



# Nuclear performances of the water-cooled lithium lead DEMO reactor: Neutronic analysis on a fully heterogeneous model

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## ABSTRACT

The development of a conceptual design for the Demonstration Fusion Power Reactor (DEMO) is a key issue within the EUROfusion roadmap. The DEMO reactor is designed to produce a fusion power of about 2 GW and generate a substantial amount of electricity, relying on a closed tritium fuel cycle: it implies that the breeding blanket (BB) shall guarantee a suitable tritium production to enable a continuous operation without any external supply.

The Water-Cooled Lithium Lead (WCLL) concept is a candidate for the DEMO BB: it uses liquid Lithium Lead as breeder and neutron multiplier and water in PWR condition as coolant. The neutronics analyses carried out in the past have been performed using a semi-heterogeneous representation of the BB, since the complexity of its structure makes the generation of a detailed MCNP model a very demanding and challenging task. Results highlighted good performances for the WCLL BB, both in terms of shielding effectiveness and tritium self-sufficiency.

A recently updated assessment of the tritium breeding ratio (TBR) requirement for DEMO, considering margins for calculation uncertainties and incomplete models of the whole machine, led to the definition of a tentative 1.15 value for the TBR. Moreover, the implementation of an accurate BB neutronics model, consistent with the engineering design, is recommended for the evaluation of the tritium self-sufficiency. In order to tackle these issues, an MCNP model of the DEMO tokamak, integrating a fully heterogeneous WCLL BB has been developed for the first time, including an accurate description of the FW water channels, as well as a comprehensive definition of the breeding zone inner structure. A complete assessment of the WCLL BB nuclear performances, through 3D neutron and gamma transport simulations, has been carried out by means the MCNP Monte Carlo code and JEFF nuclear libraries.

## 1. Introduction

In the frame of the EUROfusion roadmap, the development of a breeding blanket (BB) system that guarantees the DEMO reactor [1] Tritium self-sufficiency is a fundamental issue. The Water-Cooled Lithium Lead (WCLL) concept, that encompass water in PWR (Pressurized Water Reactor) conditions as coolant and liquid Lithium Lead as

breeder and neutron multiplier, is presently a reliable and promising candidate as DEMO BB; during the last years, its design development reached a significant level of maturity and soundness, satisfying the nuclear design limits in terms of Tritium Breeding Ratio (TBR) and shielding performances.

All the neutronics analyses performed so far on the WCLL BB made use of simplified semi-heterogeneous geometry of the blanket layout,

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because the complexity of its structure makes the generation of a detailed MCNP model a very demanding and challenging task. Up to now, the modelling approach was based on the segmentation of the BB into radial sectors with specifically defined material mixture to represent the components embedded in each layer. Even if this methodology allowed a reliable estimation of the nuclear responses, the TBR is particularly sensitive to the effect of the water moderation: thus, the implementation of an accurate BB neutronics model, with a proper definition of the first wall (FW) and breeding zone cooling channels, is recommended. Moreover, a recently updated assessment of the TBR requirement for DEMO, considering margins for calculation uncertainties and incomplete models of the whole machine, to the definition of a tentative 1.15 value for the total TBR [2].

Taking into account the above-mentioned issues, an MCNP model of the DEMO tokamak, integrating a fully heterogeneous WCLL BB has been developed for the first time, including an accurate description of the FW water channels, as well as a comprehensive definition of the breeding zone inner structure.

A comprehensive nuclear analysis has been carried out on the WCLL DEMO present design, aimed at verifying its compliancy with the design targets both in terms of tritium self-sufficiency and shielding performances [3], providing data for thermo-mechanical studies and guidelines for the optimization of the BB layout future development.

The nuclear responses have been assessed through three-dimensional coupled neutron and gamma transport simulations by means of the MCNP5v1.6 Monte Carlo code [4] and the Joint Evaluated Fusion File JEFF 3.3 nuclear data libraries [5].

## 2. The WCLL breeding blanket

The present WCLL BB design is based on a single-module-segment (SMS) concept where the basic inboard and outboard Breeding Units (BUs) are replicated along the poloidal direction (94 and 104 BUs for each poloidal sector in inboard and outboard respectively). The inboard and outboard BUs are represented in Figs. 1 and 2, respectively: they include the FW and side walls, stiffening and internal baffle plates, back supporting structure (BSS), cooling pipes, LiPb manifolds and water manifolds for the FW, side walls and breeder zone cooling circuit.

With respect to the previous WCLL BB concept [6,7] the layout of the

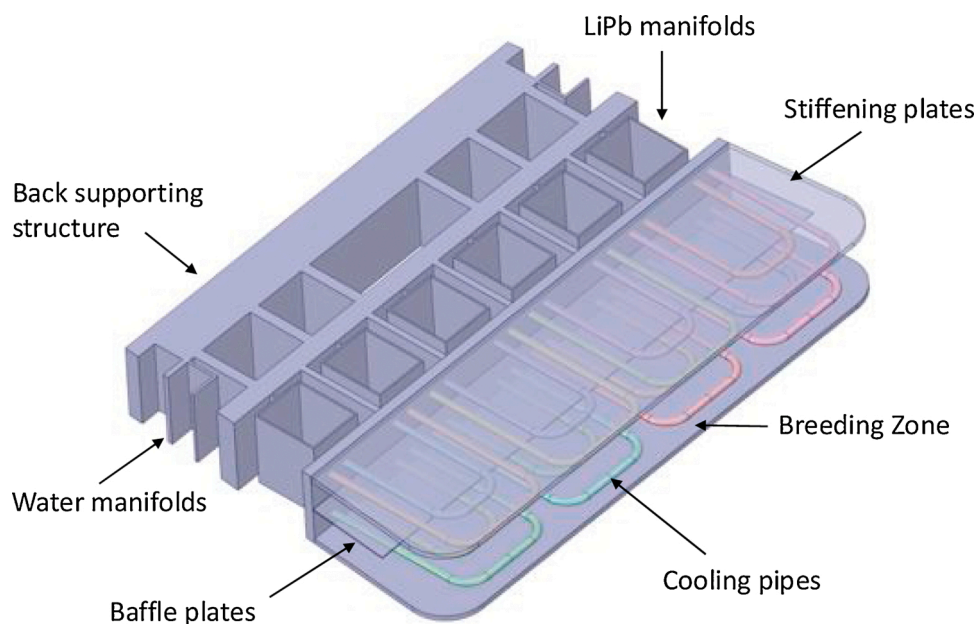
cooling pipes inside the inboard breeder zone has been completely updated: the latest configuration is based on ‘U’ shaped inlet/outlet cooling channels extending inside the breeder zone and connected to the water manifolds through the BSS. As far as the outboard is concerned, the complex cooling pipes assembly has been kept unaltered. Each inboard BU encloses 16 inlet/outlet water pipes, resulting in 1504 cooling pipes for each poloidal sector; as far as the outboard is concerned, each BU contains 44 inlet/outlet water pipes (4576 cooling pipes for each poloidal sector). A significant update with respect to the 2018 WCLL DEMO BB structure is related to the poloidal distribution of the FW water channels. As specified in [7], the previous design relied on a homogenous positioning of the channels (6 for each BU both in inboard and outboard): the updated thermo-mechanical analyses led to a new layout in which the inboard sector of the BB can be sufficiently cooled even reducing the FW water channels of each BU to 4, except for the upper area of the machine (corresponding to the inboard sector #7 in the multi-module segment blanket layout [8]), where a more efficient heat removal system is needed (Fig. 3).

The distribution of the FW cooling channels in the outboard sector is unchanged (i.e. 6 channels for each BU, Fig. 4). The overall FW cooling system consists of 447 and 624 channels for each inboard and outboard poloidal sector.

## 3. WCLL blanket MCNP model

The DEMO reactor baseline layout used in the present studies is the EU DEMO1 2017 reference configuration model representing a  $11.25^\circ$  toroidal sector of the tokamak [9], with plasma parameters shown in Table 2. The model is provided with reflective boundary surfaces defined for the planes that toroidally delimit the geometry, in order to simulate the whole  $360^\circ$  tokamak extension.

The generation of the MCNP geometry of the WCLL complex structure is based on the preliminary customization of the DEMO 1 2017 baseline model that has been split into sectors to host the universes dedicated to the description of the inboard/outboard main components: armour, FW and side walls with cooling channels, caps, BUs, BSS, manifolds. In particular, the area dedicated to host the breeder zone has been segmented through the definition of the stiffening plates that enclose each BU. Successively, the CAD file of each WCLL BB component



**Fig. 1.** Perspective view of the Inboard BU. The FW, side walls and armour have been removed to show the inner cooling pipes layout. The channels that connect the BZ cooling pipes to the water manifolds are not shown in the picture.

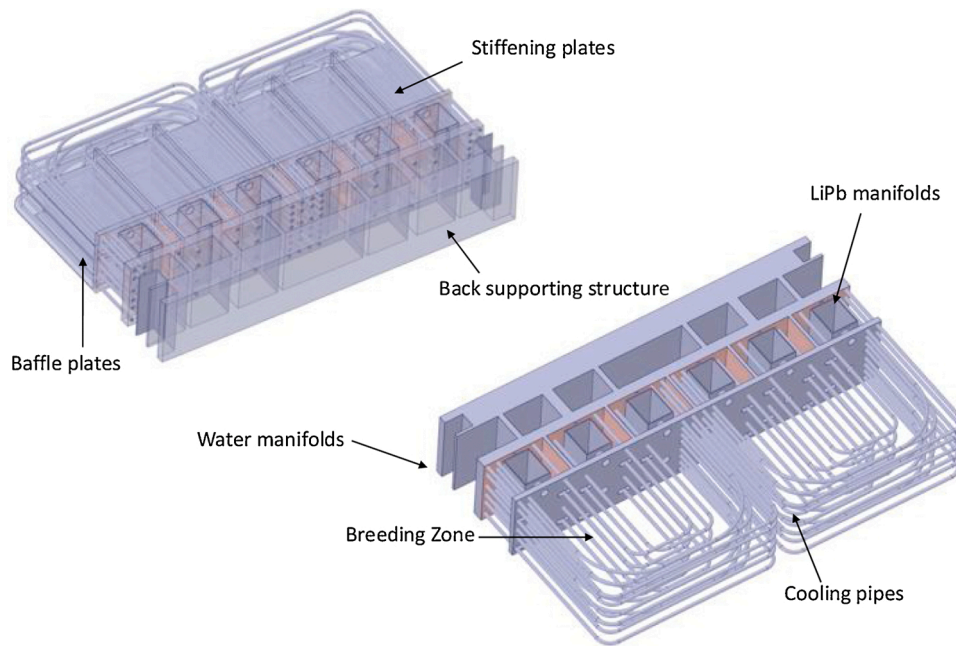


Fig. 2. Perspective view of the Outboard BU. The FW, side walls and armour have been removed to show the inner cooling pipes layout.

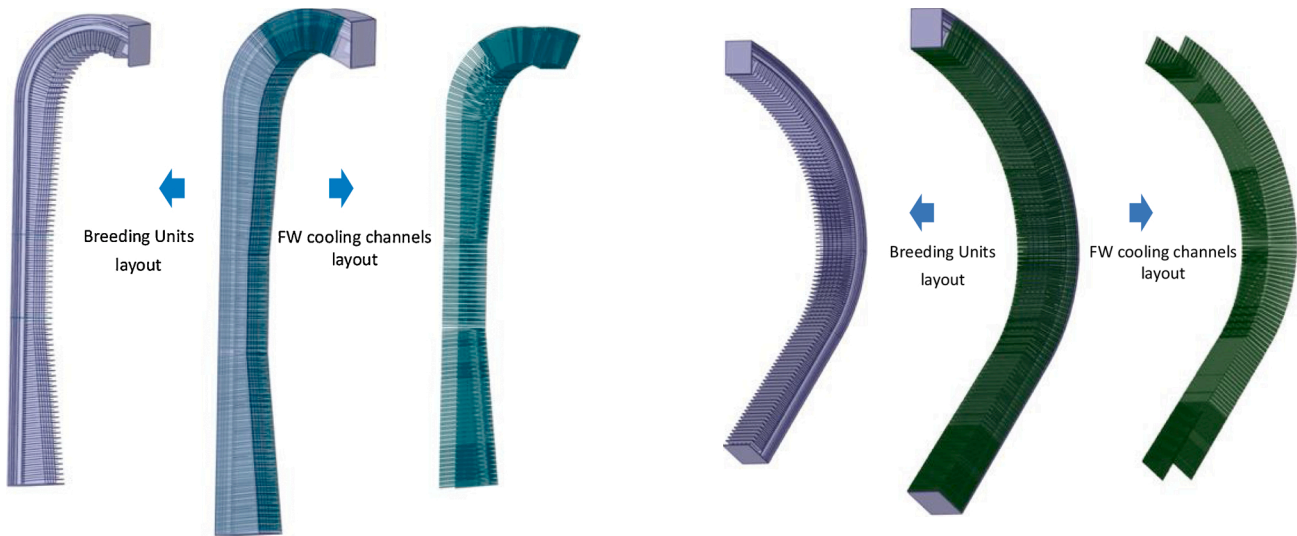


Fig. 3. WCLL blanket inboard structure: the figure in the middle shows the overall system, the breakdown into the FW cooling channels positioning and the arrangement of the BUs are shown on the right and left respectively.

Fig. 4. WCLL blanket outboard structure: the figure in the middle shows the overall system, the breakdown into the FW cooling channels positioning and the arrangement of the BUs are shown on the right and left respectively.

has been singularly pre-processed, converted into the equivalent MCNP geometrical representation and manually integrated into the modified 2017 DEMO 1 generic MCNP model, by means of the MCNP ‘universe’ and ‘fill’ features (i.e. specific envelopes has been defined for each DEMO WCLL sub-component in order to be filled with the proper inner structure). As far as the breeder zone is concerned, the internal layout of the inboard and outboard BUs located at the equatorial plane have been replicated along the toroidal/poloidal direction by means of proper rotation matrixes applied to the original geometry.

The pre-processing and simplification of the WCLL BB CAD model has been performed by means of the 3D modelling software Ansys SpaceClaim 2019 [10], in order to generate a CAD model suitable for neutronics analyses and the conversion into the equivalent MCNP geometrical representation has been carried out by means of the CAD-to-MCNP interface embedded in the SuperMC code [11]: the

obtained WCLL DEMO MCNP model is shown in Fig. 5: the different radial extension of the inboard/outboard module has been handled preserving the distance between the FW and the BB cooling channels.

As far as the materials definition is concerned, each cell of the model presents homogenous materials: Eurofer, SS-316 L, LiPb enriched at 90 % in <sup>6</sup>Li, with compositions according to the provided specifications [12]. The only exception is related to the area where the BZ cooling pipes are connected to the water manifolds through the LiPb manifolds (pink cells in Fig. 5), where a specific homogeneous compound has been defined (94.69 % LiPb, 1.8 % Water, 3.51 % Eurofer). In the actual WCLL DEMO reactor, the water pressure and temperature status can be assumed to be close to the PWR one (pressure 15.5 MPa, temperature around 312 °C); in order to accurately represent these conditions, an average 0.700 g/cm<sup>3</sup> density for the water has been assumed.

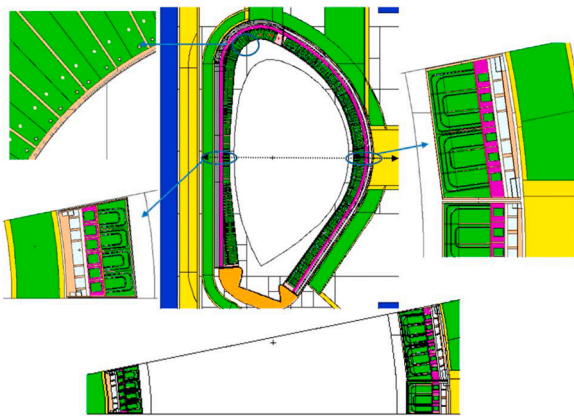


Fig. 5. WCLL DEMO MCNP model: poloidal section showing the inboard and outboard breeding blanket (top) and toroidal section along the equatorial plane (bottom). Details of the inboard/outboard BZ cooling pipes structure are shown, as well as an enlargement of the FW cooling channels (top left frame).

#### 4. Nuclear analyses

The MCNP DEMO model integrating the WCLL blanket has been used to assess the nuclear performances of the WCLL DEMO in terms of shielding capability to protect the TFC and tritium self-sufficiency of the machine. Neutron flux, nuclear heating, damage and He-production radial profiles have been assessed on the equatorial mid-plane, along a single BU both for inboard and outboard. Results have been normalized to 1998 MW fusion power (neutron yield:  $7.095 \cdot 10^{20}$  n/s), according to the plasma parameters specified in Table 1. The simulations have been performed using standard MCNP cell-based (F4, F6, F1, F2 tallies) and mesh tallies (FMESH tally), with proper multiplier to calculate the nuclear quantities of interest for the WCLL design development, performances assessment and verification of design requirements [13,14].

##### 4.1. Neutron wall loading

The poloidal distribution of the Neutron Wall Loading has been estimated for inboard and outboard poloidal sectors using as separation surfaces for the tallies the same planes that defined the blanket modules in the multi-module configuration [8].

Fig. 6 shows the result for 1998 MW of fusion power: the maximum values are in the outboard and inboard equatorial zone ( $1.33 \text{ MW/m}^2$  and  $1.1 \text{ MW/m}^2$  respectively), while the poloidal average is  $0.93 \text{ MW/m}^2$ .

##### 4.2. Tritium breeding ratio

The verification of the tritium self-sufficiency for the WCLL DEMO reactor has been carried out through the assessment of the total tritium breeding ratio (TBR) by means of track-length (F4 tally) with proper tally multipliers (FM card) for each component of the BB that contributes to the tritium generation (i.e. breeder zones enclosed in each BU

Table 2  
Nuclear power deposition in the WCLL BB components.

Component	Inboard (MW)	Outboard (MW)
W armour	20.78	43.9
First wall	75.9	175.3
Breeding zone	348.1	848.6
Side walls	19.6	37.4
Caps	1.9	2.2
Stiffening plates	13.4	35.3
LiPb Manifold	17.4	33.8
H <sub>2</sub> O Manifold/BSS	14.9	27.8
Total	512	1204.3

and LiPb manifolds), taking into account both the neutron capture reactions on  $^6\text{Li}$  and  $^7\text{Li}$  isotopes. The resulting total TBR for this configuration is 1.15, thus the 1.1 design target for tritium self-sufficiency is satisfied: 69.7 % of the tritium is produced in the outboard sector, while 30.3 % is generated in the inboard. With respect to the previous calculations, performed using a layered representation for the BZ and manifolds structure (total TBR = 1.138 [8]), an increase of about 1% in the total TBR has been assessed: this enhancement in the tritium generation, apart from the approximation due to the usage of a homogenous model, is mainly due to the following issues concerning the amount of water in the inboard sector of the BB:

- Significant decrease of the water content in the inboard FW with respect to the previous WCLL BB design with 6 F W cooling channels for each BU (about 21 %). The water in the FW provides a neutron moderation effect resulting in an enhancement of the probability that they could interact with the lithium nuclei (i.e. the neutron absorption cross section on lithium increases with the reduction of the incident neutron energy) and in a reduction of both the Pb(n,2n) interactions and absorption in the steel components. On the other hand, an excessive quantity of water in the FW drastically inhibits the neutron streaming towards the innermost breeding blanket sectors. The new layout with a reduced number of cooling channels shows beneficial effects in terms of tritium generation, providing an additional contribution to the total TBR from the breeder zone area close to the manifolds and from the LiPb manifolds, which is determining in the achievement of the design target.
- Reduction of the water content in the inboard BUs with respect to the previous layout, where the same configuration of cooling pipes was used in inboard and outboard. Apart from the above-mentioned considerations about effect of the water amount on the neutron streaming, that can be extended also to the breeder zone, the removal of pipes and coolant inside the BUs allows a significant gain (about 8%) in terms of breeder effective volume (present layout:  $14,775 \text{ cm}^3$  of water in the equatorial outboard BU,  $5314 \text{ cm}^3$  of water in the equatorial inboard BU).

As mentioned above, a tentative requirement on the DEMO Tritium self-sufficiency recommending that the total TBR should be, at least, 1.15 has been recently proposed [2]. This value takes into account the removal of effective breeder volume due to the impact of the in-vessel components, the losses due to the radioactive decay of tritium and the necessity to provide the start-up inventory for a following D–T power plant. Despite this challenging requirement, the modification introduced in the inboard sector of the latest WCLL BB layout allowed a determining increase in the total tritium generation, allowing the satisfaction of the proposed design limit.

##### 4.3. Nuclear power deposition

The breakdown of the nuclear power deposition due to neutrons and secondary gammas in the WCLL blanket components is provided in Table 2: it has been assessed by mean of F6 tallies (i.e. energy deposition

Table 1  
Main parameters of the DEMO baseline configuration.

N° of Toroidal Field Coils	16
Major radius (m)	8.938
Minor radius (m)	2.883
Aspect ratio	3.1
Plasma elongation	1.65
Plasma triangularity	0.33
Fusion power	1998
Average neutron wall loading ( $\text{MW/m}^2$ )	1.04
Net electric power	500

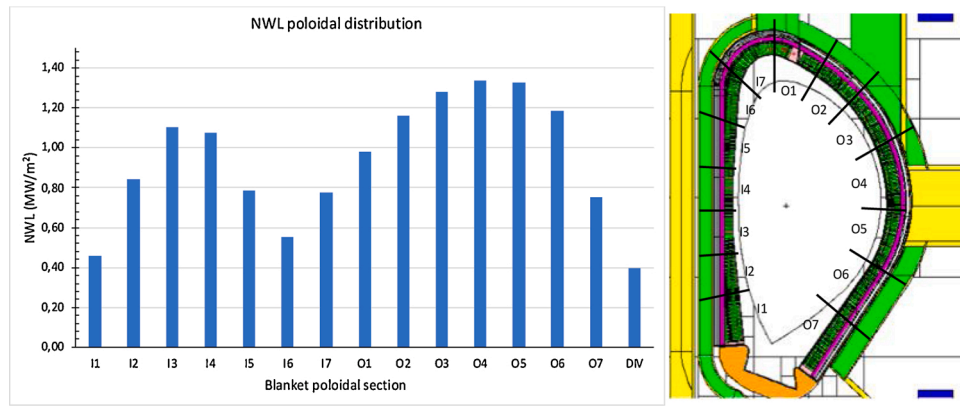


Fig. 6. Neutron Wall Loading poloidal distribution (results are normalized to 1998 MW of fusion power).

tallies) on all the system elements.

About 81.6 % of the total nuclear power (1716.4 MW), is deposited on the breeding blanket/manifold/BSS system: in particular, about 73 % is deposited on the BZ, side walls and caps, 14.7 % on the FW and about 3.8 % on the W armour. Moreover, the breakdown of the nuclear power distribution in the inboard and outboard blanket segments shows that most of the power is deposited in the outboard (70.2 %).

#### 4.4. Shielding performances

The assessment of the WCLL BB shielding performances have been performed through the evaluation of the neutron flux, nuclear heating, dpa and He-production in steel components along the inboard and outboard mid-plane. The nuclear quantities are averaged over a poloidal extension covering a single BU both in inboard and in outboard (13.5 cm), making use of the FMESH tally feature of MCNP. The total and fast

( $E > 100$  keV) neutron fluxes radial profiles are shown in Fig. 7 for the inboard and outboard sectors. The total neutron fluxes at the inboard and outboard W armour are  $5.5 \cdot 10^{14}$  n/cm<sup>2</sup>/s and  $6.1 \cdot 10^{14}$  n/cm<sup>2</sup>/s respectively. In inboard, the blanket/manifold system provides an attenuation of more than two orders of magnitude to the VV inner shell and the neutron flux further decreases of three orders of magnitude across the VV, being  $5.1 \cdot 10^8$  n/cm<sup>2</sup>/s (total), and  $1.55 \cdot 10^8$  n/cm<sup>2</sup>/s (fast) on the TFC: thus, the WCLL BB shielding capability ensure that the  $10^9$  n/cm<sup>2</sup>/s design limit for the fast neutron flux on the TFC is fully satisfied. As far as the outboard is concerned, the larger BB radial extension provides an attenuation of the neutron flux across the blanket/manifold system of about 3 orders of magnitude.

Fig. 8 shows the radial profiles of the nuclear heating density evaluated in W (armour), Eurofer and PbLi (blanket) and SS316 L (Vacuum Vessel and TFC) for the inboard and outboard sectors. As far as the inboard is concerned, the highest values are: 25.7 W/cm<sup>3</sup> on W armour,

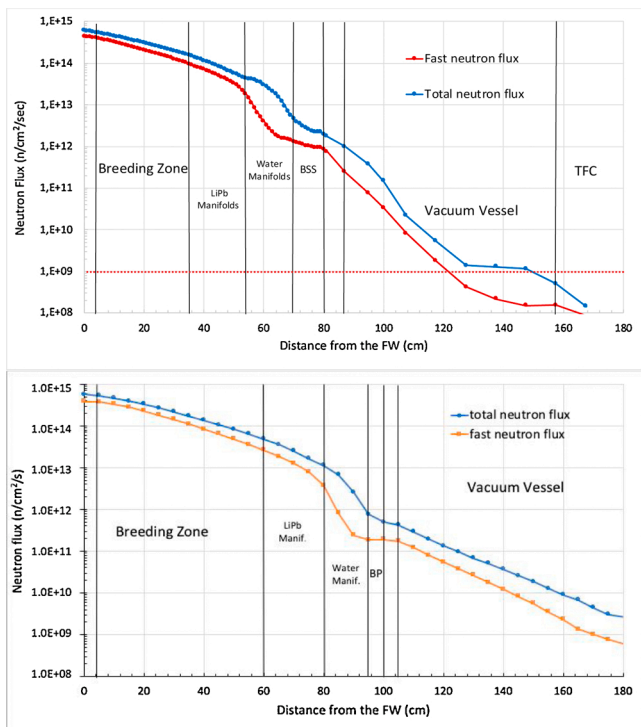


Fig. 7. Radial profile of the total (blue) and fast (red) neutron flux at the equatorial plane for the Inboard (upper panel) and outboard (lower panel). The dotted red line indicates the design target for the fast neutron flux on the TFC ( $10^9$  n/cm<sup>2</sup>/s). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

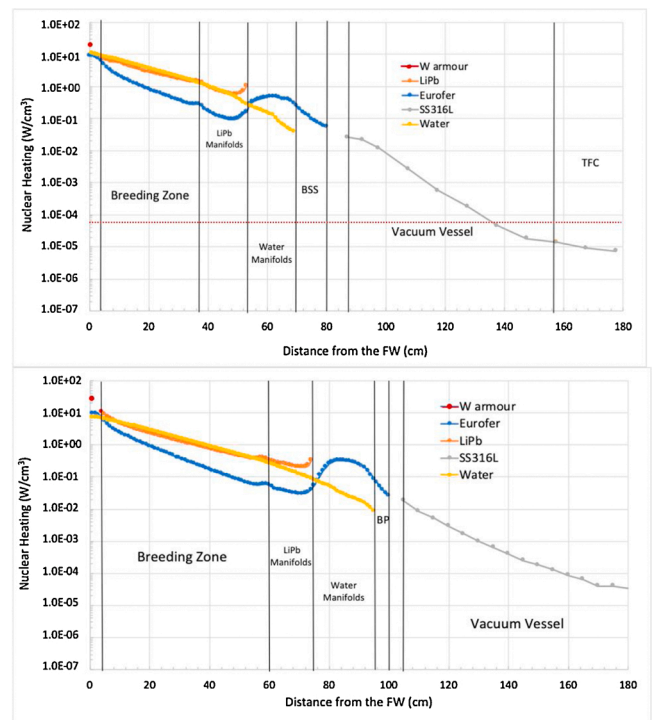


Fig. 8. Nuclear heating radial profile evaluated in W armour, Eurofer, PbLi and SS316 L for the inboard (upper panel) and outboard (lower panel) sectors. The dotted red line indicates the design target for the heat load on the TFC ( $5 \cdot 10^{-5}$  W/cm<sup>3</sup>). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

8.8 W/cm<sup>3</sup> on Eurofer in the FW and 4·10<sup>-2</sup> W/cm<sup>3</sup> on the VV inner shell SS316 L. On the coils, the maximum nuclear heating density is 2.2·10<sup>-5</sup> W/cm<sup>3</sup>, so the 5·10<sup>-5</sup> W/cm<sup>3</sup> design limit is satisfied and the shielding capabilities of the BB system ensure sufficient protection of the TFC. As far as the outboard segment is concerned, the heat load on the W armour is 27.4 W/cm<sup>3</sup>, while the highest values assessed for the FW Eurofer and SS316 L VV inner shell are 9.6 W/cm<sup>3</sup> and 1.8·10<sup>-2</sup> W/cm<sup>3</sup> respectively.

The radiation damage has been assessed in terms of dpa per FPY (dpa/FPY) produced in the structural steel of the blanket (Eurofer) and in the Vacuum Vessel (SS316 L). Fig. 9 provides the radial profiles in the equatorial area for the inboard and outboard BUs. In inboard, the maximum damage assessed for the Eurofer FW is 9.1 dpa/FPY and it decreases to 8.7·10<sup>-3</sup> dpa/FPY in the SS316 L VV inner shell. As far as the outboard is concerned, the highest values are 10.6 dpa/FPY on the FW and 2.46·10<sup>-3</sup> dpa/FPY on the VV. Considering the design limit of 2.75 dpa integrated over 6 FPY, the cumulated damages over the DEMO lifetime for the VV inner shell stainless steel are 0.059 dpa and 0.015 dpa in inboard and outboard respectively: in both cases the design target limit is fulfilled. It's presently foreseen [15] that the first BB installed on DEMO has to withstand a 20 dpa damage limit for the FW Eurofer; successively the BB will be replaced with a second set of modules with a 50 dpa damage limit. In both cases the present design of the WCLL BB satisfy the design targets.

The aim of the Helium production calculation is to verify that the gas generated at locations where re-welding of steel components is required, is lower than 1 appm at the end of DEMO lifetime: the most critical locations in terms of steel reweldability are the vessel zones (e.g. close to vessel ports) thus the Helium production has been assessed in terms of appm/FPY produced in the structural steel of the blanket (Eurofer) and in the SS316 L steel of the VV. The He-production radial profiles evaluated in the equatorial area are shown in Fig. 10. In inboard, the He-production in the FW (Eurofer) is 82.7 appm/FPY, it decreases to 6.85·10<sup>-2</sup> appm/FPY in the VV inner shell, and it's less than 10<sup>-5</sup> appm/

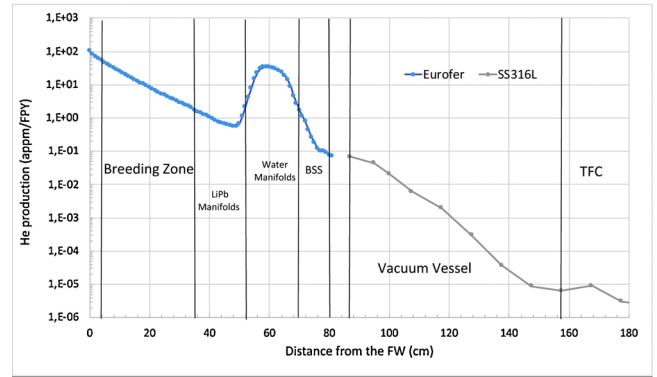
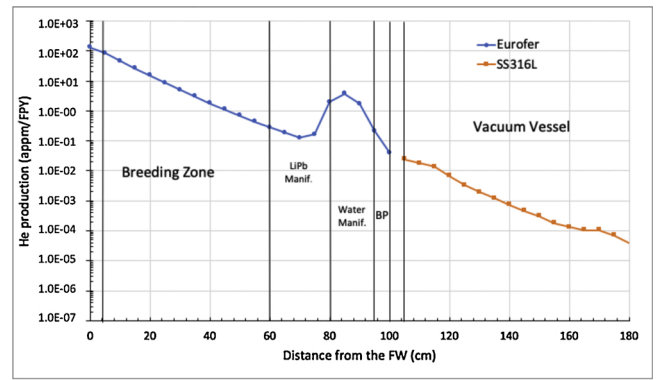


Fig. 10. Radial profile of the He production on Eurofer (up to the manifolds) and SS-316, evaluated in the inboard (upper panel) and outboard (lower panel) mid-plane.

FPY on TFC. As far as the outboard BU is concerned, the maximum in FW Eurofer is 114 appm/FPY and in VV inner shell is 2.4·10<sup>-2</sup> appm/FPY. The maximum cumulated He-production in the VV, assessed through the integration over 6 FPY lifetime, is 0.4 appm for the inboard and 0.15 for the outboard: in both cases the limit of 1 appm [16] is fulfilled.

Both the He production and nuclear heating radial profiles show a peak behind the PbLi manifold that is due to the high amount of water that is present in the water manifolds (about 86 % in volume of water). The effect of water moderation induces a softer neutron spectrum: as a consequence, the He-production is enhanced in adjacent zone through the reactions with <sup>10</sup>B in Eurofer and, at the same time, the heat load increases, because of higher gamma generation in adjacent steel.

### 5. Conclusions

A detailed MCNP model of the WCLL DEMO reactor has been generated for the first time, including an accurate description of the BB subcomponents: the necessity to develop such a complex model has been driven by the fact that, for a reliable assessment of the BB performances, the usage of a model which is as much as possible consistent with the engineering CAD model is required.

The assessment of the WCLL DEMO nuclear performances highlights that the actual design targets, both in terms of Tritium self-sufficiency and shielding capabilities, are satisfied. The total TBR evaluated taking into account the contribution of both <sup>6</sup>Li and <sup>7</sup>Li isotopes, results to be 1.15; as far as the shielding effectiveness of the BB is concerned, the combined WCLL blanket, manifolds and VV system provides a sufficient protection to the TFC from the radiation streaming: the fast neutron flux evaluated on the inboard TFC winding pack is 1.55·10<sup>8</sup> n/cm<sup>2</sup>/s (design target: 10<sup>9</sup> n/cm<sup>2</sup>/s), and the nuclear heating due to neutrons and secondary photons is 2.2·10<sup>-5</sup> W/cm<sup>3</sup> (design target: 5·10<sup>-5</sup> W/cm<sup>3</sup>). The assessment of the damage on the VV stainless steel highlighted that its integrity is guaranteed over the 6 FPY DEMO lifetime: 0.052 and 0.015

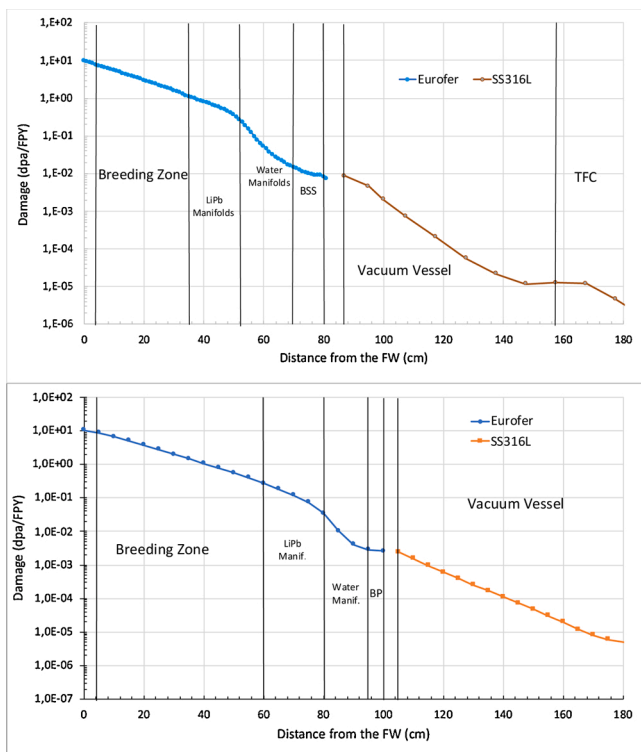


Fig. 9. Radial profile of the damage on Eurofer (up to the manifolds) and SS-316, evaluated in the inboard (upper panel) and outboard (lower panel) mid-plane.

dpa for the inboard and outboard VV inner shell respectively. As far as the Helium production is concerned, the maximum cumulated He-production, assessed through the integration over the 6 FPY lifetime, is 0.4 appm and 0.15 for the inboard and for the outboard, respectively: in both cases the limit of 1 appm is fulfilled.

During the last years, the WCLL BB design reached a more mature and advanced stage of development, achieving promising results in terms of nuclear performances. However, some improvement on the design of some sub-components (e.g. manifolds) are presently ongoing and the impact of these modifications on the neutronics responses need to be assessed in the near future.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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