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Thermal and structural analysis of the European water-cooled lithium lead breeding blanket concept in the L-H mode transition

G. Bongiovì [a,*], M. Siccinio [b,c], G.A. Spagnuolo [b], I. Catanzaro [a], P. Chiovaro [a], P.A. Di Maio [a], E. Fable [c], A. Quartararo [a], E. Vallone [a]

[a] Università degli Studi di Palermo, Viale delle Scienze, Edificio 6, Palermo 90128, Italy
[b] Fusion Technology Department – Programme Management Unit, EUROfusion Consortium, Boltzmannstraße 2 bei München, Garching 85748, Germany
[c] Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 2 bei München, Garching 85748, Germany

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ABSTRACT

The design of a breeding blanket system (BB) which reliably fulfils the prescribed requirements is pivotal for the construction of the EU DEMO fusion reactor. For this reason, the BB conceptual design activities require a tighter interaction with plasma physics modelling, so to employ relevant boundary conditions to compare, and then down-select, the BB design alternatives. The preliminary thermo-mechanical study herein reported highlights the importance to assess in deep the BB performance during plasma operational transients. In particular, analyses of the BB thermal and mechanical transients during plasma ramp-up have been carried out, with focus on the L-H transition. Attention has been paid to the Water-Cooled Lithium Lead (WCLL) BB concept, one of the two driver blanket candidates for the EU DEMO project. Adopting DEMO-relevant plasma configurations, the fusion power and the radiative power time evolutions during the plasma ramp-up phase have been modelled under different assumptions using the code ASTRA. The obtained power transients have been used to calculate the time-dependent nuclear power density and radiative heat flux the WCLL BB is subjected to, in order to perform the corresponding transient thermal analysis. Then, the structural analysis has been carried out in order to verify the fulfilment of the RCC-MRx structural design criteria in the most critical time steps. The performed thermo-mechanical analysis has been carried out adopting the Abaqus FEM code. Results obtained are presented and critically discussed, highlighting their importance for the EU DEMO integrated design.

1. Introduction

The conceptual design of the Breeding Blanket (BB) system for the European DEMO fusion reactor cannot leave the plasma physics constraints out of consideration, to ensure the full integration between the physical and technological features. In this regard, the assessment of the DEMO BB during the nominal plasma transient scenarios plays a crucial role. Indeed, the power transients arising during plasma transients may jeopardise the structural integrity of the BB. In particular, they may generate high demanding loads, even more intense than those experienced in steady-state (i.e. at the end of flat top). Therefore, in the present work, the thermal and structural analysis of the EU DEMO BB in the nominal plasma ramp-up phase is presented. Attention has been paid to the Water-Cooled Lithium Lead (WCLL) BB concept as it is one of the most credible candidates for the future DEMO engineering design. The occurrence of the L-H mode transition has been taken into account.

The first section describes the plasma physics calculation aimed at predicting the time evolution of neutron flux and radiative heat flux on the BB First Wall (FW) during the ramp-up, considering that the plasma transitions from L to H mode. Then, in the following, the transient thermal analysis is presented focussing on the maximum temperature achieved during the transient timesteps. Afterwards, the correlated structural assessment aimed at verifying the compliance of the predicted stress with the RCC-MRx structural design code is reported. Finally, conclusion is given to frame the obtained results in the future DEMO BB design activities.

2. Fusion and radiative power transients calculations

In order to determine the time evolution of the neutron flux and of the radiative heat flux on the FW, the 1.5-D plasma transport code ASTRA [1–3] has been employed. In the simulations, the plasma current

* Corresponding author.
E-mail address: gaetano.bongiovi@unipa.it (G. Bongiovì).

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I_p is varied linearly from 0 to the nominal value of 20 MA, which is reached at t = 600 s (that is the end of the ramp-up phase). On the same footing, the plasma density n_p is ramped linearly at the same rate until the nominal value is reached. We recall incidentally that the maximum achievable plasma density is limited by the value of the plasma current [4], so the parallel evolution of the two quantities is in some sense natural. During the ramp, the plasma transitions from the so-called low-confinement mode (L-mode) to the high-confinement mode (H-mode). To allow this transition taking place, the power P_{sep} carried by charged particles crossing the plasma separatrix must exceed a certain threshold, which depends on the plasma conditions and is typically evaluated by employing experiment-based scaling laws, e.g. [5]. To achieve this, an instantaneous increase in auxiliary heating power from P_{aux} = 30 MW to P_{aux} = 130 MW is imposed in ASTRA.

As visible in Fig. 1, two cases have been considered, with different times at which the L-H transition takes place (at t = 100 s and t = 300 s, indicated as LH_100 and LH_300, respectively). The latest case, under the adopted assumptions, corresponds to an L-H transition at higher plasma density. When the L-H transition takes place, the corresponding fast increase in plasma confinement leads to a "jump" in the fusion power P_{fus}, occurring in a short time lapse (few seconds). Since the fusion power is proportional to n_p^2, it is easy to understand that a later access to H-mode is associated with a higher amplitude excursion in P_{fus}, as seen in Fig. 1. Similarly, the radiative power P_{rad}, which is obtained in ASTRA by seeding the plasma with high-Z impurities (Xenon, in this case), must follow the fusion power load in order to protect the divertor from an excessive heat load [6]. Goal of the present work is to evaluate the impact of such fast transitions on the blanket and on the first wall by means of thermomechanical analyses. It is important to note that:

- the ramp trajectories proposed here do not have to be understood as optimized. In fact, they represent limit test cases which are suitable for the sake of investigation, simply obtained by increasing the P_{aux} from 30 to 130 MW. In an optimised ramp trajectory, the variation in fusion power will be kept as small as possible (e.g. by modulating auxiliary power or plasma composition);
- as one can observe in Fig. 1, an early transition to H-mode causes a later achievement of the nominal, steady-state fusion power. This is a consequence of the fact that, in H-mode, the relaxation of the current profile is slower by virtue of the higher plasma temperature, and thus an early access leads to a longer time to convergence. Again, this optimisation is beyond the scope of the present work.

3. Thermal and structural transient analysis

In order to investigate the thermal and structural performances of the DEMO WCLL BB during the plasma start-up phase, attention has been focussed on the Central Outboard Blanket (COB) segment [7]. In particular, its equatorial region, given by a couple of poloidally adjacent slices [7], has been assessed since it is normally the most representative one. Therefore, a 3D geometric model (Fig. 2) encompassing the proper portion of the Segment Box (SB), namely the combination of FW, Side Walls (SWs), manifolds and Back-Supporting Structure (BSS), the horizontal and vertical Stiffening Plates (SPsh and SPsv), the baffle plates, the Double Walled Tubes (DWTs) and the tungsten armour (the latter in orange in Fig. 2) has been considered.

Moreover, both the breeder and cooling water domain have been included in the model (represented in yellow and pale blue in Fig. 2, respectively) in order to simulate more realistically the heat transfer occurring within SB and DWTs. As to the latter, the "alternative 24" configuration has been considered, foreseeing 24 tubes per slice with the crosscut in the front region [8].

Considering such a geometric configuration, a proper 3D FEM model

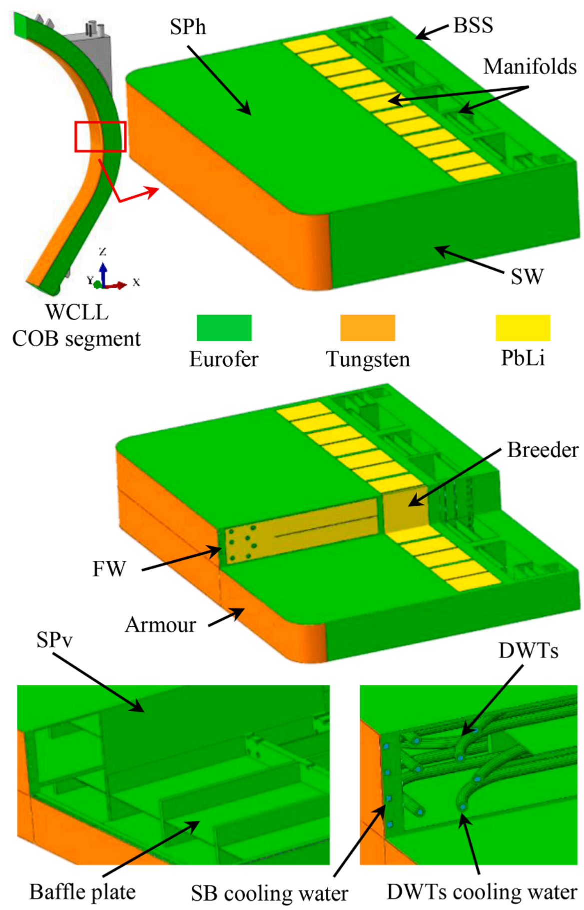

Fig. 2. Geometric model of the WCLL COB equatorial region.

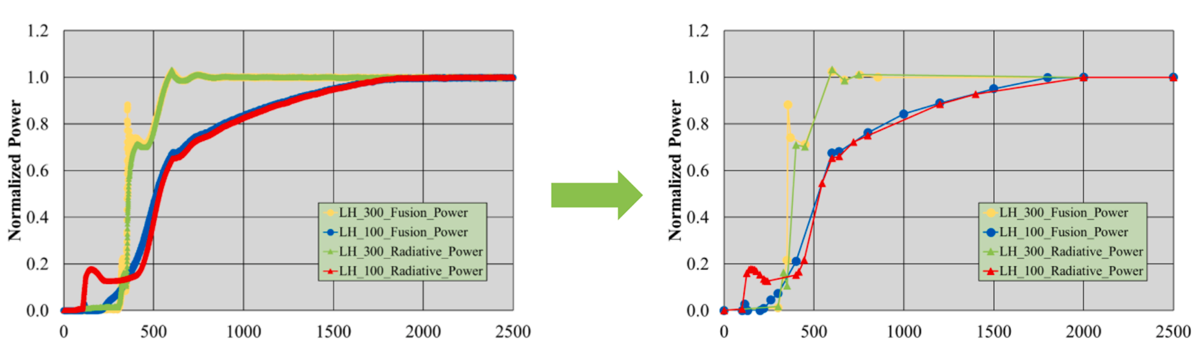

Fig. 1. Time evolution of fusion power P_{fus} and radiative power P_{rad} calculated with ASTRA for the cases with L-H transition at t = 100 s and t = 300 s. The left plot shows the original ASTRA results, while the right plot highlights the points employed for the thermomechanical analysis.

has been set-up adopting the commercial Abaqus code. A spatial discretization grid consisting of ~6.26 M nodes connected in ~4.62 M elements has been generated. The Reduced-Activation Ferritic Martensitic (RAFM) Eurofer steel has been assumed as structural material. Temperature-dependent properties of structural and functional (i. e. tungsten, eutectic PbLi breeder and water) materials have been implemented in the model.

From a separate campaign of transient thermal analysis, here not reported for the sake of brevity, the 3D thermal field achieved at the end of a plasma pulse has been obtained and imposed as initial condition for the transient thermal assessment. In particular, the imposed thermal field has been obtained from a transient analysis in which, starting from the steady state conditions (i.e. the end of flat top), a linear plasma ramp-down lasting for 600 s (with volumetric nuclear power and plasma heat flux linearly decreasing) is followed by a dwell period of further 600 s. During this transient, the nominal cooling and the volumetric decay heat power have been supposed to occur. Then, the thermal field achieved at the end of dwell has been assumed as initial condition for the ramp-up transient thermal analysis here reported. As an example, the initial thermal field imposed to the Eurofer (with the exception of DWTs, here not shown for the sake of clarity as well as the tungsten armour) and to the breeder is shown in Fig. 3.

Specifically, two different transient ramp-up scenarios have been investigated, as shown in Fig. 1. The first, called LH_100, foresees L-H mode transition after 100 s whereas the second, called LH_300, envisages it at 300 s. For both scenarios, thermal and mechanical analyses have been carried out in order to assess the BB behaviour.

3.1. Thermal transient analysis

The following set of loads and boundary conditions, properly characterised for LH_100 or LH_300 case, has been assumed:

- time-dependent volumetric nuclear heating
- time-dependent plasma heat flux
- timed-dependent forced convective heat transfer
- thermal boundary conditions
- thermal coupling conditions

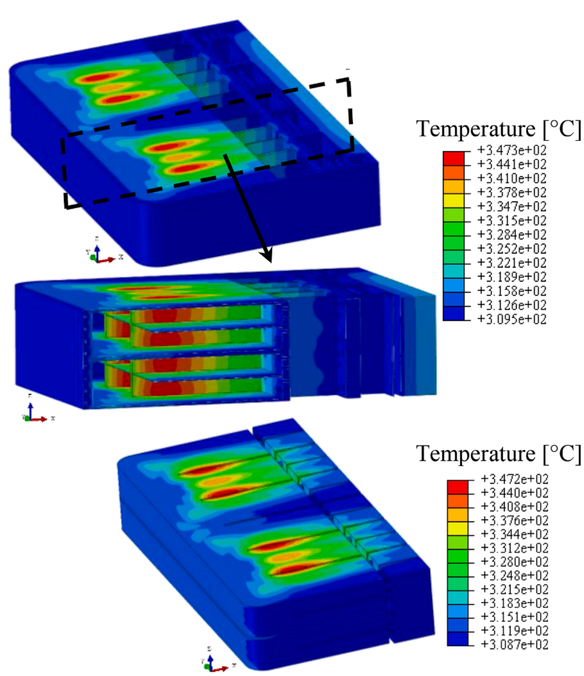

Fig. 3. The temperature initial condition.

The 3D spatial distribution of the nuclear power density, deposited within both structural and functional materials, calculated at the end of plasma flat top (namely in steady state conditions [9]) has been scaled over the time. To this goal, the normalised fusion power profiles shown in Fig. 1 have been used, coherently with the case investigated..

Similarly, the non-uniform radiative plasma heat flux acting onto the tungsten armour in steady-state conditions (0.27 MW/m^2 onto the straight part, decreasing to 0 according to a cosine law onto the bends) has been made time-dependent using the purposely calculated normalised radiative power profiles shown in Fig. 1.

As to the forced convective water cooling, a 1D FEM approach has been adopted. Indeed, the water domain has been represented in the model to simulate the heat transfer with SB (in counter-current) and DWTs walls. In particular, assigning a bulk temperature, a mass flow rate per unit area and a Heat Transfer Coefficient (HTC) value (Table 1) to the nodes belonging to the inlet section of the water domain of each channel, it is possible obtaining the 1D profile of the bulk temperature along the channel abscissa. Hence, the heat transfer convective condition is characterised, for each node of the wall, by the imposed HTC value and the calculated (i.e. position dependent) bulk temperature. In the present study, constant (equal to the steady-state values) nominal mass flow rates and HTCs (Table 1) have been assumed. Instead, a time-dependent bulk temperature [7] has been considered at the inlet section of each channel. Lastly, as reported in [7], the water recirculation in the DWTs has been taken into account, so that the water mixing temperature at the exit of the 1st round is automatically calculated and imposed as inlet temperature for the 2nd one.

Regarding thermal boundary conditions, a uniform temperature of 311.5 °C has been imposed on the nodes lying onto the water manifolds surfaces, whereas both SWs and BSS have been considered adiabatic.

Lastly, a periodic coupling condition has been imposed in between the upper and lower radial-toroidal surfaces of the model, whereas the DWTs and the SB have been considered as tied. A pure diffusive heat transfer has been supposed in between the breeder and steel.

Results in terms of 3D thermal field at different time steps are shown in Fig. 4. Moreover, in Fig. 5, the trends vs. time of the maximum temperatures achieved within FW-SW, BSS, SPsh, SPsv and DWTs are shown.

Results allow predicting that the maximum Eurofer temperature never overtakes 550 °C, that is the suggested limit fot this material. Moreover, it must be further noticed that the maximum Eurofer temperature is lower than 425 °C (i.e. the thermal creep activation temperature) in the LH_100 case. Moreover, after the 600 s ramp-up the maximum temperature continues increasing toward the steady state values, achieved after 2500 s in LH_100 case and after 2000 s in LH_300 case. In any case, during the ramp-up the temperatures are not greater than those achieved in steady state. Hence, one can conclude that, from the thermal standpoint, the ramp-up phase is not more demanding than the end of flat top, regardless of the time instant when the L-H mode transition occurs.

3.2. Structural transient analysis

For each timestep of the thermal analysis, a specific static structural analysis has been performed, considering the following set of loads and boundary conditions:

- time-dependent thermal field

Table 1
Mass flow rate per unit area and HTC.

	MFR [kg/m^2 s]	HTC [W/(m^2°C)]
SB	2986.7	35285.7
DWTs–1st	1493.9	34365.6
DWTs–2nd	2987.7	19737.8

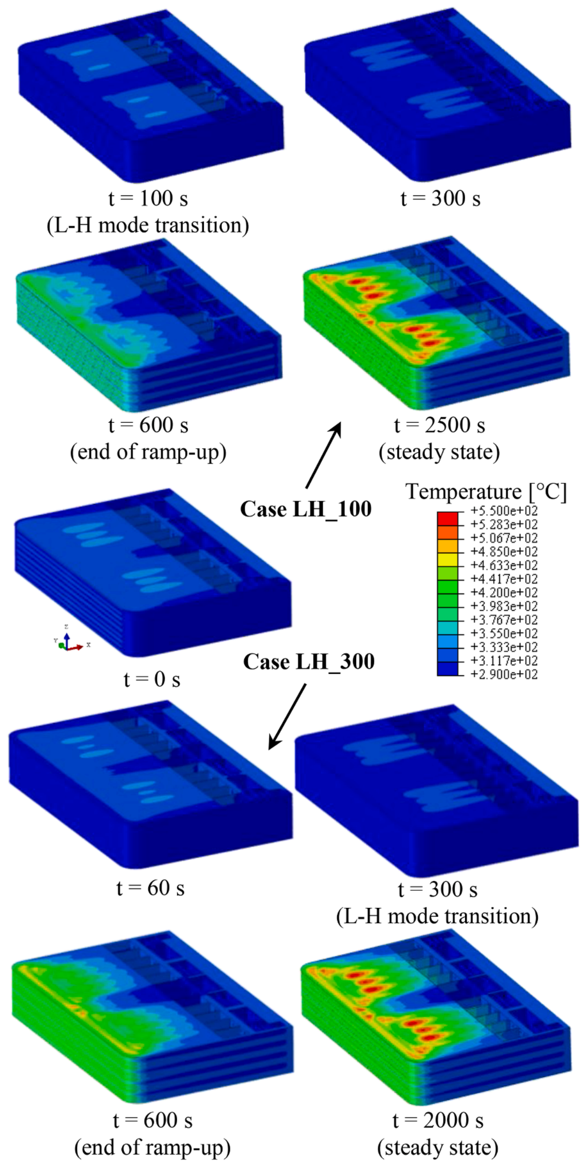

Fig. 4. Thermal field.

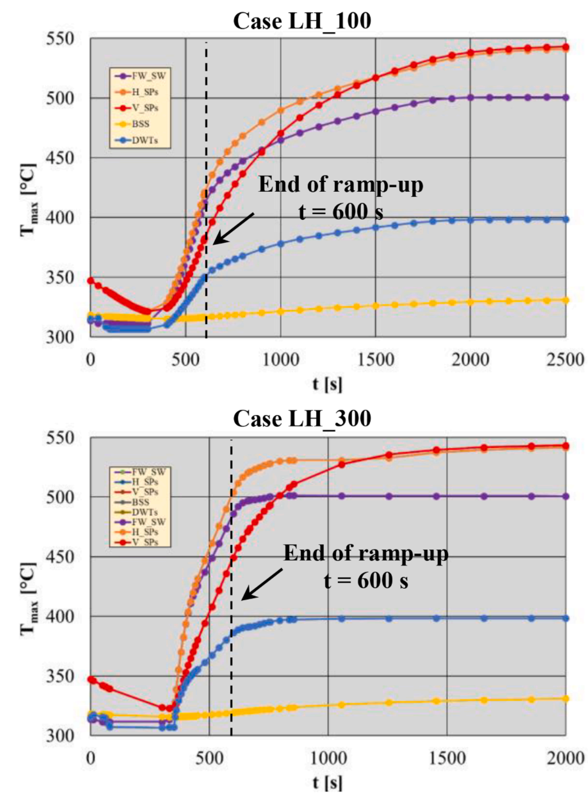

Fig. 5. Maximum temperature vs. time.

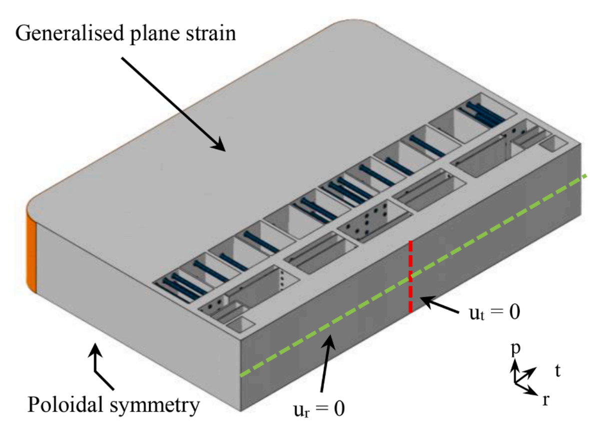

Fig. 6. The mechanical restraints [11].

- internal pressures
- mechanical restraints

The time dependent 3D thermal fields calculated in both the LH_100 and LH_300 cases have been considered, in order to carry out a different structural analysis for each time step of the thermal transient.

The cooling water and breeder domains have been excluded from the FEM model in the structural analysis. Their effect has been simulated imposing, onto the water wetted surfaces, a pressure of 17.825 MPa. Instead, a pressure of 0.575 MPa has been applied to the breeding wetted surfaces. These are the pressure design values, as prescribed by the BB Load Specifications [10].

Lastly, in order to simulate the poloidal continuity of the segment, a poloidal symmetry condition has been imposed on the nodes laying onto the lower surface of the model whereas a generalised plane strain condition has been imposed on the nodes laying onto the upper surface. In addition, radial and toroidal displacement has been prevented to nodes located along two barycentric lines onto the back face of the BSS, as shown in Fig. 6 (taken from [11]).

Results obtained in terms of Von Mises equivalent stress field are reported in Fig. 7 for different timesteps in both the LH_100 and LH_300 cases.

Here it can be observed that the stress level achieved during the ramp-up is less intense than the steady state one. This result is in agreement with the thermal outcomes, and it means, basically, that the ramp-up should not be a concern, as long as the structure is able to withstand the steady state loads.

Lastly, in order to check the fulfilment of the RCC-MRx structural design criteria, a set of paths has been built and a stress linearization procedure has been carried out. The paths have been set-up in those regions where particularly intense Von Mises stress values arose (Fig. 8). In particular, three paths have been obtained throughout the FW thickness, two within the horizontal SP separating the two simulated slices and one path within a vertical SP.

The Level A criteria has been then applied assuming the pertinent temperature-dependent stress limits at 20 dpa, evaluating them at the path average temperature. As expected, it has been found that the most

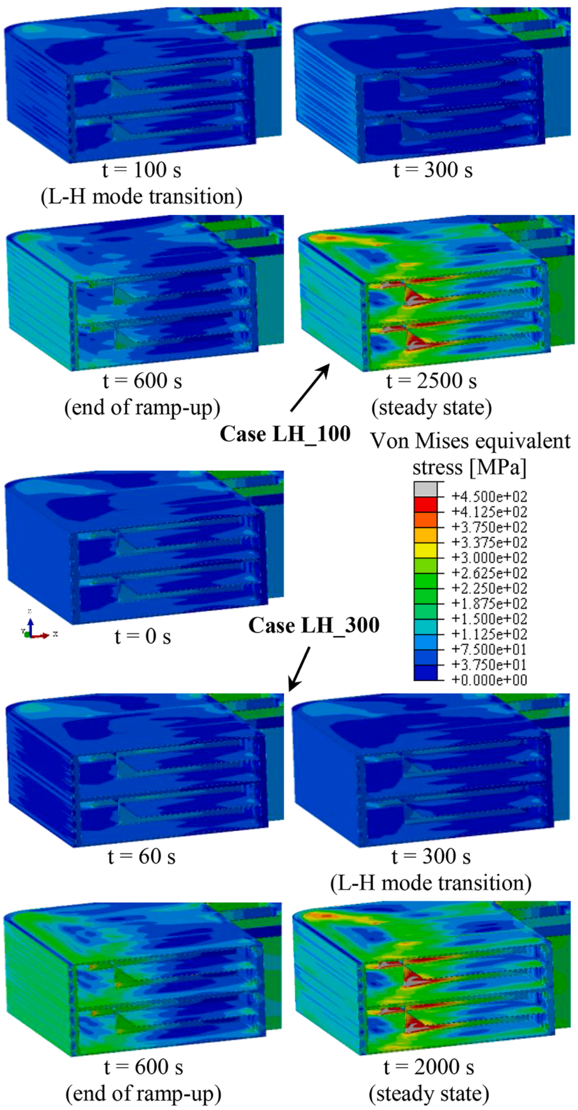

Fig. 7. Equivalent Von Mises stress field – section view.

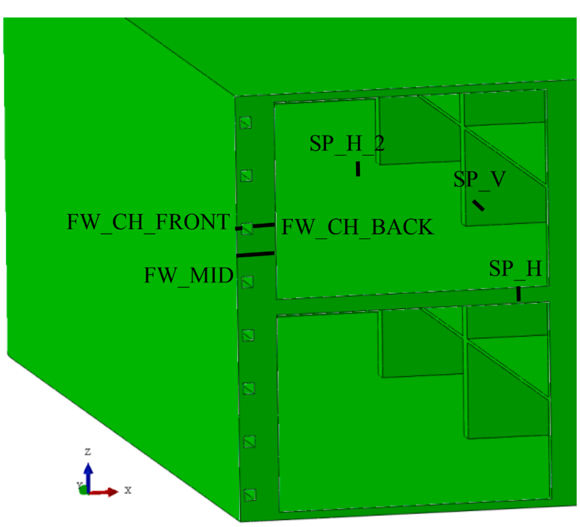

Fig. 8. Path locations.

critical criterion has been that against the Immediate Plastic Flow Localisation (IPFL), $(P+Q)_m$ / S_{em}, which involves primary plus secondary membrane stress. The time evolution of the $(P+Q)_m$ / S_{em} ratio is reported in Fig. 9. Since the other criteria are largely fulfilled along all the considered paths, the full set of results is not reported for the sake of brevity.

From the obtained results, it can be concluded that the ramp-up scenario should not represent a critical operational phase for the WCLL BB. Indeed, even the most critical RCC-MRx criterion is widely fulfilled with a considerable margin, especially in LH_100 where the stress intensity is half of the limit in the worst case (that is the path obtained within the SPv). On the other hand, the curves show that the structural performances significantly worsen going toward the steady state, but this behaviour is well known for the WCLL BB, depending on the attachment system and, in this specific case of a local model, on the excessive conservativeness of the adopted boundary conditions. Indeed, this results trend is valid for the SPs, whereas the paths located within the FW largely fulfil the criterion during the whole transient scenario.

4. Conclusion

In the frame of the conceptual design of the EU DEMO BB, the plasma power transients during the ramp-up phase have been calculated, taking into account the L-H mode transitions. Then, the thermal and structural assessment of the equatorial region of the WCLL COB segment under the ramp-up transient has been carried out in order to assess its response under the non-linear nuclear and radiative power trends.

The obtained results allow concluding that, whatever is the considered ramp-up scenario, the maximum Eurofer temperature does not overtake the suggested limit of 550° C. From the structural standpoint, during ramp-up the considered RCC-MRx criteria are largely fulfilled. A more relaxed behaviour is predicted in case of L to H mode transition at 100 s where, in the worst case, the primary plus secondary membrane stress reaches half of the stress limit at the end of the ramp-up. After

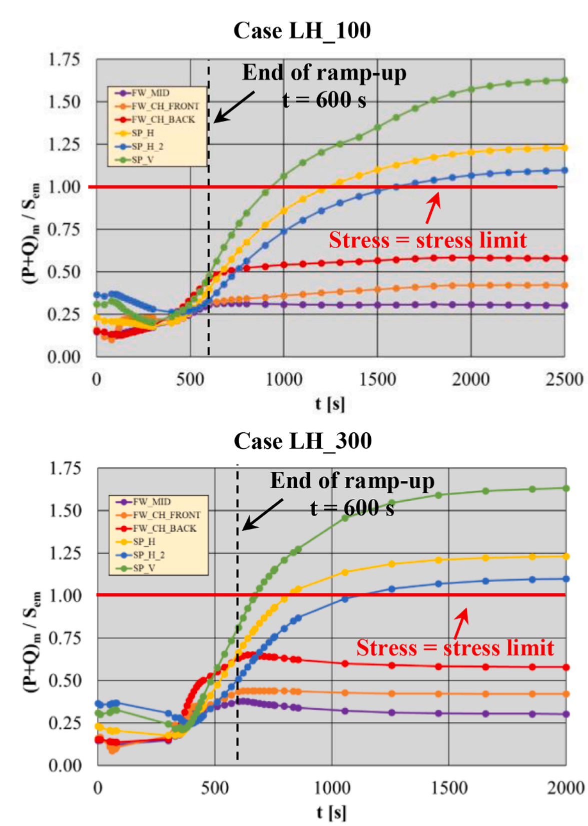

Fig. 9. IPFL criterion vs. time.

ramp-up, criticalities are predicted within SPs (amplified by the selected boundary conditions) whereas the FW is safe in any case. In general, it can be stated that the plasma ramp-up should not be a concern for the WCLL BB, as long as the structure is able to withstand the steady state loads.

CRediT authorship contribution statement

G. Bongiovì: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **M. Siccinio:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **G.A. Spagnuolo:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology. **I. Catanzaro:** Conceptualization, Data curation, Formal analysis, Investigation. **P. Chiovaro:** Conceptualization, Data curation, Formal analysis, Investigation. **P.A. Di Maio:** Conceptualization, Project administration, Supervision. **E. Fable:** Conceptualization, Formal analysis, Methodology. **A. Quartararo:** Conceptualization, Data curation, Formal analysis, Investigation. **E. Vallone:** Conceptualization, Data curation, Formal analysis, Investigation.

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.

Data availability

Data will be made available on request.

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