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Design and preliminary analyses of the new Water Cooled Lithium Lead TBM for ITER

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In the European strategy, DEMO is the intermediate step between ITER and a commercial fusion power plant. In this framework, one of the goal of DEMO is to be a Breeding Blanket test facility. The Breeding Blanket, which is not present in ITER, is one of the key components for the future deployment of nuclear fusion electricity as it accomplishes the functions of tritium breeding and nuclear to thermal power conversion.

Due to time constraints lead by the construction schedule of DEMO, a new strategy to consider in DEMO a “driver” Breeding Blanket that needs limited technological extrapolation has been chosen, while “advanced” Breeding Blanket concepts will be tested in the next phases. In this context, ITER will allow to test technologies to provide relevant contributions in terms of Return of eXperience to the DEMO “driver” Breeding Blanket project by the mean of Test Blanket Modules (TBM) to be installed in different ITER Vacuum Vessel Ports.

Among the possible “driver” Breeding Blanket, the Water Cooled Lithium Lead (WCLL) concept comes out. In this framework, a realignment of the DEMO Breeding Blanket and TBM programs has started in 2017, leading to a new TBM development relevant of the DEMO WCLL BB. The WCLL TBM is therefore an essential component in ITER that will provide crucial information for the development of the DEMO “driver” blanket.

This paper aims at presenting the development process and design status of WCLL TBM. After recalling the main features of the WCLL TBM, conceptual design analyses are presented and discussed.

Keywords: ITER, WCLL, TBM, Breeding Blanket

1. Introduction

In the European strategy, DEMO is the intermediate step between ITER and a commercial fusion power plant [1]. In this framework, one of the goal of DEMO is to be a Breeding Blanket (BB) test facility. The Breeding Blanket, which is not present in ITER, is one of the key components for the future deployment of nuclear fusion electricity as it accomplishes the functions of tritium breeding and nuclear to thermal power conversion.

Due to time constraints lead by the construction schedule of DEMO, a new strategy to consider in DEMO a “driver” Breeding Blanket that needs limited technological extrapolation has been chosen, while “advanced” Breeding Blanket concepts will be tested in the next phases. In this context, ITER will allow to test technologies to provide relevant contributions in terms of Return of eXperience to the DEMO “driver” Breeding Blanket project by the mean of Test Blanket Modules (TBM) to be installed in different ITER Vacuum Vessel (VV) Ports.

Among the possible “driver” Breeding Blanket, the Water Cooled Lithium Lead (WCLL) concept stands out as a more near-term technological option. A realignment of the DEMO Breeding Blanket and TBM programs has started in 2017 [2], leading to a new TBM development relevant of the DEMO WCLL BB. The WCLL TBM is

therefore an essential component in ITER that will provide crucial information for the development of the DEMO “driver” blanket.

This paper presents the development process and design status of WCLL TBM. After recalling the main features of the WCLL TBM, conceptual design analyses are presented and discussed.

2. WCLL TBM design description

The WCLL TBM, which will be installed in the ITER Equatorial Port #16, is designed following the same overall technological features and thermo-hydraulic parameters as the European DEMO WCLL BB described in [3] such as Reduced Activation Ferritic-Martensitic (RAFMs) Eurofer-97 steel as structural material, slowly flowing Pb–15.7Li liquid metal as tritium breeder and neutron multiplier, and water pressurized at 15.5 MPa with a target value of inlet/outlet temperatures of 295 °C / 328°C as coolant. Moreover, it has been designed following also the ITER requirements [4] and requirements related to nuclear pressurized equipments ([5], [6]). The WCLL TBM has been also designed with HCLL/HCPB design in mind [7], in order to take benefits from already existing licensing and manufacturing Return of eXperience.

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The design of the WCLL TBM described in this paper is only at an early stage linked to the first of the two phases to be concluded by the conceptual design review (CDR) scheduled by mid 2020.

2.1. Mechanical design description

A global view, internal structure and an exploded view of the WCLL TBM is shown in Fig. 1. The TBM box is formed by a vertical 30 mm thick U-shaped First Wall (FW) facing the plasma, self-cooled by 32 vertical 7×7 mm² single pass square cross section channels and with 3 mm thick front wall. The box is closed on both sides by Side Caps (SC). The SC are self-cooled to decrease the thermal stresses but might be designed without cooling channel, to be confirmed in the next design phase. The box is closed on its back by four successive plates (Back Plates-BP) that act as manifolds for the coolant and breeder flow distribution. The BP are radially connected between them by means of several rods (Stiffening and Tie rods) that provide the required tying action to withstand the effect of the water circuit internal pressure in the manifold area. Poloidal-radial

and toroidal-radial 15 mm thick plates stiffen the TBM box in order to withstand the accidental internal pressurization at the coolant pressure. The corresponding Stiffening Grid (SG) forms 16 internal cells (Breeding Units - BUs) in which the Pb-15.7Li circulates at few mm/s for external tritium extraction purposes. SG does not have to be self-cooled thanks to water cooling capacity, contrary to HCLL/HCPB TBM. In order to remove heat deposited in the SG and Pb-15.7Li, 4 parallel radial-toroidal Double Wall Tubes (DWT) are inserted in each BU and welded to a common Back Plate (note that only 3 DWT per BU are present in the 2 top and bottom BUs), they replace the HCLL/HCPB cooling plates functions [7]. The DWT are developed in the framework of the DEMO WCLL BB [8]. The rationales are a hydraulic diameter of 8 mm for DEMO relevancy, and two concentric tubes of respectively 1.25 mm and 1.5 mm thick, joint by a Fe interlayer to limit the propagation of failure between the tubes while ensuring enough thermal conductivity.

The present weight of the WCLL TBM (without Pb-15.7Li), including attachments, is equal to 1540 kg.

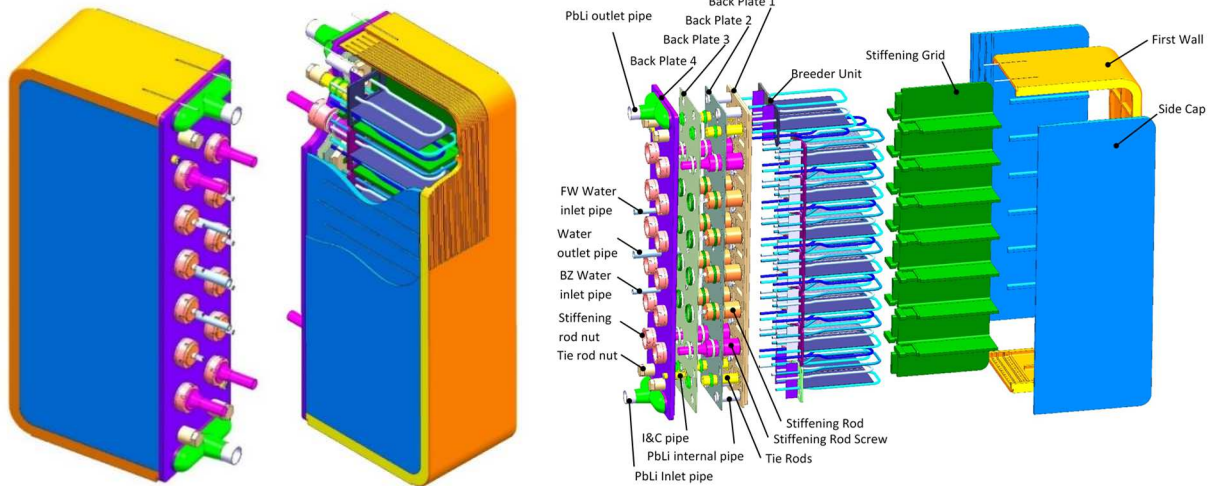


Fig. 1. WCLL TBM global views, internal structures and exploded view of the WCLL TBM

2.2. Cooling flow description

The cooling/heat extraction of the WCLL TBM structure and breeder is insured by pressurised water distributed and organised by three back manifolds, each one distribute/collect the coolant in the various cooling structures of the TBM. The flow path follows the same scheme as the reference WCLL DEMO blanket (in-parallel FW and BZ cooling scheme, instead of in-series as it is for the HCLL/HCPB TBM [7]). The water flow path is presented by the colored scheme in Fig. 2 and with the cuts of the TBM in Fig. 3. One of the requirements being to limit to 3 the number of coolant tubes exiting the TBM, two inlet pipes are present on back top and bottom of the TBM to feed respectively the Manifold 1 - FW and the Manifold 2 - DWT/SC while only one bigger pipe is present on the back of the TBM, in the middle, for both FW and DWT/SC outlet collected in the common Manifold 3.

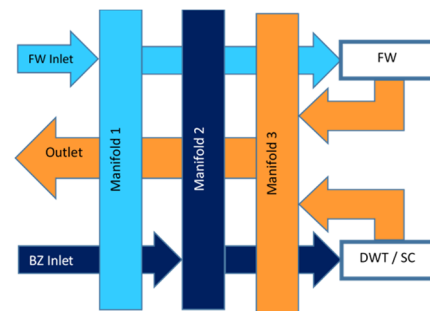


Fig. 2. Water flow scheme of the TBM, color highlighted

The total mass flow rate has been evaluated to 3.27 kg/s on the basis of the target inlet/outlet temperatures and the total power deposited in the module, due to the heat flux of 0.3 MW/m² on the FW [4] and the nuclear heating in the structure and Pb-15.7Li. Nuclear power data are derived from neutronic analysis performed on a former WCLL design [9]. The distribution of water inside the FW and the DWT/SC are independent and the mass flow rate has been estimated respectively equal to

1.79 kg/s and 1.48 kg/s. This preliminary evaluation considers that the coolant flowing in the FW will extract only the heat flux and the nuclear heating deposited on the FW structure and water, while the coolant flowing

inside the DWT/SC will extract only the nuclear heating deposited in the SG, SC, DWT structure and water, and Pb-15.7Li.

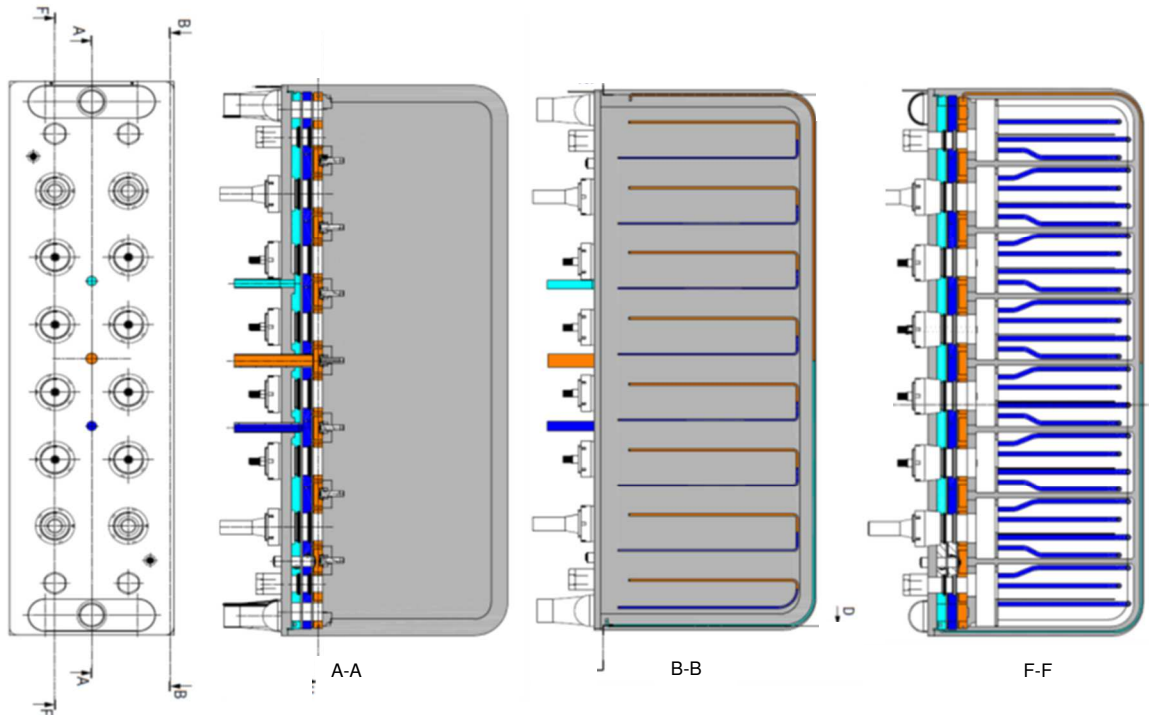


Fig. 3. Water flow scheme inside the TBM through cuts, color highlighted

2.3. Breeder flow description

The tritium breeding function is ensured by liquid Pb-15.7Li circulating in the inner volume defined by the TBM structure. The principle of the circulation path inside the TBM is based on dividing the PbLi volume in two main areas: the Pb-15.7Li manifold, at the rear of the BU BPs, and the actual Pb-15.7Li circulation in the BUs. The liquid metal enters from the bottom of the TBM, then it fills the region behind the BUs back plates (manifold), where it is distributed to all the BUs in parallel.

The design of the WCLL TBM Pb-15.7 manifold follows the concept of the HCLL one with optimization. Indeed, the design of the HCLL TBM [7] integrated a poloidally step-shaped wall, which was electrically conducting, to separate the Pb-15.7Li flows in the manifold. This solution was chosen because of the presence of the Cooling Plates BU manifold, but forced the liquid metal to flow along a series of contractions and expansions and electric currents induced in the fluid can pass through the dividing wall causing an electromagnetic coupling of adjacent fluid domains. In this configuration, 80 % of the total Pb-15.7Li pressure loss of the HCLL TBM was occurring along the Pb-15.7Li manifold [10]. The WCLL TBM Pb-15.7Li manifold has thus been optimized since the manifold poloidal ducts are separated by straight walls (Manifold Baffle Plates in Fig. 4), allowing straight upward flow of the Pb-15.7Li, that may have a positive consequence regarding pressure loss reduction.

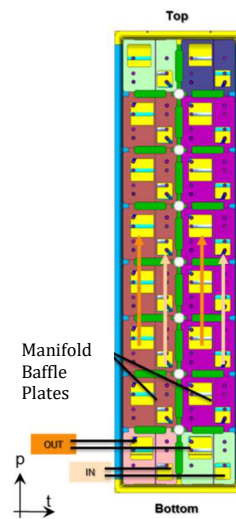


Fig. 4. Cut in the Pb-15.7Li manifold showing Pb-15.7Li circulation

Each BU is split in 2 in the poloidal direction thanks to a BU Baffle Plate – which has no structural function – that is attached to the BUs back plate and stops before the FW (Fig. 5). For each BUs (poloidally), it enters in the lowest half BU through square openings in the BU Back Plates, it radially circulates towards the plasma passing between the DWTs; it then goes to the half BU above around the Baffle Plate, and exits from the opening in the BU back plates. Note that the WCLL does not have nozzles between the horizontal plates of the SG and the FW, allowing a more stiff structure and an easy welding of the SG to the FW, unlike HCLL TBM [7], as

well as a possible reduction of Pb–15.7Li pressure loss [10]. The inlet/outlet circuits in the Pb–15.7Li distribution circuit are delimited by the auxiliary walls welded to the BU BP. The total volume of Pb–15.7Li inside the TBM equals to 0.266 m³.

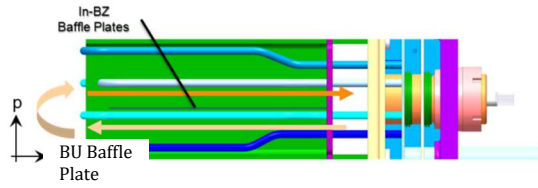


Fig. 5. Cut in a BU showing Pb–15.7Li circulation

3. Preliminary design analysis

Several thermal and mechanical analyses under the most relevant load combinations have been carried out in order to select the best design configuration and to prove that the functional and design requirements are met. However, the results consist only in preliminary outputs that will be further developed and detailed during studies and activities which will have to be carried out in view of the WCLL-TBS Conceptual Design Review, planned for mid-2020. Moreover, only the results related to the design described in §2 are shown in this paper.

3.1. Operating conditions and loads

Two operating conditions are studied in which specific loads have been applied:

Normal Operating condition (NO), in which the TBM box is subjected to two main thermal loads: heat radiation from the plasma (0.3 MW/m² [4]) and a volumetric heat load deposited in the breeder, water and on structural material [9]. Moreover, the pressure of the coolant (15.5 MPa) is applied as mechanical load inside the cooling channels. However, only thermal calculation has been performed in NO during this phase.

Accidental Condition, in which an in-box Loss Of Coolant Accident (LOCA) is foreseen resulting in an over pressurization of the TBM box. Thus, considering a safety margin of 20%, a pressure of 18.6 MPa (15.5 MPa + 20%) is applied on all the Pb-15.6Li wetted surfaces of the TBM.

3.2. Water coolant thermal limits

In case of the use of water as coolant, criteria are verified in order to check the margin from the nucleate boiling regime and the departure from nucleate boiling (critical heat flux).

Free convection regime is desired inside the cooling channels. Indeed, even if it is favorable from the heat transfer standpoint nucleate boiling regime could be jeopardizing from the corrosion/vibration standpoints especially in this case of long thin channels. However, the prevention of onset of nucleate boiling in the water channels is not a requirement for the WCLL TBM. Some limited nucleate boiling could be allowed. The verification of this criterion is on the other hand required to check the values of the heat-transfer coefficients to use in thermo-hydraulic analyses. This is required for the correct application of the critical heat flux correlation.

The Jens-Lottes correlation [12] is used to calculate the Onset of Nucleate Boiling (ONB) temperature and to prevent sub nucleate boiling regime to occur.

However, if the heat flux is higher than the critical heat flux, the bulk fluid may boil, or in some cases, regions of the bulk fluid may boil where the fluid travels in small channels. Thus large bubbles form, sometimes blocking the passage of the fluid. These results in a Departure from Nucleate Boiling Ratio (DNBR) in which steam bubbles no longer break away from the solid surface of the channel, bubbles dominate the channel or surface, and the heat flux extraction capability dramatically decreases. Vapor essentially insulates the bulk liquid from the hot surface. This condition must be avoided in the TBM following [4]. The Rohsenow correlation [13] is used to calculate Departure from Nucleate Boiling Ratio (DNBR).

Alternative approaches are also possible. ITER, for example, has developed a specific procedure to evaluate CHF onset in plasma facing components [14]. The approach used in DEMO WCLL breeding blanket studies is instead base on the Groeneveld look up tables [15]. The different approaches should be benchmarked w.r.t. the thermodynamic parameters and characteristics of flows in the FW (essentially 1 side heating) and DWTs (uniform heating) to assess their applicability in the WCLL TBM.

3.3. Codes & Standards

The 2018 edition of the RCC-MRx [16] is proposed to be used to verify the integrity of the structure since it provides an ensemble of consistent design, manufacturing and materials rules, in order to implement, in particular, regulation requirements related to PED directive [5] and French ESPN order [6]. It provides rules for high temperature operation (significant creep) and for the design of irradiated components (significant irradiation). More importantly, the new 2018 edition includes new and consolidated data for Eurofer97 steel. RCC-MRx is today the only available (nuclear) code to include this material. To ensure coherency between design, manufacturing, in-service inspection and proof testing, only one code shall be used and shall be accepted by the ITER Org. [4].

According to [7], the HCLL/HCPB TBM were considered as RCC-MRx Class 1 components, and so could be the WCLL TBM.

3.4. Thermo-hydraulic and thermal analysis of the FW

Thermal steady state analysis on different FW geometries have been performed for NO condition with the finite element method using Abaqus [17] resulting in the design shown in §2. The fluid cooling is modelled by solving a 1D advection equation and the coupling between solid and coolant is ensured by means of a weak coupling procedure using Dittus Boelter equation [11] to calculate convective Heat Transfer Coefficient (HTC). The choice of the geometry has been made in order to keep the channels dimensions and pitch of DEMO

WCLL as close as possible, keeping the thickness of the HCLL TBM FW while verifying that the WCLL FW is capable of removing the heat generated by nuclear reactions with appropriate water temperatures and keeping the structures within the acceptable temperature window.

In this configuration, the HTC equals to around 17000 W/m²K, while mass flow rate per channels equals to 0.055 kg/s, and thus velocity equals to 1.72 m/s well under the 8 m/s limit usually considered to limit erosion. Thermal results on the FW presented in Fig. 6 show that maximum temperature on the structure is around 400 °C, far below 550 °C for which mechanical properties of Eurofer decrease. Outlet temperature of water is equal to 328 °C as expected, and a rise of temperature occurs near the bends, equal to 330 °C. DNBR is well above 1 with a margin of 5.7, ensuring safe margin against the presence of bulk boiling beyond the critical heat flux.

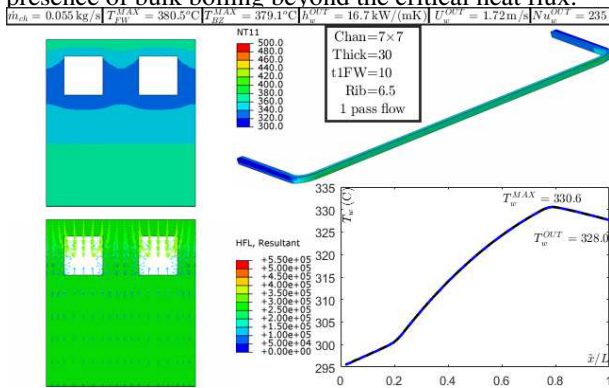


Fig. 6. Thermal field on the FW [°C] (top-left), thermal flux (bottom-left), mesh of two channels (top-right), and evolution of coolant temperature along the channel (bottom-right)

3.5. Thermo-hydraulic and thermal analysis of one quarter of TBM

Extensive thermal steady state analysis of different configurations of DWT layout for NO condition with finite element method have been carried out using Abaqus [17], resulting in the design shown in §2. One quarter of TBM box is simulated, considering symmetry planes. The same modeling methodology has been used as for the FW analysis in §3.4. The choice of the geometry has been made on the basis of DEMO WCLL BB relevancy while minimizing the deviations from HCLL TBM design in order to take advantage of the already developed manufacturing technics, and using the same strategy adopted for the FW.

In this configuration, the HTC in the DWT equals to around 7600 W/m²K, while mass flow rate per DWT equals to 0.0207 kg/s, and thus velocity equals to 0.66 m/s, well under the 8 m/s limit usually considered to limit erosion. Thermal field on the different components of the model is presented in Fig. 7. It shows that maximum temperature on the structure is below 550 °C for every parts. Especially, maximum temperature on the FW, SC, hSG, vSG and BP are respectively equals to 450 °C, 462 °C, 502 °C, 525 °C, 318 °C. The vSG is clearly the hotter component, and maximum temperature is spotted near the FW, where the bends of the DWTs are

located. The temperature in the vSG could be reduced by implementing antisymmetry of the tube layout in the two toroidal adjacent BUs. The maximum Pb-16Li/steel interface temperature is evaluated a little bit below 530 °C, but has to be confirmed with more thermal consistent analysis. Fig. 8 shows the evolution of temperature of the coolant along FW channels and along the DWTs channels. It can be observed a discrepancy between the estimated and real outlet temperatures of the water of both FW channels (331 °C) and DWTs (322 °C). Water outlet temperature of the DWTs is colder than the one of the FW channels. This can be explained because the mass flow rate calculated for both the FW and the DWTs was an estimation that was neglecting any heat transmitted from the Pb-15.7Li and SG to the FW. By looking at the results, we can observe that this is not true and there is a non-negligible heat transmitted from the Pb-15.7Li to the internal surface of the FW. In a future stage of the design, these mass flows must be further optimized to ensure the targeted outlet temperature. DNBR is well above 1 with a margin of 5.5, ensuring safe margin against the presence of bulk boiling beyond the critical heat flux.

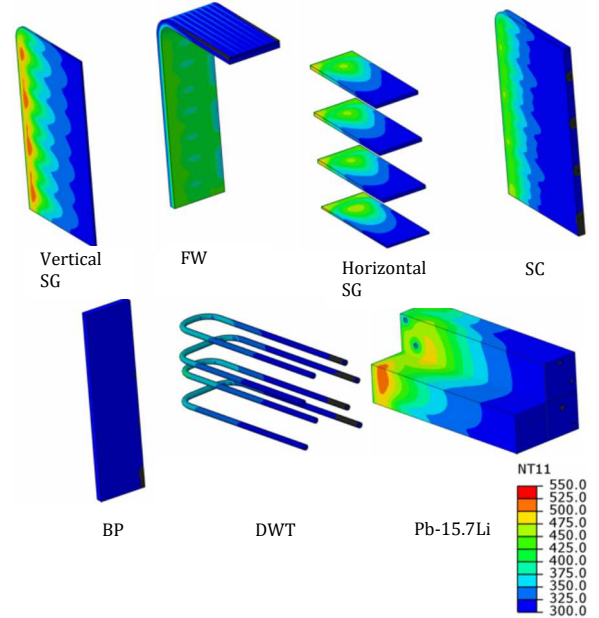


Fig. 7. Temperature field on the different parts of the WCLL TBM model [°C]

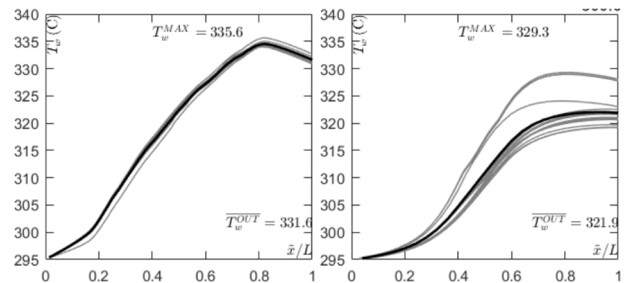


Fig. 8. Temperature evolution of the coolant along the FW channels (left) and DWT channels (right) on steady state NO condition.

3.6. Mechanical analysis of one quarter of TBM in case of in-box LOCA

Mechanical calculation on different WCLL TBM box geometries have been performed in case of in-box LOCA (over pressurization of the box at 18.6 MPa) on one quarter of model with finite element method using Cast3m [18] resulting in the design shown in §2. Different FW overall thickness, front wall thickness, SG thicknesses have been tested and primary stresses have been analyzed with the RCC-MRx [16] rules considering Level D criteria. The Von Mises stress field on the design described in §2 is shown on Fig. 9. The stress limit SmD is taken from the RCC-MRx at 550 °C equals to 238 MPa (consequently $1.5SmD = 357$ MPa). This value is very conservative considering the actual results of thermal analyses. Different areas of the box have been analyzed, leading to design a FW with 3 mm thick front wall near the plasma, and 10 mm thick front wall on top and bottom. In this configuration, the maximum Von Mises membrane and membrane plus bending stresses occur in the FW due to the bending of large surfaces under pressure and equals respectively to 215 MPa and 246 MPa, the Level D criteria is respected everywhere in the TBM.

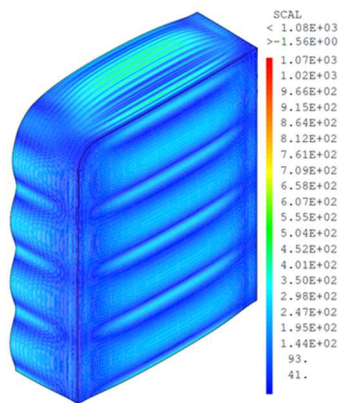


Fig. 9. Von Mises stress field in case of LOCA on one quarter of WCLL TBM [MPa]

4. Conclusions

This paper presents the design of the new Water Cooled Lithium Lead (WCLL) TBM for ITER. Mechanical as well as coolant and breeder paths are described. Preliminary thermal and mechanical calculation have been carried out with finite element method, showing a thermal behavior in steady state Normal Operating condition, and a mechanical behavior in case of in-box Loss Of Coolant Accident compliant with the material properties and RCC-MRx criteria.

However, optimization such as mass flow distribution between FW and DWTs shall must be assessed and more accurate thermal and thermo-mechanical analysis will be performed in the next phase of the design activity of the WCLL TBM.

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633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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