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Recent progress in developing a feasible and integrated conceptual design of the WCLL BB in EUROfusion Project

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The water-cooled lithium-lead breeding blanket is in the pre-conceptual design phase. It is a candidate option for European DEMO nuclear fusion reactor. This breeding blanket concept relies on the liquid lithium-lead as breeder-multiplier, pressurized water as coolant and EUROFER as structural material. Current design is based on DEMO 2017 specifications. Two separate water systems are in charge of cooling the first wall and the breeding zone: thermo-dynamic cycle is 295-328°C at 15.5 MPa. The breeder enters and exits from the breeding zone at 330°C. Cornerstones of the design are the single module segment approach and the water manifold between the breeding blanket box and the back supporting structure. This plate with a thickness of 100mm supports the breeding blanket and is attached to the vacuum vessel. It is in charge to withstand the loads due to normal operation and selected postulated initiating events. Rationale and progresses of the design are presented and substantiated by engineering evaluations and analyses. Water and lithium lead manifolds are designed and integrated with the two consistent primary heat transport systems, based on a reliable pressurized water reactor operating experience, and six lithium lead systems. Open issues, areas of research and development needs are finally pointed out.

Keywords: WCLL, Breeding Blanket, DEMO, EUROfusion.

1. Introductory remarks

The Breeding Blanket (BB) [1] is a key component for the future deployment of nuclear fusion electricity. This component, bounding large part of the plasma chamber, shall ensure to accomplish three main functions: sufficient shielding performances, a reliable tritium (T) production and an efficient heat extraction for electricity production. The Water-Cooled Lithium-Lead (WCLL) BB relies on pressurized water as coolant and Lithium-Lead (PbLi) enriched at 90% in ^{6}Li as breeder, neutron multiplier and T carrier. Current design (2018), based on DEMO 2017[2] specifications, derives from the outcomes of the design studies[3],[4],[5] and R&D activities [6] conducted in the framework of the EUROfusion Programme [7].

DEMO power plant is a pulsed machine with a burn time of two hours (power pulse) and a dwell time of 10 minutes, because of central solenoid recharge time and vacuum pump performances. This implies that the Power Conversion System (PCS) includes the Energy Storage System (ESS) with HITEC molten salt as secondary fluid, ensuring that the turbine works continuously during the dwell time [8]. The average Neutron Wall Load is 1.05 MW/m^2 and radial nuclear power densities in materials are calculated by MCNP5 code on the basis of the data available (i.e. DEMO2015) [9]. The thermal power deposited in the First Wall (FW) during pulse [10] is due to the heat flux (i.e. thermal radiation, mainly, and the charged particles) and the volumetric heat deposition, both variables along the poloidal profile. Details on requirements and assumptions of DEMO and the breeding blanket are provided in Ref. [2].

2. Description of WCLL BB 2018

The design is based on DEMO2017 baseline [11], subdivided into 16 sectors with two inboard and three outboard segments each. Compared with the former design, the space allocated for the BB has been reduced of 300 mm in radial direction. Following the preliminary studies done in 2016 [12], the WCLL BB relies on the Single Module Segment (SMS) approach, with a breeding element repeated along the poloidal direction. The rationale behind this choice is based on the considerations that the SMS

- allows more design options [13]-[17], including the removal of the PbLi manifold and its integration in the Breeding Zone (BZ), thus enhancing the compactness in radial direction;
- maximizes the TBR performances [9], because the continuity of the structures and the reduction of the steel of the caps;

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- eliminates the neutron streaming between the modules, thus enhancing shielding performances;
- facilitates the PbLi fill and drain procedures;
- may allow the removal of He bubbles if formed in the BZ and not dissolved in the PbLi [6], [18].

2.1 The manifold region

The segment is attached with the vacuum vessel through the Back Supporting Structure (BSS). This is a plate 100 mm thick (Fig. 1), which is the main structural support in charge of ensuring, under postulated load conditions, thermo-mechanical performances compliant with the rules prescribed by the safety codes. Structural analyses of the segment[12], [19] and sector are carried out with different load combinations: gravity, thermal and electro-magnetic [20]. The combination of the former two loads represents the Normal Operation conditions. Differently, the combination of the three loads, represents the occurrence of the postulated Central Major Disruption event. Both load conditions have been verified with the Level A criteria in SDC-IC code using Abaqus FEM code.

Considering the volumetric power density deposited due to neutron flux, it was evaluated that, on the opposite of the outboard, the inboard BSS requires the availability of a coolant system[4]. This analysis was a further motivation to integrate the water manifolds between the BSS and the PbLi manifolds. The water manifolds are connected with the integrated First Wall (FW) and the BZ coolant systems. Coolant flows at 295°C in the inlet manifolds, whereas 328°C is the temperature at the outlet. The integrated water manifolds are designed to accomplish the following main functions.

- To be connected with a coolant system capable to ensure a symmetric thermal field in the BZ and FW[16]. Moreover, because the different lengths of the Double Wall Tubes (DWT), “high” and “low” pressure inlet manifold zones are foreseen to provide an optimal flow distribution in the tubes. These manifolds have almost the same absolute pressure, but the “low” pressure inlet manifold is connected to the shorter DWT and with the “high” pressure inlet manifold in order to compensate the pressure drops of the parallel flow paths.
- To ensure that the structural material in the inboard segment manifold zone (i.e. BSS) are kept at low temperature (i.e. <350°C).
- To maximize the shielding performances of the BB zone[9], removing the presence of any undesired void space.

The PbLi manifolds are placed between the water coolant manifold and breeding zones. It is based on a coaxial square structures. The structural function is in charge of the outer EUROFER plates, whereas the inner sheets are used to separate the inlet (outer) from the outlet (inner) manifolds. PbLi temperature is uniform at about 330 °C. The PbLi manifold design is challenging because:

- it shall withstand the maximum pressure of 18.6MPa, in accidental conditions;
- it shall be integrated with the feeding and draining pipes of the PbLi loop systems and the BZ, ensuring that the overall pressure drops of the PbLi system are reasonably low (i.e. < 2.0 MPa);
- considering the significant reduction of space in radial direction of DEMO2017, it shall contribute to the TBR performances;
- it shall ensure a uniform PbLi distribution in toroidal direction and an efficient recirculation in the BZ;
- potential risks for PbLi water contact[21] shall be minimized and limited to the rupture of the DWT.

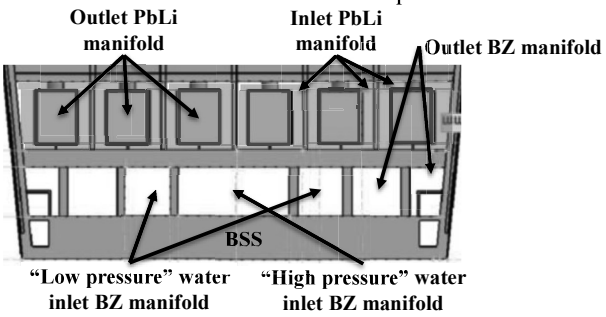


Fig. 1. WCLL2018 inboard segment: layout of the BSS, water and PbLi manifolds.

One of the main concerns for the feasibility of the PbLi manifold and its integration approach is the MHD pressure loss. To achieve an acceptable value, the PbLi flow path in the blanket is designed to maintain throughout a relatively low velocity (e.g. 13mm/s in the outer manifold and 0.01mm/s in the breeding zone). The WCLL outboard blanket is taken as reference and the pressure loss therein is estimated according to literature correlations for laminar, inertia-less, inviscid MHD pressure-driven flow. The MHD pressure drop has two main contributions: the term 2D accounting for the losses due to the cross-sectional currents encountered, evaluated according with Ref. [22], and the term 3D [23] representing the losses due to streamwise currents, featured in complex geometrical elements and/or non-uniform boundary conditions. The PbLi path is divided in six hydraulic regions and the calculated pressure losses are summarized in Tab. 1. Nearly 52% of the total pressure loss is localized in the feeding and draining pipe due to the high velocity (≈55 mm/s) and the electrical contact with a thick, well-conducting wall, (c≈0.156), whereas the breeding zone contribution is negligible.

Table 1. MHD pressure losses in the PbLi hydraulic path

#	Hydraulic Path	Pressure drop [kPa]
1	Feeding Pipe	253
2	Inlet Manifold	89
3	Spinal Channel	251
4	Breeding Zone	15
5	Outlet Manifold	111
6	Draining Pipe	253
	Outboard Total	972

2.2 The breeding and FW zones

The breeding zone is reinforced by stiffening plates in order to safely withstand the thermo-mechanical and

electro-magnetic loads postulated in normal, off normal and accidental conditions. The stiffening approach constrains the Pbli flow path, as well as affects the DWT layout (Fig. 2). Reliable parametric analyses, supporting the optimization of the plates thickness, imply the enhancement of the TBR performances. In the SMS approach, the study of the stiffening performances has to distinguish between the upper and lower caps and the other zones. In this last case, the analyses reported in Ref. [13] demonstrates that the configuration with the vertical and the horizontal plates having a thickness of 12 mm and 10 mm, respectively, has a minimum margin of RCC-MRx design rules equal to 12.5%. It is highlighted that this configuration has a reduction of the steel in the breeding zone equal to 11.3%, if compared with the configuration WCLL 2016, see also Ref. [24].

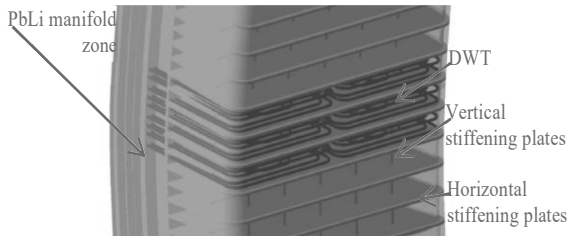


Fig. 2. WCLL 2018 OB segment: BZ and stiffening plates.

The BZ cooling approach relies on a breeding cell repeated along the poloidal direction. The main design features and constraints are hereafter synthetized.

- The coolant flows in DWT, having inner and outer diameters equal to 8mm and 13.5mm, respectively.
- The main DWT manufacturing requirements are: maximum curvature radius 3 times the external diameter; the minimum distance between tube axes 26mm; and the number of curvatures limited to 2.
- The DWT layout shall ensure that the temperature of the structural material is below the limit, thus 550°C; shall provide a symmetric thermal field in toroidal direction; shall be compatible with the manifold approach; and shall not cross the stiffening plates in the BZ.

The reference configuration WCLL 2018 (Fig. 3) is based on 20 DWT. The approach fulfils the design requirements above, including, on the opposite of WCLL 2016, the manufacturing requirements and the temperature field symmetry. Moreover, the tube layout provides an overall pipe length reduction of about 25% and a reduction of steel in the first 175mm of BZ of about 50%. Preliminary thermal-hydraulic analyses [16] are carried out using ANSYS CFX 18.1 modelling the coolant, the PbLi, the EUROFER and the tungsten. No hot spot, exceeding the limit, is calculated (Fig. 4), although in the poloidal direction the buoyancy forces are suppressed and only inertial forces are considered (conservative assumption). Efforts are in progress to calculate the thermal and the flow fields through the MHD analysis.

The FW integrated in the breeding blanket is in charge of: 1) removing the surface loads; 2) ensuring the structural integrity of the BZ; 3) delivering the coolant to the FW Primary Heat Transfer System heat exchanger for an efficient power conversion into electricity. On the plasma facing area, the FW is coated by the tungsten layer of 2 mm. The square cooling channels have a side equal to 7mm and are placed with the horizontal axes at 6.5mm from the FW surface. With the pitch of 13.5 mm, the geometry is optimized [25] in order to achieve the best compromise between thermal-hydraulic and thermo-mechanics performances. System [26] and CFD [27] code analyses have demonstrated that, if the FW heat flux exceed about 1.34 MW/m², the integrated FW shall be protected with a dedicated detached system. Moreover, when this heat load is below 0.4 MW/m², it is possible to increase the pitch up to 22.5 mm, without relevant variations of the temperature distribution of the metallic structure, i.e. the maximum temperature remains below 450 °C. This outcome implies that having reliable and accurate thermal loads of the FW in all operative conditions, it is possible to choose the appropriate pitch (larger than 13.5 mm) in order to maximize the thermo-mechanical and TBR performances, minimizing the amount of water [28]. Finally, it must be stressed that the evaluation of the DNB condition has demonstrated that the boiling crisis is excluded.

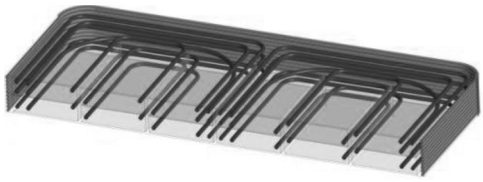


Fig. 3. WCLL 2018 OB equatorial breeding cell geometry.

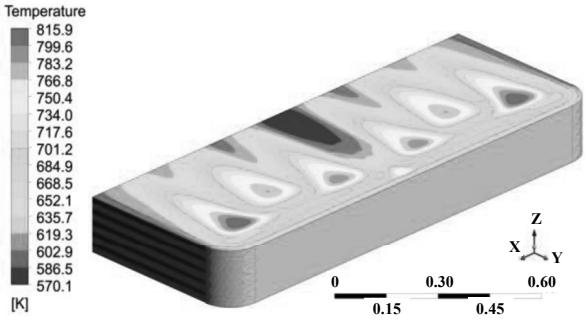


Fig. 4. WCLL 2018 OB equatorial breeding cell: Eurofer and Tungsten domain temperature

3. Integration with the PbLi loop

The PbLi loop [6] is aimed at circulating the PbLi through the blanket at about 328°C, carrying the T generated in the BB (about 270-280g/day) towards the Tritium Extraction and Removal System (TER), contributing in the T extraction, controlling PbLi chemistry, purifying the PbLi from the impurities. In general, it is designed to ensure a reliable and safe operation of the system. The total amount of PbLi is about 1.000 m^3 divided into six loops. This is stored in dedicated tanks when DEMO power plant is in shutdown conditions. These tanks are placed in the lower part of the circuit to facilitate the drainage by gravity.

Each PbLi loop (Fig. 5) is composed by a charge tank, a storage tank, an expansion/He relief tank, a safety tank connected to the storage and expansion tanks in

case of overpressure, a pumping system, a TER, a heat exchanger and a purification system. The integration of the PbLi loop with the BB is designed by means of the upper port for the loops connected with the outboard segments. On the opposite, the inner connections with the inboard segments are through the lower port, while the outlets are through the upper port. This different integration is due to the different PbLi mass flow rates feeding the inboard and outboard segments. Indeed, being the connecting PbLi pipe dimension driven mainly by the pressure drops connected with the presence of the magnetic field, it was calculated that the optimum pipe diameter for the outboard segment is DN200, sect. 2.1, Tab. 1. This dimension is not compatible with the space reservation in the lower port of the Vacuum Vessel (currently equal to DN80).

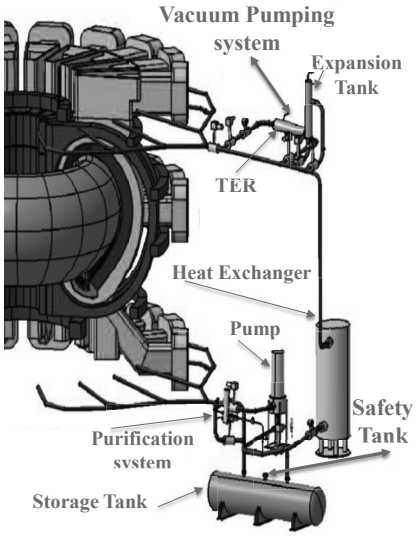


Fig. 5. Layout of a PbLi loop for WCLL BB inboard segments.

4. Integration with the PHTS and PCS

The water-cooled Primary Heat Transfer System (PHTS) is constituted by two independent systems (Fig. 6): the BZ PHTS and FW PHTS [29]. The total mass flow rates are 7761.2 kg/s and 2271.6 kg/s, respectively. The BB water manifolds are connected with the sector collectors and distributors with pipelines routed through the upper port. The largest inlet and outlet pipes are DN200 and are connected with the BZ system of the outboard segment. In general, the pipe diameter is chosen minimizing the diameter size, but accounting for the maximum velocity limit of 7m/s for the pipelines in EUROFER inside the bio-shield.

During the pulse mode the BZ-PHTS delivers the power (1483.2 MW_{th}) to the steam turbine by means of two Once Through Steam Generators (OTSG). The steam is super-heated (300.0 °C) at the pressure of 6.4 MPa. The thermal power transported by the FW-PHTS (439.8 MW_{th}) is exchanged through two horizontal Intermediate Heat Exchangers, tubes and shell type, to an Intermediate Heat Transfer System (IHTS) using HITEC molten salt as coolant. The reference configuration assumes the temperature cycle 295.0-328.0 °C for the primary water coolant system and 280.0-320.0 °C for the intermediate molten salt coolant system. The IHTS exchanges heat power to the Power Conversion System (PCS) by means of 4 Helical Coil Steam Generators. These are operated for delivering super-heated steam at the nominal conditions (i.e. 6.4 MPa, 300.0 °C). The overall pumping power of the PHTSs are 4.2 MW and 13.5 MW, for the FW and the BZ main coolant pumps, respectively. During pulse, 173.9 MW_{th} out of 439.8 MW_{th} are stored in the Energy Storage System (ESS), whereas the remaining are bypassed towards the PCS, thus the steam turbine. When the plasma is off, the ESS, consisting into two tanks of about 11000 m^3, feeds the PCS with the thermal energy needed to keep the PCS feed water components on and the turbine at the nominal power. The analyses on the proposed configuration [30] showed that the water cooled DEMO power plant, operated in pulse mode, can provide a constant gross electrical power of about 760 MW, with a gross efficiency of 36%.

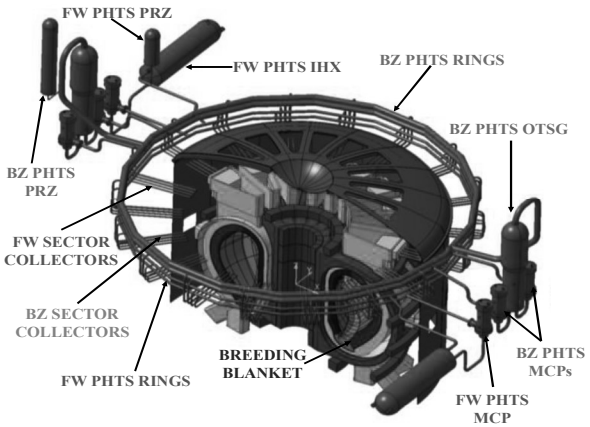


Fig. 6. Layout of the FW and BZ PHTS.

5. Conclusive remarks

The preliminary conceptual design of the WCLL BB is up-dated at the version 2018, accounting for the availability of the new DEMO 2017 baseline, characterized by a remarkable radial reduction of the BB space. Cornerstones are single module segment approach and the water manifold between the breeding blanket box and the back supporting structure. The integration of the water coolant systems is defined. On the opposite the integration of the PbLi systems is proposed and shall be further investigated evaluating if the He is always dissolved in the liquid metal and exploiting if the electrical insulation of inlet and outlet pipes can be considered. WCLL BB 2018 is characterized by a meaningful steel reduction, derived from the thermo-mechanics and thermos-hydraulics studies (i.e. stiffeners and tubes). Moreover, the studies on the FW have confirmed the cooling limit, but also the margin available for adapting the channel pitch to the thermal load specifications. Having reliable and accurate thermal loads of the FW in all operative conditions, this will allow to enhance both the thermo-mechanic and the TBR performances. Current reference design will be further studied and optimized for the pre-Conceptual Design Review planned in 2020. Moreover, R&D programs are ongoing and in tight connection with the design activities. Relevant examples are: the manufacturing

studies; the quantification of the T permeation in the cooling system and of the He bubble formation in the BZ; and the demonstration that the pressure, temperature and H_2 formation during "in-box-LOCA" does not compromise the structural integrity of the BB box.

Acknowledgments

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