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Neutronic analyses in support of the WCLL DEMO design development

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In the frame of the EUROfusion Consortium program, the Water Cooled Lithium Lead (WCLL) option has been chosen as a candidate for the breeding blanket (BB) of the European fusion power demonstration plant (DEMO) conceptual design. Neutronic analyses play a fundamental role in the development of the WCLL blanket, providing guidelines for its design based on the evaluation of the nuclear performances.

A detailed three-dimensional MCNP model of the latest WCLL layout has been generated and integrated in a DEMO MCNP generic model suitably designed for neutronic analyses. Three-dimensional neutron and gamma transport simulations have been performed using the MCNP5v1.6 Monte Carlo code and JEFF 3.2 nuclear data libraries, in order to assess the WCLL-DEMO tritium self-sufficiency and the shielding capabilities of the breeding blanket/manifold system to protect the vacuum vessel and toroidal field coils. Furthermore, radial profiles of the neutron flux, nuclear heating, neutron damage and he-production have been assessed in the Inboard and Outboard equatorial planes.

The outcome of the present study highlights the potential and suitability of the WCLL breeding blanket for the application to DEMO, both in terms of tritium production and shielding performances.

Keywords: DEMO, WCLL, neutronics, nuclear, shielding, TBR, MCNP

1. Introduction

The neutronic calculations on the WCLL breeding blanket aim at the evaluation of the nuclear performances of the present design of the blanket concept, providing feedback for its future development.

Three-dimensional coupled neutron and gamma transport simulations have been performed according to specifications [1] by means of the MCNP5v1.6 Monte Carlo code [2] and JEFF 3.2 nuclear data libraries [3]. The main objective of the present studies is the verification the WCLL DEMO tritium self-sufficiency, the shielding capabilities of the BB/manifold system. Moreover, the radial profiles of the nuclear loads (neutron flux, nuclear heating, neutron damage and he-production) have been assessed at equatorial level, providing indication about their behaviour on the first wall (FW), BB, supporting structures and manifolds.

Neutronics studies carried-out in 2015 were based on the DEMO1 2015 configuration, integrating a WCLL breeding blanket represented by homogenized compounds with volume percentage of each material extracted by the engineering CAD files. The results showed that the tritium breeding capability was sufficient to achieve the required Tritium Breeding Ratio (TBR) ≥ 1.1 [4] to ensure self-sufficiency and the shielding performances were sufficient to protect the super-conducting toroidal field coils (TFC), mainly because of the heavy BSS/manifold configuration [5,6].

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The present studies have been performed using an upgraded MCNP WCLL DEMO model, introducing a detailed description of the breeding blanket in the Inboard and Outboard equatorial modules: analyses have been carried out in order to support the WCLL blanket improvement and to verify its suitability in terms of neutronics requirements. Moreover, a new layout of the WCLL DEMO, based on a single module approach, is presently under development: the nuclear analyses of this novel design are currently ongoing, however a first assessment of the TBR is provided.

2. Multi-module WCLL DEMO MCNP model

The WCLL DEMO MCNP model is based on a generic Multi-Module-Segment (MMS) geometry representing a 10° sector of the machine and it integrates a detailed geometry of the breeding blanket structure in the Inboard and Outboard equatorial modules, while specific homogenized compounds have been defined to represent the other blanket modules (Table 1), according to the design specifications [6].

Table 1: volume percentage of the materials used in the compounds to represent the main WCLL BB components.

materials	Armour	Fist Wall	Breeding Zone	Back Plate	Manifolds
Eurofer	-	86.1	16.13	97.2	44.9
H_2O	-	13.9	1.46	0.91	44.1
LiPb*	-	-	82.41	1.89	-
Tungsten	100	-	-	-	-
void	-	-	-	-	-

** 90% enriched in Li-6*

The layout of the blanket module includes a Eurofer steel box with FW, caps, back wall and a back-supporting structure (BSS) with inlet/outline pipes for the water and the LiPb. The box is filled with the LiPb liquid metal and reinforced by horizontal and vertically arranged stiffening plates. The development of a detailed MCNP model of the WCLL Outboard #4 blanket module (OB#4, Fig. 1) has been performed though the preprocessing and simplification of the original CAD file by means of the 3D modeling software Ansys SpaceClaim 2015 [7] in order in order to generate a model suitable for neutronic analyses. A single breeding unit (BU: the components included between two neighbouring stiffening plates, red area in fig. 2), containing 21 cooling water pipes embedded in the LiPb breeder, has been isolated and singularly converted into the equivalent MCNP geometry through the CAD-to-MCNP interface MCAM (SuperMC_MCAM5.2 [8]).

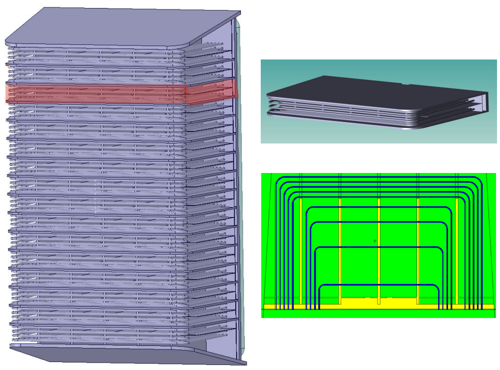

Fig. 1. WCLL blanket module: overview of the BB inner structure (left panel) detail of a BU (top right) and a section of the equivalent MCNP model along the cooling pipes axis.

Successively, the single breeding unit has been recursively integrated filling the DEMO MCNP generic model Inboard and Outboard (full and halved) blanket modules #4. As far as the Inboard module (IB#4) integration is concerned, the development of detailed Inboard configuration was based on adaptation of Outboard layout by keeping the distance between the FW and the outermost cooling channel (Fig. 2).

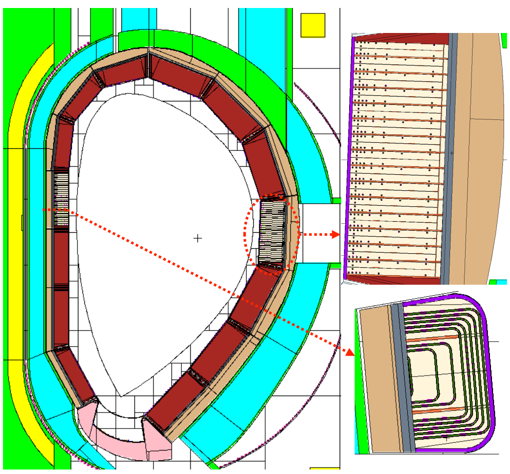

Fig. 2. MMS WCLL DEMO MCNP model integrating the detailed blanket in the IB#4 and OB#4.

3. Nuclear analysis

The model so far described has been used to evaluate the performances of the WCLL DEMO in terms of shielding capability to protect the Toroidal Field Coils and tritium self-sufficiency. Moreover, the neutron flux, nuclear heating, damage and He-production radial profiles have been assessed on the equatorial mid plane, thus taking into account the detailed description of the breeding blanket structure. Results have been normalized to 2037 MW fusion power (neutron yield: 7.232×10^{20} n/s), according to the plasma parameters specified in Table 2. Standard cell-based (F4/F6 tallies) and mesh tallies (FMESH tally) with proper multiplier have been used to calculate the nuclear quantities of interest for the WCLL design development, performances assessment and verification of design requirements.

Table 2: main parameters of the DEMO baseline configuration.

N° of Toroidal Field Coils	18
Major radius (m)	9.072
Minor radius (m)	2.927
Aspect ratio	3.1
Plasma elongation	1.59
Plasma triangularity	0.33
Fusion power	2037
Average neutron wall loading	1.05
Net electric power	500

3.1 Neutron Wall Loading and Tritium Breeding Ratio

The poloidal distribution of the neutron wall loading for 2037 MW of fusion power is shown in Fig. 3: the maximum NWL values have been obtained for the outboard equatorial modules O3-O4 (1.33 MW/m^2). In the inboard the maximum is 1.1 MW/m^2, while the poloidal average is about 1 MW/m^2.

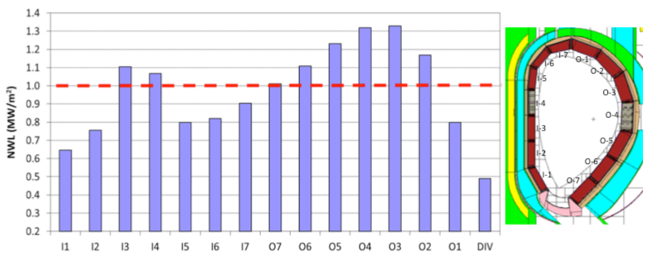

Fig. 3. Neutron Wall Loading poloidal distribution

The tritium breeding ratio (TBR) has been calculated using track-length estimator (F4 tally) with proper tally multipliers (FM card) that take into account the cross sections of the reactions producing tritium on Li-6 and Li-7. The global TBR evaluated on a full homogeneous model is 1.14, so the results confirm that the present WCLL design fully achieve the design target. The effect of heterogeneity has been quantified through the comparison between the TBR produced in the heterogeneous blanket modules (OB#4 and IB#4) and the corresponding values obtained using the homogenized material. The assessed correction factors showed that the detailed and more realistic description of the breeding blanket could provide a further increase in the total TBR of about 3% [9]: this evaluation has to be confirmed through the calculation performed on a full heterogeneous WCLL DEMO.

Moreover, a dedicated study to evaluate the impact of the variation of the Outboard breeding zone radial thickness on the global TBR has been performed: results [10] show that most of the Tritium (about 82%) is generated in the 30 cm of BU closer to the plasma and that the TBR saturates at a BU radial size of about 1 m.

3.2 Shielding Performances

Neutron flux, nuclear heating, dpa and He-production in steel components have been calculated along the inboard and outboard mid-plane. The nuclear quantities are averaged on a poloidal extension of 50 cm (from z=10 to z=60 mm), thus considering the detailed breeding blanket description. The FMESH tally feature of MCNP has been applied to evaluate the nuclear responses.

The total and fast (E>100 keV) neutron fluxes radial profiles (Fig. 4) at the Inboard FW are $5x10^{14}$ n/cm^2/s and $3.4x10^{14}$ n/cm^2/s respectively; the blanket/manifold system provides an attenuation of more than two orders of magnitudes to the VV inner shell and the neutron flux further decreases of several orders of magnitude across the VV, being $4.8x10^8$ n/cm^2/s (total), and $2.9x10^8$ n/cm^2/s (fast) on the TFC, well below the 10^9 n/cm^2/s design limit [4].

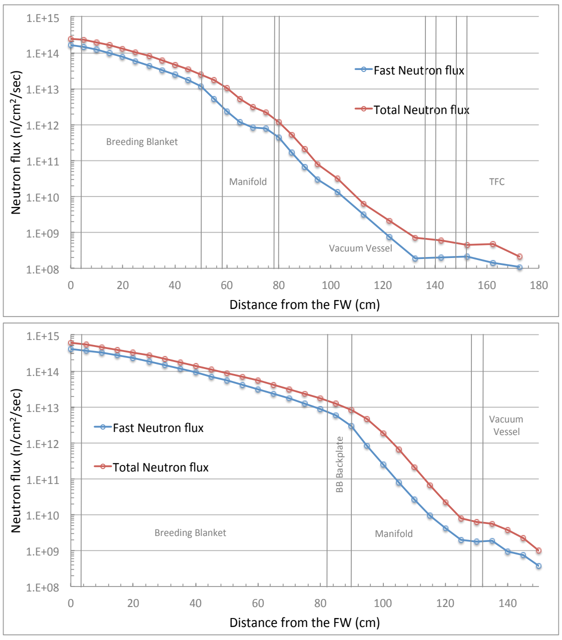

Fig. 4. Inboard (top) and Outboard (bottom) radial profile of the total and fast neutron flux.

The radial profiles of the nuclear heating evaluated on steel components are plotted in fig. 5: the maximum values at the FW Eurofer are ~7.5 W/cm^3 for the Inboard and ~9.2 W/cm^3 for the Outboard. At the VV inner shell the heat load decreases to 0.1 W/cm^3 in the Inboard and to $2x10^{-3}$ W/cm^3 in the outboard. In the TFC winding pack the heat load density is $1.4x10^{-5}$ W/cm^3, thus satisfying the design limit of 50 W/m^3 [4].

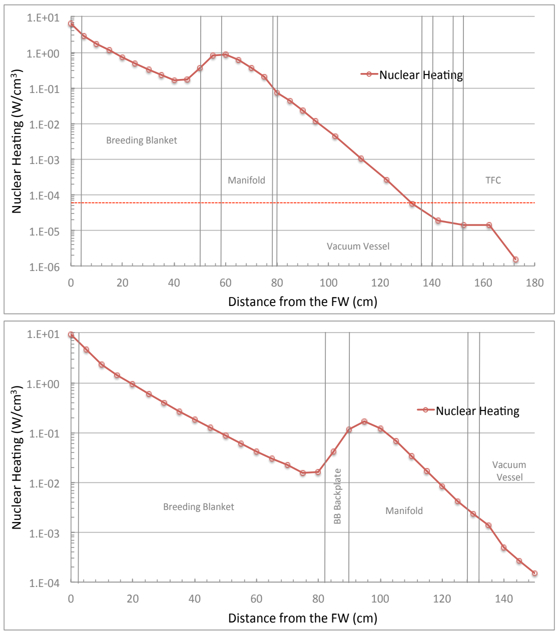

Fig. 5. Inboard (top) and Outboard (bottom) nuclear heating radial profiles in steel (the red dotted line indicates the design limit for the TFC).

Fig. 6 show the radial profile of the damage on Eurofer and SS-316 per full-power year (FPY): the 9.8 dpa/FPY value assessed at the Inboard FW decreases to ~$6.2x10^{-3}$ dpa/FPY at the VV. Considering the limit of 2.75 dpa foreseen on the VV steel [4], the present configuration ensures a sufficient protection over the whole DEMO lifetime. As far as the Outboard is concerned, the ~10 dpa/FPY peak value obtained at the FW lowers to $3.3x10^{-5}$ dpa/FPY at the VV inner shell steel.

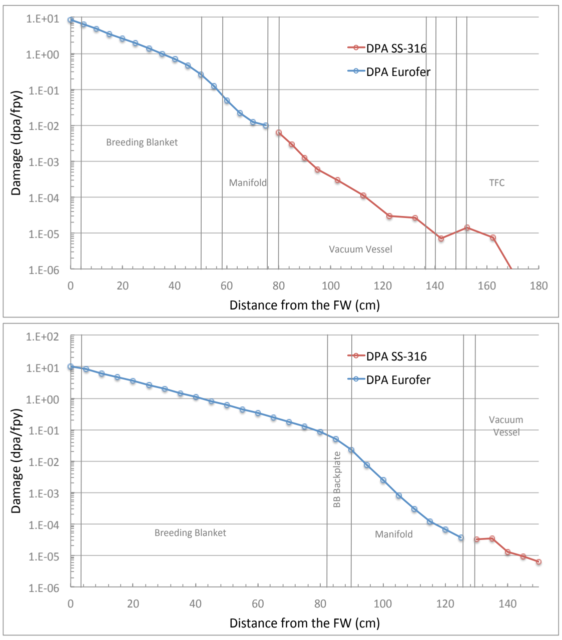

Fig. 6. Inboard (top) and Outboard (bottom) damage radial profiles on Eurofer (up to the manifolds) and SS-316.

As far as the He-production in steel is concerned (Fig. 7) the estimation performed on the Inboard area highlights a reduction of about 2 orders of magnitude from the FW (100 appm/FPY) to the VV (1 appm/FPY);

as far as the Outboard is concerned, the He-production drops of more than 4 orders of magnitude from the FW to the VV. Behind the Vacuum Vessel the He-production drops to values below 10^{-4} appm/FPY.

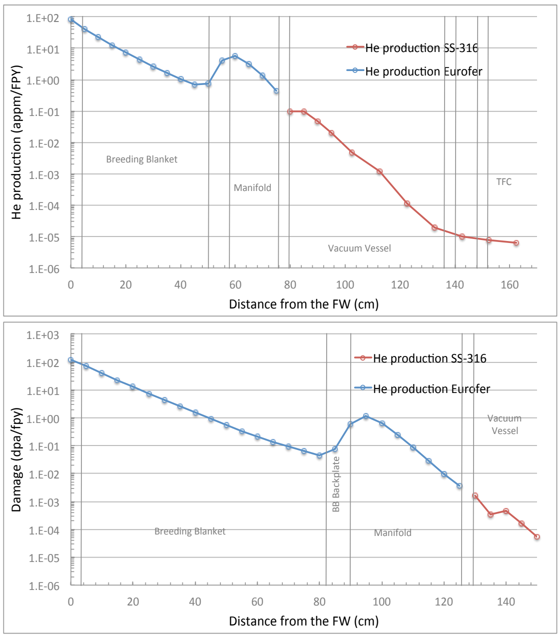

Fig. 7. Inboard (top) and Outboard (bottom) He-production radial profiles on Eurofer (up to the manifolds) and SS-316.

4. Single-module WCLL DEMO MCNP model

The latest WCLL BB layout, that is presently under development, is based on a novel single-module-segment (SMS) concept where a basic BU is replicated along the poloidal direction, filling the available space in Inboard and Outboard (fig.8) [11].

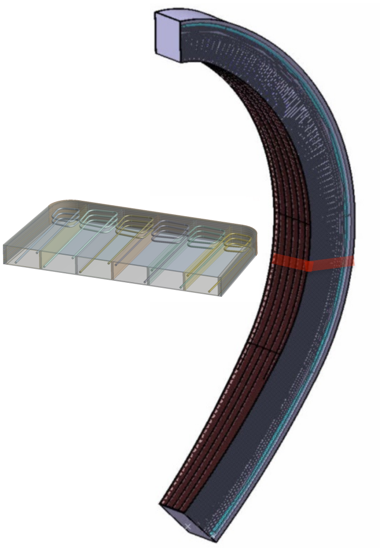

Fig. 8. WCLL SMS: overview of the Outboard module and detail of a single BU (highlighted in red).

The single BU includes the FW and side walls, top and bottom caps, internal stiffening and baffle plates, BSS, cooling pipes, LiPb manifolds, water manifolds for FW and breeding zone cooling. The BU cooling pipes are characterised by a complex helicoidal path in the area close to the FW thus, in order to obtain a reliable equivalent MCNP model, an approach based on the segmentation of the BB into radial sectors with specifically defined material mixture has been chosen (Table 3).

Table 3: radial segmentation of the SMS WCLL breeding blanket MCNP model with materials volume percentage for each layer.

component	Thickness (mm)	W	LiPb	$H_2$0	Eurofer
Armour	2	100	-	-	-
First Wall	3	-	-	-	100
	7	-	-	50.74	49.26
	15	-	-	1.65	98.35
Breeding Zone	25	-	91.11	-	8.89
	14	-	61.91	10.26	27.83
	32	-	84.79	2.25	12.96
	32	-	78.98	4.26	16.76
	32	-	84.11	2.46	13.43
	32	-	83.67	2.5	13.83
	80	-	80.8	1.38	17.83
	80	-	80.56	1.41	18.03
	80	-	81.87	0.95	17.18
	80	-	81.34	1.19	17.47
	80	-	81.86	0.99	17.15
	80	-	81.93	0.98	17.1
	80	-	80.64	1.44	17.92
	73	-	81.71	1.07	17.22
LiPb Manifolds	30	-	-	-	100
	40	-	38.23	-	61.77
	30	-	-	-	100
	40	-	38.18	-	61.82
Back Plate	30	-	-	-	100
H_2O manifolds	200	-	-	93.36	6.64
BSS	100	-	-	-	100

The obtained SMS WCLL DEMO MCNP model is shown in Fig. 9: also in this case the reduced radial extension of the Inboard module has been handled through the removal of the innermost sectors of the breeding zone.

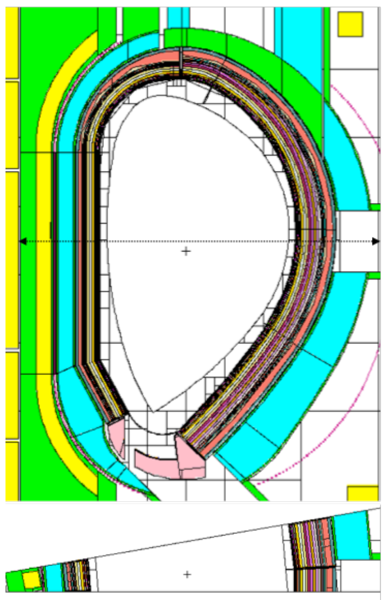

Fig. 9. SMS WCLL DEMO MCNP model: poloidal section showing the Inboard and Outboard breeding blanket (top) and toroidal section along the equatorial plane (bottom).

4.1 TBR assessment on the SMS WCLL DEMO

The 'quasi-heterogeneous' WCLL DEMO MCNP model based on the SMS approach so far described has been used to perform a preliminary assessment of the total TBR. Track-length estimators (F4 tally) with proper tally multipliers (FM card) for each sector that contributes to the Tritium generation (e.g. the BU sectors and the LiPb manifolds) have been considered, taking into account the neutron capture reactions on both the Li-6 and Li-7 isotopes. The resulting total TBR for this configuration is 1.133, thus the design target for Tritium self-sufficiency is satisfied also in this configuration.

With respect to the MMS concept, the total TBR is slightly reduced: thus, a dedicated study has been carried out in order to investigate the individual contribution of the BB/manifold layers on the TBR of the OB module. The results are shown in figure 10: the layer that provides the most significant Tritium breeding in Outboard region is the 1st in the breeding zone (24%) and the relative contributions decrease progressively through the outer layers. Generally, the results of this study show that most of the Tritium in Outboard is produced in the first 50 cm of the BU (~95% TBR).

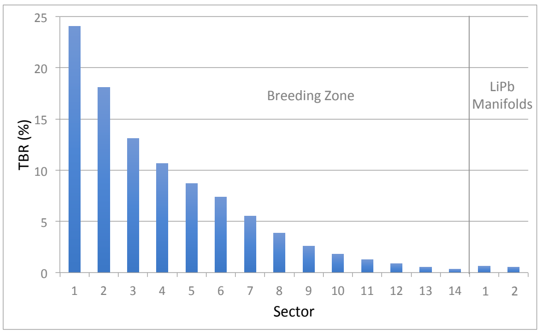

Fig. 10. Percentage contributions to the TBR in Outboard region relative to the breeding zone layers and LiPb manifolds. Results are normalised to the Outboard TBR evaluated on a 10° sector of the machine, including 1 full and 1 half SMS (fig. 9).

5. Conclusion and future activities

The presented studies have been carried out on the recent MMS WCLL DEMO, integrating the latest blanket design. The outcome of the performed studies highlighted the following issues:

- The design target for Tritium self-sufficiency is satisfied, being the total TBR about 1.14. The impact of the heterogeneous blanket module integrated in the OB#4 and IB#4 on the Tritium production have been estimated, resulting in a 3% gain on the total TBR. However, it is design dependent and it should be verified in full heterogeneous model.
- The combined BB/Manifold/VV system is sufficient to protect the TFC from the radiation streaming: the fast neutron flux evaluated on the TFC winding pack is 2.9×10^8 n/cm^2/s (design target: 10^9 n/cm^2/s), and the and the nuclear heating is 1.4×10^{-5} W/cm^3 (design target: 50 W/m^3).
- The damage on the VV stainless steel is ~6.2×10^{-3} dpa/FPY, thus the shielding capabilities of the BB and Manifold structures are sufficient to guarantee the integrity of the VV over the 6 FPY DEMO lifetime.
- The main nuclear responses evaluated in Eurofer reach the following peak values at the FW: ~9.2 W/cm3 nuclear heating density, ~10 dpa/FPY damage, 100 appm/FPY He-production.

The WCLL design team has recently developed an updated concept of the WCLL BB based on a SMS approach; the MCNP model of the SMS WCLL DEMO has been generated and the nuclear analyses in support of its design are presently ongoing. A first assessment of the global TBR has been carried out and the results highlight that the tritium self-sufficiency is guaranteed also in this configuration. An enhancement of the shielding performances for the SMS WCLL BB has to be expected because the removal of the poloidal gaps reduces drastically the direct neutron streaming from the plasma to the outer structures of the machine (VV, TFC).

Acknowledgments

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