on the influence of First Wall (FW) cooling water configuration on its nuclear performances in order to gain useful indications for its pre-conceptual design. To this purpose a parametric analysis has been carried out to assess the potential effects of both the lay-out (channel radial positions) and the amount (channel radial widths) of FW cooling water on the WCLL BB nuclear response.

The study has been performed following a computational approach based on the Monte Carlo method and adopting the Monte Carlo N-Particle (MCNP5-1.60) code [6] along with the JEFF-3.2 transport cross section libraries [7].

2. WCLL BB MCNP model

The MCNP model of the WCLL BB Single Module Segment (SMS) concept has been implemented in the 2015 MCNP DEMO generic model [8, 9]. It represents a 10° toroidal slice of the whole DEMO reactor, taking into account half a sector of the machine including one inboard segment and one and half outboard segment. As far as the WCLL BB is concerned, the semi-heterogeneous MCNP model developed by ENEA-Frascati has been adopted for calculations. A detailed description of this model can be found in [10].

Both the outboard and the inboard segments of the WCLL BB have been simulated, with the Back Supporting Structure (BSS), by a layered arrangement of homogeneous volumes, with a fine segmentation in the radial direction and a rough one in the poloidal direction, as shown in figures 1 and 2.

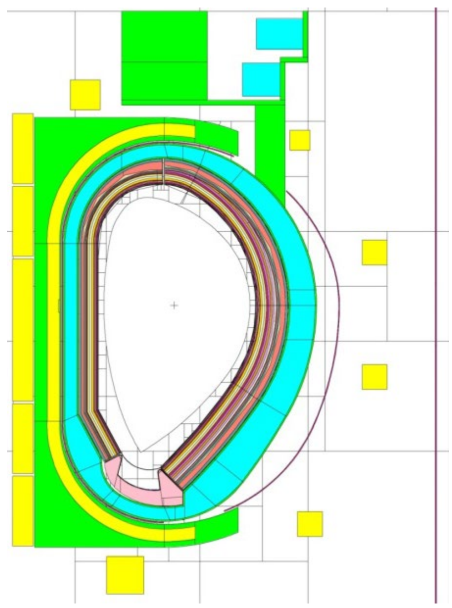

Fig. 1. Poloidal radial section of the WCLL BB MCNP model.

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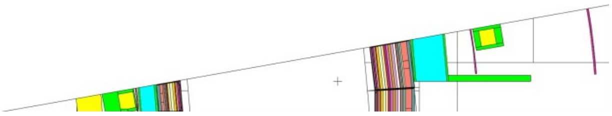

Fig. 2. Toroidal radial section of the WCLL BB MCNP model.

Regarding the material composition of the model adopted, Table 1 shows it as function of the radial direction.

Table 1. WCLL BB material composition.

Layer		Thickness [cm]	W [%]	Eurofer [%]	LiPb [%]	Water [%]
1	W-Armour	0.2	100.00	0.00	0.00	0.00
2	FW	0.3	0.00	100.00	0.00	0.00
3		0.7	0.00	49.80	0.00	50.20
4		1.5	0.00	98.36	0.00	1.64
5	Breeder Zone	2.5	0.00	8.89	91.11	0.00
6		1.4	0.00	27.82	61.92	10.26
7		3.2	0.00	13.31	84.30	2.39
8		3.2	0.00	16.76	78.98	4.26
9		3.2	0.00	13.43	84.11	2.46
10		3.2	0.00	13.50	84.01	2.49
11		8.0	0.00	17.70	80.92	1.38
12		8.0	0.00	17.96	80.63	1.41
13		8.0	0.00	17.18	81.87	0.95
14		8.0	0.00	17.53	81.25	1.22
15		8.0	0.00	17.18	81.83	0.99
16		8.0	0.00	17.13	81.89	0.98
17		8.0	0.00	17.87	80.68	1.45
18		7.3	0.00	17.25	81.68	1.07
19	PbLi Manifolds	3	0.00	100.00	0.00	0.00
20		4	0.00	61.77	38.23	0.00
21		3	0.00	100.00	0.00	0.00
22		4	0.00	61.82	38.18	0.00
23	Back Plate	3	0.00	100.00	0.00	0.00
24	Water Manifolds	20	0.00	6.64	0.00	93.36
25	BSS	10	0.00	100.00	0.00	0.00
	Side Wall and caps	-	0.00	85.81	0.00	14.19

3. Results

The evaluation of the nuclear response of the WCLL BB, under irradiation in DEMO, for different FW configurations has been focused on the assessment of such quantities as neutron flux, nuclear power deposition together with its volumetric density and Tritium Breeding Ratio (TBR).

In particular, to assess the influence of the water lay-out in the FW channels on the nuclear response of the this BB concept, five different radial positions have been taken into account for these channels while to assess the influence of the water amount in the FW channels, three different radial widths have been considered for them.

The analyses have been carried out by simulating a large number of histories (up to 10^{10}) so that the results obtained are affected by relative errors lower than 1%, even in the regions more distant from plasma. The assessed nuclear responses have been normalized to the DEMO nominal fusion power of 2037 MW.

3.1. Preliminary analyses

Preliminary nuclear analyses have been performed to assess the nuclear response of the WCLL BB in terms of global quantities such as total nuclear power deposition and TBR. The results obtained are summarized in Tables 2 and 3.

Table 2. Nuclear power deposited [MW].

WCLL BB	
Outboard	$1.2744 \cdot 10^3$
Inboard	$5.3814 \cdot 10^2$
TOTAL	$1.8126 \cdot 10^3$

Table 3. Tritium Breeding Ratio.

	WCLL BB		
	From Li^6	**From Li^7**	**TOTAL**
Outboard	$8.053 \cdot 10^{-1}$	$3.402 \cdot 10^{-4}$	$8.056 \cdot 10^{-1}$
Inboard	$3.252 \cdot 10^{-1}$	$1.215 \cdot 10^{-4}$	$3.253 \cdot 10^{-1}$
TOTAL	1.130	$4.617 \cdot 10^{-4}$	1.131

3.2. Influence of FW water configuration on TBR

The study carried out has shown that the configuration of water in the FW-SWs system has almost no impact on the total nuclear power deposited, while it has a not negligible influence on the blanket tritium breeding performances.

As far as the FW channels lay-out is concerned, it has been modified taking into account four new positions. In particular, a radial shift ΔS of these channels in three different positive radial locations and in one negative radial location, with respect to the original design position, have been considered (Fig. 5). Table 4 shows the results obtained.

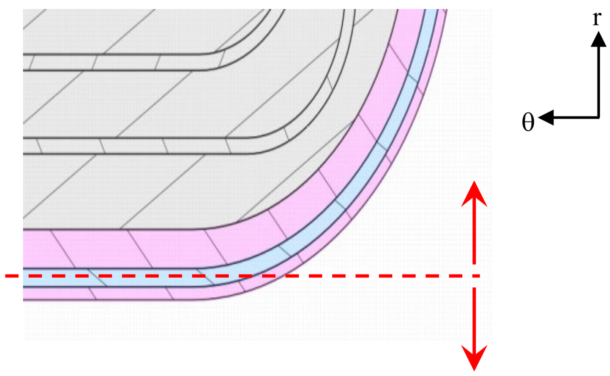

Fig. 5. FW channel shifting in the radial direction.

Table 4. Influence of FW water lay-out on TBR.

ΔS [mm]	TBR Deviation	
-1	1.1302	-0.06%
0	1.1309	-
1	1.1362	0.47%
2	1.1415	0.94%
3	1.1465	1.39%

TBR increases shifting the channel in the positive radial direction and decreases shifting the channel in the opposite direction most likely due to the reduction of the steel layer between cooling channels and breeder that contributes to decrease the neutron absorption reactions before the interaction with lithium.

Regarding the influence of water amount in the FW, two new radial widths (ΔW) have been considered for the channels, the first is 1 mm smaller and the second is 1 mm larger. Table 5 shows the results obtained.

Table 5. Influence of FW water amount on TBR.

ΔW [mm]	TBR Deviation	
-1	1.1747	3.88%
0	1.1309	-
1	1.1305	-0.03%

Naturally, as expected, TBR increases with a smaller amount of water and decreases with a greater one.

Nevertheless, it has to be observed that the increase of the TBR value is much more pronounced than decrease, highlighting again the strong influence of water on the WCLL breeding performance.

3.3. Influence of FW water configuration on neutron flux and volumetric density of power

The radial profiles of the total neutron flux (Φ) and of the volumetric density of power deposited by neutrons and photons (q''') have been evaluated in an equatorial zone of the outboard segment of the WCLL BB for both the reference model and the alternative configurations which present the most relevant deviations in term of TBR, namely the model with a 3 mm shift of FW channels in the positive radial direction and the model with 1 mm smaller width FW channels.

In particular, for those quantities, average values on a poloidal extension equal to that of a breeder cell (13,5 cm) and all along the toroidal range of the whole segment have been calculated. Figures 4 and 5 show, respectively, the radial profile of flux and the volumetric density of nuclear power deposited in the first 5 cm of the blanket, corresponding to the first 5 layers (see Tab. 1) of the aforementioned models, where differences are not negligible.

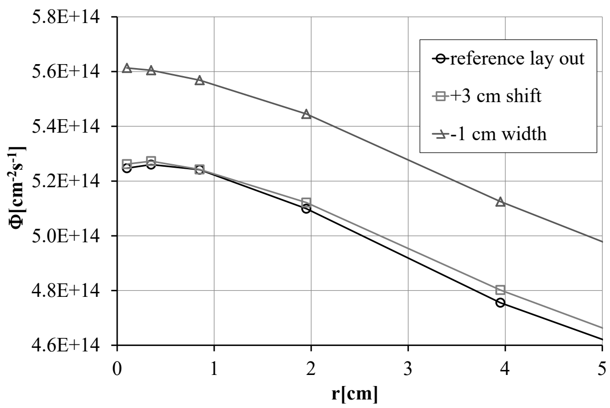

Fig. 4. Neutron flux radial profile.

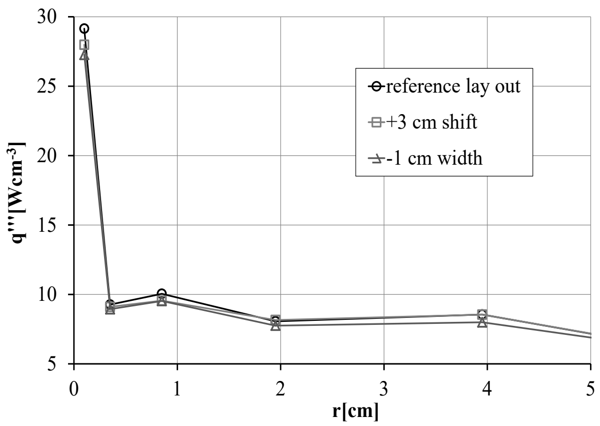

Fig. 5. Volumetric density of nuclear power radial profile.

It can be observed in figure 4 that the decrease of the amount of water in the FW makes the neutron flux to increase and it has a certain impact also on the shape of its radial profile as the maximum disappears.

On the other hand, the channel shift in the positive radial direction makes the flux to increase slightly with respect to the reference model.

As far as the volumetric density of nuclear power deposited is concerned, differences among models are less pronounced than in the flux, even if, as expected, the decrease of the amount of water makes the power density to slightly decrease as well as the shift of channels.

4. Conclusions

In the framework of the EUROfusion WPIC R&D activities, a collaboration among University of Palermo, ENEA Brasimone and ENEA Frascati has been started in order to assess the potential influence of FW water configuration on the nuclear performances of the WCLL BB concept under irradiation in DEMO.

Within this context, an intense research campaign has been carried out at the University of Palermo whose results have shown that water configuration in the FW has not a negligible influence on the tritium breeding performance of the WCLL BB concept both in terms of water amount and of channels position. In fact, the TBR increases when water channels are moved forward in the radial direction as well as once their poloidal width is reduced. These conclusions should be taken into account in the pre-conceptual design of this blanket line as they clash with thermo-mechanical considerations for which channels should be located as close as possible to the plasma facing surface of the blanket to make the structure suitable to withstand to thermal loads.

As far as the nuclear power deposited and its volumetric density radial profile are concerned, differences among the FW configurations taken into account are not very pronounced and they are due to the effectiveness of water in moderating neutrons making the reaction rate to increase and so the power deposited.

In conclusion, the outcomes obtained supply some rough information for the development of this BB line and represent a start point for more refined neutronic investigations which overcome the limit related to the semi heterogeneous models used. Moreover, a further development of this work will consider also the influence of the Breeder Zone cooling water configuration on the nuclear response of the WCLL BB to gain a more detailed insight of the nuclear behaviour of this blanket concept.

Acknowledgments

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