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OVERVIEW OF THE DCLL BREEDING BLANKET FOR HELIAS 5-B AND FURTHER STEPS TOWARDS A NOVEL QI DEVICE

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Abstract

As part of EUROfusion's mission to bring stellarators to technological maturity, the Stellarator Power Plant Studies (SPPS) WPPRD began in 2021 to develop a HELIAS-class power plant. Building on DEMO tokamak experience, European teams are designing a Dual Coolant Lead-Lithium (DCLL) breeding blanket (BB) for HELIAS. This concept uses liquid PbLi as breeder/coolant and decoupled helium cooling for the first wall (FW). Two key adaptations address HELIAS's complex geometry: a detached FW using Capillary Porous System (CPS) technology, and a quasi-toroidal segmentation (QTS) with PbLi flow aligned to magnetic field lines. QTS reduces magnetohydrodynamic (MHD) pressure drop by up to two orders of magnitude, potentially eliminating electrical insulation needs. Remote handling (RH) is rethought for 3D stellarators, where traditional vertical-port extraction is impractical. Alternatives include enlarged fixed coils, movable coils for temporary large ports, and detachable vessel periods. The detached FW strategy shifts maintenance from large BB segments to smaller, easily replaceable FW panels, extending BB lifetime. CPS designs with Li in tungsten matrices were analysed thermally, hydraulically, and neutronically, showing potential to lower displacement-per-atom (dpa) damage while maintaining tritium breeding. Be-based moderators behind the FW CPS matrix improved TBR while reducing back-structure damage. To accelerate design and analysis, HeliasGeom and SHANE tools were developed to rapidly generate realistic 3D parametric geometries for CAD, neutronic, and thermal-hydraulic coupling. Preliminary 3D studies addressed TBR optimisation, MHD in non-uniform fields (via GridapMHD), and multi-scale thermal–mechanical assessments. Finally, the adaptation of HELIAS 5-B DCLL BB to CIEMAT-QI configurations, a family of recently obtained next-generation optimized magnetic configurations, is discussed. These innovations collectively advance stellarator blanket technology, integration, and maintainability toward viable power plant concepts.

1. INTRODUCTION

The development of a Dual Coolant Lead-Lithium (DCLL) Breeding Blanket (BB) for the HELIAS 5-B stellarator is a cornerstone activity within the EUROfusion Stellarator Power Plant Studies (SPPS) Prospective R&D Work Package (WPPRD). It aims to bring the stellarator line to technological maturity by solving engineering and integration challenges inherent to large-scale stellarator reactors. The HELIAS concept offers intrinsic advantages in steady-state operation and plasma stability, but its complex three-dimensional geometry imposes constraints for blanket design, maintenance access, and component integration.

Building on previous European BB designs for DEMO tokamak configurations, the DCLL BB concept was adapted to the complex three-dimensional geometry and operational requirements of HELIAS-class devices.

The DCLL BB concept adapted to the HELIAS configuration, utilises a liquid PbLi breeder and decoupled cooling circuits for the First Wall (FW) and breeder region, based on helium and PbLi respectively, allowing independent optimisation of breeding and thermal management. A major innovation in the HELIAS DCLL BB programme is the adoption of a decoupled first wall concept based on Capillary Porous System (CPS) technology. This approach shifts most neutron damage from the breeding blanket (BB) to replaceable FW panels, thereby extending BB service life and simplifying maintenance operations.

For HELIAS, a quasi-toroidal segmentation (QTS) has been proposed, with PbLi flow aligned predominantly with the magnetic field to minimise magnetohydrodynamic (MHD) pressure drop, potentially eliminating the need for electrical insulation layers. This segmentation also facilitates remote maintenance by enabling more accessible extraction paths for BB modules. Figure 1 shows a comparison of a tokamak oriented quasi-poloidal segmentation (QPS), and the QTS adopted for HELIAS 5-B to align the PbLi flow to the magnetic lines.

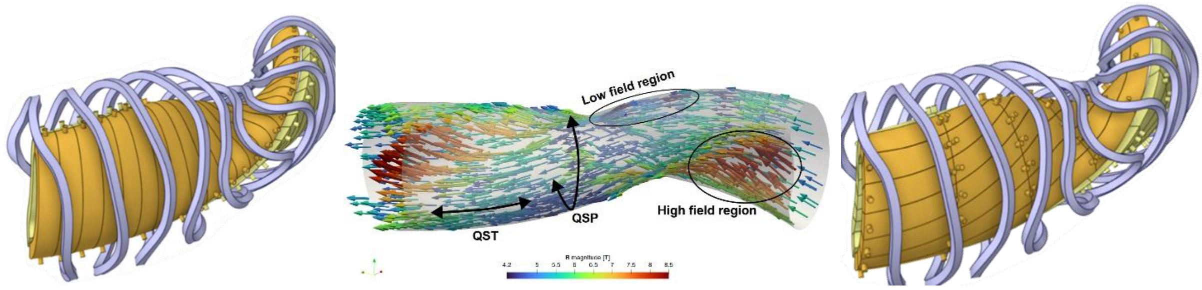

FIG. 1. Quasi-poloidal segmentation QPS (left), B-field vector field (center) and Quasi-toroidal segmentation (QTS) (right) for HELIAS 5B showing PbLi flow alignment with the magnetic field.

Building on this concept, the current research programme [1] addresses four interconnected objectives:

1. MHD validation and optimisation (Section2) – Pressure drops under HELIAS-relevant, non-uniform magnetic fields are quantified, and the applicability of empirical correlations (e.g., Miyazaki et al. [2]) is assessed using advanced numerical tools such as GridapMHD. These studies support the optimisation of PbLi flow paths to minimise magnetohydrodynamic effects.
2. Innovative FW design (Section 3) – CPS-based decoupled FW is developed and evaluated to minimise neutron damage to the BB, extend component lifetime, and facilitate maintenance by enabling independent replacement of the FW. Capillarity, thermal-hydraulic, mechanical and neutronic studies have been carried out to get a viable FW design considering also integration and interphases with in-vessel components.
3. Remote Maintenance (RM) strategies (Section 4) – novel solutions as fixed enlarged coil configurations and innovative coil geometries are investigated to enable large ports for BB module replacement, addressing the limited access inherent to stellarator layouts.
4. Variable radial-build optimisation (Section 6) – Unlike tokamak designs, where repeated blanket and shielding structures encircle the plasma uniformly, stellarators require location-specific radial builds and BB designs around the full 360° toroidal and poloidal directions. Optimisation focuses on enhancing tritium breeding ratio (TBR) and coil shielding while adapting to local constraints, including cases where breeding zones must be reduced or omitted to improve shielding performance in high-demand areas.

These objectives are pursued through a combination of CAD-based parametric modelling, *ad-hoc* prepared tools (Section 5 and 7), coupled neutronic/thermal-hydraulic/mechanical simulations, and conceptual RM studies, with the overarching aim of demonstrating the technical feasibility of a DCLL BB for HELIAS 5-B and assessing the adaptability of solutions to CIEMAT-QI configurations, a novel family of advanced quasi-isodynamic (QI) stellarator configurations (Section 8).

2. DCLL BREEDING BLANKET MHD ANALYSIS

The DCLL BB QTS was designed to mitigate the MHD pressure drop arising from the electric coupling between PbLi and steel walls, both good conductors. This is a promising alternative to other mitigation strategies like insulated walls or flow channel inserts, which involve manufacturing and design challenges. This strategy relies on aligning the PbLi flow with the magnetic field, thereby minimizing the normal component of the field and the resulting Lorentz force, which causes MHD pressure drop. Perfect alignment is not possible in HELIAS due to field non-uniformity and geometrical constraints, so accurate prediction of pressure drop remains necessary. Previous estimates [1] of the pressure drop relied on Miyazaki's correlation [2], valid for smoothly varying fields, though its applicability to HELIAS is unclear. Therefore, current work benchmarks this correlation against 3D MHD simulations performed with GridapMHD [3][4], a novel finite-element MHD code capable of resolving currents in complex geometries at lower meshing cost. To limit computational expense, the model assumes straight channels, piecewise-linear magnetic field profiles (Fig 2), and scaled-down Hartmann numbers (Ha ~1500 vs. ~4500 actual). Two channels were tested—one in a high-B region and one in a low-B region (see Fig. 1), representative of the high non-uniformity of HELIAS's field. Note that the normal field component is higher in the low-B-region channel since field-flow alignment there happens to be worse. Additionally, a high-Ha uniform-field case (Ha ~ 4500) was included to verify it the field component parallel to the flow is negligible by simulating at high Ha the full field or only the normal component.

The simulation results, summarized in Table 1 (as normalized pressure drop per unit length for each channel), show that Miyazaki's correlation gives reasonable estimates, though with slight underestimation in variable-field cases. They also confirm that the parallel field component can be neglected. While these results are not directly generalizable, the methodology provides a solid framework to extend validation to different magnetic-field conditions (as slope and magnitude), as well as to channels with different geometrical configuration or materials. A more complete study, including the actual QTS geometry under HELIAS fields, is currently underway.

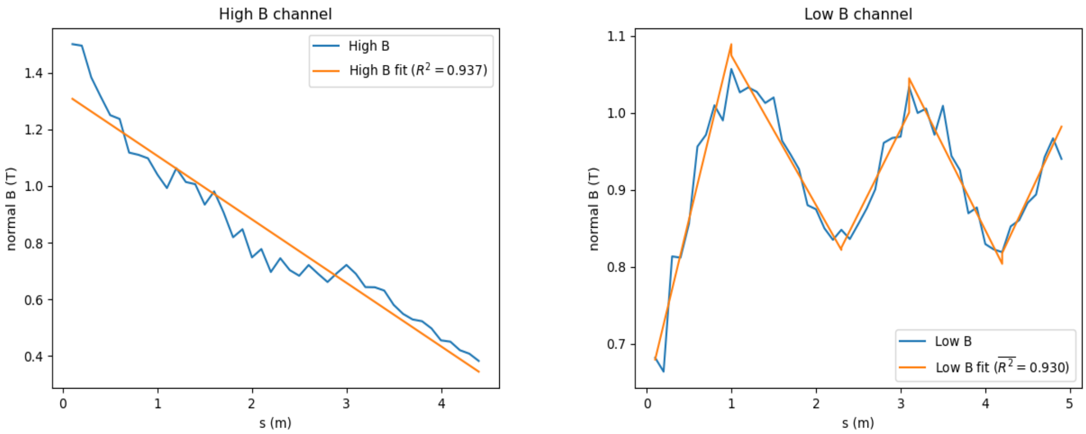

FIG. 2. Piecewise linear fits of the normal B component for a high-B-region (left) and low-B-region (right) HELIAS channels.

TABLE 1. Normalized pressure drop per normalized unit length for each channel comparing the results of the simulations and Miyazaki's hypothesis.

Case	Source	k_p	Relative difference
Ha = 4500 (uniform)	Normal field (sim.)	$1.887\cdot10^{-2}$	—
	Full field (sim.)	$1.858\cdot10^{-2}$	–1.5%
	Correlation	$1.951\cdot10^{-2}$	+3.4%
High B channel	Simulation	$4.65\cdot10^{-2}$	—
	Correlation	$4.02\cdot10^{-2}$	–13%
Low B channel	Simulation	$2.78\cdot10^{-2}$	—
	Correlation	$2.32\cdot10^{-2}$	–16%

3. DECOUPLED FIRST WALL DESIGN

A novel decoupled FW concept developed to transfer most neutron damage to replaceable FW panels based on CPS technology has been proposed and extensively assessed, with Li selected as the PFM [1][5]. The CPS consists of a tungsten porous matrix infiltrated with liquid lithium, replenished from a reservoir, and actively cooled to keep surface temperatures below 500 °C. Two cooling configurations were studied: helium-cooled with a static lithium reservoir, and lithium-cooled where lithium serves as both coolant and reservoir fluid. Figure 3 illustrates the helium- and lithium-cooled CPS FW configurations. Geometric models for both designs have been generated using VBA scripts in CATIA, enabling efficient exploration of design parameters. Parametric thermo-hydraulic simulations examined the effect of channel size, spacing, and flow parameters. These evaluations have shown that the lithium-cooled concept offers superior thermal efficiency (but with uncertainties in pressure stability and corrosion behaviour) making it the most promising candidate for further development.

In parallel, thermo-mechanical analyses have been carried out on the lithium-based configuration, using detailed FEM models to validate the structural integrity of the design under relevant operational loads. The results have confirmed the feasibility of the decoupled FW approach, which stands out as an innovative and potential solution for stellarator reactor systems.

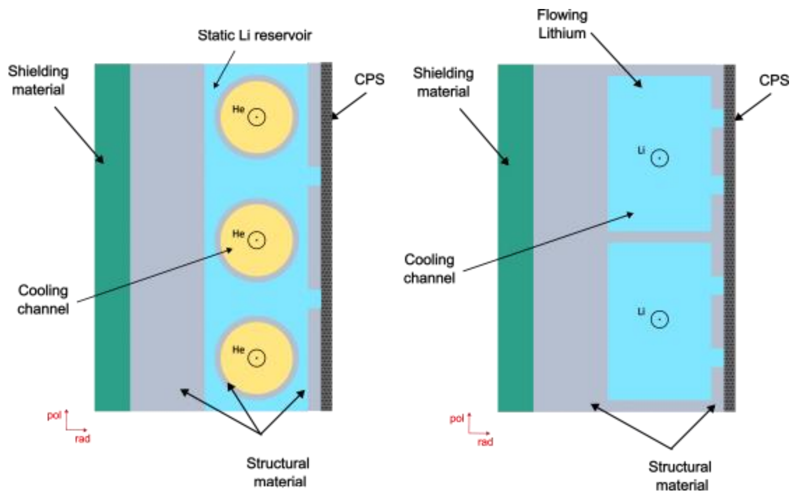

FIG. 3. CPS-based FW concepts. Helium-cooled design: almost static Li reservoir + He active cooling (left); lithium-cooled design: Li used as coolant and LM reservoir (right)

An essential requirement for CPS operation is maintaining proper replenishment of the liquid metal (LM) to ensure continuous wetting of the metallic mesh /porous structure. Several forces, including Lorentz, inertial, and viscous effects, can significantly influence capillary behaviour within the LM. Stable fluid circulation is sustained when the capillary pressure generated in the porous structure exceeds the total pressure losses along the vapour–liquid path. These losses arise from liquid–vapour phase transition, hydrodynamic resistance, hydrostatic effects, and MHD interactions. An adequate consistent overpressure must therefore be maintained in the capillary to drive LM flow from the reservoir toward the plasma-facing surface, as illustrated in Figure 4.

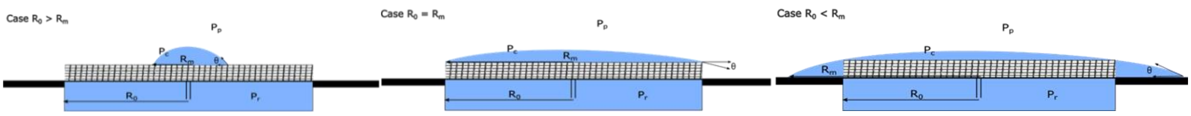

FIG. 4. Importance of the overpressure in the spreading of LM in a CPS.

Capillary behaviour under operating conditions was numerically assessed using 2D multiphase CFD in ANSYS Fluent, modelling helium and lithium tanks connected by a CPS-type capillary. Under the assumption of perfect wetting between lithium and the CPS surface (θ = 0°) and constant thermophysical properties at 450 °C, the results indicate a rapid capillary-driven rise of lithium governed by surface tension effects. This initial ascent is subsequently followed by lateral spreading across the CPS surface, accompanied by a progressive deceleration as the distance from the capillary increases (Fig 5). The system reached a quasi-steady state with a meniscus radius of 0.32 mm, closely matching theoretical predictions (≈0.31 mm) based on hydraulic and hydrodynamic pressure drop models. This agreement validated the numerical approach for reproducing the key physical mechanisms of capillary-driven transport. The findings provide guidance on porosity requirements for CPS designs and inform structural integration strategies. Nevertheless, further research is required to address more complex scenarios, including lithium behaviour under forced convection or temperature gradients, as well as continuous flow conditions through the CPS channels.

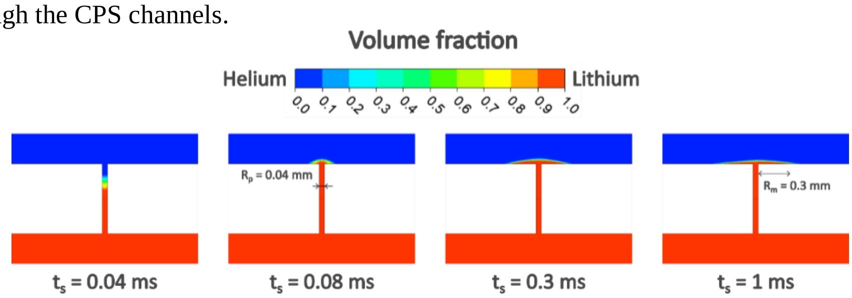

FIG. 5. Li evolution in the capillary at different time steps.

Different CPS FW configurations have been implemented also in the neutronic models and several FW substrate materials chosen according to different neutronic criteria (shielding, neutron multiplication) [6]. Parametric studies changing the thickness of the CPS substrate at expenses of the breeder zone from 1 to 8 cm in order to define an optimal dimension have been also carried out to achieve the best compromise among T breeding (TBR) and damage (displacement per atom, DPA) in the Eurofer BB structure (which directly influence its replacement).

A tentative Be-based reflector of 4 cm, enclosed in a Eurofer box, has been preliminary chosen as substrate material for the CPS FW, as the results provided (Fig. 6) have shown that such neutron multipliers can offset tritium breeding losses due to breeder volume reduction increasing instead the TBR up to 1.45, while reducing the DPA in the BB a 40% from the baseline configuration with standard FW (which provided 1.33 TBR and 16.47 DPA/FPY in the most impacted BB region). A higher DPA reduction over 50% can be inclusive achieved if higher thicknesses (8cm) are considered. The concept therefore offers a promising pathway to extend BB operational life and simplify maintenance by decoupling FW replacement cycles from BB replacement schedules.

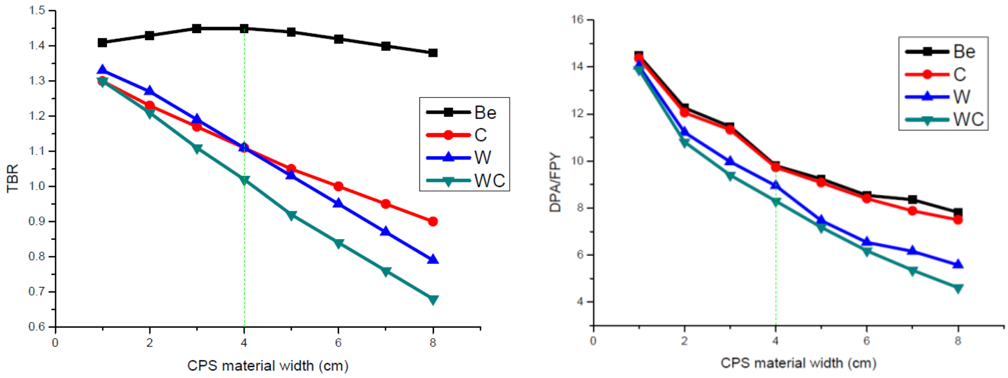

FIG. 6. Resulting TBR and DPA/FPY (in the Eurofer BB) provided by increase supporting structure CPS FW from 1 to 8 cm considering different substrate materials

4. REMOTE MAINTENANCE STRATEGIES

One of the major engineering constraints in stellarators is the limited access between coils for in-vessel component replacement. Conventional vertical port strategies from tokamaks are not directly applicable due to the complex coil and vacuum vessel geometry in stellarators. Past studies on movable coils and detachable periods found mechanical, operational, and licensing challenges. Recently, the focus shifted to fixed larger coil designs enabling larger access ports. Two approaches were pursued: enlarging fixed coils at strategic positions to moderately increase port size, as performed for NCSX stellarator [7] (Fig 7 left) and modifying coil geometries to create very large ports (Fig 7 right).

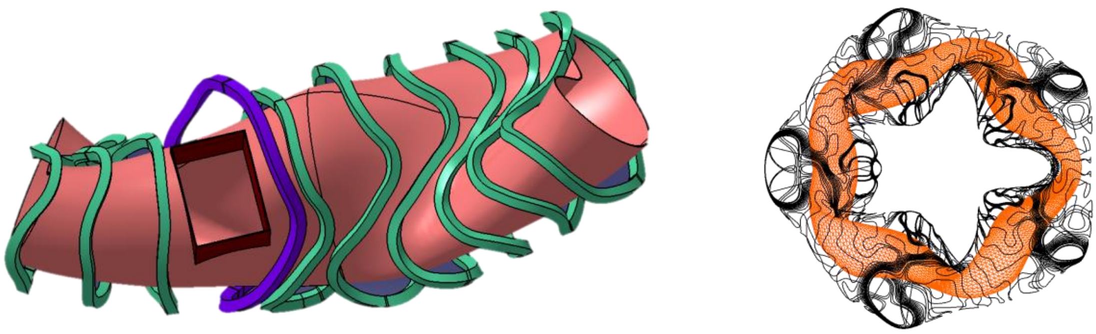

FIG.7. Innovative coil geometries for large ports in HELIAS configurations.

The latter approach was inspired by HSR3 coil designs [8] and evaluated through intermediate configurations between 3 and 5 periods, including HSR4-like and low-aspect-ratio HELIAS 5p variants. For HELIAS 5p, winding surface modifications were explored to create very large outboard openings. Using this “Sequential Method,” (HSR4-like first and low-aspect-ratio HELIAS 5p later) these intermediate configurations were tested to find coil configurations allowing large ports. The low-aspect-ratio variant of HELIAS_5p achieved port sizes comparable to HSR3; however, this came at the cost of reduced plasma volume and degraded confinement, indicating the need for further optimisation. The study concluded that fixed-coil large-port designs are mechanically simpler and avoid the complexity of moving superconducting coils, though producing very large ports in high-aspect-ratio HELIAS 5p configurations remains challenging. However, if huge ports are sought, like in the ‘Sequential Method’, the shape of some coils is complex. The methodologies developed are considered promising for future quasi-isodynamic (QI) stellarator designs, where coil shapes and spacing can be optimised from the outset to balance magnetic performance with maintenance accessibility.

5. HELIASGEOM MODELLING TOOL DEVELOPMENT

In the initial stage of the research activity, the lack of tools to represent quickly and realistically 3D complex geometries, was identified as a major bottleneck for the progress of the work [1][9]. To accelerate the DCLL HELIAS design and overcome such issue two *ad-hoc* tools, SHANE and HeliasGeom [10], have been developed (Fig 8) for building parametric CAD models suitable for neutronic analysis workflow. This approach improves the convergence toward a viable design, speeding-up the coupling of the CAD modelling with the neutronic and thermal-hydraulic analyses. In particular, HeliasGeom enables the creation of parametric layered models representing the different stellarator components and including specific detailed coils. Afterwards, the model is translated into the neutronic model using GEOUNED [11].

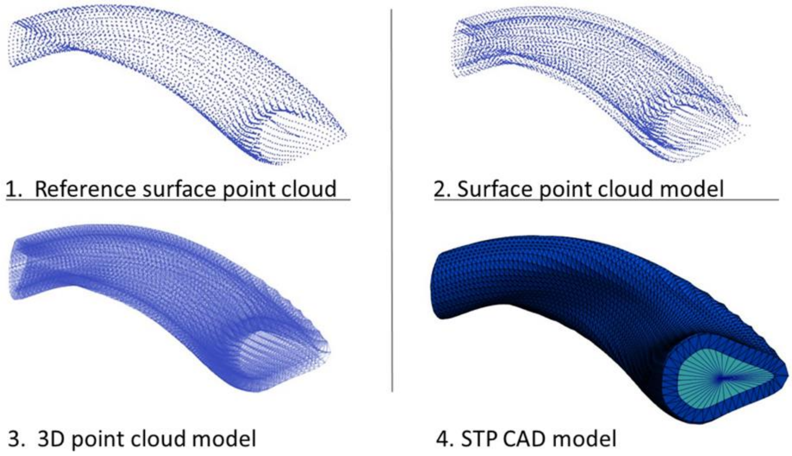

FIG. 8. Sequence employed by HeliasGeom tool to get tetrahedralized STP model

This code system was recently upgraded to incorporate detailed external 3D geometries into selected regions of the layered model (Fig. 9, left). The methodology relies on intersecting a container cell—representing the boundary of the detailed 3D model—with the parametric stellarator layered model generated by HeliasGeom. The process defines the subset of cells that act as containers in the MCNP model, within which the detailed geometry is then introduced as a universe. This approach significantly improves neutronic modelling accuracy for complex structures such as BB modules.

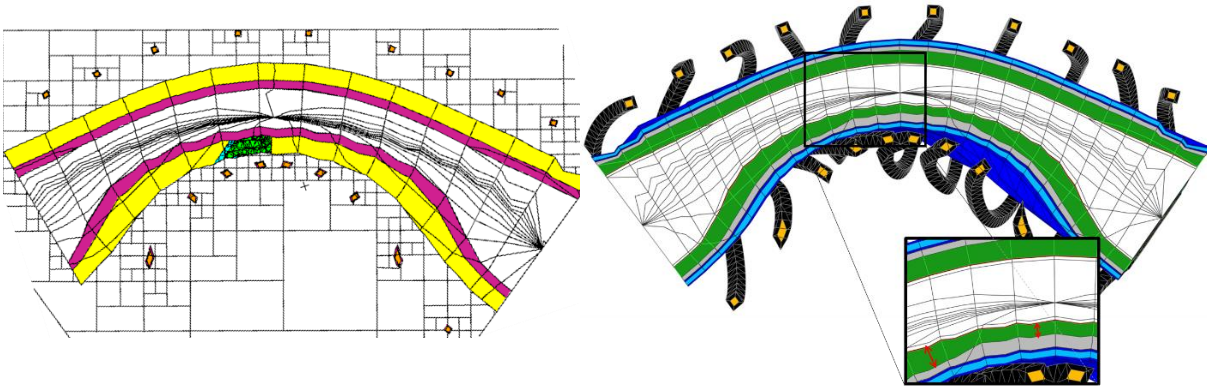

FIG. 9. HeliasGeom models:(left) integrating detailed CAD geometries for stellarator components and (right) allowing for a variable radial build especially visible in the green (BB) and grey (Shielding) layers

In its initial version, the methodology produced layers of constant thickness throughout the model, limiting the ability to optimise the coil–plasma space from a neutronic perspective. To overcome this constraint, HeliasGeom was further enhanced to allow precise control over coil–plasma spacing, enabling the generation of variable-thickness layers in both poloidal and toroidal directions (Fig. 9, right).

6. RADIAL BUILD OPTIMIZATION

Preliminary configurations with different radial builds have been generated and assessed. One promising case, with 57 cm of breeder (split into two channels of 29 cm and 28 cm) plus 10 cm of Eurofer steel and a helium manifold, yielded a TBR of 1.42. However, coil shielding limits were exceeded by two orders of magnitude in specific inboard regions (Fig. 10, left). Using the novel features of HeliasGeom, these initial equidistant-layer designs were refined into variable-layer configurations, modifying both radial build and shielding materials to balance TBR and shielding. Alternative materials (steel+water, WC, W_2B_5) and increased shielding thickness in the critical inboard area (up to 40 cm, at the expense of the second breeder channel) were tested. This optimized configuration achieved a TBR of 1.34 while reducing nuclear loads on the coils by over two orders of magnitude (Fig. 10, left). Even with standard steel+water shielding, quench limits were satisfied, leaving a comfortable margin above the T breeding target of 1.15 for future adjustments.

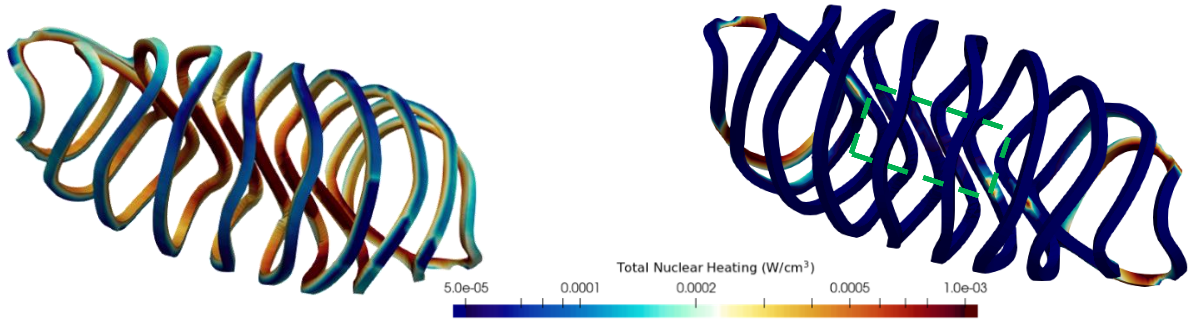

FIG. 10. Total Nuclear Heating at the coils: (left) for the 3D equidistant layers configuration; (right) for the variable layers configuration with W_2B_5 shield. The lower limit of the scale represents the required limit for avoid quenching (5e-5 W/cm^3).

7. DCLL BB HELIAS SEGMENTS DESIGNS

Two final detailed BB segments have been specifically designed: one corresponding to a more conventional radial build of about 80 cm BB (Fig 11) and another based on the optimized configuration proposed in Section 6, intended for a more critical zone where most of the breeder space has been replaced by an enhanced shielding system. The first design incorporates four parallel PbLi circuits (two front, two rear) that mainly follow the toroidal direction, each about 4.7 m long. With PbLi inlet and outlet temperatures of 300 °C and 650 °C, respectively, the channel cross-section yields mean velocities as low as 2.7 cm/s in the front channels (closer to the plasma) and 0.6 cm/s in the rear channels. The second design, with the breeding zone reduced to 40 cm, includes only two (front) channels. It has been verified that the resulting cross-section can withstand the expected PbLi pressure. Despite halving the number of channels, the impact on the average PbLi velocity is minor due to the exponential nature of nuclear heating.

Since each of the 84 segments within a sector is different, a dedicated tool was developed to automatically extract key parameters from the geometrical model (volume, cross-section, length, aspect ratio) and compute mass flow rates and average velocities. By accounting for the variable nuclear heating profiles in each segment, it has been possible to reduce the global mass flow rate by 7% compared to using a uniform profile.

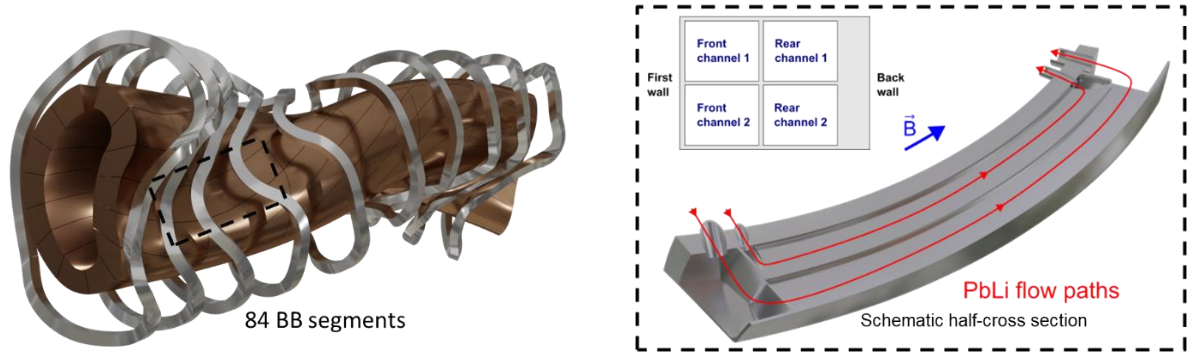

FIG. 11. DCLL BB segments for the HELIAS 5-B device showing the detailed structure inside one of the standard radial build configuration with 4 PbLi channels

A multi-scale approach, developed and tested at the University of Palermo, has been applied to the new DCLL BB, conceived according to a toroidal segmentation scheme, to investigate its thermal and structural behaviour. The necessary inputs are the geometric layout, the loading scenario and the cooling scheme that can be provided from the other tools and/or analysis described in this paper. Then, the procedure automatically sets the FEM models, manages the mashing operations, assigns loads and boundary conditions, runs the analyses and post-processes the results in view of the prescribed design requirements thanks to purposely developed Python scripts integrated into the Ansys Workbench environment. An *ad-hoc* iterative 1-D analytical approach allows considering the thermal-hydraulics of the coolant fluids in the thermal analysis when cooling channels are modelled. The procedure is based on the adoptions of different classes of models, such as homogeneous, semi-heterogeneous and fully heterogeneous, to be called in a back and forward way in order to investigate specific regions adopting detailed (i.e. heterogeneous) models, where boundary conditions come from more rough (i.e. homogeneous) models representing bigger components. In this way, reliable results can be obtained strongly reducing the modelling effort and the computational burden, allowing the simultaneous investigation of several regions of interest.

8. ADAPTATION TO CIEMAT-QI CONFIGURATIONS

Recently, a number of next-generation optimized stellarator configurations have been computationally obtained. The CIEMAT-QI family of configurations [12, 13] are among the most advanced ones. Based on its predicted physics performance, the most developed representative of this family, the configuration CIEMAT-QI4X [14], qualifies as a potential candidate to be the basis of stellarator reactor designs. Detailed studies are needed to show that CIEMAT-QI4X is compatible with reactor technology requirements and, in particular, with the integration of a breeding blanket. Building upon the design principles and reactor-oriented developments established for the HELIAS reactor, these are now being applied to CIEMAT-QI4X. As a first step, a preliminary radial build with equidistant layers—directly comparable to the initial HELIAS case described in Section 6—was implemented. Unlike HELIAS, however, CIEMAT-QI4X features a minimum coil–plasma separation of 1.48 m versus 1.62 m in HELIAS, which required a reduction of the breeder to two channels of 24 cm each. This configuration yielded a TBR of 1.31, showing that the design allows for coils capable of reproducing the magnetic field with sufficient fidelity to preserve the main physics properties, while simultaneously enabling a BB with an adequate TBR. Specific BB improvements and assessment for the CIEMAT-QI4X [Sánchez, to be published] are underway.

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