WPS2-CPR(18) 20145

G Bongiovi et al.

Preliminary structural assessment of the HELIAS 5-B breeding blanket

Preprint of Paper to be submitted for publication in Proceeding of
30th Symposium on Fusion Technology (SOFT)

Preliminary structural assessment of the HELIAS 5-B breeding blanket

G. Bongiovì[a]*, A. Häußler[a], P. Arena[b] and the W7-X team

[a]Karlsruhe Institute of Technology (KIT), Institute for Neutron Physics and Reactor Technology (INR),
Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, GERMANY
[b]Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici, Università di Palermo,
Viale delle Scienze, I-90128 Palermo, ITALY

The European Roadmap to the realisation of fusion energy, carried out by the EUROfusion consortium, considers the stellarator concept as a possible long-term alternative to a tokamak fusion power plant. To this purpose a pivotal issue is the design of a HELIcal-axis Advanced Stellarator (HELIAS) machine equipped with a tritium Breeding Blanket (BB), considering the achievements and the design experience acquired in the pre-conceptual design phase of the tokamak DEMO BB. Therefore, within the framework of EUROfusion Work Package S2 R&D activity, a research campaign has been launched at KIT.

The scope of the research has been the determination of a preliminary BB segmentation scheme able to ensure, under the assumed loading conditions, that no overlapping may occur among the BB neighbouring regions. To this purpose, the Helium-Cooled Pebble Bed (HCPB) and the Water-Cooled Lithium Lead (WCLL) BB concepts, listed among those presently considered for the design of the DEMO tokamak fusion reactor, have been taken into account. A 3D CAD model of a HELIAS 5-B torus sector has been adopted, focussing attention on its central region. Due to the early stage of the HELIAS 5-B BB R&D activities, the considered CAD model includes homogenized blanket modules without internal details. Hence, in order to simulate the features of the HCPB and WCLL BB concepts, equivalent material properties have been purposely calculated and assumed. Moreover, a proper nominal steady state loading scenario, based on the DEMO HCPB and WCLL thermomechanical analyses, has been taken into account.

A theoretical-numerical approach, based on the Finite Element Method (FEM), has been followed and the qualified ANSYS commercial FEM code has been adopted. The obtained results are herewith presented and critically discussed.

Keywords: HELIAS, stellarator, breeding blanket, thermomechanics, FEM analysis.

1. Introduction

Within the framework of EUROfusion action, the stellarator concept is considered as a possible long-term alternative to tokamak for the construction of the first fusion power plant [1]. To this purpose, the Work Package S2 (WPS2) promotes R&D activities aimed at studying the feasibility of a HELIcal-axis Advanced Stellarator (HELIAS) machine equipped with a tritium Breeding Blanket (BB). In particular, attention is being paid to the HELIAS 5-B machine, formed by 5 torus BB sectors of 72 ° each [2,3].

Since the development of the stellarator concept-based machine is at early stage compared to tokamak, design choices, analysis tools and assumptions already conceived for the latter are being adapted, with the pertinent modifications, to the former in order to bridge the gap between the two concepts development. To this end, a preliminary structural assessment is in progress at KIT in order to attain a feasible BB segmentation strategy, determining proper gap amount among BB adjacent regions, on the basis of views reported in [2].

The HELIAS 5-B BB far end regions, namely the so-called "triangular" and "bean shape" section regions (Fig. 1), have been already studied to this end [4] providing encouraging results. In this paper, the central region of one HELIAS 5-B BB sector is assessed in order to determine, coherently with the outcomes of the far end regions analyses, a preliminary BB segmentation scheme able to ensure that no overlapping occurs among BB neighbouring regions considering an initial 20 mm gap between segments. To this purpose, the Helium-Cooled Pebble Bed (HCPB) and the Water-Cooled Lithium Lead (WCLL) BB concepts, presently developed for the DEMO tokamak machine [5-10], have been considered. A strict interaction with the DEMO BB design teams (University of Palermo and KIT labs) has been launched and the qualified ANSYS code, based on the Finite Element Method (FEM), has been adopted.

2. The HELIAS 5-B BB geometric model

According to [2], a Multi-Module Segmentation scheme is envisaged for the HELIAS 5-B BB. In comparison with DEMO BB, HELIAS 5-B modules are generally bigger and can be considered as BB segments (or large modules) [11]. A 3D geometric model of half HELIAS-5B torus sector (Fig. 1 A and B), including the Vacuum Vessel (VV) and dummy BB segments (full blocks without internal details), has been considered for this study. It includes 8 BB rings which have been modified so to be separated by 20 mm gaps (Fig. 1 C). Each ring encompasses 5 BB segments [2], edited so to be separated, in their turn, by 20 mm gaps (Fig. 1 C).

---

author's email: gaetano.bongiovi@kit.edu

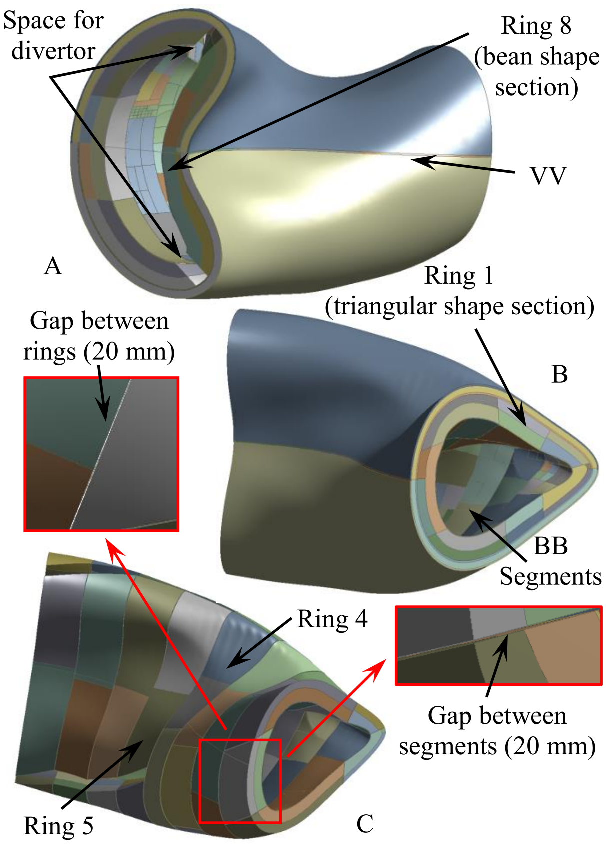

Fig. 1. The HELIAS 5-B BB geometric model.

3. The 3D FEM model

A 3D FEM model reproducing the central region of a HELIAS 5-B BB sector, given by the Ring 4 and Ring 5 (Fig. 1), has been set-up. It includes the proper portion of VV and, within each segment, the Back Supporting Structure (BSS), the Breeding Zone (BZ) and the First Wall (FW) can be identified (Fig. 2).

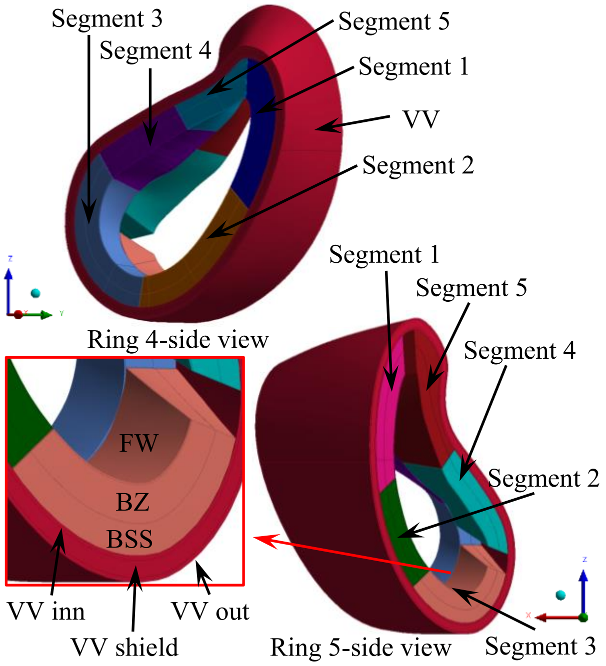

Fig. 2. The HELIAS 5-B BB central region model.

A mesh independence analysis has allowed selecting a spatial discretization grid composed by ~1.4M nodes connected in ~6.8M linear tetrahedral elements.

3.1 Loads, boundary conditions and assumptions

Both HCPB and WCLL BB concepts have been considered in this study. Concerning the thermal state, spatially-averaged temperatures (T_{av}) of FW, BZ and BSS have been calculated from the DEMO HCPB and WCLL BB thermal analysis [12,13] and imposed (Table 1). Moreover the VV (inner, shield and outer) has been assumed at the uniform temperature of 200 °C [14].

Regarding gravity load, the global Z direction has been considered as the vertical one (Fig. 2). Furthermore, since the set-up model is formed by dummy components, proper equivalent densities (ρ_{eq}) have been calculated and adopted in order to consider the masses of the structural materials (Eurofer for the BB, AISI 316 for the VV), breeders and coolant. In particular, assuming the same material percentages as the HCPB and WCLL DEMO BB [16], the ρ_{eq} values have been calculated at the aforesaid average temperatures (Table 1).

Table 1. Average temperatures and equivalent densities.

Component	HCPB		WCLL	
	T_{av} [°C]	ρ_{eq} [kg/m^3]	T_{av} [°C]	ρ_{eq} [kg/m^3]
FW	445.8	5022.7	373.0	6779.2
BZ	588.0	1413.2	343.5	9329.0
BSS	328.5	4715.7	300.0	3875.3
VV shield	200.0	5079.7	200.0	5079.7

In order to simulate the continuity of the VV, a symmetry boundary condition along the direction normal to each VV side faces (local toroidal directions) has been imposed to nodes highlighted in red in Fig. 3 B and C. Moreover, in order to reproduce the effect of the pendulum supports typically envisaged for a stellarator machine [15], displacement along the global Z direction has been prevented to nodes highlighted in red in Fig. 3 A. Lastly, purely for numerical reasons, one node on the VV top and one on the bottom have been constrained along the global X direction.

Furthermore an equivalent Young´s Modulus equal to the 10 % of the actual one, for Eurofer and AISI 316, has been assumed in dummy components in order to ensure that their displacement is comparable with that of the real structure [17]. However, regarding VV inner and outer layers, the actual AISI 316 properties have been assumed since they are not homogenized components.

On the basis of the above described loads, boundary conditions and assumptions, steady sate structural analysis has been performed considering a reference temperature of 20 °C.

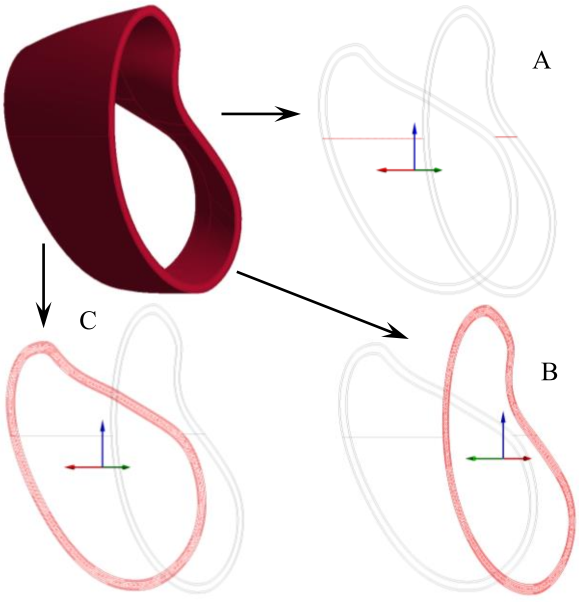

Fig. 3. The mechanical boundary conditions on the VV.

4. Results

The obtained results have allowed predicting the displacement field of HELIAS 5-B BB central region, for both HCPB and WCLL BB concepts. The potential overlapping between adjacent BB segments, initially separated by 20 mm gaps, has been investigated.

Since the highest displacement has been obtained for the HCPB BB, displacement field relevant to WCLL BB is not shown for sake of brevity. Instead, the displacement field calculated for the HCPB BB is depicted in Fig. 4. As it can be observed, a maximum displacement of ~ 47.5 mm, located in Ring 4 nearby Segment 1-2 interface, has been calculated. As to Ring 5, a maximum displacement of ~ 41.7 has been carried out.

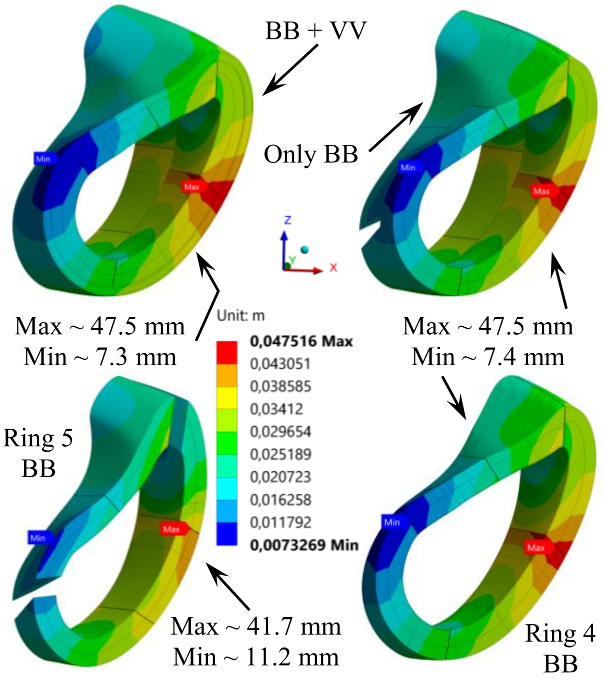

Fig. 4. HELIAS 5-B HCPB BB displacement field [m].

In Fig. 5, deformed (displacement 3D contour map isotropically amplified by a factor 15) vs. un-deformed (wireframe view) shape is reported for the HCPB BB, in order to highlight the deformation experienced by the structure. It can be observed that the “outer” BB region generally drifts apart plasma whereas the “inner” BB moves towards it.

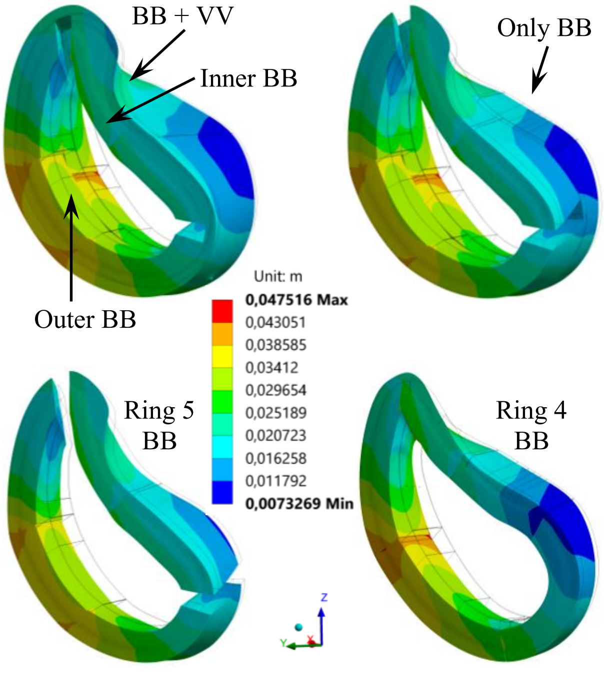

Fig. 5. HELIAS 5-B HCPB BB deformed vs. un-deformed.

Furthermore, the amount of the residual gaps has been checked in order to verify that, within each ring, no overlapping potentially occurs between neighbouring BB segments. It has to be noted that, as to Ring 5, interfaces between Segment 3-4 and 5-1 are not defined since these segments face to divertor. Actually, there is no divertor in the model but a large open space is assumed between inner and outer blanket, top and bottom (Fig. 1).

Results, reported in Table 2 and 3, indicate that, as expected, WCLL BB concept shows the highest residual gaps due to its components’ lower average temperatures. As to HCPB BB, narrow residual gaps have been calculated for the Segment 1-2 interface in both Ring 4 and 5 (Fig. 6). In this case, although overlapping is not predicted, some manufacturing issues may arise because the residual gap (less than 5 mm) may be not sufficient to accommodate manufacturing tolerances.

Table 2. Residual gaps amount between segments - HCPB.

Segment interface	Max gap [mm]		Min gap [mm]	
	Ring 4	Ring 5	Ring 4	Ring 5
1-2	2.8	4.6	2.1	3.9
2-3	13.6	9.3	13.4	9.0
3-4	9.8	N/A	9.7	N/A
4-5	13.7	21.0	12.5	20.0
5-1	13.9	N/A	7.7	N/A

Table 3. Residual gaps amount between segments - WCLL.

Segment interface	Max gap [mm]		Min gap [mm]	
	Ring 4	Ring 5	Ring 4	Ring 5
1-2	16.2	15.6	15.6	15.3
2-3	22.1	18.7	21.6	18.5
3-4	15.6	N/A	15.6	N/A
4-5	8.6	19.6	8.6	19.5
5-1	17.7	N/A	14.6	N/A

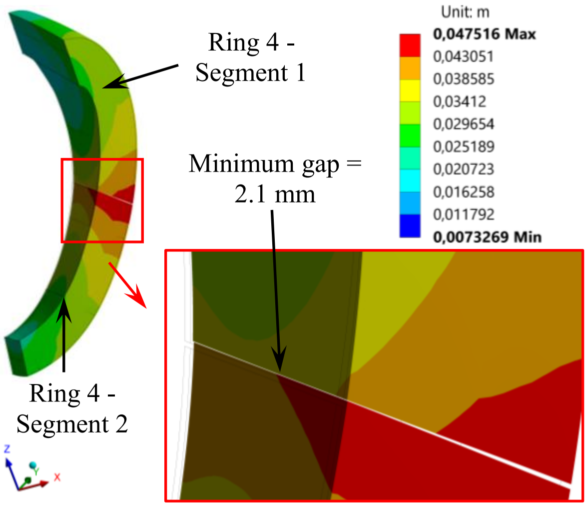

Fig. 6. HELIAS 5-B HCPB BB - Ring 4 - Segment 1-2 gap.

As to Ring 5, the maximum displacement towards the divertor has been assessed as well (Table 4). Segment 4 and Segment 5 show a considerable displacement which should be taken into account in the follow-up studies.

Table 4. Ring 5 max. displacement towards divertor.

Segment	HCPB	WCLL
	Displacement [mm]	Displacement [mm]
1	-10.2	-14.2
3	-8.0	-10.5
4	15.9	13.4
5	24.0	21.6

Moreover, maximum displacement along the local toroidal directions towards adjacent BB rings (namely towards Ring 3 and Ring 6) has been assessed (Table 5). No particular concern arises from this assessment, since displacement less than 10 mm are predicted.

Table 5. Max. toroidal displacement towards adjacent rings.

Segment	Max. displacement [mm] HCPB		Max. displacement [mm] WCLL	
	Ring 4	Ring 5	Ring 4	Ring 5
1	8.5	4.9	3.9	1.9
2	4.9	4.4	1.8	1.6
3	3.5	4.4	2.1	1.5
4	5.4	3.2	3.3	0.1
5	3.0	5.3	0.0	2.3

Lastly, the residual gap between Ring 4 and 5 along the toroidal direction has been investigated. Results have allowed predicting, as to HCPB BB, a minimum residual gap of 7.8 mm whereas, regarding WCLL, a minimum value of 14.2 mm has been calculated. These results may allow avoiding the overlapping between the two assessed rings along the toroidal direction.

5. Conclusion

Within the framework of the EUROfusion R&D activities supported by the WPS2, a preliminary investigation has been launched at KIT, in collaboration with University of Palermo, in order to assess, from the structural point of view, the feasibility of the HELIAS 5-B BB. In particular, the scope of this preliminary study has been the demonstration of the viability of the proposed segmentation strategy, also in view of the outcomes already shown in [4].

A BB geometric layout made of segments (large modules) separated by 20 mm gaps has been developed and assessed, adopting a steady state loading scenario drawn from DEMO BB thermomechanical analysis, in order to check if overlapping between neighbouring segments may occur. Both HCPB and WCLL BB concepts, already under consideration for the tokamak DEMO reactor, have been considered.

Results have shown that, in principle, both the concepts can be taken into account for the HELIAS 5-B BB potential design but, as expected, the BB conceived according the HCPB concept has shown the most critical behaviour. As to it, the obtained results allow concluding that, even though BB segments overlapping may be excluded in the HELIAS 5-B BB central region, further analysis is necessary, adopting more realistic models, in order to confirm these preliminary outcomes. Moreover, displacement towards divertor openings represents a strong concern to be considered for the future.

In particular, neutronic data [4] should be implemented in order to allow the full investigation of the thermomechanical performances of the HELIAS 5-B BB under relevant loading conditions. To this purpose, the design of BB segments internal details (Cooling Plates, manifolds, …) will be launched. Lastly, manufacturing issues should be taken into account as well, in order to properly define the minimum acceptable value for the residual gaps between the BB segments.

Acknowledgment

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] F. Romanelli, et al., Fusion Electricity – A Roadmap to the Realisation of Fusion Energy, European Fusion Development Agreement (EFDA), 2012, 2017 (ISBN 978-3-00-040720-8T).

[2] F. Schauer et al., HELIAS 5-B magnet system structure and maintenance concept, Fus. Eng. Des. 88 (2013) 1619-1622.

[3] F. Warmer et al., From W7-X to a HELIAS fusion power plant: On engineering considerations for next-step stellarator devices, Fus. Eng. Des. 123 (2017) 47-53.

[4] U. Fischer et al., Nuclear design issues of a stellarator fusion power plant with breeder blanket in comparison to tokamaks, paper presented at 27th IAEA Fusion Energy Conference (FEC 2018).

[5] G. Zhou et al., Preliminary steady state and transient thermal analysis of the new HCPB blanket for EU DEMO reactor, Fus. Eng. Des. 17 (2016) 7047-7052.

[6] F. Hernández et al., A new HCPB breeding blanket for the EU DEMO: Evolution, rationale and preliminary performances, Fus. Eng. Des. 124 (2017) 882-886.

[7] F. Hernández et al., Overview of the HCPB Research Activities in EUROfusion, IEEE Trans. on Pl. Sc. 46 (2018) 2247-2261.

[8] A. Del Nevo et al., WCLL breeding blanket design and integration for DEMO 2015: status and perspectives, Fus. Eng. Des. 124 (2017) 682-686.

[9] E. Martelli et al., Advancements in DEMO WCLL breeding blanket design and integration, Int. J. Energy Res. 42 (2018); 27-52.

[10] A. Tassone et al., Recent Progress in the WCLL Breeding Blanket Design for the DEMO Fusion Reactor, IEEE Trans. on Pl. Sc. 46 (2018) 1446-1457.

[11] G. Bongiovì et al., Multi-Module vs. Single-Module concept: Comparison of thermomechanical performances for the DEMO Water-Cooled Lithium Lead breeding blanket, Fus. Eng. Des. (2018) https://doi.org/10.1016/j.fusengdes.2018.05.037

[12] G. Zhou et al., Transient thermal analysis and structural assessment of an ex-vessel LOCA event on the EU DEMO HCPB breeding blanket and the attachment system, Fus. Eng. Des. (2017) https://doi.org/10.1016/j.fusengdes.2017.12.017.

[13] P. A. Di Maio et al., On the thermo-mechanical behavior of DEMO water-cooled lithium lead equatorial outboard blanket module, Fus. Eng. Des. 124 (2017) 725-729.

[14] G. Federici et al., European DEMO design strategy and consequences for materials, Nucl. Fusion 57 (2017), 092002.

[15] B. Missal et al., Mechanical experiments about pendulum support of vacuum vessel W7-X, Fus. Eng. Des. 83 (2008) 1610-1613.

[16] G. A. Spagnuolo, EFDA_D_2N5LUV v1.0 - Blanket Material Composition For Neutronics - January2017, IDM document ref. 2N5LUV.

[17] P. A. Di Maio et al., Structural analysis of the back supporting structure of the DEMO WCLL outboard blanket, Fus. Eng. Des. 124 (2017) 944-947.