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Nuclear analyses in support of the water-cooled lithium lead breeding blanket design development: a prospective strategy to achieve the tritium self-sufficiency

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ABSTRACT

The development of a closed tritium fuel cycle is essential for the sustainable operation of future fusion power plants. Within the EUROfusion roadmap, the Water-Cooled Lithium Lead (WCLL) breeding blanket is a key candidate for the Demonstration Fusion Power Reactor (DEMO). It uses pressurized water as coolant and a liquid lithium-lead (LiPb) eutectic alloy as both breeder and neutron multiplier. The current WCLL design features modular inboard and outboard Breeding Units (BUs) composed of helical Double Wall Tubes (DWTs) immersed in LiPb. This configuration improves heat removal and reduces the water inventory in the Breeding Zone, thereby potentially increasing tritium generation.

This work presents an assessment of the WCLL DEMO nuclear performances in terms of shielding effectiveness and tritium self-sufficiency, based on 3D radiation transport simulations performed using the Monte Carlo MCNP code and JEFF nuclear data libraries. A detailed MCNP model has been developed, including a fully heterogeneous representation of the Breeding Zone and first wall (FW) water channels. Radial profiles of fast and total neutron fluxes, along with nuclear heating, are evaluated at the equatorial level, providing 3D maps of these quantities as well. The total Tritium Breeding Ratio (TBR) has been evaluated, accounting for contributions from both the BZ and LiPb manifolds.

To further enhance tritium generation and support the long-term viability of the WCLL concept, design modifications to the latest layout have been explored through a prospective approach. The effectiveness of these modifications has been assessed by means of parametric studies and discussed in light of their potential impact on overall reactor performance.

1. Introduction

One of the EUROfusion roadmap key missions for the exploitation of nuclear fusion as a sustainable and reliable energy source relies on the development of a BB that ensures the tritium self-sufficiency. DEMO, as well as future commercial fusion power plants must guarantees a suitable tritium production rate, have a controlled inventory and also provide enough tritium surplus to allow successor power plants to start up.

The WCLL concept is one of the most promising candidates as DEMO BB: it encompass water in PWR (Pressurized Water Reactor) conditions as coolant and liquid Lithium Lead (90 % ^{6}Li enriched) as neutron multiplier and breeder.

During the past decade, the WCLL BB concept underwent several design revisions and improvements: it was initially based on a Multi-Module-Segment (MMS) DEMO layout [1] where both inboard and outboard area of the blanket are divided into seven units with straight

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FW, attached to a common Back Supporting Structure (BSS). Thermo-mechanical and thermo-hydraulic analyses [2,3], along with nuclear performance assessments [4,5], have shown promising results and identified margins for further improvements. Nevertheless, the MMS architecture presents some drawbacks: the presence of poloidal gaps between the contiguous segments leads to a significant neutron leakage and a reduction of the effective breeding volume.

From 2017 onward, the structure of the BB for DEMO has been radically modified, passing from a MMS concept to a Single-Module-Segment (SMS) layout, which rely on the replication of an elemental Breeding Unit (BU) along the poloidal direction in inboard and outboard [6].

The transition from the MMS to the SMS concept introduces significant design developments aimed at enhancing overall system performances. The removal of the poloidal gaps between MMS modules. not only mitigates neutron streaming, thereby improving shielding effectiveness, but also contributes to an increase in the effective breeding volume, thus maximising the tritium generation Furthermore, the SMS configuration improve the robustness of the segment structure against high electromagnetic loads derived from possible plasma disruptions and simplify the filling and drainage procedures of both the breeder and coolant in the different regions of the blanket.

Since the SMS layout has been adopted, the architecture of the WCLL BB underwent several upgrades, relying on few keystones, such as the adoption of DWTs for the cooling system of the BZ, and two independent water circuits for the BZ and FW.

The configuration of an elemental inboard and outboard BU was based on C-shaped BZ cooling pipes and poloidally distributed FW water channels to keep the temperature of the BZ and FW structural material (i.e. Eurofer and Tungsten) below the 550 °C design limit. The thermo-hydraulic and thermo-mechanical analyses pointed out that the BZ-manifolds system guarantee a suitable mitigation of the heat loads (Fig. 1); moreover, the assessment of the nuclear performances, carried out on a simplified layered model [7], showed that the WCLL BB was compliant with the recommended radiation shielding requirements on the Vacuum Vessel (VV) and Toroidal Field Coils (TFC) and ensured the tritium self-sufficiency (Total TBR=1.138, TBR design limit≥1.1 [8,9]). The nuclear design activities have been also complemented with experimental campaigns carried out at the Frascati Neutron Generator (FNG) facility [10], aimed at validating the theoretical results, in terms of tritium generation and shielding effectiveness, through the irradiation of a WCLL BB mock-up with 14 MeV neutrons.

In 2020 a new tentative requirement on the DEMO tritium self-sufficiency has been proposed [11], recommending that the total TBR should be, at least, 1.15. This value accounts for several key factors, including the radioactive decay of tritium (~5.5 % per year), the expected losses during tritium processing within the fuel cycle, the reduction of effective breeder volume due to the presence of in-vessel components (e.g., diagnostics and heating systems), uncertainties in nuclear data, statistical uncertainties inherent in Monte Carlo calculations, modeling and design assumptions, lithium burn-up effects and the need to provide a start-up tritium inventory for a subsequent D-T power plant.

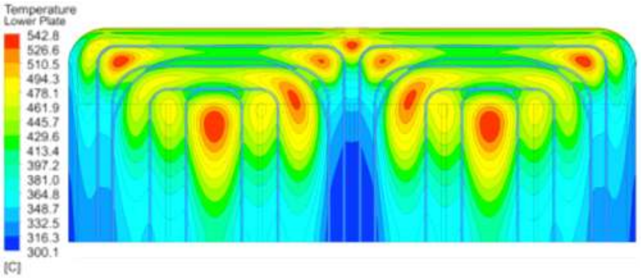

Fig. 1. Section of the outboard equatorial BU thermal field during DEMO operations, showing the arrangement of the BZ C-shaped DWTs cooling system [12].

The necessity to satisfy the new design limit in terms of TBR drove further improvements in the WCLL BB concept based on C-shaped DWTs: the latest layout, as a result of the pre-conceptual design phase [12], relies on a BZ structure embedding a number of DWTs ranging from 20 to 24 in each BU according to the poloidal positioning of the elemental unit (Fig. 2); a far as the FW is concerned, 4 cooling channels for each BU is foreseen both in inboard and outboard, except for the inboard upper area of the machine and the outboard region close to the Divertor where 6 water channels are needed for a more efficient heat removal.

The nuclear analyses on the optimized design of the WCLL BB and manifolds system have been carried out, for the first time, on a fully heterogenous neutronic model consistent with the engineering design of the breeding blanket [13]. The results of the study highlighted promising nuclear performances, showing effective shielding and satisfactory tritium self-sufficiency. Table 1 presents a comparison between the previous MMS and the latest SMS WCLL DEMO configurations, focusing on key parameters such as total TBR, fast neutron flux, and nuclear heating on the TFC.

Despite the promising results and the advanced level of maturity reached, the WCLL DEMO architecture based on C-shaped DWTs for the BZ showed some drawbacks: this structure relies on a huge number of pipes that jeopardize the reliability of the whole system because of the numerous welds; moreover, a more standardized DWTs design, to facilitate the BB manufacturability is needed, as well as a simplification of the water flow distribution in the manifolds. These issues, together with the necessity to maximize the tritium generation through the reduction of the water amount in the BZ, without compromising the cooling efficiency, resulted in the development of a completely revised concept based on helicoidal-shaped DWTs [14–16].

This new layout consists of 12 inlet/outlet DWTs for each BU both in for the inboard and outboard sector (Fig. 3).

The helicoidal-shaped DWTs provide satisfactory performances in terms of cooling efficiency: the thermo-mechanical analyses showed that the maximum temperature reached by the Eurofer structural components during operations is 541.5 °C (Fig. 4).

Although outside the scope of the present work, it's ought to be highlighted that, in the WCLL blanket concept, Magnetohydrodynamic (MHD) effects play a critical role in determining the performance of the system. Since LiPb alloy used as a breeder material is an electrically conducting fluid, its flow behavior is significantly influenced by the

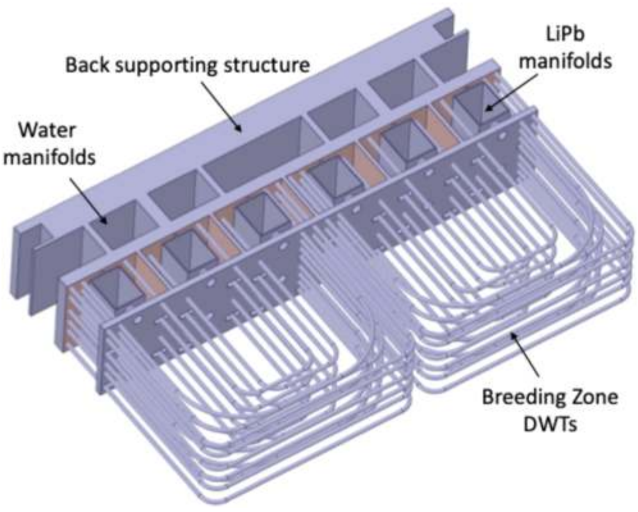

Fig. 2. Perspective view of the outboard WCLL BB equatorial BU with 24 DWTs. The stiffening/baffle plates, FW, side walls and W armor have been removed to show the inner layout if the cooling system.

Table 1
Nuclear performances of the WCLL DEMO reactor based on the MMS [4] and SMS [13] concepts.

WCLL DEMO concept	MMS	SMS
Total TBR	1.131	1.15
Fast ($E > 100$ keV) neutron flux on the TFC ($n/cm^2/sec$)	2.9×10^8	1.55×10^8
Nuclear heating on the TFC (W/cm^3)	1.4×10^{-5}	2.2×10^{-5}

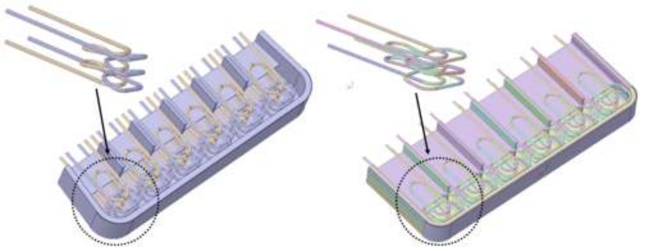

Fig. 3. Inboard (left) and outboard (right) BU with helicoidal-shaped DWTs.

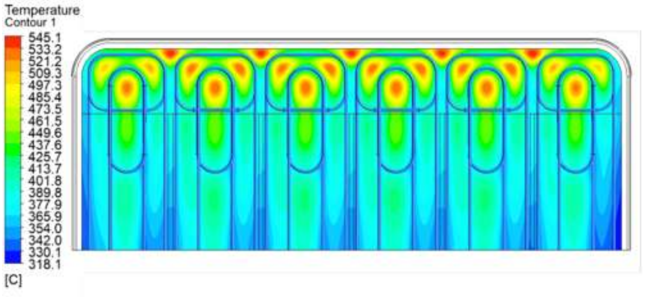

Fig. 4. Section of the outboard equatorial BU thermal field during DEMO operations, showing the arrangement of the BZ helicoidal-shaped DWTs cooling system [14].

strong magnetic fields present in a fusion reactor. The interaction between the conductive fluid and the magnetic field induces electric currents within the fluid, which in turn generate Lorentz forces that oppose the motion of the fluid. This leads to increased pressure drops, altered flow profiles, and a potential reduction in heat transfer efficiency. As a result, MHD effects can have a not negligible impact on the thermal-hydraulic performance of the blanket and manifolds system and have to be thoroughly assessed in both the design and operational phases. A detailed insight into the MHD analyses conducted for the C-shaped and helicoidal DWTs WCLL concepts are provided in [17] and [18] respectively.

Considering that the overall water mass in the BZ is reduced by 8.1 % in the helicoidal DWTs concept compared to the 24 C-shaped DWTs configuration, this design is expected to yield an increased total TBR. This is due to the replacement of water volume with breeder material (LiPb). However, it is important to note that the impact of water on tritium generation cannot be solely attributed to the coolant-to-breeder volume ratio, as other factors also play a significant role. As will be discussed in greater detail in the following sections, the presence and distribution of water within the breeding zone (BZ) have a decisive influence on the behavior of neutrons, particularly in terms of their moderation, transport, and interaction with surrounding materials. Given water's high scattering cross section and its effectiveness as a neutron moderator, even small variations in its spatial distribution can significantly alter the local neutron spectrum. This, in turn, directly affects the probability of neutron capture by lithium nuclei, which is a critical process for tritium production in fusion reactor systems. Therefore, understanding and accurately modeling the water content and its configuration within the BZ is essential for optimizing neutron economy and maximizing the efficiency of lithium-based breeding reactions.

2. WCLL DEMO reactor layout

As mentioned above, the WCLL DEMO reactor architecture relies on the replication of an elemental BU in both inboard and outboard poloidal direction. Each BU is enclosed in two adjacent horizontal stiffening plates that reinforce the structure against thermo-mechanical and electro-magnetic loads under both operational and accidental conditions and determine the LiPb flow path [19].

The onboard sector (Fig. 5) encompasses 94 BUs. The FW water channels distribution is not uniform but varies poloidally according to the necessity to provide a more effective heat removal: 4 cooling channels are foreseen for each BU, except for the upper area of the machine (inboard module #7 in the MMS blanket concept [1]) where the BUs are equipped with 10 channels.

The outboard sector comprises 104 Breeding Units (BUs). Similar to the inboard sector, the allocation of First Wall (FW) water cooling channels is not regular across the elemental Breeding Blanket (BB) cells. In particular, the BUs located near the divertor region—specifically within outboard modules #6 and #7, according to the MMS blanket concept [1]—contain six cooling channels per unit. In contrast, the upper BUs are each equipped with four cooling channels. This non-uniform distribution reflects the differing thermal loads and cooling requirements across the blanket structure. Fig. 6

The BUs are fixed to a stainless-steel BSS that separates the BZ from the manifolds system and provides LiPb and water feedthroughs. The LiPb manifolds consist of rectangular parallel ducts (6 for the outboard sector (Fig. 7) and 4 for the inboard one) extended all over the poloidal direction. As far as the water manifolds are concerned, a spinal layout has been adopted in order to properly route the coolant from the upper ports (where it is fed) to the bottom area of the segment. The inlet and outlet manifold sections are not uniform along the poloidal direction, in order to keep the fluid speed as much as possible constant [12].

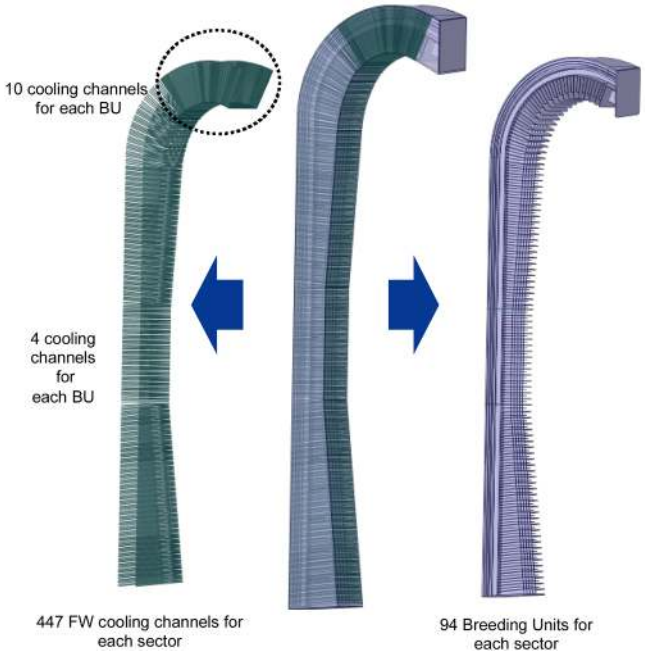

Fig. 5. WCLL DEMO inboard sector structure: BU layout (right) and poloidal distribution of the FW cooling channels (left).

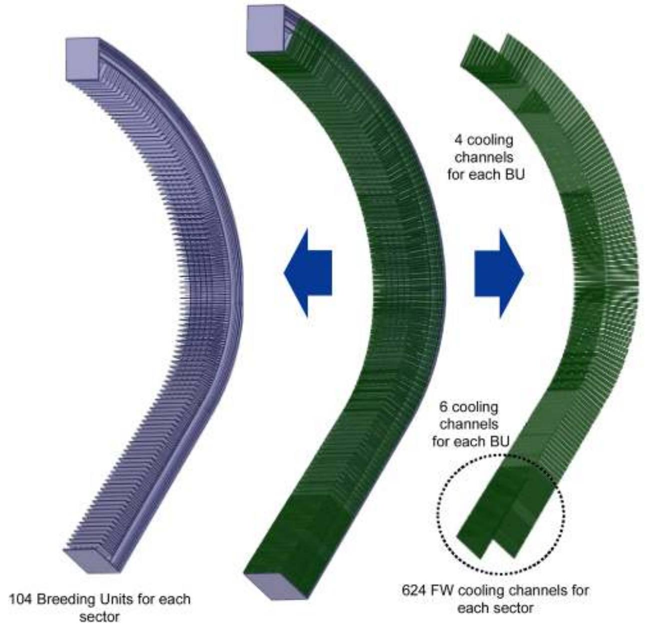

Fig. 6. WCLL DEMO outboard sector structure: BU layout (left) and poloidal distribution of the FW cooling channels (right).

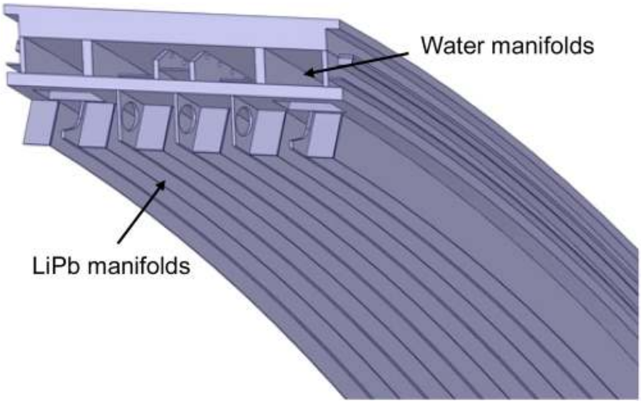

Fig. 7. WCLL DEMO outboard sector LiPb and water manifold structure.

3. Assessment of the WCLL DEMO nuclear performances

The nuclear analyses are aimed at verifying the performances, in terms of shielding effectiveness and tritium self-sufficiency, of the WCLL BB concept with helicoidal-shaped DWTs. The studies are conducted by means of the MCNP5v1.6 Monte Carlo code [20] and the JEFF 3.3 nuclear data libraries [21], using a DEMO reactor MCNP model based on the EU DEMO1 2017 [22] configuration, which main parameters are provided in Table 2. It consists of a 11.25° toroidal sector of the machine, with toroidally bounding surfaces defined as reflective. This boundary condition accounts for neutrons and photons generated in adjacent sectors of the machine, enabling a reliable and representative simulation of the entire tokamak. One of the mayor changes introduced in the EU DEMO1 2017 design is the reduction of the outboard BB thickness from 130 cm to 100 cm. This aspect severely impacted the breeding performances of the blanket concepts based on LiPb as neutron multiplier since, for reasons related to the underlying physical phenomena, they require a larger blanket radial extension to enhance their multiplication efficiency with respect to those relying on Beryllium (i.e. Helium-cooled Pebble Bed BB [23]).

Table 2
EU Demo1 2017 reactor main parameters.

Minor radius (m)	2.883
Aspect ratio	3.1
Plasma elongation	1.65
Plasma triangularity	0.33
Fusion power	1998
Neutron yield (n/s)	7.095×10^{20}
Average neutron wall loading (MW/m^2)	1.04
Net electric power	500

The WCLL DEMO reactor so far described is quite a complex structure: each inboard sector encompasses 447 FW cooling channels and 1128 BZ DWTs; in the outboard sector 624 FW water channels and 1248 DWTs are present. The generation of a detailed and reliable MCNP geometry, which is compliant with the requirements for nuclear analyses [11], is a key issue, since modelling assumption have a not negligible effect on the reliability of the TBR assessment: as a matter of fact, the tritium generation rate in a water-cooled BB, is substantially affected by the water distribution in the BZ as shown in a dedicated following section.

3.1. MCNP model generation

The MCNP WCLL DEMO model with helicoidal-shaped DWTs has been developed according to the same approach used in [13]. Such methodology relies on a preliminary segmentation of the EU DEMO1 2017 baseline model into sectors that are suitably defined to host the main WCLL BB subcomponents: Tungsten armour, FW and side walls with cooling channels, caps, BZ, BSS, water and LiPb manifolds. The BZ has been further split into cells defined by means of the surfaces that bound the stiffening plates, thus enclosing a BU each. The engineering CAD files describing the inboard and the outboard subcomponents have been pre-processed and simplified by means of the 3D modelling software Ansys SpaceClaim 2019 [24], in order to generate equivalent 'step' file suitable for neutronic analyses. In particular, the simplification phase of the actual BUs cooling pipes is quite challenging since the helicoidally shaped tubes were described with non-analytic surfaces that are not suitable for the conversion into the MCNP geometry. Consequently, the tubes inner and outer walls have been represented with a series of cylindrical surfaces, trying to maintain the original volume of the pipes (volumes deviation <0.1 %). The modified WCLL subcomponents engineering files have been converted into their equivalent MCNP geometrical representations using the CAD-to-MCNP interface provided by the SuperMC code [25]: in particular, each inboard BU (Fig. 8) consists of 997 cells and 1216 surfaces, while the outboard one (Fig. 9) consists of 1422 cells and 2034 surfaces.

The integration of the WCLL BB subcomponents MCNP models has been carried out using the MCNP 'universe' feature: each element of the

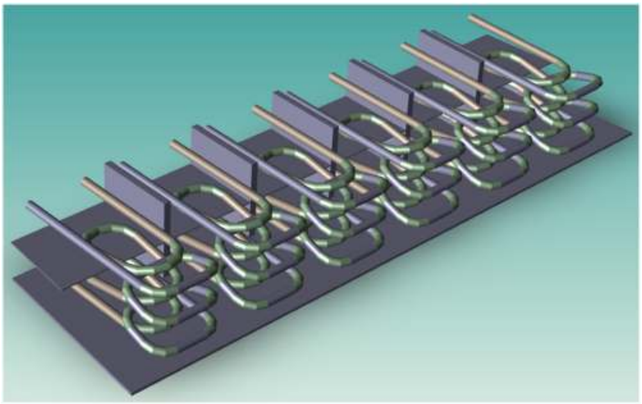

Fig. 8. Inboard BU MCNP model of the WCLL BB integrating helicoidal-shaped DWTs.

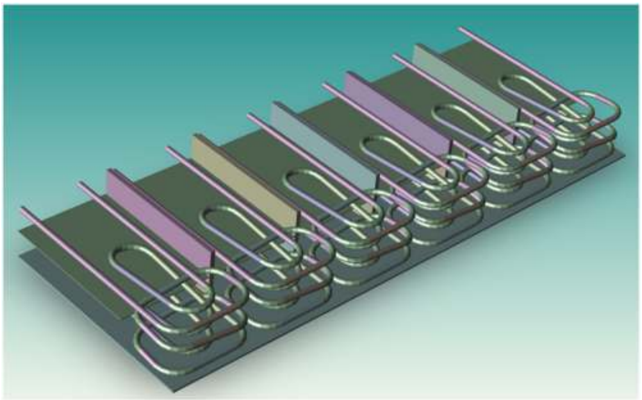

Fig. 9. Outboard BU MCNP model of the WCLL BB integrating helicoidal-shaped DWTs.

BB (namely: BUs, LiPb and water manifolds, FW) in enclosed and isolated from the rest of the geometry, allowing the modification of a single feature without altering the neighboring ones. This approach allows an easier and smoother adjustment of the model with the introduction of the latest design changes. The obtained WCLL DEMO MCNP model is shown in Fig. 10: the inboard and outboard BUs have been integrated by means of proper roto-translation matrixes applied to the ‘universes’ describing the equatorial ones and handling the different radial extension of the inboard/outboard modules through the preservation of the distance between the FW and the BZ DWTs. Each component defined in the model has been complemented with materials definition according to the provided specifications [8]: each cell of the model has been associated to a distinct material (Eurofer, SS-316 L, LiPb, water) except for the area where the BZ cooling pipes are connected to the water manifolds through the LiPb manifolds, where a specific 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 (temperature ~312 °C, pressure 15.5 MPa,) resulting in the assumption of an average 0.700 gr/cm^3 density for the water. In order to accurately modeling thermal neutron flux distribution as well as the neutron absorption in cooling water, S (α,β) treatment has been considered in the calculations.

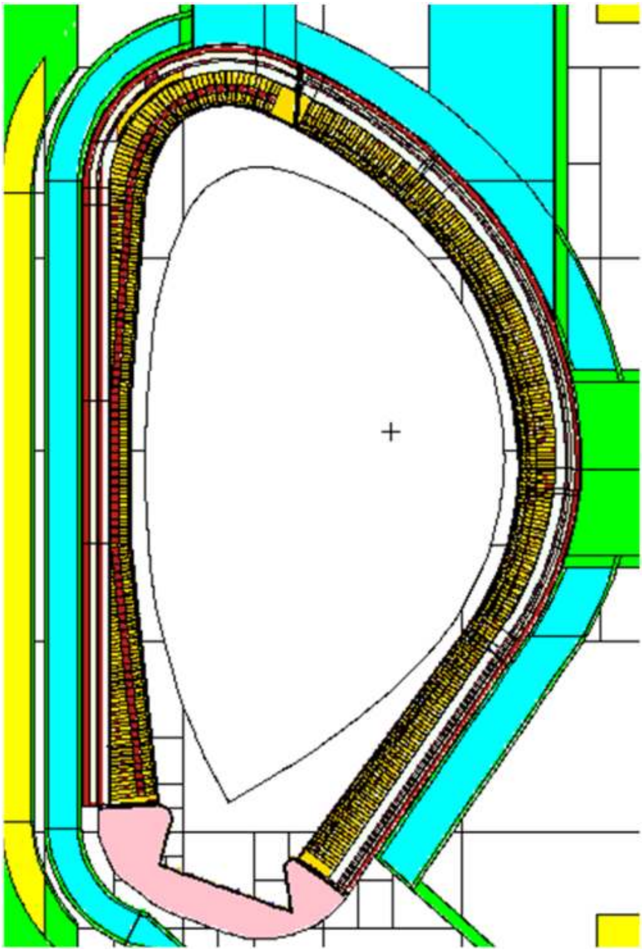

Fig. 10. Poloidal section of the WCLL DEMO MCNP model. In reference to the colored figure: SS-316 L (green), 60 % SS-316 L + 40 % water (light blue, to represent water cooled VV), Eurofer (dark red), LiPb (ochre).

3.2. *WCLL DEMO nuclear analyses*

The WCLL DEMO MCNP model has been used to assess the nuclear performances of the DEMO reactor, equipped with the WCLL BB, both in terms of effectiveness in shielding the TFC from the radiation streaming as well as in terms of tritium self-sufficiency to ensure an adequate tritium generation. The radial profiles of the neutron flux (breakdown into total and fast component), nuclear heating, damage and He-production have been assessed along the equatorial inboard and outboard BUs, where the nuclear loads are expected to be higher and thus providing a conservative evaluation. Results are provided for 1998 MW of fusion power, corresponding to a $7.095 \cdot 10^{20}$ n/s neutron yield, in compliance with the plasma parameters defined in Table 1.

The poloidal distribution of the neutron wall loading (NWL) does not present a significant change with respect to the previous analyses [4,7,13] since the main machine parameters has been kept fixed. Fig. 11 shows the NWL poloidal distribution for 1998 MW of fusion power: the average value is 0.93 MW/m^2, with a maximum of 1.1 MW/m^2 for the inboard equatorial zone and 1.33 MW/m^2 for the outboard one. The NWL data has been used to scale the radial profile of the nuclear heating, evaluated in the inboard and outboard midplane, to obtain the volumetric heat power density input data for the thermo-mechanical analyses of different area of the poloidal sectors [26].

Table 3 provides the nuclear power deposition due to neutrons and secondary gammas in the WCLL blanket components, assessed on all the reactor subcomponents. Results show that about 70 % of the whole nuclear power (1198.7 MW) is deposited on the BZ, while only 91 MW (5.3 %) are released on the manifolds structures, thus highlighting the shielding effectiveness of the WCLL BZ that is successively investigated in detail.

The evaluation of the neutron flux, nuclear heating, damage and He-production in steel components along the inboard and outboard equatorial plane provide fundamental data to verify the WCLL BB capabilities both in terms of radiation shielding performances and structural materials embrittlement [27]. The calculated radial profiles are averaged over a single BU both in inboard and in outboard (13.5 cm);

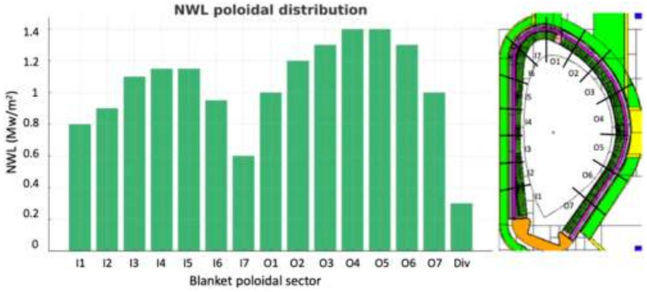

Fig. 11. Poloidal distribution of the NWL (the inboard and outboard sectors have been segmented according to the MMS DEMO concept [1]).

Table 3
Nuclear power deposition in the WCLL BB components.

Component	MW	%
W armour	64.9	3.78
First Wall/Side Walls Caps	321.1	18.2
Breeding Zone	1198.7	69.82
Manifolds	91	5.3
Stiffening Plates	49.26	2.9
Total	1716	100

additionally, the spatial distribution of the neutron flux and heat load are provided by means of 3D maps.

Figs. 12 and 13 show the total and fast ($E > 100$ keV) neutron fluxes radial profiles for the inboard and outboard equatorial BU. A 3D map of the neutron flux spatial distribution is provided in Fig. 14. The total neutron flux impinging on the Tungsten armour is 4.6×10^{14} n/cm^2/s and 6.2×10^{14} n/cm^2/s for the inboard and outboard sector. At the level of the inboard VV inner shell the neutron flux is reduced of more than two orders of magnitude and, at the TFC, results to be 3.6×10^8 n/cm^2/s and 2×10^8 n/cm^2/s for the total and fast component respectively: as a consequence, the 10^9 n/cm^2/s design target [28] for the fast neutron flux impacting on the TFC is fully satisfied.

The nuclear heating density radial profile evaluated on Eurofer and LiPb (blanket) and SS316L (Vacuum Vessel and TFC) is shown in Figs. 15 and 16 for the inboard and outboard. The peak values assessed for the Tungsten armour in inboard and outboard are 24.5 W/cm^3 and 26.9 W/cm^3; on the SS316L VV inner shell they decrease down to 2.2×10^{-2} W/cm^3 and 4.8×10^{-2} W/cm^3 respectively. On the coils, the maximum nuclear heating density is 7.4×10^{-6} W/cm^3 (comprising 2.12×10^{-7} W/cm^3 from neutron deposition and 7.19×10^{-6} W/cm^3 from secondary gamma deposition). Given that the design limit is 5×10^{-5} W/cm^3 [28], the shielding capabilities of the WCLL breeding blanket are deemed sufficient to ensure reliable protection of the TFC. The 3D map of the nuclear hating density spatial distribution (Fig. 17) reveals a significant increase in the heat load at the equatorial port joints with the VV, primarily due to the neutron streaming through the gaps between the port walls and the port plug.

The radiation damage has been assessed by means of the Norgett-Robinson-Torrens (NRT) methodology [29], evaluating the displacements per atom integrated over a full power year (dpa/FPY) for the structural steel of the BB (Eurofer) and VV (SS316L). The damage radial profiles calculated in the inboard and outboard equatorial area are provided in Figs. 18 and 19 respectively. In the inboard FW Eurofer, a 8.9 dpa/FPY maximum damage has been recorded while for the outboard sector the peak value on the FW is 11.2 dpa/FPY. A design limit of 2.75 dpa integrated over 6 FPY DEMO lifetime has been set for

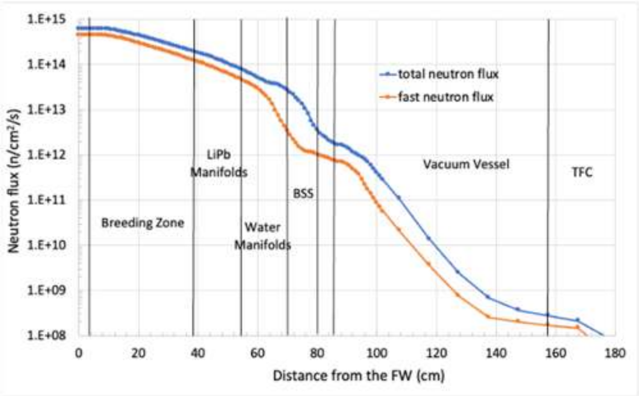

Fig. 12. Total (blue) and fast (red) neutron flux radial profile at the equatorial plane for the inboard BU. The dotted red line indicates the design target for the fast neutron flux on the TFC (10^9n/cm^2/s, [28]).

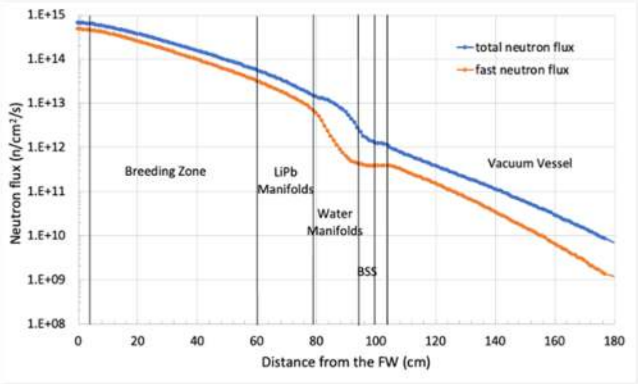

Fig. 13. Total (blue) and fast (red) neutron flux radial profile at the equatorial plane for the outboard BU.

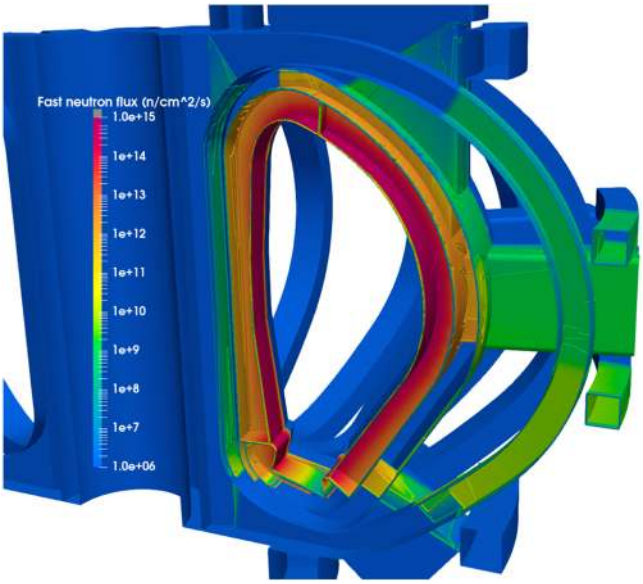

Fig. 14. 3D map of the fast neutron flux spatial distribution. The gradient observed in the upper and lower area of the TFC is due to the extent of the mesh used for neutron flux calculations, which does not poloidally cover the entire volume of the TF coils.

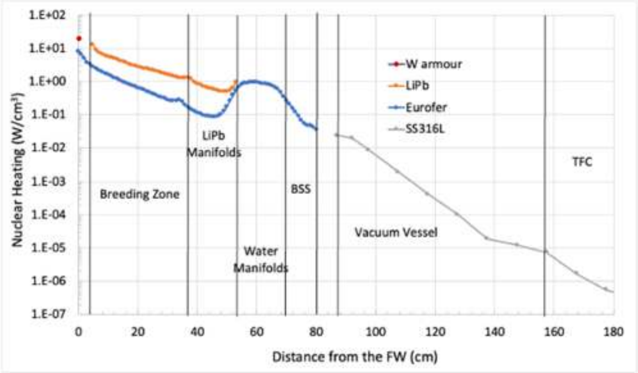

Fig. 15. Breakdown of the nuclear heating density radial profile deposited on the DEMO WCLL BB structural materials computed at the equatorial plane for the inboard BU. The dotted red line indicates the design target for the heat load on the TFC (5×10^{-5} W/cm^3, [28]).

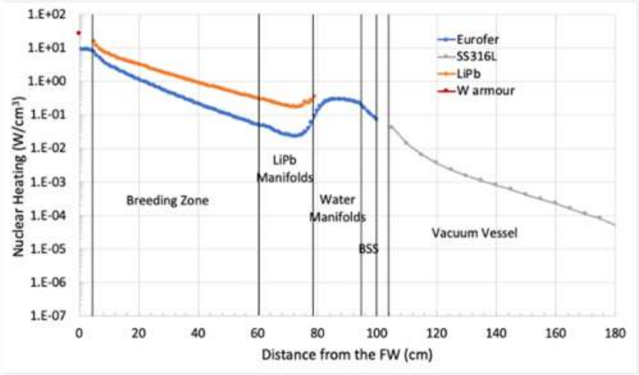

Fig. 16. Breakdown of the nuclear heating density radial profile deposited on the DEMO WCLL BB structural materials computed at the equatorial plane for the outboard BU.

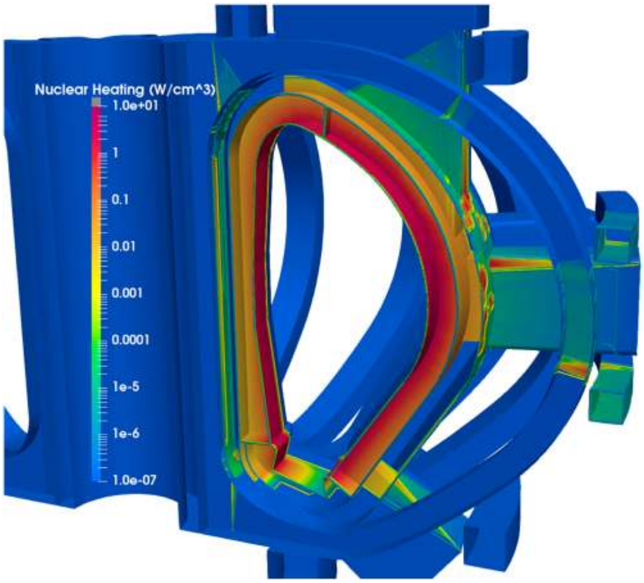

Fig. 17. 3D map of the nuclear heating density spatial distribution.

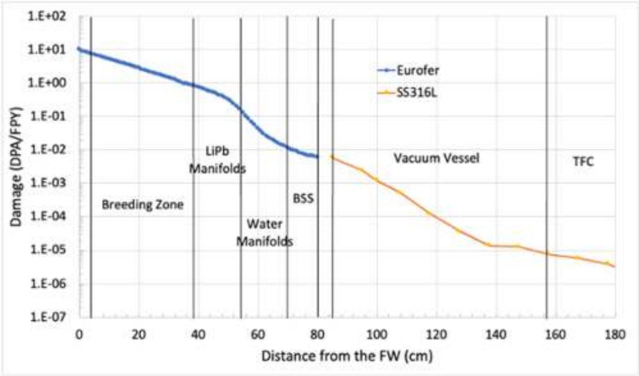

Fig. 18. Radial profile of the damage on Eurofer (up to the BSS) and SS-316, evaluated in the inboard BU.

the VV steel, in order to ensure its structural integrity and physical properties during plasma operations: the analyses carried out show that on the SS316L VV inner shell the damage is 5.77×10^{-3} dpa/FPY for the inboard sector and 3.35×10^{-3} dpa/FPY for the outboard one. Integrating those values over 6 FPY, the resulting cumulated damage is

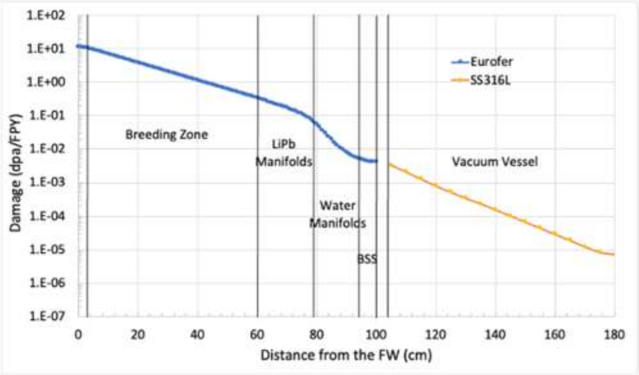

Fig. 19. Radial profile of the damage on Eurofer (up to the BSS) and SS-316, evaluated in the outboard BU.

0.034 dpa (inboard) and 0.02 dpa (outboard).

It's also ought to be highlighted that, according to the DEMO operational strategy, a first BB with a 20 dpa damage limit for the FW Eurofer will be installed and it will be successively replaced with a second set of blankets with an optimized layout, that shall be able to withstand a 50 dpa damage limit [28]. In both cases the present design of the WCLL BB ensures the design targets achievement.

The evaluation of Helium production is intended for the gas generation assessment on specific components where steel re-welding is required; it has been calculated as atomic part per million over a full power year (appm/FPY) produced in the BB and VV structural steel (Eurofer and SS316L, Boron content in weight percentage 0.002 % and 0.001 % respectively). The He-production radial profiles evaluated for the equatorial BUs are shown in Figs. 20 and 21 for the inboard and outboard BU respectively.

In particular, the peak values, estimated on critical locations in terms of steel re-weldability (i.e. VV area close to the equatorial port) provided the following results: 2.7×10^{-2} appm/FPY and 6.9×10^{-2} appm/FPY in the inboard and outboard VV inner shell: the integration of such values over 6 FPY lifetime led to 0.2 appm for the inboard and 0.41 for the outboard respectively: in both cases the limit of 1 appm is fulfilled [30]. As for the previous studies performed on different WCLL BB concepts [4,7,13] a typical characteristic of the nuclear heating and He production radial profiles is a peak localised across the water manifold: this effect is due to the water moderation on neutrons that induces a softer spectrum. As a consequence, the He-production is enhanced in adjacent zone through the neutron reactions with ^{10}B and the higher gamma generation in neighbouring steel causes an increase in the deposited heat load.

Uncertainty factors, commonly referred to as safety factors, are applied in nuclear analyses to introduce conservative margins on

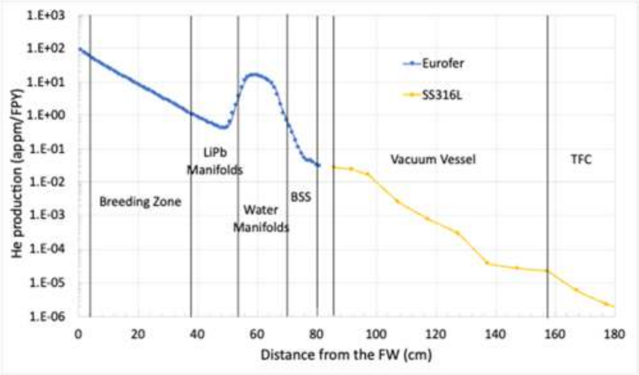

Fig. 20. Radial profile of the Helium production (appm/FPY) evaluated in inboard BU.

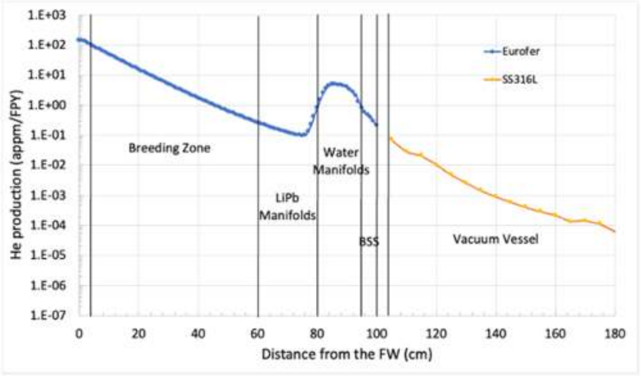

Fig. 21. Radial profile of the Helium production (appm/FPY) evaluated in outboard BU.

calculated parameters such as radiation fluxes and nuclear heating. These margins account for both modeling uncertainties and potential sources of systematic and random errors, thereby ensuring that predicted values are not underestimated. According to the methodology established by the ITER Organization, the safety factor is defined as:

$$Safety\ factor = \sigma_{systematic} + 2\sigma_{random}$$

where random uncertainties are summed in quadrature. In the present study, systematic uncertainties are attributed to the plasma neutron source (assumed at 10 %), nuclear data (10 %), and the homogenization of components not explicitly modeled in the geometry but contributing to neutron backscattering toward the breeding blanket, such as the divertor and vacuum vessel (contributing an additional 10 %). Random uncertainties stem from statistical fluctuations in the Monte Carlo tallies (<10 % in all cases). Based on the above formulation, the resulting safety factor is 1.5. Even after applying this factor to the calculated nuclear responses, the results remain safely below the established design limits, as summarized in Table 4.

The analyses conducted on the latest WCLL BB layout to evaluate its radiation shielding effectiveness, show the beneficial effect of the water in terms of neutron moderation (Table 4), confirming the results of the studies conducted on the previous WCLL concepts [4,7,12]. On the downside, the WCLL blanket suffers from a comparative low tritium breeding performance due to the high amount of water required in the front region of the blanket for cooling purposes. This has a detrimental effect on the neutron multiplication and, consequently, on the tritium generation: a detailed insight on this issue, as well as a proposed strategy to achieve the tritium self-sufficiency is provided in the following section.

Table 4
Shielding performances of the WCLL BB: assessed parameters and design limits (DEMO lifetime~6 FPY [28]).

Parameter	WCLL BB	WCLL BB (including safety factors)	Design limit
Fast neutron flux on TCF (n/cm^2/s)	2×10^8	3.01×10^8	10^9
Nuclear heating on TFC (W/cm^3)	7.4×10^{-6}	1.13×10^{-5}	5×10^{-5}
Damage on VV (dpa-6 FPY)	0.034 (IB) 0.02 (OB)	0.052 (IB) 0.031 (OB)	2.75
Helium production on VV (appm-6 FPY)	0.2 (IB) 0.41 (OB)	0.31 (IB) 0.63 (OB)	1

4. WCLL tritium breeding ratio: present status and perspectives

The assessment of the total Tritium Breeding Ratio (TBR) aimed at the verification of the WCLL DEMO reactor tritium self-sufficiency has been carried out using track-length (F4) tallies with proper multipliers (FM cards) for each subcomponent of the BB that contributes to the tritium generation (i.e. breeding zones enclosed in each BU and LiPb manifolds), taking into account both the neutron capture reactions on ^{6}Li and ^{7}Li isotopes. The resulting total TBR is 1.142, thus the obtained value is still below the design target for tritium self-sufficiency (1.15), despite the reduced amount of water of the present WCLL architecture based on helicoidal DWTs with respect to the previous one that relied on C-shaped DWTs: about 8.1 % with respect to the 24 DWTs configuration designed for the equatorial area (Fig. 2).

Apart from its essential role of temperature mitigation of the BB structural components and carrier of the generated energy to produce electricity, the water present in the BZ provides a moderation effect that drive the neutron transport: it enhances the probability that neutrons could interact with the Lithium nuclei, since the (n,T) reaction cross section increases with the reduction of the incident neutron energy (Fig. 22) but, on the other side, decreases the neutrons multiplication through (n,2n) reactions on Lead, which are characterised by relatively high energy thresholds ranging from 6.75 MeV to 8.5 MeV, depending on the considered Lead isotope (Fig 23).

The quantity of generated tritium in the BZ is the result of the combination of the above-mentioned physical phenomena, thus it’s not simply ruled by the water amount variation, even its removal corresponds to an additional effective breeding volume. Taking into account the previous considerations about the effect of water on the inelastic scattering reactions that characterize the transport, absorption and multiplication of neutrons inside the BZ, a more detailed insight into their effect on the tritium generation has been performed.

As a first approach, a Tritium Generation Rate (TGR) analysis has been carried out, with the aim of investigating which sector of the BZ mostly contributes to the total TBR in both radial and toroidal direction. The Inboard and Outboard TGR radial profiles (Figs. 24 and 25), calculated in the equatorial BUs, show a very similar behaviour with a maximum behind the FW ($5{\cdot}10^{12}$ mol/cm^3/sec and 5.5 mol/cm^3/sec for the inboard and outboard respectively) and a constant reduction of the tritium generation along the Breeding Zone and LiPb manifold. Such behaviour is due to the high amount of the water in the BZ area close to the FW that reduces the energy of the incident neutrons, eventually below the threshold for neutron multiplication on Lead: as a consequence, the tritium generation decrease along the BZ radial direction.

The tritium generation poloidal profile (Fig. 26), computed on the BZ only, highlights that most of the tritium is produced in the Outboard

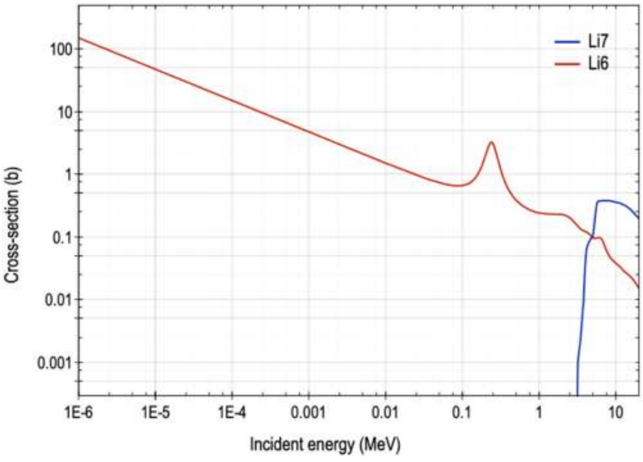

Fig. 22. Li(n,T) reaction cross section (JEFF 3.3 nuclear data library [18]).

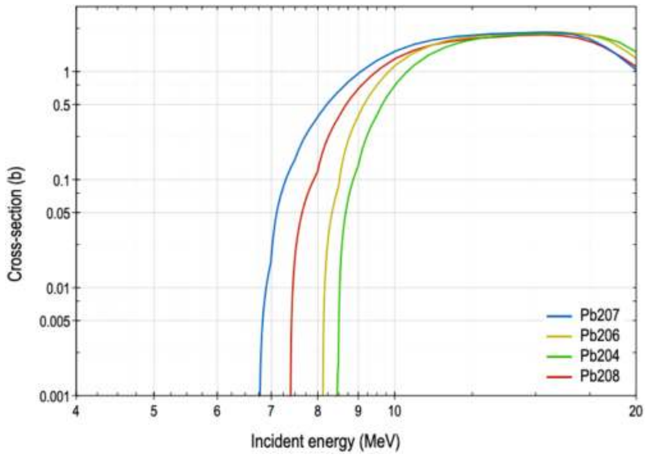

Fig. 23. Pb(n,2n) reaction cross section (JEFF 3.3 nuclear data library [18]).

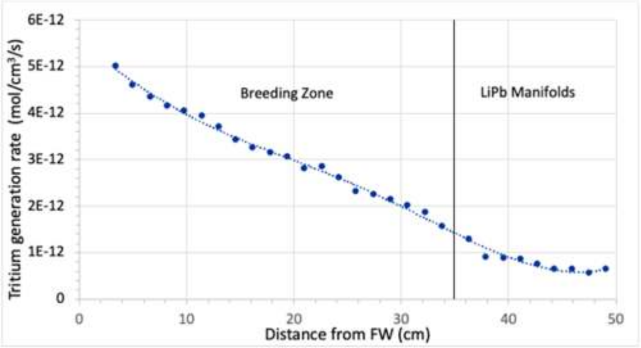

Fig. 24. Radial profile of the TGR evaluated in the inboard BU.

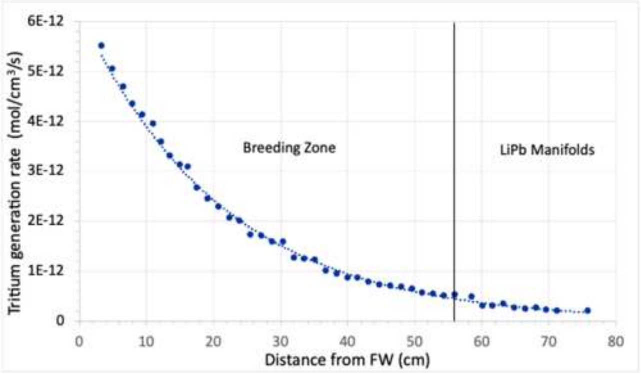

Fig. 25. Radial profile of the TGR evaluated in the outboard BU.

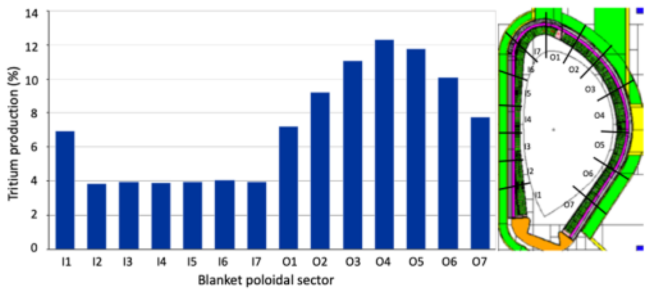

Fig. 26. Poloidal profile of the TGR evaluated in the BZ.

sector, with a peak corresponding to the OB4 segment of the previous multi-module configuration (12.2 % of the whole generation in the BZ). This result is due to the harder neutron spectrum impinging on the equatorial outboard sector of the machine.

The outcome of the performed studies, as well as the observations about the phenomenology of the physical processes behind the tritium generation in the WCLL BB, lead to the identification of a key issue related to the water effect in the BZ: the parameter that mostly influences the probability of the (n,T) reactions on Li nuclei is the distribution of water with respect to the incident neutrons. This deduction is clearly confirmed though the comparison of the total TBR assessment performed on the previous WCLL configuration integrating C-shaped DWTs, which resulted to be higher with respect to the one calculated for the current BB layout, even if the latter has a significant reduction in the total amount of water. It’s ought to be highlighted, in fact, that the helicoidal-shaped DWTs structure, designed to optimise the cooling performances of the circuit, presents a higher water concentration in the area of the BZ closer to the FW (peak value at about 1.8 cm from the FW) where, as explained above, the neutrons moderation has a critical impact on both their multiplication through inelastic scattering on Pb and on the capture reactions on Li occurring in the outermost region of the BZ.

Taking into account the above mentioned issues, a possible strategy to achieve the tritium self-sufficiency for the actual design of the WCLL DEMO reactor relies on the application of an outward radial shift to the helicoidal-shaped DWTs with respect to the FW both in the inboard and outboard sectors: the idea behind this approach is the improvement of neutrons multiplication in the BZ area close to the FW and, consequently, an enhanced tritium production due to the water-moderated neutrons interactions on Li.

To this end, a dedicated parametric analyses, aimed verifying this hypothesis, been carried out performing TBR calculations for different DWTs displacements, with a step of 5 mm each. This design change has been implemented into the WCLL DEMO MCNP model defining specific translations to the surfaces that defines the structure of the elemental inboard and outboard equatorial BUs.

The result of this study is reported in Table 5. As expected, the radial shift of the cooling pipes provides a beneficial effect on the tritium generation: a 15 mm radial displacement allows to achieve the TBR design target (1.15), thus confirming the accuracy of the deductions concerning the water effect on neutron transport in the BZ and opening up promising perspectives for the future improvement of the WCLL BB.

Nevertheless, the feasibility of such design modifications has to be investigated by means of thermal and thermo-mechanical analyses aimed at verifying their impact on the temperature field inside the BUs. In this regards, a possible key aspect is related to the effect of the FW water amount and positioning. A specific study carried out to assess the influence of those parameters on the WCLL BB tritium breeding performance [31] showed that a shift of the FW cooling channel towards the BZ enhance the tritium generation: in particular, a 3 mm radial displacement provides an increment of the total TBR up to 1.4 %. This result is particularly interesting because the possibility to move the FW cooling channels closer to the BZ could provide a more effective cooling in the surroundings, thus balancing the eventual temperature rise in the internal area of the BZ due to the helicoidal DWTs shift. Besides, it’s

Table 5
Impact of the radial shift of the helicoidal-shaped DWTs on the total TBR (statistical error below 1 %).

BZ cooling pipes radial shift (mm)	Total TBR
0	1.142
5	1.144
10	1.147
15	1.5
20	1.155

ought to be highlighted that, since the thermo-mechanical analyses are commonly conducted on the inboard and outboard equatorial BUs, thus adopting a quite conservative approach, a more specific evaluation of the cooling requirements for the other sector of the machine could lead to a reduction of the water amount along the poloidal direction, resulting in a wider margin for a further TBR improvement. To this purpose, the analysis workflow [32,33] already set-up for the thermo-mechanical assessment of the WCLL outboard segment equipped with the C-shaped DWTs could be applied.

5. Conclusions and highlights

One of the mandatory requirements in the frame of the EUROfusion roadmap for the DEMO reactor is the achievement of fuel self-sufficiency, which relies on the design of a suitable blanket concept capable of ensuring tritium breeding and extraction.

One of the most promising and attractive candidate for the DEMO breeding blanket is the WCLL, which uses water as coolant and LiPb as neutron multiplier and breeder.

During the last decade, the WCLL BB design underwent several improvements and advancements, reaching a mature level of development: one of the major critical points that remained unsolved is the issue related to its effectiveness in ensuring a suitable tritium generation. This issue is strictly related to the underlying physical phenomena that rule the neutron mitigation due to the water used as coolant: whilst the moderation effect ensures reliable performances in terms of radiation shielding on the TFC and VV, on the other hand it has a detrimental impact on the neutron multiplication and, consequently, on the TBR.

The latest WCLL BB architecture, based on helicoidal DWTs, is characterized by a reduced amount of water in the BZ with respect to the previous layouts; nevertheless, the calculated total TBR is still below the 1.15 design limit. This aftermath entailed a more detailed analysis of the mechanisms behind the tritium production in the BZ: as a result, a prospective approach based on possible design changes is presented and discussed. The proposed strategy provides guidelines for a further improvement of the WCLL BB design and opens up promising perspectives to guarantee the tritium self-sufficiency.

CRediT authorship contribution statement

F. Moro: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **P. Arena:** Writing – review & editing, Validation, Supervision, Investigation. **G. Bongiovi:** Writing – review & editing. **I. Catanzaro:** Writing – review & editing, Visualization. **S. Cesaroni:** Writing – review & editing, Visualization, Validation. **A. Colangeli:** Writing – review & editing, Visualization, Validation. **M. Damiano:** Writing – review & editing, Visualization, Validation. **A. Del Nevo:** Writing – review & editing, Visualization, Project administration, Funding acquisition. **D. Flammini:** Writing – review & editing, Visualization, Validation. **N. Fonnesu:** Writing – review & editing, Visualization, Validation. **V. Imbriani:** Writing – review & editing, Visualization, Validation, Data curation. **M. Lungaroni:** Writing – review & editing, Visualization, Validation. **P. Maccari:** Writing – review & editing, Validation, Data curation. **R. Mozzillo:** Writing – review & editing, Visualization, Data curation. **S. Noce:** Writing – review & editing, Visualization, Formal analysis, Data curation. **A. Previti:** Writing – review & editing, Visualization, Validation. **R. Villari:** Writing – review & editing, Visualization, Validation. **Virginie Lombardi:** Data curation, Writing – review & editing.

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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Data availability

Data will be made available on request.

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