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Exploratory thermo-mechanical assessment of a pin of the Helium Cooled Pebble Bed breeding blanket concept with a modular pin monoblock design for the EU DEMO nuclear fusion reactor

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ABSTRACT

The Helium-Cooled Pebble-Bed (HCPB) Breeding Blanket (BB) concept is one of the two candidates for the driver blanket of the EU-DEMO nuclear fusion reactor. It shall adopt gaseous helium at 8.0 MPa as coolant and tritium carrier together with solid tritium breeder and neutron multiplier. With the aim of overcoming the critical issues that emerged during the DEMO pre-conceptual design phase, potential HCPB BB design variants are under development in the frame of the DEMO R&D. Among them, the concept envisaging a modular pin monoblock presents the advantages of having all the functional materials contained in a pin structure and of avoiding the need for a first wall, remarkably easing manufacturing. Hence, in this work, a campaign of thermo-mechanical scoping analyses aimed at assessing the performances of this novel BB concept is presented. Starting from a previous thermofluid-dynamic assessment presented in another work, different geometric layouts have been assessed in view of the rules prescribed by the RCC-MRx structural design code. In particular, a multi-scale analysis has been carried out assessing, in a first phase, the global thermo-mechanical performances of the equatorial region of the Central Outboard Blanket segment moving, in a second phase, to the detailed structural analysis of the pin internals. The results obtained from the investigation of two promising geometric configurations have been quite encouraging, showing the conceptual feasibility of this potential HCPB BB variant, and thus paving the way for future and more accurate pre-conceptual analysis.

1. Introduction

The Helium-Cooled Pebble-Bed (HCPB) Breeding Blanket (BB) is one of the candidate driver breeding blankets for the EU DEMO fusion reactor. A new variant of the HCPB BB, namely the HCPB monoblock, has recently emerged in the frame of DEMO Central Team (DCT) studies [1] conducted with the aim of developing conceptual design solutions capable of overcoming the critical issues characterising so far the HCPB BB design [2]. Specifically, the HCPB monoblock foresees a pin monoblock design where all BB functional materials are contained inside fuel-breeder pins without a First Wall (FW).

The multi-physics scoping analysis reported in [1] has allowed to select two pin internal architectures, namely the case 2 and case 5 geometric layouts shown in Fig. 1, that exhibit rather promising thermal and fluid-dynamic behaviour. A detailed description of the two architectures and the rationale behind them can be found in [1] and is omitted here for the sake of brevity. Nevertheless, it is worth recalling that the case 2 configuration features a layer of stagnant helium interposed between two metal sheets and foresees that the coolant flows through the pin domain twice before exiting. In contrast, the case 5 geometry has a simpler design with no stagnant helium and a "one way" helium flow path from inlet to outlet.

Then, the objective of the work herein reported has been the preliminary investigation of the thermo-mechanical performances of these two pin geometric options selected downstream of the thermofluid-dynamic preliminary design optimization.

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In this regard the University of Palermo, in strict contact with the DCT, conducted an exploratory analysis to preliminarily investigate the structural behaviour of the HCPB monoblock BB concept, designed according to the two different design options (case 2 and case 5) previously optimized from the thermo-fluid dynamic standpoint, under steady-state nominal and design loading conditions. In this way, a preliminary coupled optimization encompassing both thermofluid-dynamic and structural aspects has been performed, as done in the past for other critical BB components [3,4]. To this purpose the "sub modelling" technique, already adopted in the frame of DEMO breeding blanket design [5,6], has been employed in order to assess the structural performances of the two geometric configurations with an increased level of detail, properly taking into account the structural effects of the surrounding pins onto the local behaviour of the assessed one. The 3D thermal fields necessary for the structural analysis have been built on the basis of the 2D temperature spatial distributions resulting from the analysis reported in [1] and properly mapped as part of the activity herein reported. Afterwards, two classes of models have been developed. In a first part of the study (described in Section 2), "global models" have been set up and adopted to assess the overall structural performances of the equatorial region of the HCPB monoblock Central Outboard Blanket (COB) segment. In this phase, the overall behaviour of a cluster of pins has been assessed not considering the internal of each of them. Then, in the second part (described in Section 3), "sub models" of a single pin have been developed and used to assess in detail the structural performances of the pin internals designed according to both case 2 and case 5 architectures, properly considering as boundary conditions the displacement fields previously calculated in global model analyses. To this purpose, the verification of the RCC-MRx structural design criteria [7] has been checked, together with the deformation of the pins' internal metal sheets that may obstruct the helium flow.

Then in Section 4 the conclusions are given, focussing on the conceptual soundness of the proposed BB variant that has been judged as worthy of a pre-conceptual design phase aimed at performing more detailed investigations to further optimize the design solutions conceived so far.

The work has been performed adopting a theoretical-numerical approach based on the Finite Element Method (FEM), thanks to the adoption of the Ansys Workbench calculation suite.

2. The global model analysis

In order to perform the structural assessment of the HCPB monoblock COB segment designed according to two different pin architectures selected after a previous thermofluid-dynamic optimization study [1], a multi-level approach has been adopted. First, starting from the geometric model of a half-slice of the pin monoblock, a "global model" has been set up and adopted to obtain an overall structural response of the assessed blanket segment. Then, in order to study in detail the structural behaviour of the pin conceived according to the two selected architectures (case 2 and case 5), specific "sub models" have been developed and adopted to assess the aptitude of the proposed geometric alternatives to withstand the nominal and design loads envisaged for the DEMO HCPB monoblock COB segment. The advantage of using this technique is that, when the local behaviour is assessed with the scope to highlight the differences between the two design options, the boundary conditions (in terms of displacement field) are directly obtained from the global model analysis rather than arbitrarily imposed. Hence, they are somehow representative of the global behaviour of the system, allowing to properly take into account the effect of the system's global behaviour on the local thermomechanical performances.

2.1. The global geometric model

Starting from the provided geometric layout of half slice of the pin monoblock, a more extended geometric model has been created. Exploiting the COB segment intrinsic toroidal symmetry, a triplet of poloidally adjacent half slices has been created properly duplicating upward and downward the provided geometry, so as to represent a considerable portion of the equatorial region of the HCPB monoblock COB segment. Hence, imposing boundary conditions on the top and on the bottom of the triplet of slices would allow the central one to be far enough for the assumed mechanical restraints, so that the results can be retained reliable. Therefore, the 3D geometric model shown in Fig. 2 has been generated and adopted for the first part of the campaign of structural analysis.

It has to be noted that the so-generated 3D geometric model includes the pins' external envelope (consisting of the pin cap, shell and plug) plus the proper portion of the manifolds region, of the side wall and of the Back Supporting Structure (BSS), as depicted in Fig. 3. Moreover, the connecting regions to form the so-called honeycomb configuration have been included too. Therefore, it can be observed that the global model layout is independent, from the geometric point of view, from the pin internal architecture, namely from the specific design option (case 2 and case 5) considered. This aspect will be considered in a second phase, when the local models (i.e. the sub models) will be set up assuming as boundary conditions the results obtained from global model analyses.

2.2. The global FEM models

Once obtained the reference geometric configuration, proper 3D FEM models have been set up in order to assess the structural behaviour

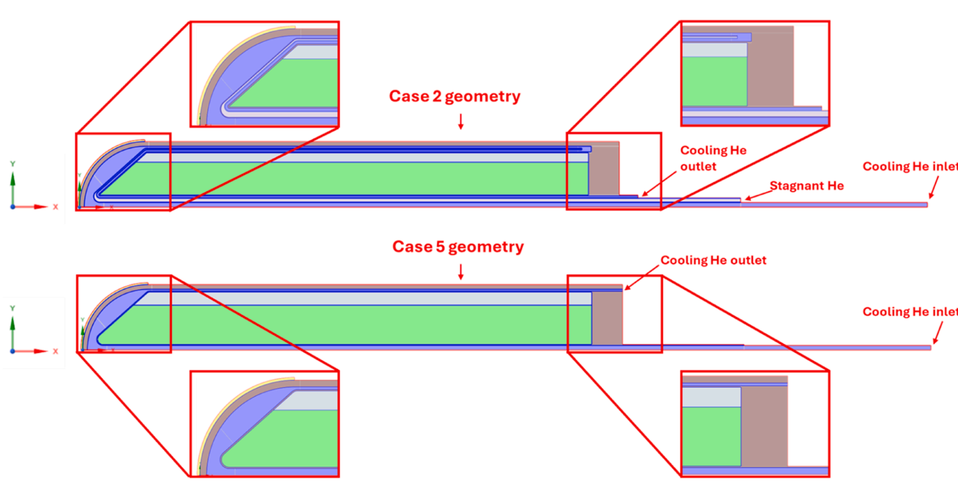

Fig. 1. Case 2 and case 5 pin layouts (symmetric about the X-axis) [1].

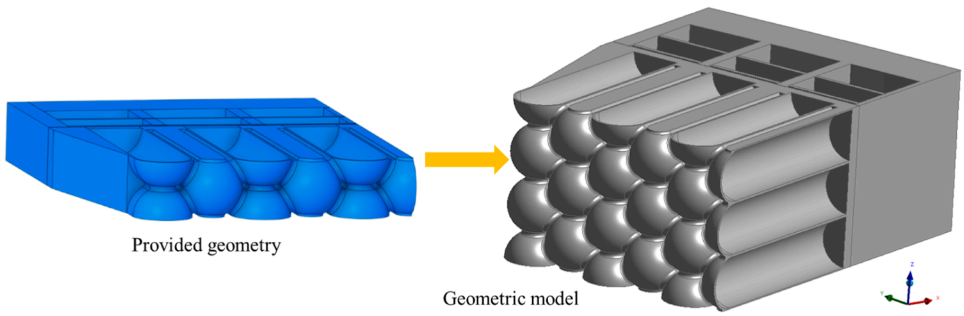

Fig. 2. Global model analysis - the 3D geometric model of the equatorial region of the COB segment.

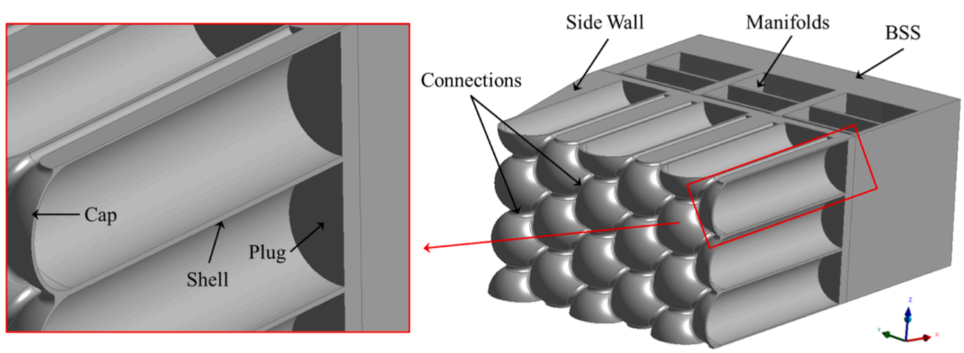

Fig. 3. Global model analysis - details of the 3D geometric model.

of the equatorial region of the HCPB monoblock COB segment conceived according to case 2 and case 5 architectures. Indeed, although the difference in pin internals does not affect the global model geometry, different loading conditions have to be imposed on the basis of the different pin internal architecture.

As a first step, a mesh composed by ~2.75 M nodes connected in ~1.28 M hexahedral and tetrahedral quadratic elements has been generated. EUROFER97 (ferritic-martensitic 9Cr-1WVTa steel, hereon referred to as “Eurofer” for the sake of readability) has been considered as structural material and its temperature-dependent thermophysical properties have been implemented [8].

2.2.1. *Global thermal analysis: loads and boundary conditions*

Once carried out the spatial discretization grid, thermal analyses have been performed to obtain 3D thermal fields to be imported into the structural calculations. To this purpose, the 2D temperature spatial distributions already obtained in the assessment reported in [1] (Fig. 4) have been properly imported into the 3D FEM models. In this regard, the assumed reference case was that foreseeing a plasma heat flux (HF) of 0.3 MW/m^2 acting onto the pin cap externals, a cooling helium temperature rise (ΔT) of 220 °C (inlet at 300 °C, outlet at 520 °C) and an internal surface roughness (μ) of 200 μm. This is the combination of parameters that allowed obtaining temperatures lower than 550 C° in all the Eurofer domain in the case 5 architecture [1].

Then, exploiting the axis-symmetric nature of the pin geometry, the calculated 2D thermal field has been revolved and applied to all the pins included in the 3D FEM model. In this phase, only the 2D thermal fields calculated for the pin envelope (cap, shell and plug) have been mapped to obtain the 3D thermal field. Then, thermal analysis is necessary to calculate the temperature in the remaining regions of the 3D geometric layout considered.

Coherently with the assumptions made in the thermofluid-dynamic optimization study, a temperature of 520 °C has been imposed on all the nodes lying in the helium-wetted surfaces of the outlet manifold, as well as a temperature value of 300 °C has been set to the nodes belonging to the coolant-wetted surfaces of the inlet manifold. Then, the symmetry faces have been considered adiabatic, as well as the side wall and BSS external surfaces.

2.2.2. *Global structural analysis: loads and boundary conditions*

Mechanical loads and boundary conditions have been applied to assess the structural behaviour of the equatorial region of the HCPB monoblock COB segment under steady-state nominal and design loading conditions.

As already said, the 3D temperature distribution calculated in the 3D thermal analysis has been imposed to ensure the consideration of the

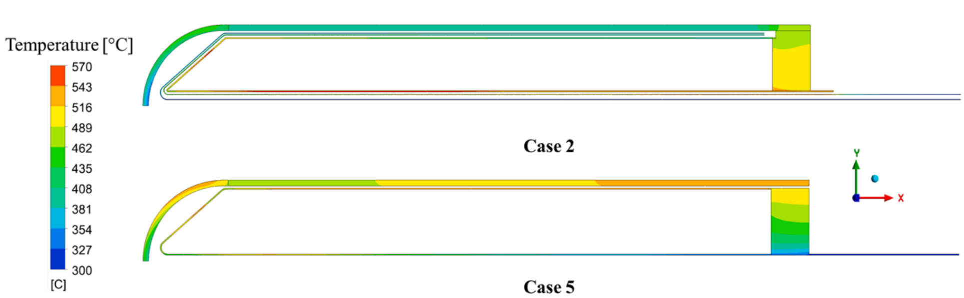

Fig. 4. 2D thermal fields from thermofluid-dynamic optimization (HF = 0.3 MW/m^2, ΔT = 220 °C, μ = 200 μm) [1].

thermally induced stress, assuming a no stress temperature of 22 °C.

Regarding pressure loads, two different scenarios have been investigated. In the first, the nominal pressure of helium, equal to 8.0 MPa, has been assumed for the pins' and manifolds' surfaces wetted by coolant and purge gas. In the second scenario the design pressure, equal to 9.2 MPa, has been conservatively considered.

Regarding mechanical restraints, a combination of boundary conditions has been imposed in order to simulate the poloidal continuity of the modelled region. In particular, a vertical symmetry condition has been imposed to the nodes laying onto the model's lower surface, whereas a Generalised Plane Strain (GPS) condition has been imposed onto the model's upper face (Fig. 5). The latter condition forces the nodes initially laying onto the model's upper face to remain onto the same plane, which can translate along the Z direction and tilt around the Y and X axes. Moreover, a Y symmetry condition has been imposed onto the toroidal plane of symmetry, so as to simulate the toroidal continuity of the modelled equatorial region. Lastly, the radial displacement (Ux) has been prevented to the nodes lying onto the red line depicted in Fig. 5 with the scope to simulate the radial action of the blanket attachment system, ensuring the numerical convergence of the structural analysis.

2.3. Results of global analyses

Once assigned the proper loads and boundary conditions, thermal and structural steady-state analyses have been run to assess the overall behaviour of the equatorial region of the HCPB monoblock COB segment.

2.3.1. Global thermal analysis

Although the temperature in most of the calculation domain has been imposed thanks to the above-mentioned boundary conditions, thermal analyses have been necessary to calculate the thermal field in the side wall, manifolds and BSS bodies as well as within the pins connecting regions. The results obtained are shown in Fig. 6. It can be observed that, on average, case 5 presents higher temperatures, which may appear contradictory when compared to the thermal fields in Fig. 4, where only case 2 layout presents temperatures higher than 550 °C in Eurofer domains. However, this apparent discrepancy can be explained by recalling that the 3D global models do not include the pins' internals, which is where the highest Eurofer temperatures occur in the case 2 layout.

2.3.2. Global structural analysis

The structural analyses under nominal and design pressure conditions have been run. The main scope of the global model structural analysis is to assess the global behaviour of the pin envelope, obtaining boundary conditions for the detailed sub model analysis. Results in terms of equivalent Von Mises stress field and displacement field are shown herein for case 2 and case 5 geometric configurations. For the sake of brevity, only results obtained under design pressure conditions are shown considering also that, qualitatively, the same trends have been observed in nominal pressure conditions. In particular, the Von Mises stress field and the total displacement 3D spatial distributions are depicted in Fig. 7 and Fig. 8 for case 2, whereas the analogous fields calculated for case 5 geometry are shown in Fig. 9 and Fig. 10, respectively. Specifically, it can be observed that reasonable values for both Von Mises stress and total displacement are predicted. Highest values are calculated, on average, in case 5 meaning that the pin envelope is more stressed in this case due to the higher temperatures. Moreover, in both the cases, no particular stress concentration is observed in the pins connection structures, meaning that the honeycomb configuration is robust enough to keep the pins in their mutual positions without suffering excessively. Indeed, as further confirmation, a quite uniform displacement distribution is predicted among the pins. Some particularly stressed regions also emerged in correspondence of sharp corners or edges as well as in the areas where boundary conditions have been defined, so being not particularly significant for the purpose of this study. It has to be further observed that high stress is also predicted within the manifolds region. Nevertheless, since the manifolds architecture has not been optimized (given the exploratory nature of this study) for the HCPB monoblock structure, representing a kind of dummy body to connect the pins, this result can be noted to draft a possible follow-up of this activity.

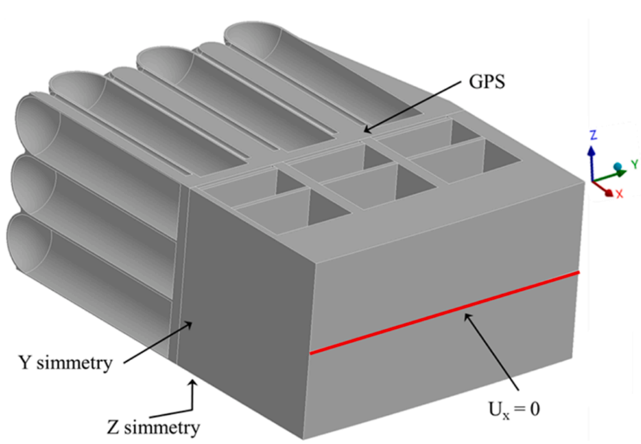

Fig. 5. Global model analysis - mechanical restraints.

3. The sub model analysis

Once assessed the overall structural behaviour of the equatorial region of the HCPB BB monoblock COB segment, the detailed analysis of a single pin conceived according to the case 2 and case 5 architecture has been performed.

3.1. The local geometric model

Starting from the global model representing the equatorial region of the HCPB monoblock COB segment, the envelope of a pin has been extracted as indicated in Fig. 11. Then, on the basis of the thermofluid-dynamic optimization study carried out in [1], the internal architecture of the pin has been added for both case 2 and case 5 geometric layouts. In particular, exploiting the axis-symmetric nature of the pin, the 2D geometry generated in the previous work has been revolved around the pin's axis to obtain the 3D geometric model. A section of the so-obtained 3D pin layouts is shown in Fig. 11. It is hereby reminded that case 5 layout foresees a “one way” cooling helium flow path from inlet to outlet in the pin domain, differently from case 2 envisaging double passage of the coolant throughout the pin. Hence, the case 2 architecture is more complex, envisaging internal metal sheets to allow the helium recirculation throughout very small annular sections.

3.2. The local FEM models

Once generated the pin geometric layouts, proper 3D FEM models have been set up in order to assess in detail their structural response under the selected loading conditions. As to case 2, a mesh composed of ~4.75 M nodes connected in ~2.01 M quadratic tetrahedral elements has been set-up, whereas regarding case 5 a spatial discretization grid consisting of ~5.43 M nodes connected in ~3.30 M quadratic tetrahedral elements has been realised. Eurofer steel has been considered also for the pin internal components.

3.2.1. Sub model structural analysis: loads and boundary conditions

In order to investigate the structural behaviour of the pin structure conceived according to the case 2 and case 5 architecture, two different scenarios (nominal pressure and design pressure, envisaging 8.0 and 9.2 MPa, respectively, for both purge gas and coolant [9]) have been

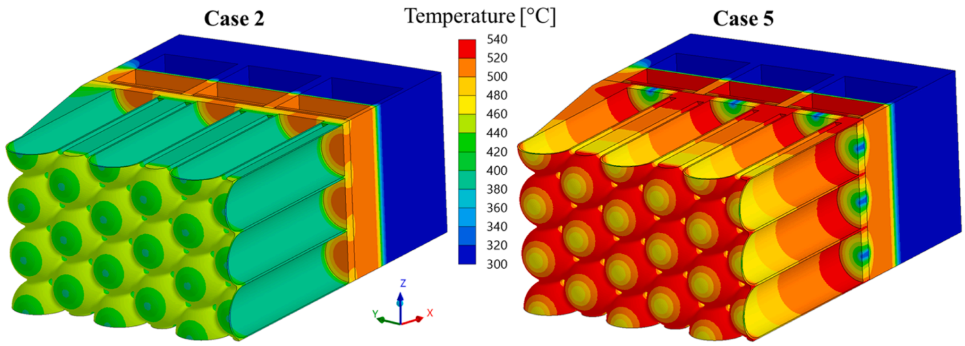

Fig. 6. Global model analysis - 3D thermal fields.

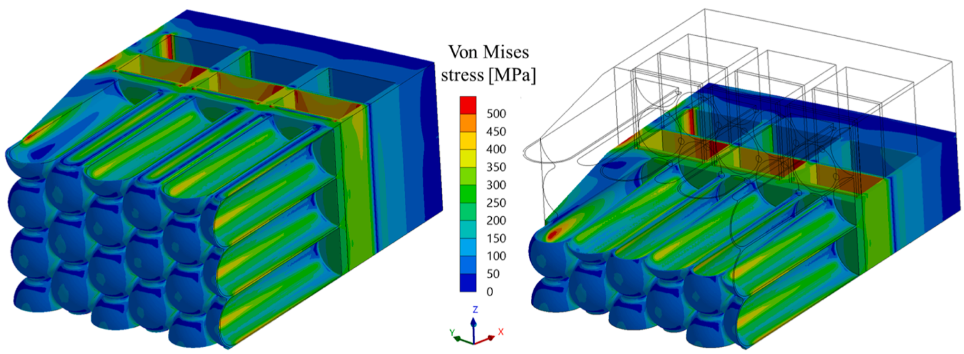

Fig. 7. Global model - case 2 - Design pressure - Von Mises equivalent stress.

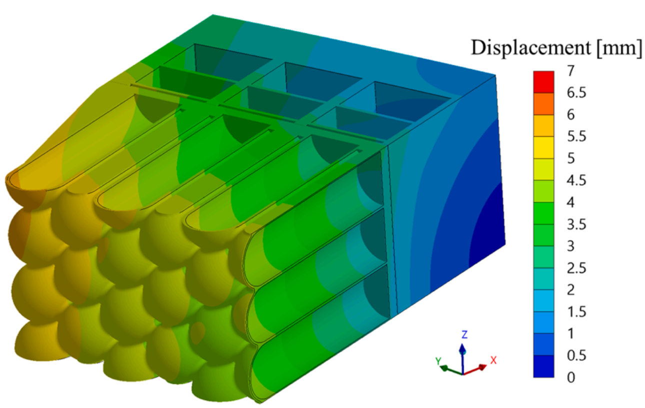

Fig. 8. Global model - case 2 - Design pressure - Total displacement.

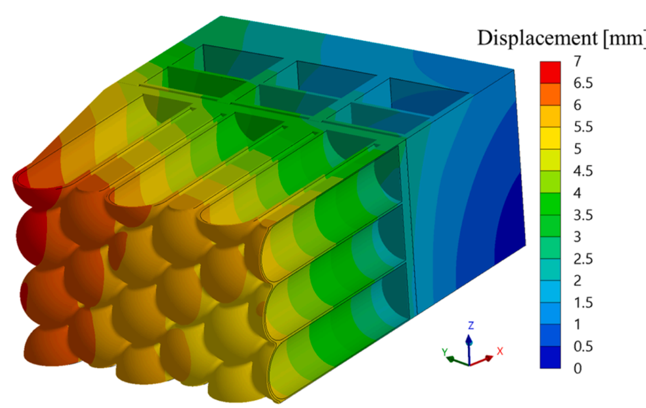

Fig. 10. Global model - case 5 - Design pressure - Total displacement.

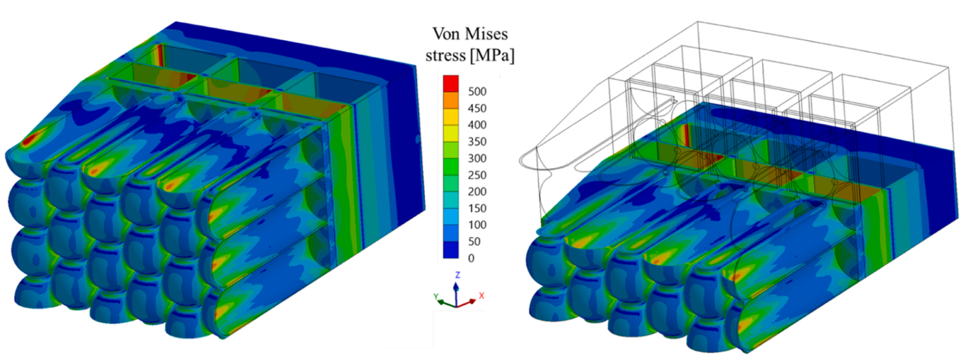

Fig. 9. Global model - case 5 - Design pressure - Von Mises equivalent stress.

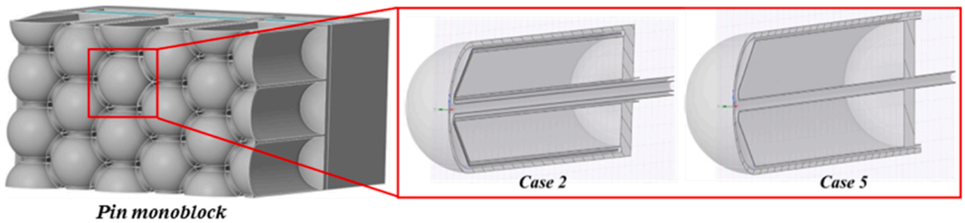

Fig. 11. Geometry of the sub models - the geometric models (view in section).

considered as already done for global model analysis. Since the contact among beryllide blocks and the pin internals is not perfect because of small gaps and/or manufacturing imperfections allowing helium permeating, also these surfaces have been assumed subjected to the purge gas pressure.

Regarding the 3D thermal field imposed to ensure the consideration of the thermal induced stress, assuming a no-stress temperature of 22 °C, a combined mapping approach has been followed for the different pin components. Indeed, as to the pin external envelope, the thermal field has been directly mapped from the global model thermal analysis. Instead, as to the pin internals, the 2D temperature spatial distributions already obtained in the assessment reported in [1] (Fig. 4) have been properly imported into the 3D FEM models exploiting the axis-symmetric nature of the pin geometry (simply revolving the 2D thermal field around the pin's axis). Hence, the resulting 3D thermal fields applied for structural analysis are shown in Fig. 12 and Fig. 13, where longitudinal sections of the pins are shown for case 2 and case 5 respectively. It is worthy to be reminded that case 5 architecture is the one showing Eurofer temperatures lower than 550 °C among those assessed.

Then, as to the boundary conditions, the displacement fields calculated from the global model analysis have been mapped onto the pin external surfaces in contact with the rest of the structure. Thus, it is possible to consider the mechanical effect of the surrounding pins on the structural behaviour of the assessed one. For both the cases, similar displacement fields have been found in nominal and design pressure load scenarios since the effect of the pressure variation is not so intense in terms of deformation of the pin externals. As an example, the displacement field mapped onto the pin externals in the design pressure load condition is shown in Fig. 14. It has to be mentioned that, in order to apply the RCC-MRx design criteria, an analysis with only secondary loads has been performed too (here not shown for the sake of brevity). In this case, a corresponding displacement field (namely a displacement field originated by a load case with the only thermal field) has been properly calculated in the global models and mapped onto the sub models external surfaces.

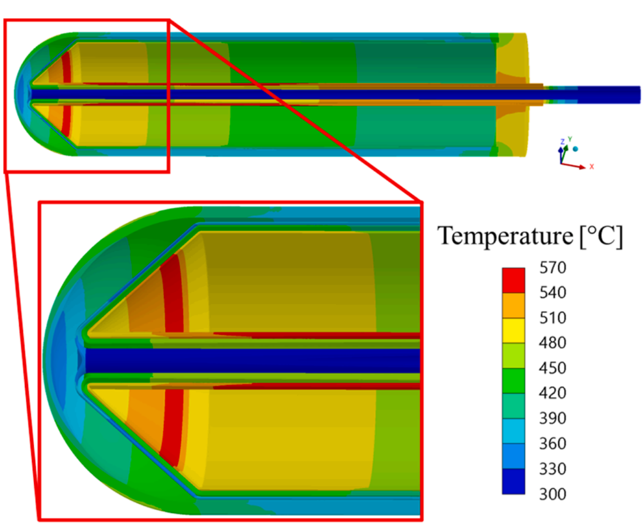

Fig. 12. Pin 3D thermal field - case 2 (view in section).

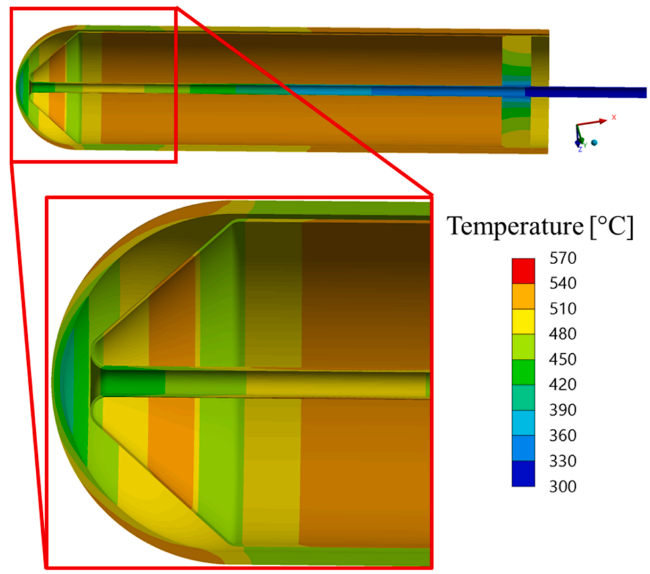

Fig. 13. Pin 3D thermal field - case 5 (view in section).

3.3. *Results of sub model analyses*

Once performed the structural analyses, results in terms of Von Mises stress and displacement of the pin internals have been checked. Then, once selected the most critical areas, paths have been built in order to carry out a stress linearization procedure aimed at the verification of the RCC-MRx criteria. In this regard, level A rules have been adopted.

Regarding Von Mises equivalent stress, for a given architecture similar distributions are obtained passing from nominal to design pressure scenario, since the most significant contribution in terms of stress is given by the thermal field. In particular, in the design pressure case, higher stress is predicted in some specific areas, such as the pin plug and the bend region in correspondence of the helium jet outlet. Also, some areas of the pin envelope experience high stress, suggesting particular care in the verification of the RCC-MRx criteria. As an example, the 3D spatial distribution of the Von Mises stress in the design pressure load case is shown in Fig. 15 for case 2 and in Fig. 16 for case 5.

In order to check the fulfilment of the RCC-MRx structural design criteria, a set of paths has been selected. They have been built throughout the thicknesses of the pertinent components in the locations where it has been chosen to perform the stress linearization procedure aimed at the criteria verification. The path locations are indicated in Fig. 17 (case 2) and Fig. 18 (case 5), shown as superimposed to section views of the Von Mises stress field calculated for the design pressure case. As it can be observed, no path has been constructed in case 2 within inner and outer metal sheets because of the low stress predicted.

The RCC-MRx rule against Immediate Excessive Deformation (IED, P_m/S_m), Immediate Plastic Instability (IPI, $(P_m+P_b)/(K_{eff}\ S_m)$) and

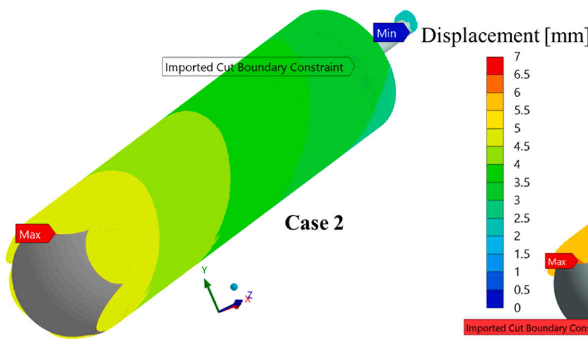

Fig. 14. Design pressure - The imposed displacement.

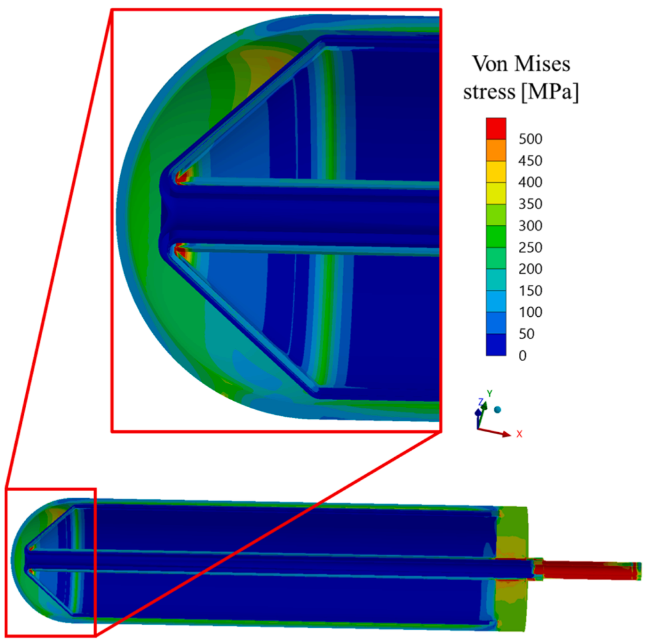

Fig. 15. Sub model - case 2 - Design pressure - Von Mises equivalent stress.

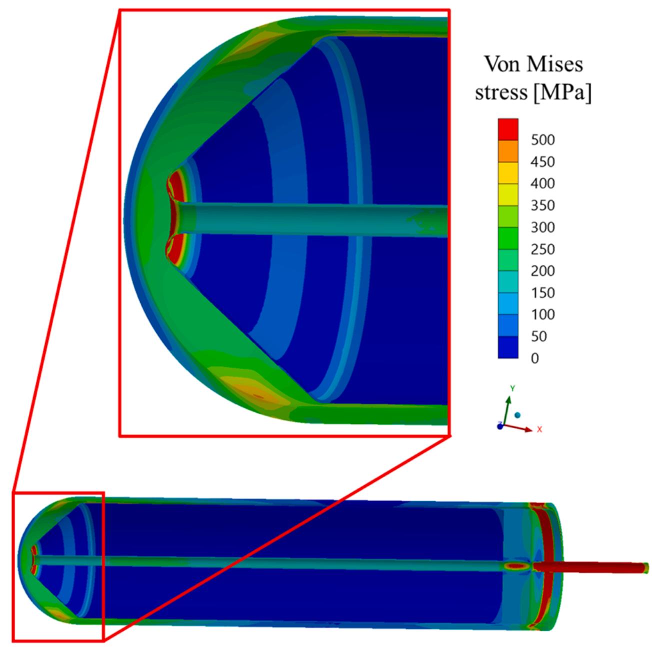

Fig. 16. Sub model - case 5 - Design pressure - Von Mises equivalent stress.

Immediate Plastic Flow Localization (IPFL, $(P_m+Q_m)/S_{em}$) have been considered, calculating the stress limits values at the path average temperature (T_{ave}) for level A scenarios. Here, with “P” and “Q” one indicates primary and secondary stress, respectively, as well as with the subscripts “m” and “b” the membrane and the bending components are intended. In the end, with “S” the stress limits are indicated whereas “K_{eff}” is a geometric factor here assumed equal to 1.5 [7]. Hence, the IED and IPI criteria are against the primary load (i.e. the pressure load), whereas the IPFL also considers the effect of the secondary load (i.e. the thermal induced stress). Regarding case 2, the obtained results are summarised in Table 1 whereas the verification of the RCC-MRx criteria fulfilment carried out for case 5 is reported in Table 2. In both the tables, T_{ave} values in between 500 °C and 550 °C are highlighted in orange, as well as values exceeding the suggested Eurofer limit of 550 °C (predicted in case 2 only) are marked in red.

Comparing the results obtained under nominal and design pressure load case, it can be noted that under design pressure some paths fulfil with a narrower margin the IED and IPI criteria (values highlighted in orange are the most critical). However, the margin increases under nominal pressure case so no particular issues are predicted under the primary stress point of view.

On the other hand, the obtained results allow concluding that, as to case 2, some minor concerns may arise on the structural integrity of the pin envelope. Indeed, a few paths within shell and cap show, under both nominal and design pressure, primary plus secondary membrane stress values (the ones considered in IPFL crierion) slightly higher than the limit (values highlighted in red). Nevertheless, since the issue is regarding the IPFL criterion, which is characterised by a high level of conservativism, and observing that the calculated stress intensities slightly exceed the limit, the overall structural behaviour of the pin envelope can be still considered quite promising. Moreover, it is also to be said that almost all the paths built within shell and caps are in the region where displacement from global model is mapped (so results might be influenced from numerical issues). Furthermore, criticalities emerge in the cladding jet bend region, particularly stressed because of the secondary stress (along the path “Cladding jet bend 1″ the equivalent stress almost doubles the stress limit). Here, a reshaping of this region should be considered. Nevertheless, the rest of the internal components exhibits very good structural performances in terms of RCC-MRx criteria verification. Also the hottest regions largely ensure quite good structural performances.

Concerning case 5, similar considerations can be done for the pin shell and cap, even though in this case the IPFL criterion is not met with a considerable margin because of the higher thermal level of the pin envelope with respect to case 2. Nevertheless, given the potential sources of uncertainty mentioned above, this configuration cannot be discarded in principle also considering that, in the worst path (“Shell 2″), the equivalent stress is about 1.5 times the limit (not overly severe given

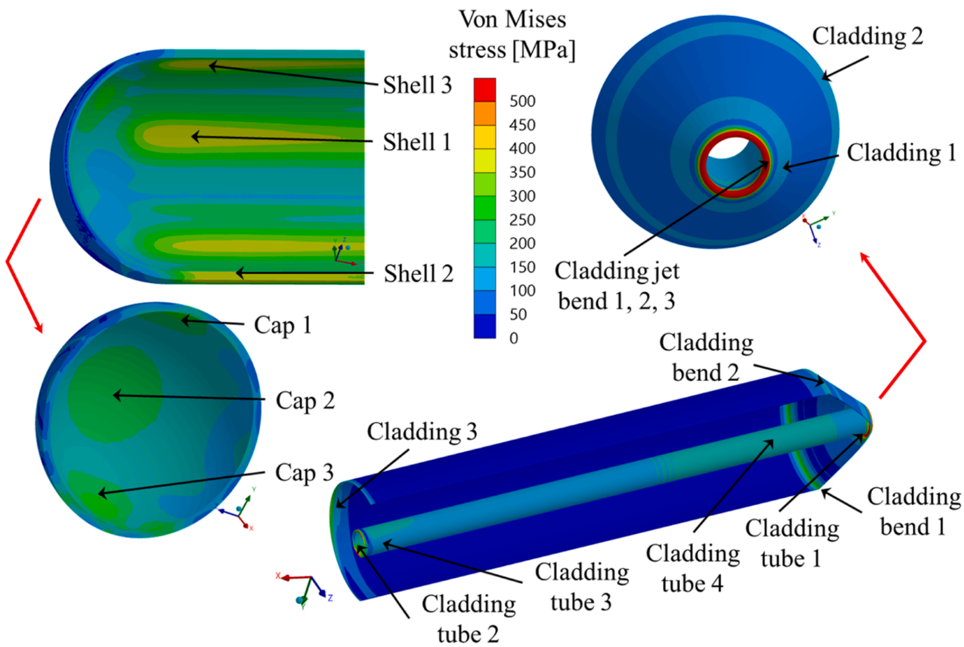

Fig. 17. Case 2 - Path locations.

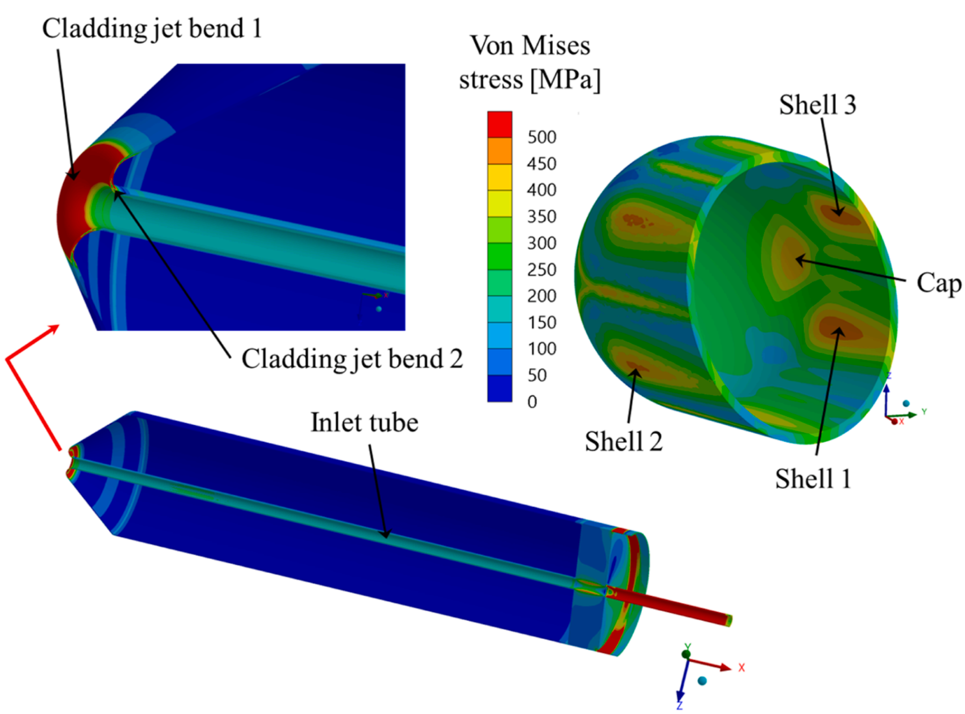

Fig. 18. Case 5 - Path locations.

the high level of conservativism affecting this criterion). In addition, no criticalities are predicted for the internal cladding, fulfilling the criteria with a good margin even in the most stressed region (still the cladding jet bend). Hence, also case 5 architecture seems to be worthy to be of further assessment.

Lastly, attention has been paid to the deformation of the case 2 internal metal sheets. Indeed, the initial distance in between the two metal sheets is of 1 mm. As an effect of the applied loads, the differential deformation could generate interferences that might obstruct the helium flow. As shown in Fig. 19, in the design pressure load case the inner metal sheets moves backward along the pin axis (namely the X direction shown in figure) more than the outer sheet, causing an overlapping in between the two. Even in the nominal pressure scenario, the initial gap is almost totally closed by the different axial movement of the two sheets (the inner moving towards negative X more than the outer). This observation could pose concerns in the development of the HCPB monoblock BB concept adopting case 2 architecture. Actually, since no contact models have been implemented in the FEM models, the mutual exchange of forces due to the contact is not taken into account in this study. So it could be that the system achieves an equilibrium configuration with a small gap in between the sheets, at the cost of an increased stress. In this case, it should be evaluated if the reduced gap has a

Table 1
RCC-MRx criteria verification - case 2.

Path	P_m/S_m		$(P_m+P_b)/(K_{eff}\ S_m)$		$(P_m+Q_m)/S_{em}$		T ave [°C]
	Nominal	*Design*	*Nominal*	*Design*	*Nominal*	*Design*	
Shell 1	0.48	0.55	0.44	0.50	1.05	1.08	392.1
Shell 2	0.55	0.63	0.39	0.45	1.10	1.14	397.4
Shell 3	0.50	0.57	0.45	0.52	1.06	1.09	392.8
Cap 1	0.65	0.75	0.47	0.54	0.61	0.59	440.5
Cap 2	0.43	0.49	0.32	0.37	0.24	0.24	375.8
Cap 3	0.82	0.95	0.65	0.75	0.68	0.65	441.2
Cladding bend 1	0.02	0.02	0.03	0.04	0.42	0.42	494.2
Cladding bend 2	0.02	0.02	0.02	0.02	0.4	0.40	493.6
Cladding jet bend 1	0.05	0.06	0.04	0.05	1.95	1.96	484.0
Cladding jet bend 2	0.04	0.04	0.04	0.05	1.35	1.35	484.0
Cladding jet bend 3	0.02	0.02	0.03	0.04	0.63	0.64	485.2
Cladding 1	0.01	0.01	0.01	0.01	0.37	0.38	495.5
Cladding 2	0.01	0.01	0.01	0.01	0.20	0.20	540.7
Cladding tube 1	0.01	0.01	0.01	0.01	0.41	0.41	489.5
Cladding tube 2	0.08	0.09	0.14	0.16	0.48	0.49	518.8
Cladding tube 3	0.06	0.07	0.10	0.11	0.41	0.41	519.0
Cladding tube 4	0.02	0.02	0.01	0.01	0.60	0.60	561.1
Cladding 3	0.40	0.45	0.41	0.48	0.47	0.50	438.3

Table 2
RCC-MRx criteria verification - case 5.

Path	P_m/S_m		$(P_m+P_b)/(K_{eff}\ S_m)$		$(P_m+Q_m)/S_{em}$		T ave [°C]
	Nominal	*Design*	*Nominal*	*Design*	*Nominal*	*Design*	
Inlet tube	0.01	0.01	0.01	0.01	0.51	0.51	516.3
Shell 1	0.55	0.63	0.39	0.45	1.36	1.40	393.0
Shell 2	0.71	0.82	0.51	0.59	1.47	1.51	529.2
Shell 3	0.65	0.74	0.52	0.59	1.28	1.31	470.5
Cap	0.70	0.81	0.51	0.58	1.00	0.97	473.7
Cladding jet bend 1	0.02	0.02	0.05	0.05	0.75	0.75	471.4
Cladding jet bend 2	0.02	0.02	0.01	0.02	0.77	0.77	516.8

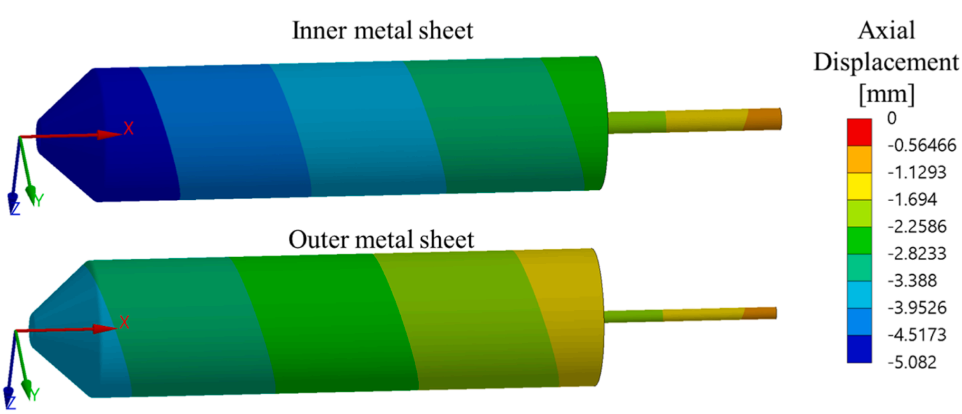

Fig. 19. Case 2 – Design pressure – Metal sheets axial displacement.

negative impact on the helium circulation. Hence, the obtained results should be taken as an alert for investigating more in deep this aspect in the follow up of the activity.

4. Conclusion

The exploratory thermo-mechanical assessment of the HCPB monoblock BB concept, envisaging a blanket structure made of a cluster of pins, has been described and critically discussed. Moving from a previous thermofluid-dynamic optimization, two promising pin architectures (case 2 and case 5) have been selected for the preliminary assessment of the pin structural performances under steady-state nominal and design pressure loads. Results have allowed to conclude that both the configurations are quite promising from the structural standpoint and in principle worthy to be assessed with more detailed models and assumptions, even though the internals of case 2 present a few criticalities. Indeed, the cladding should be reshaped in the region of the jet bend because of the predicted high stress, whereas the metal sheets foreseen to allow the helium recirculation should be equipped with spacers or slightly reshaped in order to avoid the blocking of the helium flow because of their mutual deformation. Lastly, also the manifolds region should be optimized in any case to reduce the predicted high stress.

CRediT authorship contribution statement

A. Gioè: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **F.A. Hernández:** Writing – review & editing, Supervision, Data curation, Conceptualization. **G. Bongiovì:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **I. Catanzaro:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **A. Quartararo:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **E. Vallone:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **G. Agnello:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **G.A. Spagnuolo:** Supervision, Data curation, Conceptualization. **S. d'Amico:** Supervision, Data curation, Conceptualization. **P. Chiovaro:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation, Conceptualization. **P. A. Di Maio:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation, Conceptualization.

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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