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# Optimization of the breeder zone cooling tubes of the DEMO Water-Cooled Lithium Lead breeding blanket

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The determination of an optimal configuration for the breeder zone (BZ) cooling tubes is one of the most important issues in the DEMO Water-Cooled Lithium Lead (WCLL) breeding blanket R&D activities, since BZ cooling tubes spatial distribution should ensure an efficient heat power removal from the breeder, avoiding hotspots occurrence in the thermal field. Within the framework of R&D activities supported by the HORIZON 2020 EUROfusion Consortium action on the DEMO WCLL breeding blanket design, a campaign of parametric analyses has been launched at the Department of Energy, Information Engineering and Mathematical Models of the University of Palermo (DEIM), in close cooperation with ENEA-Brasimone, in order to assess the potential influence of BZ cooling tubes number on the thermal performances of the DEMO WCLL outboard breeding blanket equatorial module under the nominal steady state operative conditions envisaged for it, optimizing their geometric configuration. In particular, attention has been focused on the toroidal-radial option for the BZ tube bundles lay-out and a parametric study has been carried out taking into account different tube bundles arrangement within the module. The study has been carried out following a theoretical-numerical approach, based on the finite element method (FEM), and adopting a qualified commercial FEM code. Results obtained are herewith presented and critically discussed.

Keywords: DEMO reactor; WCLL breeding blanket, breeder zone cooling tubes.

## 1. Introduction

Within the framework of R&D activities supported by the HORIZON 2020 EUROfusion action [1] on the DEMO Water-Cooled Lithium Lead (WCLL) breeding blanket design, a campaign of parametric analyses has been launched at DEIM, in close cooperation with ENEA-Brasimone, in order to assess the potential influence of the breeder zone (BZ) cooling tubes number on the thermal performances of the new concept of the DEMO WCLL breeding blanket, the development of which is nowadays at a conceptual phase [1-2].

To this purpose, attention has been paid to the equatorial module of the WCLL outboard breeding blanket, taking into account its first wall (FW) flat concept [1-2], equipped with toroidal-radial square cooling channels and toroidal-radial BZ cooling double walled tubes (DWTs) with a "C" shape (Fig. 1).

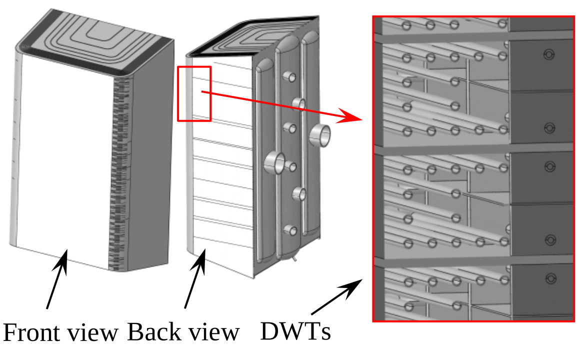


Fig. 1. 3D Geometric model of DEMO WCLL blanket module.

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The determination of an optimal configuration for the BZ cooling tubes is one of the most important issues in the DEMO WCLL breeding blanket R&D activities, since BZ cooling tubes arrangement has to ensure an efficient heat power removal from the breeder, allowing the fulfillment of the thermal-hydraulic requirements prescribed by safety codes. In particular, from the thermal-hydraulic standpoint, it has been assumed that the structural material (EUROFER) maximum allowable temperature, amounting to 550°C, cannot be exceeded and that the velocity of cooling water has to be lower than the limit value of 8 m/s [3].

Therefore, the present research campaign has been specifically intended to optimize the DWTs configuration, finding the minimum number of tubes necessary to obtain a thermal field so that the WCLL module might safely fulfill all the thermal-hydraulic requirements prescribed by safety codes. In particular, 5 different configurations have been investigated taking into account bundles of 18, 20, 22, 24, 26 BZ cooling tubes, arranged in four toroidal-radial parallel planes (Fig. 1). A theoretical-numerical approach, based on the finite element method (FEM) has been followed and a qualified commercial FEM code has been adopted. So, 5 realistic FEM models of the DEMO WCLL blanket outboard equatorial module, each one properly endowed with a different BZ cooling tubes geometric configuration, have been set up and their thermal performances under steady state nominal operative loading conditions envisaged for the DEMO WCLL breeding blanket outboard equatorial module have been investigated, paying particular attention to the fulfillment of the thermal-hydraulic safety requirements.

## 2. The optimization of the BZ cooling tubes

In order to obtain a realistic simulation of the DEMO WCLL breeding blanket outboard equatorial module thermal behavior under steady state normal operation loading conditions ensuring, at the same time, the best compromise between results accuracy and calculation time saving, each of the 5 3D FEM models set-up reproduces a central toroidal-radial slice of the module (Fig. 2), extending for a single breeder cell in the poloidal direction (p), for the whole module toroidal direction (θ ) and for the whole module radial depth (r) up to the back-plate (BP). Therefore, each model set-up includes all the breeder cells, the segment box (SB) including the proper portions of the poloidal-radial and toroidal-radial stiffening plates (SPs), a baffle plate (whose task is to spread the Pb-Li alloy) as well as the pertaining segment of the BP.

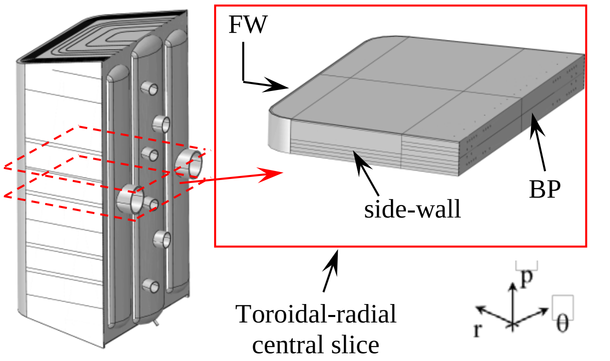


Fig. 2. The toroidal-radial WCLL blanket module central slice.

Furthermore, the Pb-Li alloy breeder has been opportunely modeled and included within each 3D geometric model, as well as the presence of the FW and DWTs cooling water has been taken into account properly modelling its geometric domain. As an example, internal details of 3D FEM model referring to 22 tubes configuration are shown in Fig. 3.

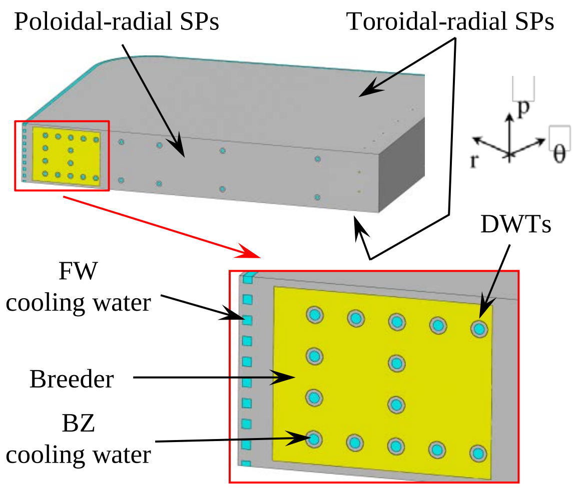


Fig. 3. Internals of 22 tubes configuration 3D FEM model.

As already mentioned, the difference among the 5 3D FEM models set-up is the BZ cooling tubes number (Fig. 4) taken into account.

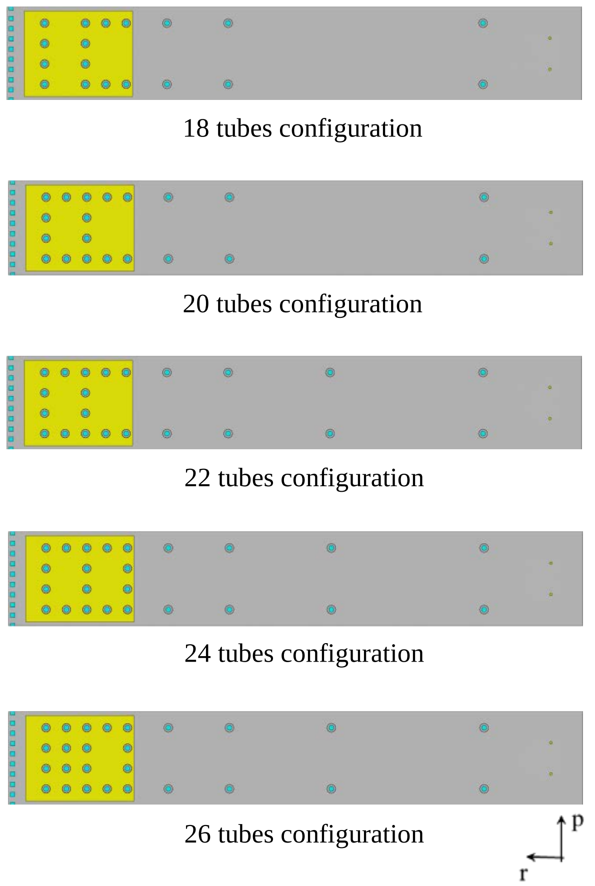


Fig. 4. The BZ cooling tubes different configurations.

For each of the investigated 3D geometric models a corresponding mesh, whose nodes and elements number depends on the BZ cooling tubes configuration considered, has been realized.

RAFM EUROFER steel has been assumed as the DEMO WCLL blanket module structural material, except for the 2 mm thick FW armor that has been supposed made of tungsten. Materials have been considered homogeneous, uniform, isotropic and linearly elastic and their thermo-mechanical properties have been assumed to depend uniquely on temperature as indicated in [4], except for tungsten density that has been assumed to be constant and equal to 19300 kg/m$^3$ [5-6].

In order to assess the thermal behavior of the 5 different 3D FEM models set-up, the thermal loads and boundary conditions relevant to the steady state normal operation loading scenario envisaged for DEMO WCLL breeding blanket concept have been imposed to the 3D FEM models.

In particular, in order to simulate the distributed heat power deposition due to the interactions between neutrons and gamma photons with nuclei, a non-uniform volumetric density of nuclear deposited heat power has been imposed to each 3D FEM model, adopting the nuclear heating spatial distribution calculated for the PPCS-A WCLL outboard breeding blanket equatorial module properly scaled according to average NWLs of DEMO and PPCS-A reactors (Fig. 5).

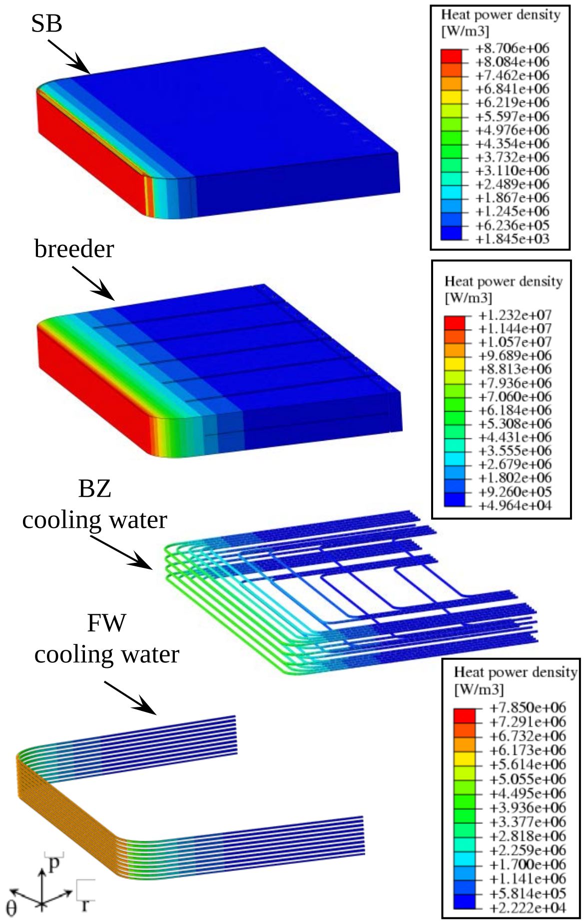


Fig. 5. Volumetric density of nuclear heat power field.

Moreover, in order to simulate heat power deposition on the FW and side-walls (SWs) plasma-facing surfaces due to particles and radiation arising from plasma, a non-uniform normal heat flux, whose maximum value amounts to 2 $MW/m^2$ [1-2], has been applied to the FW and SWs plasma-facing surfaces (Fig. 6).

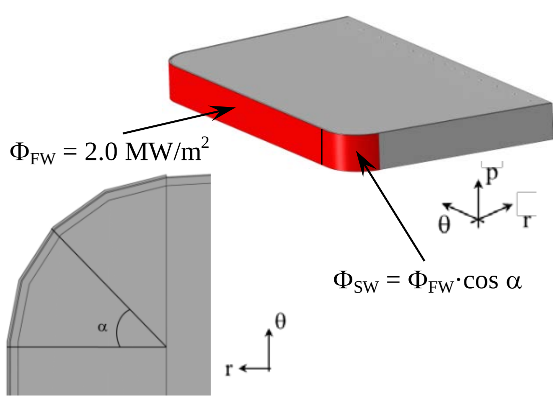


Fig. 6. Heat flux distribution on the plasma facing surfaces.

Furthermore, thermal contact models between breeder geometric domain and inner SB surfaces and between breeder and DWTs outer surfaces have been implemented imposing, conservatively, a thermal conductance value of $10^5$ $W/m^2$°C.

Finally, the simulation of the forced convective heat transfer between the coolant and the SB and DWTs has been simulated with a simplified FEM approach and adopting a proper thermal contact model between the coolant domain and the structure wetted walls. In particular, concerning FW cooling water, a counter-current flow pattern has been imposed, whereas as to BZ coolant it has been supposed flowing in a single way along the radial-toroidal-radial path, as shown in Fig. 7.

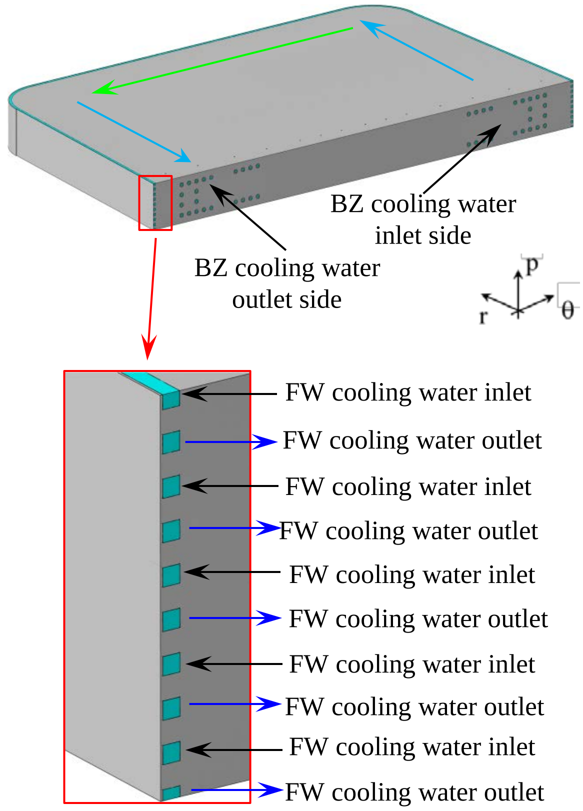


Fig. 7. Cooling water flow paths.

As to the FEM simulation of convective heat transfer, the so-called “frozen” flow field approach has been adopted, assuming fixed mass flow rates and heat transfer coefficients within each channel or tube, calculated imposing a water temperature increase of 40 °C ($\Delta T_{Design}$) between the inlet (285 °C) and the outlet headers of the module. In particular, heat transfer coefficients have been calculated using the Dittus & Bölter correlation [7].

The calculation of the mass flow rate in every single tube has been obtained, for each selected configuration, by the iterative procedure which is described in the following. Once selected the given configuration the “0” step is represented by the assessment of the initial (guess values) mass flow rates in each tube starting from the calculation of the total flow rate by an overall power balance and solving a linear system of N+1 equations, where N is the overall number of tubes. This system is composed by one equation stating that the sum of all mass flow rates in every tube is equal to the total mass flow rate former determined and N equations each expressing the unknown mass flow rates as function of the pressure drop which is the last unknown variable and it is the same for all the tubes. To express the unknown mass flow rates as function of the pressure drop the Darcy-Weisbach formula [7] has been adopted taking into account also the local hydraulic resistances. It is to be observed that the Darcy coefficients have been considered constant as its variation as function of the Reynolds number is negligible in the range of velocity considered.

The evaluation of the set of mass flow rates has allowed to assess the thermal power removed by each tube an so to start with the proper iteration. The determination of the new set of mass flow rates has been performed by a power balance for each tube imposing a water temperature increase of $\Delta T_{Design}$, using the related thermal power former calculated. This kind of thermal analysis has been iterate until the value $\Delta T_{Design}$ has been considered achieved.

## 3. Results

Parametric thermal analyses of the 5 3D FEM models set-up, each reproducing the DEMO WCLL outboard equatorial module central slice have been performed in order to select the minimum number of BZ cooling tubes which allows to fulfill all the thermal-hydraulic requirements, foreseen by safety codes, under the steady state thermal loads and boundary conditions envisaged for the DEMO WCLL nominal operative scenario.

The configurations investigated in the present campaign of analyses have taken into account bundles of 18, 20, 22, 24 and 26 BZ cooling tubes, arranged according a toroidal-radial layout. Firstly, the configuration foreseeing 18 BZ cooling tubes has been investigated, followed by the 20 tubes one and so on up to the case foreseeing 26 cooling tubes.

Maximum temperature arising within EUROFER and Pb-Li at the end of the iterative thermal analyses in each of the 5 configurations assessed are reported in Table 1, as well as the velocity maximum values of the cooling water flowing within both BZ tubes and FW channels are summarized in Table 2.

As far as both 18 and 20 BZ cooling tubes configurations are concerned, results show that this two cases do not allow the fulfilment of the safety criterion based on the EUROFER maximum temperature, since the highest temperature achieved within structural material is equal to 627.3 °C in both configurations, well above the prescribed upper limit of 550 °C.

Concerning the 22 tubes configuration, results obtained and reported in Table 1 indicate that the EUROFER maximum temperature is equal to 536.1 °C. Moreover, in this case, also the hydraulic safety criterion based on the maximum coolant velocity is met (Table 2), since the maximum coolant velocity, achieved within FW water, amounts to 6.67 m/s. These results allow to conclude that 22 is the minimum number of BZ cooling tubes necessary to ensure the complete fulfilment of the thermal-hydraulic safety codes.

Nevertheless, paying attention to results pertaining to configurations foreseeing 24 BZ cooling tubes, it can be observed that EUROFER maximum temperature further decreases, with reference to 22 tubes configuration, of about 40 °C attaining the value of 496.1 °C while the breeder maximum temperature remains substantially unaltered.

Lastly, the 26 tubes configuration allows to obtain a significant breeder maximum temperature reduction up to the value of 496.4 °C, remaining substantially unaltered, in comparison with previous assessed case, the EUROFER maximum temperature. This leads to the conclusion that 26 tubes configuration represents the best case among those assessed in the present study, since minimum $T_{Max}$ values for EUROFER and breeder are achieved being at the same time met the criterion based on the maximum coolant velocity.

For this reason the thermal fields arising within structural material, breeder and cooling water related to 26 tubes configuration have been reported in Figs. 8-10. Observing thermal field shown in Fig. 8, it can be observed that the EUROFER maximum temperature is achieved within the SB internal baffle plate, which has no structural function being designed with the main goal to favour the breeder circulation.

Moreover, as to Fig. 10, the maximum temperatures achieved by cooling water in correspondence of its outlet sections, very close to 325 °C, demonstrate the effectiveness of the thermal iterative procedure followed in the present study.

Table 1. Maximum temperatures [°C].

| Configuration | $T_{Max}$ EUROFER | $T_{Max}$ Breeder |
|---|---|---|
| **18 tubes** | 627.3 | 627.3 |
| **20 tubes** | 627.3 | 627.3 |
| **22 tubes** | 536.1 | 542.0 |
| **24 tubes** | 496.1 | 542.1 |
| **26 tubes** | 496.4 | 496.4 |

Table 2. Maximum cooling water velocity [m/s].

| Configuration | BZ tubes | FW channels |
|---|---|---|
| **18 tubes** | 2.47 | 6.64 |
| **20 tubes** | 2.06 | 6.67 |
| **22 tubes** | 2.05 | 6.67 |
| **24 tubes** | 2.06 | 6.68 |
| **26 tubes** | 1.80 | 6.63 |

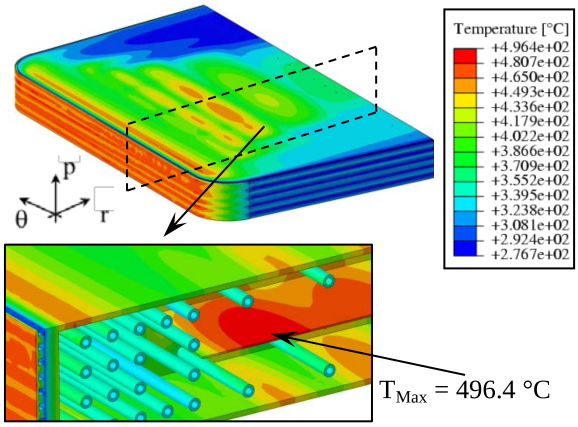


Fig. 8. 26 tubes configuration – SB and BZ tubes thermal field.

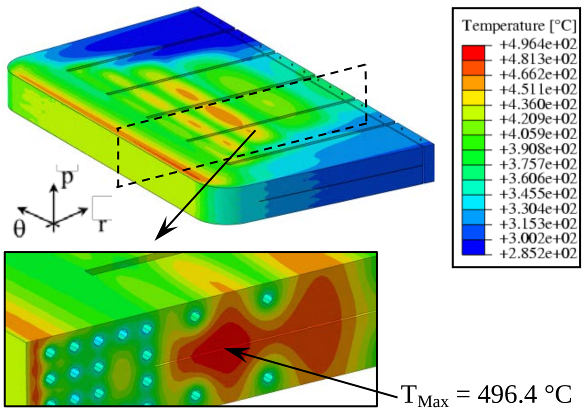


Fig. 9. 26 tubes configuration – breeder thermal field.

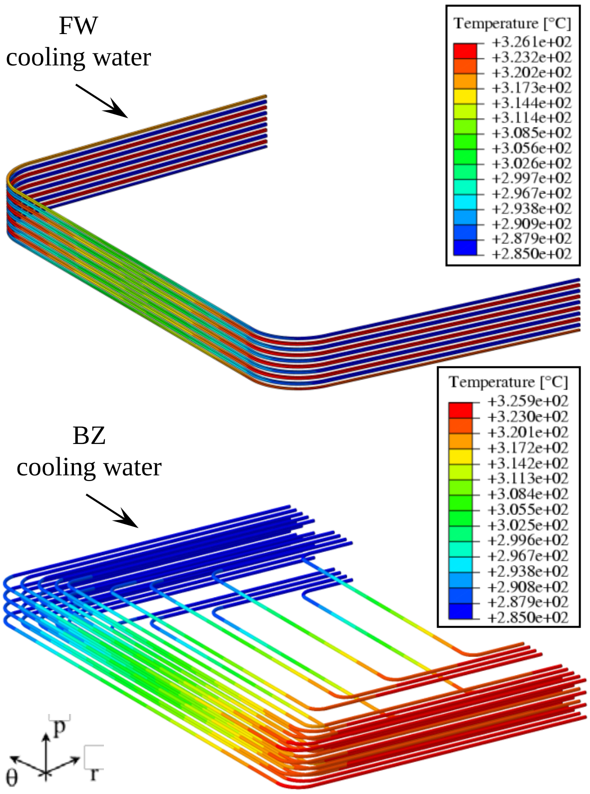


Fig. 10. 26 tubes configuration – cooling water thermal field.

## 4. Conclusions

Within the framework of the DEMO WCLL breeding blanket R&D activities a parametric research campaign has been carried out at DEIM in close collaboration with ENEA-Brasimone, in order to optimize the number of breeder zone cooling tubes, selecting the proper configuration which allows the total fulfillment of the thermal-hydraulic criteria prescribed by safety codes. To this purpose, 5 different BZ geometric configurations have been taken into account and corresponding 3D models, reproducing the central toroidal-radial slice of the DEMO WCLL breeding blanket outboard equatorial module, have been set-up. The research campaign has been carried out adopting a theoretical-numerical approach based on the finite element method and using a quoted commercial FEM code.

An iterative procedure aimed to determine the cooling water mass flow rates has been set up and parametric thermal analyses have been performed under steady state normal operation loading scenario. Results obtained have shown that, although 22 is the minimum number of tubes necessary to allow the complete fulfillment of the thermal-hydraulic safety criteria, the 26 BZ tubes configuration allows to attain, at the same time, minimum $T_{Max}$ within both SB structural material (EUROFER) and Pb-Li breeder.

## Acknowledgments

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