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

FEC2025 30th IAEA FUSION ENERGY CONFERENCE
13–18 OCTOBER 2025
CHENGDU PEOPLE'S REPUBLIC OF CHINA

Iole Palermo[1]*, Javier Alguacil[2], Arturo Alonso[1], Gaetano Bongioví[3], Iván Calvo[1], Iván Fernández-Berceruelo[1], Salvatore Giambrone[3], Guillermo G. Fonfría[1], Jose Ángel Noguerón[1], Fernando R. Urgorri[1], Vicente Queral[1], David Rapisarda[1], Edilberto Sánchez[1], David Sosa[1], José Luis Velasco[1]

*Corresponding author e-mail: iole.palermo@ciemat.es

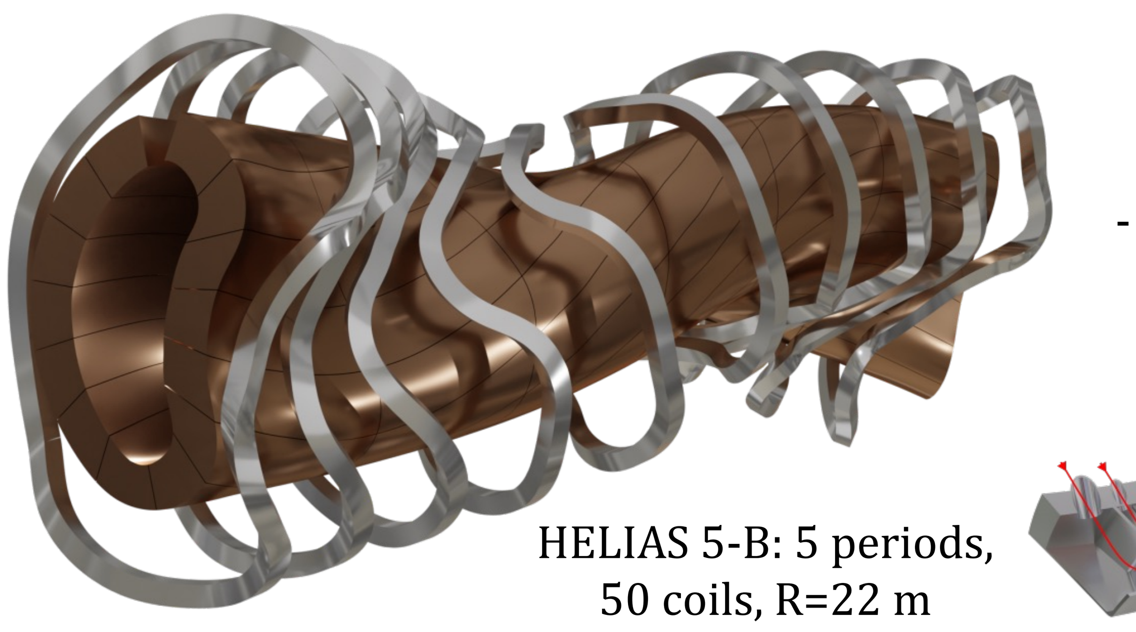
[1] CIEMAT, Fusion National Laboratory, Avda. Complutense 40 28040 Madrid,Spain
[2] Dept. Ingeniería Energética, UNED, Calle Juan del Rosal 12 28040 Madrid,Spain
[3] Università Degli Studi di Palermo, Viale delle Scienze Palermo 90128, Italy

GOBIERNO DE ESPAÑA · MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES · Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Motivation and Background

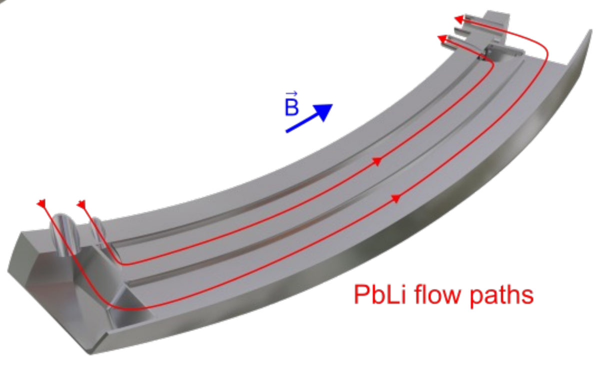
As part of EUROfusion's mission to bring stellarators to technological maturity, the Stellarator Power Plant Studies (SPPS) WPPRD began in 2021 to develop a HELIAS-class power plant.

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 cooling for the first wall (FW).



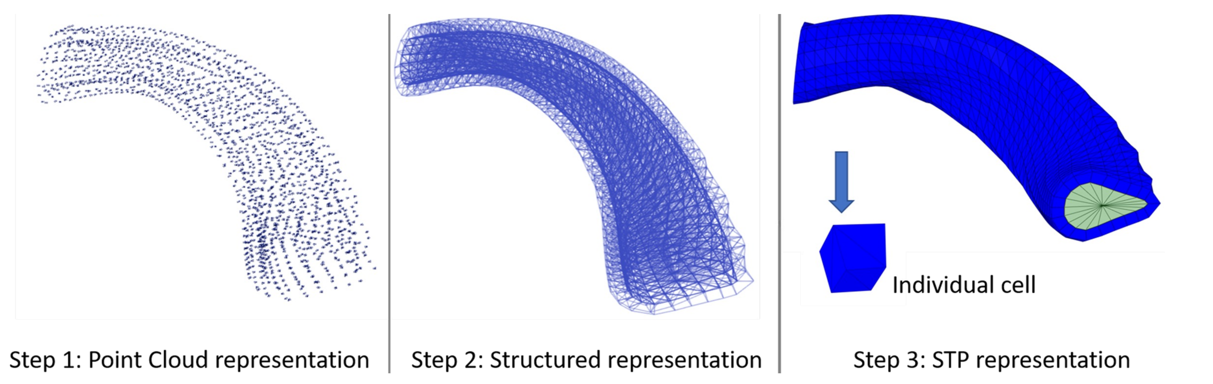
HELIAS 5-B: 5 periods, 50 coils, R=22 m
3000 MW; n source 1,065 10^{21} n/s

- *plasma stability and intrinsic steady-state capability*
- *RoX from DEMO (BB concepts, Materials, Fuel cycle)*
- *DCLL BB potential for high temperature/ high efficiency FPP*
- *specific questions for stellarators (RH, FW, 3D tools) here afforded*



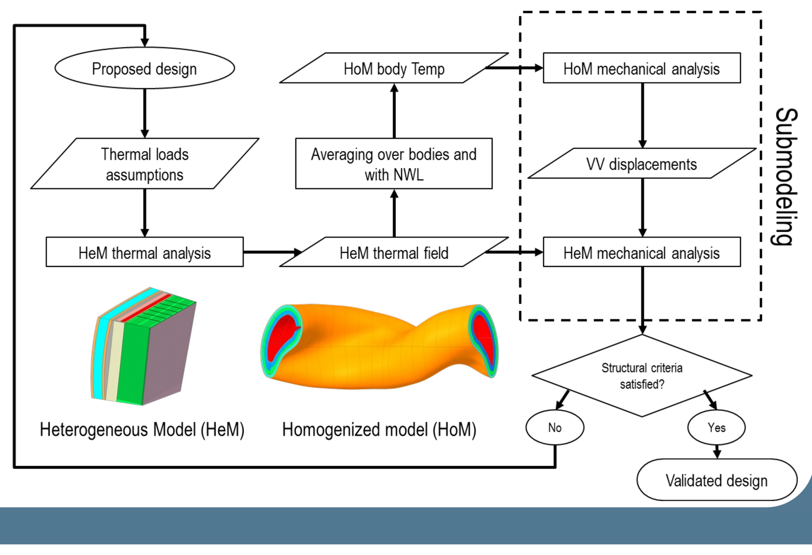
These innovations collectively advance stellarator blanket technology, integration, and maintainability toward viable power plant concepts.

Challenge 1: *ad-hoc* 3D tools development

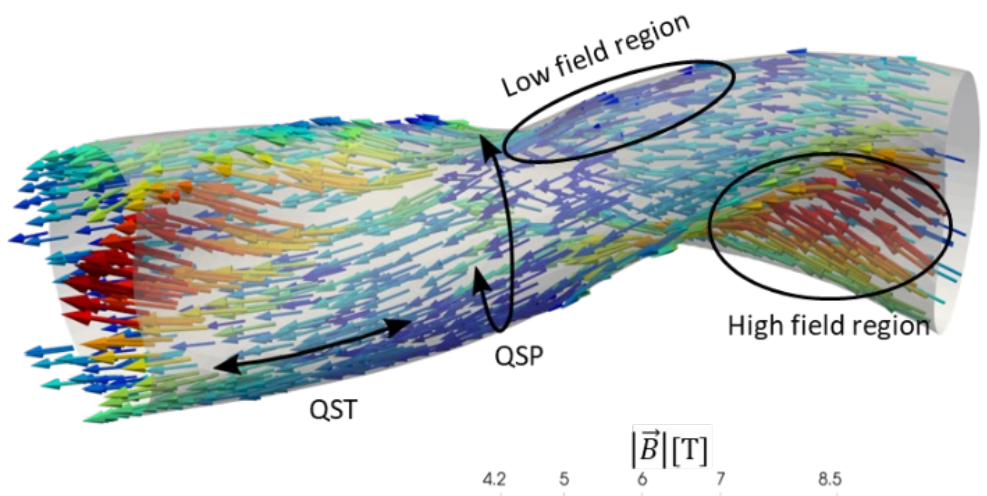


HeliasGeom and SHANE tools accelerate design by realistic 3D parametric models for CAD, neutronic, and thermal-hydraulic coupling +

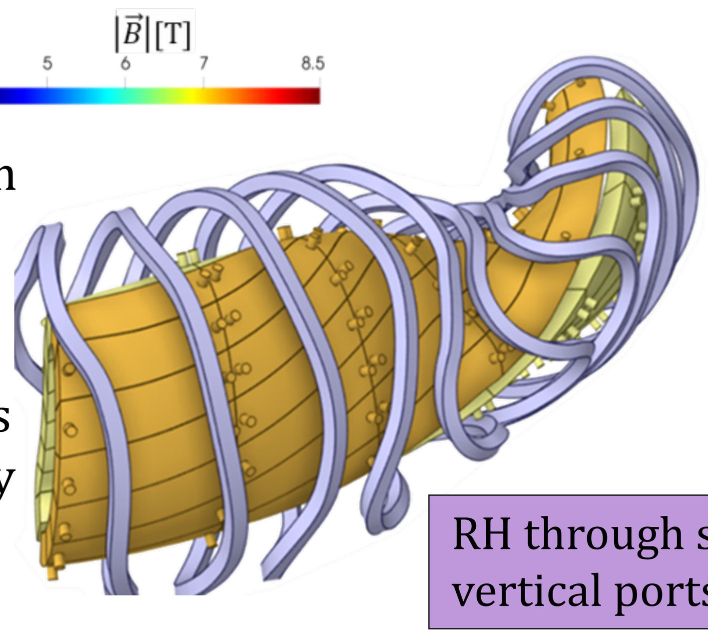
GridapMHD (CIMNE) *ad hoc* solvers for 3D validation under non-uniform B
+
Novel approach for multi-scale thermal–mechanical assessments



Challenge 2: Magneto-Hydro-Dynamics



A quasi-toroidal segmentation (QTS) with PbLi flow aligned to magnetic field lines, reduces MHD pressure drop by up to two orders of magnitude, potentially eliminating electrical insulation needs.

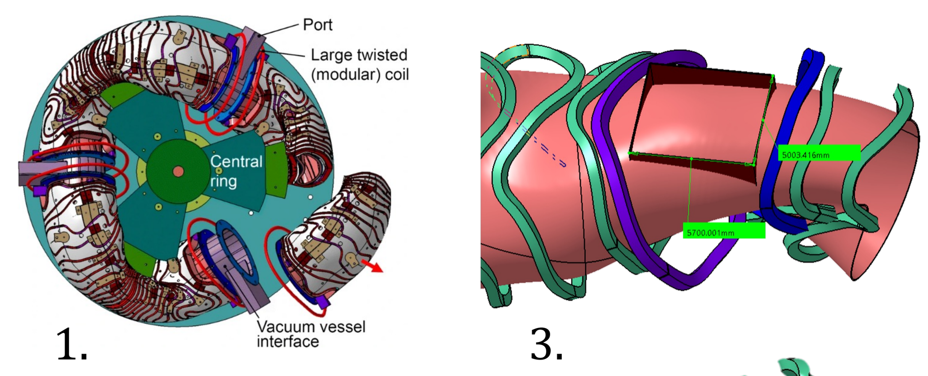


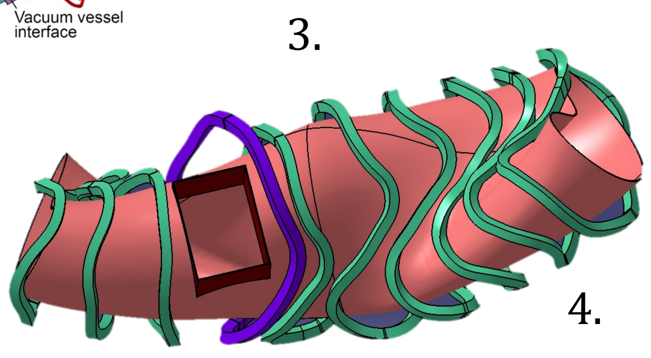
RH through standard vertical ports challenging

Challenge 3: Remote Handling

Vertical ports/ alternative strategies examined:

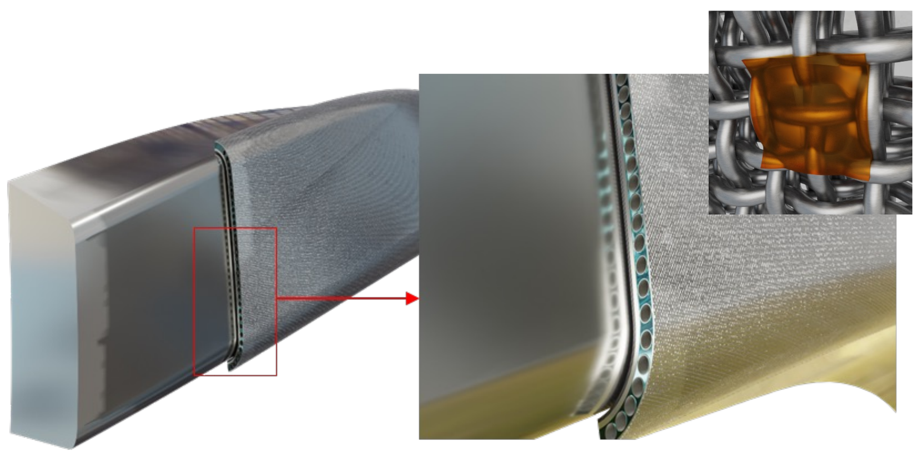
1. Detachable (half) periods
2. Splittable coils
3. Rotation or translation of coils for wide ports
4. Enlarging fixed coils at strategic positions
5. Modifying coil geometry to create large ports



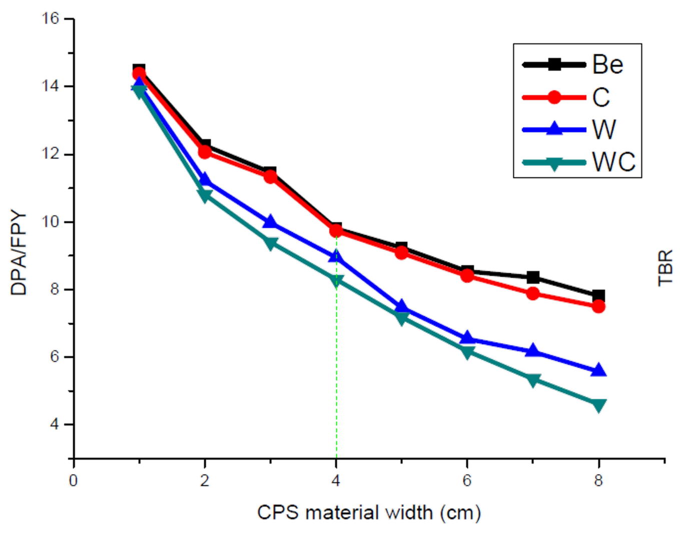


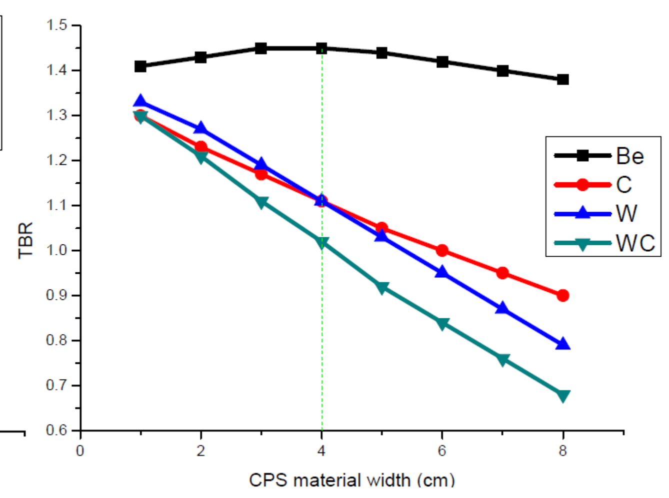
Challenge 4: FW design and integration

A conceptual design of a Capillary Porous System (CPS) FW for HELIAS has been proposed. The detached FW strategy shifts maintenance from large BB segments to smaller, easily replaceable FW panels, extending BB lifetime.

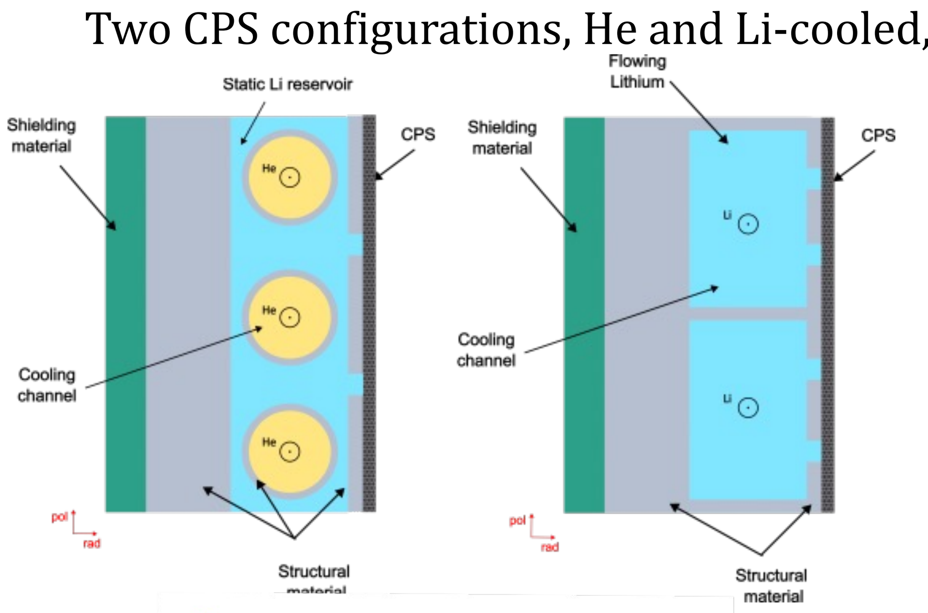


CPS designs with Li in tungsten matrices analysed thermally, hydraulically, and neutronically, show potential to lower displacement-per-atom (DPA) damage while maintaining tritium breeding (TBR). In particular Be-based moderator supports behind the CPS W matrix improve TBR (1.33 → 1.45) while reduce BB damage (-40% from 16.47 → 9.80).

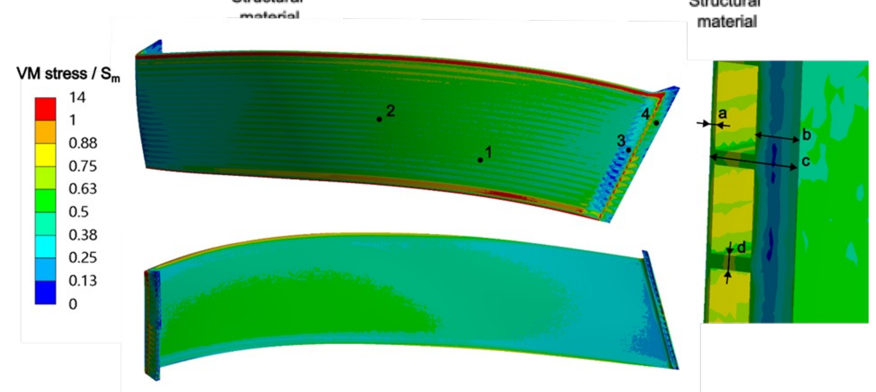




Two CPS configurations, He and Li-cooled, investigated

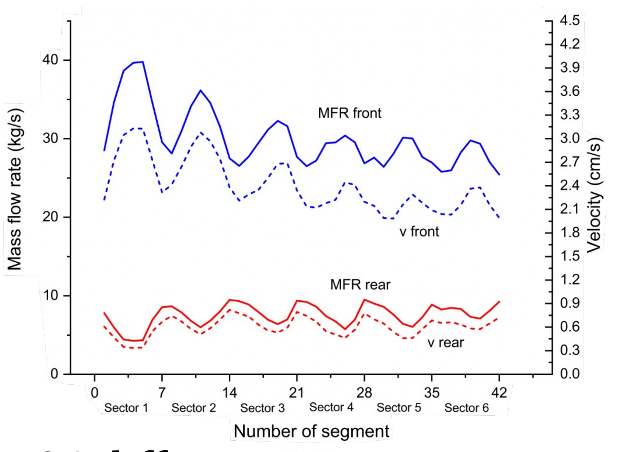


Parametric thermo-hydraulic studies to determine optimal channel dimensions and spacing shows that Li-cooling offers most favorable thermal performance.



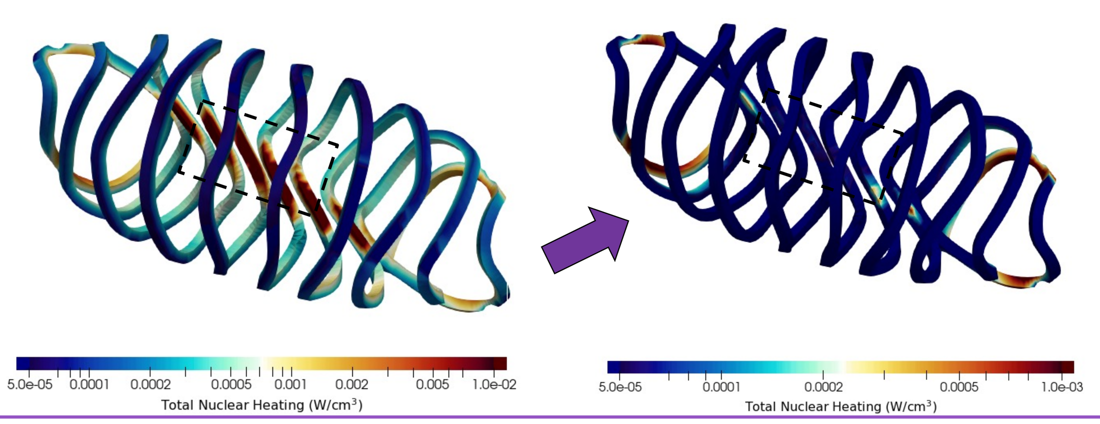
Thermo-mechanical analyses validated the structural integrity of the design under relevant operational loads.

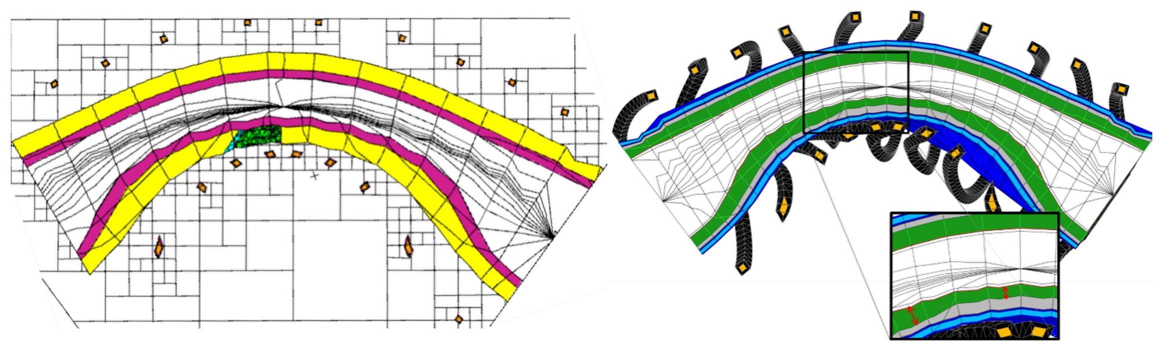
Challenge 5: First integral BB stellarator reactor design with variable radial build



84 different BB segments
Velocities 1 order < DEMO

3D studies for TBR, shielding, hydraulic optimizations, MHD in non-uniform fields and multi-scale thermal–mechanical assessments.





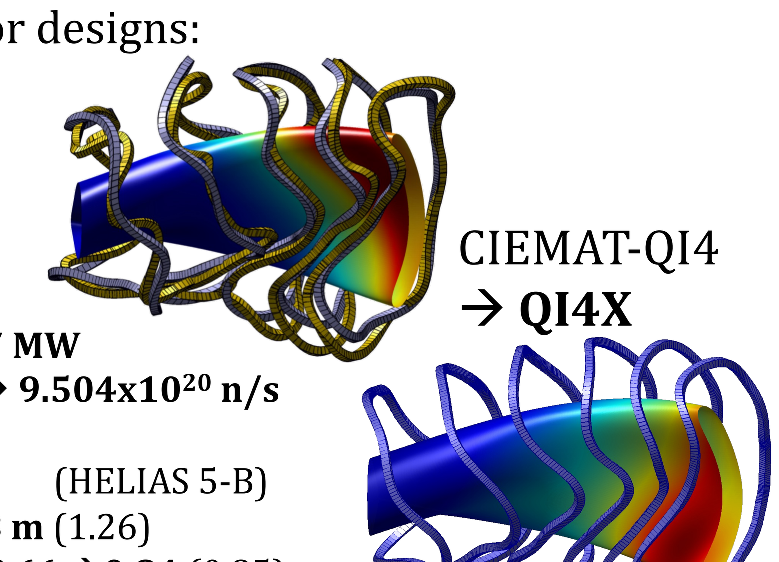
Homogen	baseline	improved	Detailed	equidistant 1	*equidistant 2**	Variable**
W	0.1	0.1	**W**			
FW	2	2	**FW**	2.5	2.5	2.5
BZ mix	80	59	**BZ pure PbLi**	38	29	60_40
			stiff grid	2.2	2	
			BZ pure PbLi	36	28	
			Back wall/shield	18	10	20_40
TBR	**1.33**	**1.26**		**1.51**	**1.42**	**1.34**

**with improved shielding in a specific zone providing a reduction > 2 orders of magnitude of shielding responses → quench limits ~ fulfilled and still margin up to 1.15 TBR_{target} for ports and divertor

Challenge 6: Adaptation to a novel QI device

Advances in quasi-isodynamic (QI) configurations with improved fast-ion confinement prompted adaptation of HELIAS 5-B DCLL BB concepts to new CIEMAT-QI stellarator designs:

40 → **48 coils**
R=16 → **18.5 m**
A=9.94 → **10.43**
B=6 → **5.5 T**
Fus Power: 2750 → **2677 MW**
n source: 9.78x10^{20} n/s → **9.504x10^{20} n/s**



CIEMAT-QI4 → **QI4X**

(HELIAS 5-B)
Max curvature: 1.01→**1.8 m** (1.26)
Min coil-coil separation: 0.66 →**0.84** (0.85)
Min coil-plasma separation: 1.62 →**1.48 m** (1.62)
Min FW+BB+shield thickness: 77 cm → **73.5 cm***62.5effective (71.5*)
TBR: 1.39 → **1.31** (1.42*)

References

[1] **I. Palermo et al.**, *Challenges towards an acceleration in stellarator reactors engineering: The Dual Coolant Lithium-Lead Breeding Blanket Helical-axis advanced stellarator case,* 289 (2024) Energy 129970, https://doi.org/10.1016/j.energy.2023.129970.
[2] **J. Alguacil et al.**, *Fast generation of parametric neutronic models for stellarator: coupling HeliasGeom and GEOUNED*, Fusion Eng. Des., 203 (2024) 114470, https://doi.org/10.1016/j.fusengdes.2024.114470
[3] **D. Sosa, I. Palermo**, *Neutronic Assessments towards a Novel First Wall Design for a Stellarator Fusion Reactor with Dual Coolant Lithium Lead Breeding Blanket*. Energies, 16 (2023), 4430, https://doi.org/10.3390/en16114430.
[4] **V. Queral, et al.,** Coil geometry with large openings for a HSR3-like stellarator reactor for fast replacement of in-vessel components, 2025 https://doi.org/10.48550/arXiv.2501.04640
[5] **E. Sánchez et al.**, *A quasi-isodynamic configuration with good confinement of fast ions at low plasma β*, 2023 Nucl. Fusion 63 066037 https://doi.org/10.1088/1741-4326/accd82

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES · Cofinanciado por la Unión Europea · AGENCIA ESTATAL DE INVESTIGACIÓN · Laboratorio Nacional de Fusión · UNED · UNIVERSITÀ DEGLI STUDI DI PALERMO · EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.
The work has been also partially developed in the framework of the E4XTREM project (Investigación, diseño, Estudio y Ensayo de componentes sometidos a Entornos EXtremos para validación industrial de Tecnologías de Envolturas REgeneradoras asociadas al desarrollo de REactores de fusión Magnética), ref. PLEC2024-011136, funded by MICIU/ AEI/ 10.13039/ 501100011033/ FEDER, UE.