Accelerating stellarator reactor engineering: design and integration of the *Dual Coolant Lithium Lead Breeding Blanket* for HELIAS

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P1A Blanket Technology I – 11th September 2023

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  - SHANE and HeliasGeom tools
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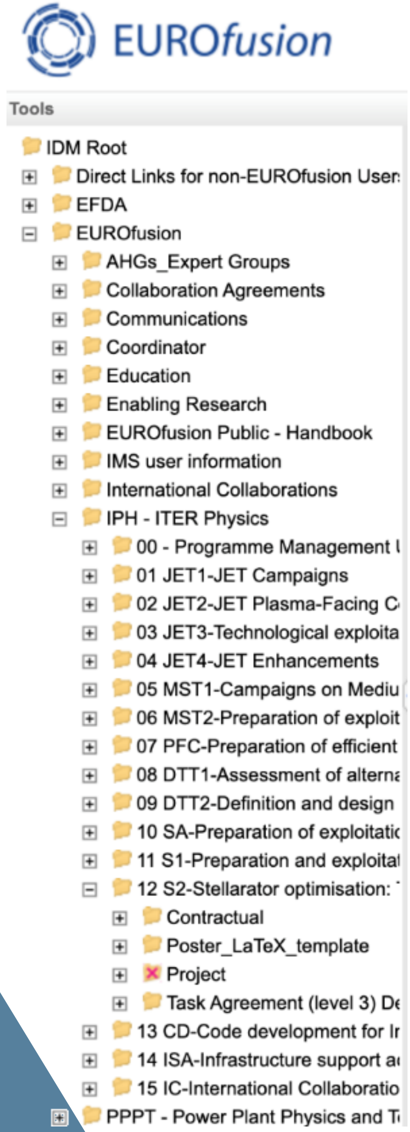
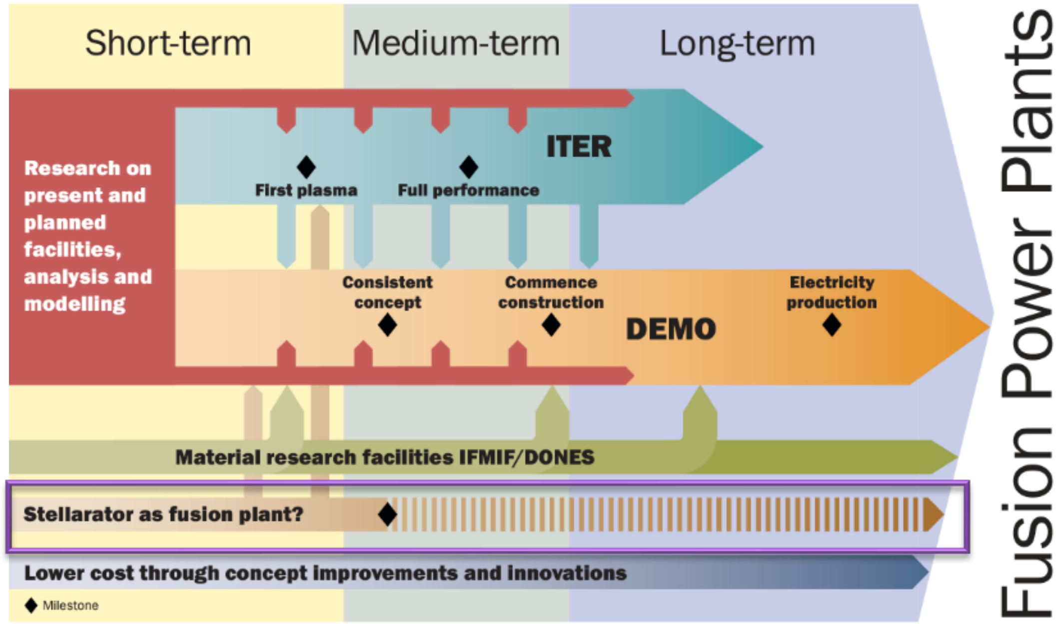
Stellarators development: from Physics to Technology





"EUROFUSION GA (23) 43 - 4.4 - Addendum to Roadmap Version 15a (28-June-2023), New approach to the European Roadmap to fusion energy" has been recently approved by the EUROfusion General Assembly of 18-19 July 2023. The analysis includes this novel positioning on the role of stellarators as FPPs: "In order to proceed along the fastest route... DEMO must be a tokamak. However, **though stellarators are less mature than tokamaks, they have conceptual advantages**, such as improved plasma stability and intrinsic steady-state capability... For this reason, **the conceptual design for stellarator based FPPs should be carried out in parallel to the construction of DEMO.** Most of the basic technological program is in common between tokamaks and stellarators and has to be pursued regardless of the final choice of configuration for the FPP. Yet, **device specific questions for the stellarator FPP should be addressed in order to fully qualify this alternative."**

KN 4: Ambrogio Fasoli*: Recent Progress and Plans in the EUROfusion Program,* **FRIDAY 15TH**

P3B4: Felix Warmer et al. *European Efforts and Advances in Stellarator Power Plant Studies,* **Tuesday 12**

How to face the challenges - EU missions for the realization of fusion

Laboratorio Nacional de Fusión
Ciemat

M1. Plasma regimes of operation:

Demonstrate plasma scenarios (based on the tokamak configuration) that increase the success margin of ITER and satisfy the requirements of DEMO.

M2. Heat-exhaust systems:

Demonstrate an integrated approach that can handle the large power leaving ITER and DEMO plasmas.

M3. Neutron tolerant materials:

Develop materials that withstand the large 14MeV neutron flux for long periods while retaining adequate physical properties.

M4. Tritium self-sufficiency:

Find an effective technological solution for the breeding blanket which also drives the generators.

M5. Implementation of the intrinsic safety features of fusion:

Ensure safety is integral to the design of DEMO using the experience gained with ITER.

M6. Integrated DEMO design and system development:

Bring together the plasma and all the systems coherently, resolving issues by targeted R&D activities

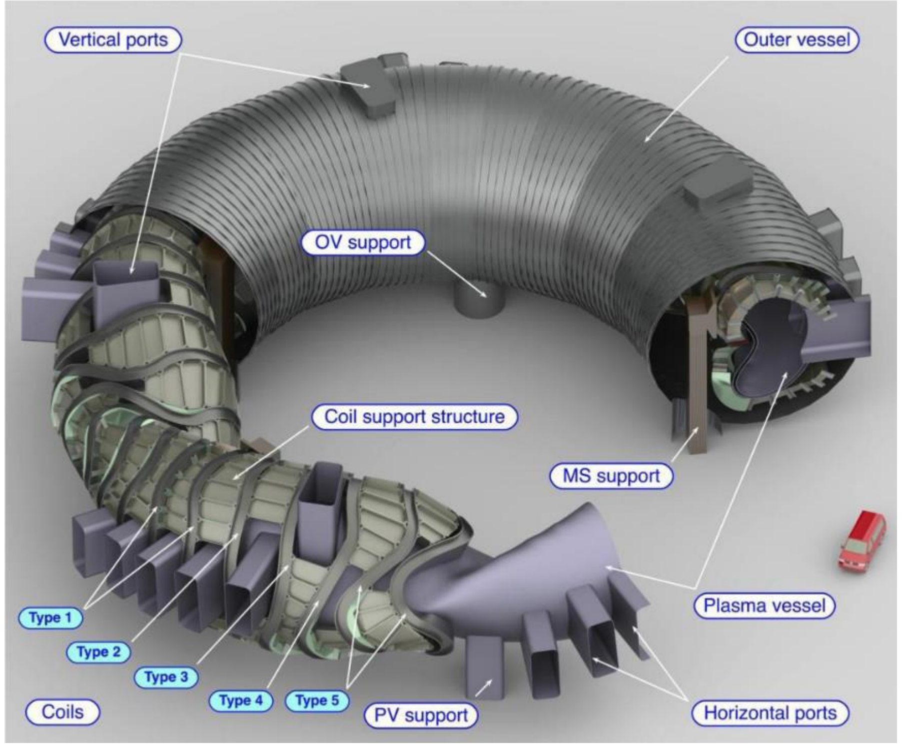
M7. Competitive cost of electricity:

Ensure the economic potential of fusion by minimising the DEMO capital and lifetime costs and developing long-term technologies to further reduce power plant costs.

M8. Stellarator:

Bring the stellarator line to maturity to determine the feasibility of a stellarator power plant.

Stellarators (Mission 8): *…it is expected that a combination of further experiments/facilities and conceptual or engineering design activities for stellarator power plants will be pursued with industry engagement in view of possible deployment. It is expected that* ***similar approaches to those for the tokamak DEMO will be pursued for blankets and other technologies, sharing solutions****….*



Among the Eurofusion Programme, the Stellarator Power Plant Studies (SPPS) Prospective R&D Work Package (WPPRD) aims to cover the engineering activities for the development of an *Helical-Axis Advanced Stellarator* (HELIAS) fusion reactor. Under such ambitious programme and exploiting previous experience in *Breeding Blanket* (BB) designs for *DEMO tokamak* reactors, CIEMAT is leading the development of a conceptual design of a *Dual Coolant Lithium-Lead* (DCLL) BB for HELIAS.

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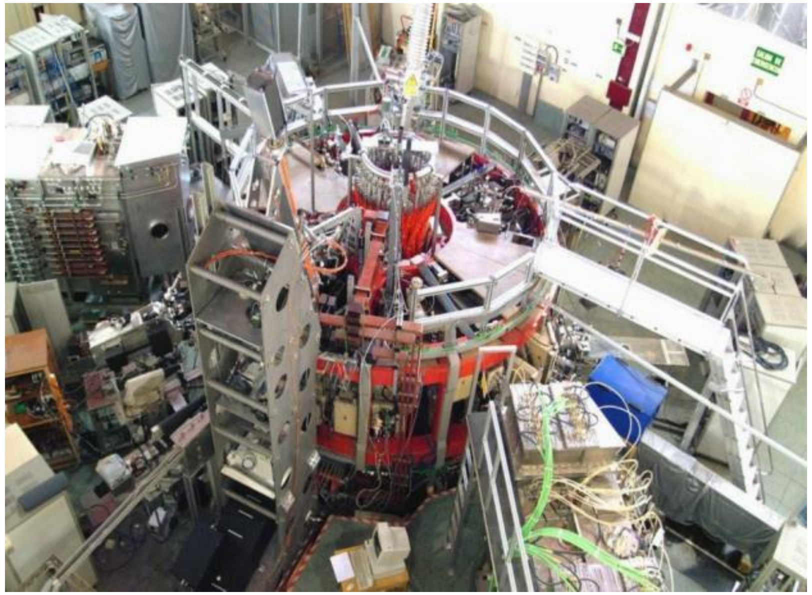
CIEMAT program for HELIAS-DCLL

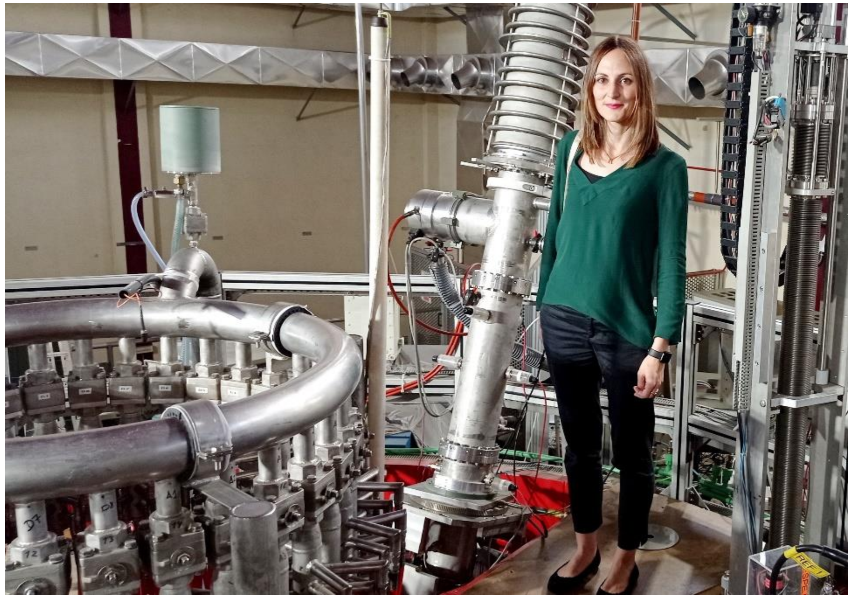
- **Reasons:**
  - TJ-II stellarator → CIEMAT has historically worked on plasma physics (both experiments / theory)
  - Breeding blanket technologies for DEMO tokamak (**DCLL**, but also participation in WCLL, HCPB and other ceramic breeding concepts as WLCB and Li_8PbO_6) and ITER TBM
  - As the design is still in a very conceptual phase, the **BB design should have a big role** in determining the constraints for the other systems (VV, Divertor) and including it from the very beginning in the definition of Remote Operations/Safety/Auxiliary Systems.



The main **advantages**
- Wider design margins due to the double cooling system
- Lower tritium inventory (and can avoid HTO)
- No safety issue related to water cooling
- No safety issue related to Be multiplier
- Well suited for presently available nuclear materials
- Well suited for Eurofer (upper temperature limited)
- Potential for high-temperature and higher plant efficiency

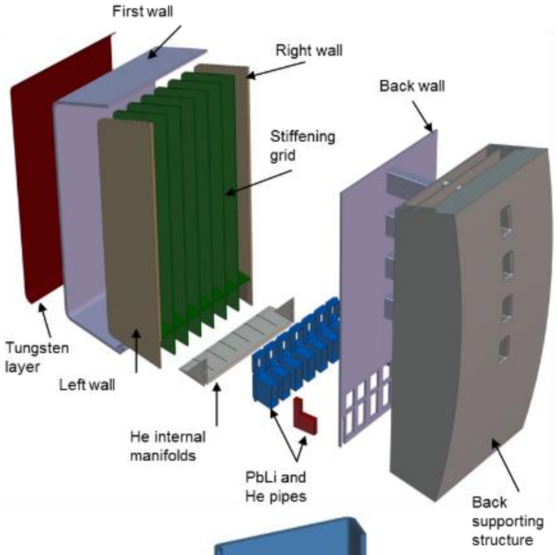
The main **concerns**
- Not tested in ITER (TBM)
- relatively high PbLi velocity
- MHD problems
- Corrosion problems

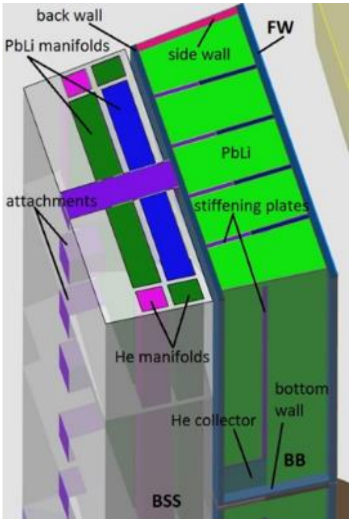
last 2 issues also could undermine the HCLL and WCLL.

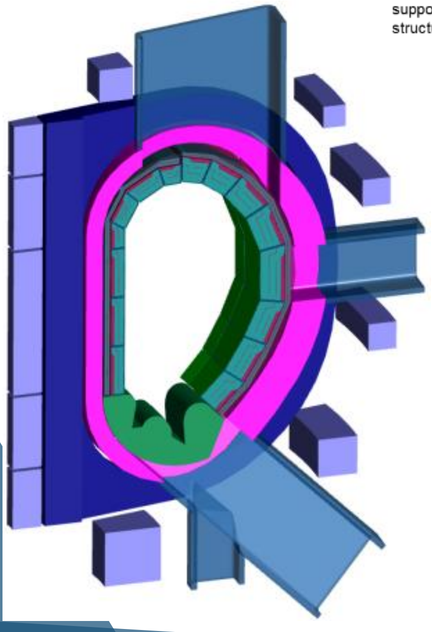


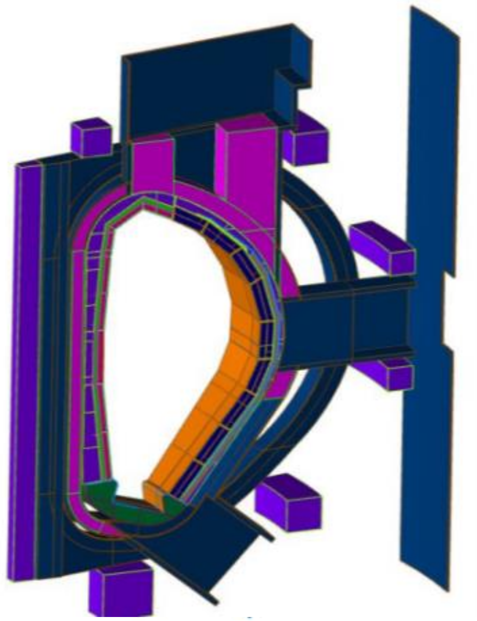
- All these advantages made the **DCLL BB** concept probably one of the concepts with **highest long term potential** of improvement and of the most adaptable to the physic and technology challenges which poses the stellarator configuration.

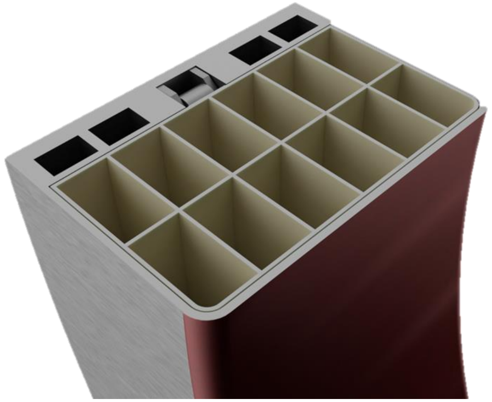
DCLL DEMO evolution from LT-MMS to HT-SMS BB

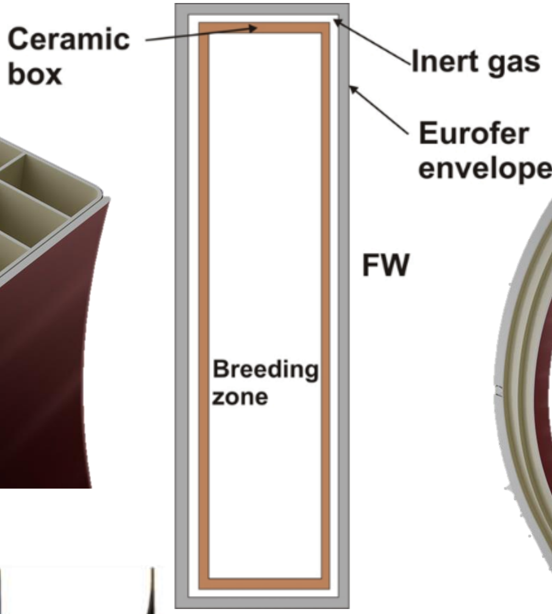


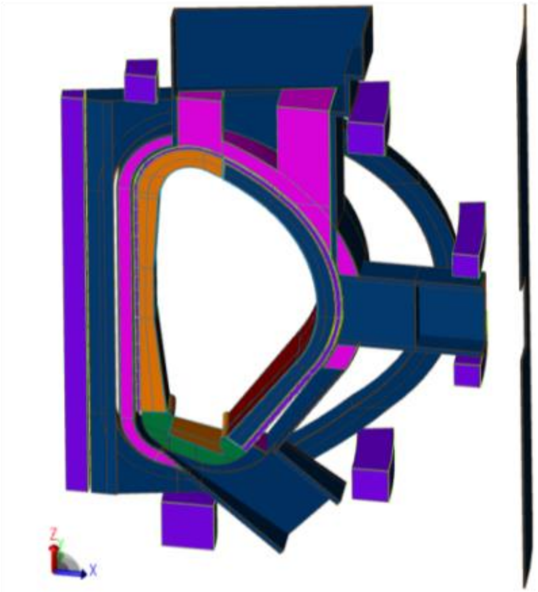




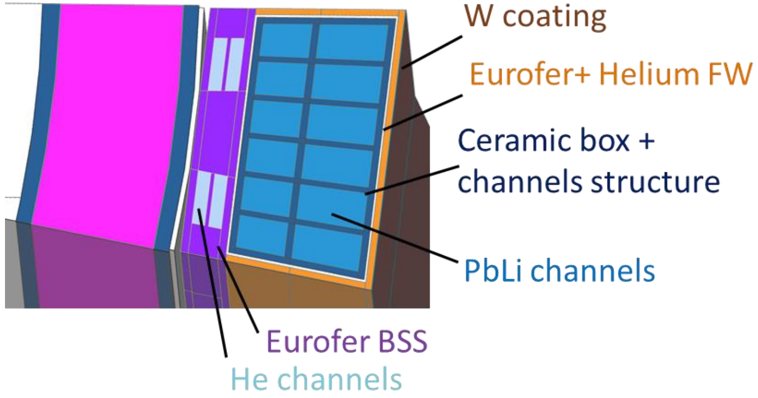








I. Fernández-Berceruelo, et al., *Progress in design and experimental activities for the development of an advanced Breeding Blanket*, Contributed talk at the next 29th IAEA Fusion Energy Conference (FEC 2023), 16-21 October 2023, London, United Kingdom



Strategy for selection of DCLL technologies in HELIAS 5-B

Main functional requirements									
T production and transfer outside the BB		Power extraction		Shielding capability	Safety features				
TBR	Tritium extraction	Pressure drop	Cooling circuits Integration with the Plant	Shielding	T production	Dpa	Activation/ Inventories/decay heat	Chemical reactivity	Wastes

FW concepts:		
Standard FW		
Decoupled FW	decoupled standard	
	dec. + CPS (Li+W+steel or no steel)	with cooling
		without cooling
	(instead of Li)	
BB Segmentation:		
Modules		
Big toroidal segments		
Big polidal segments		
Continuos toroidal "rings"		
BB materials structure:		
Standard Eurofer box		
ODS		
Ceramic HT		
BB breeder		
PbLi		
Molten salts		

FW concepts:
Standard FW
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BB materials structure:
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Molten salts

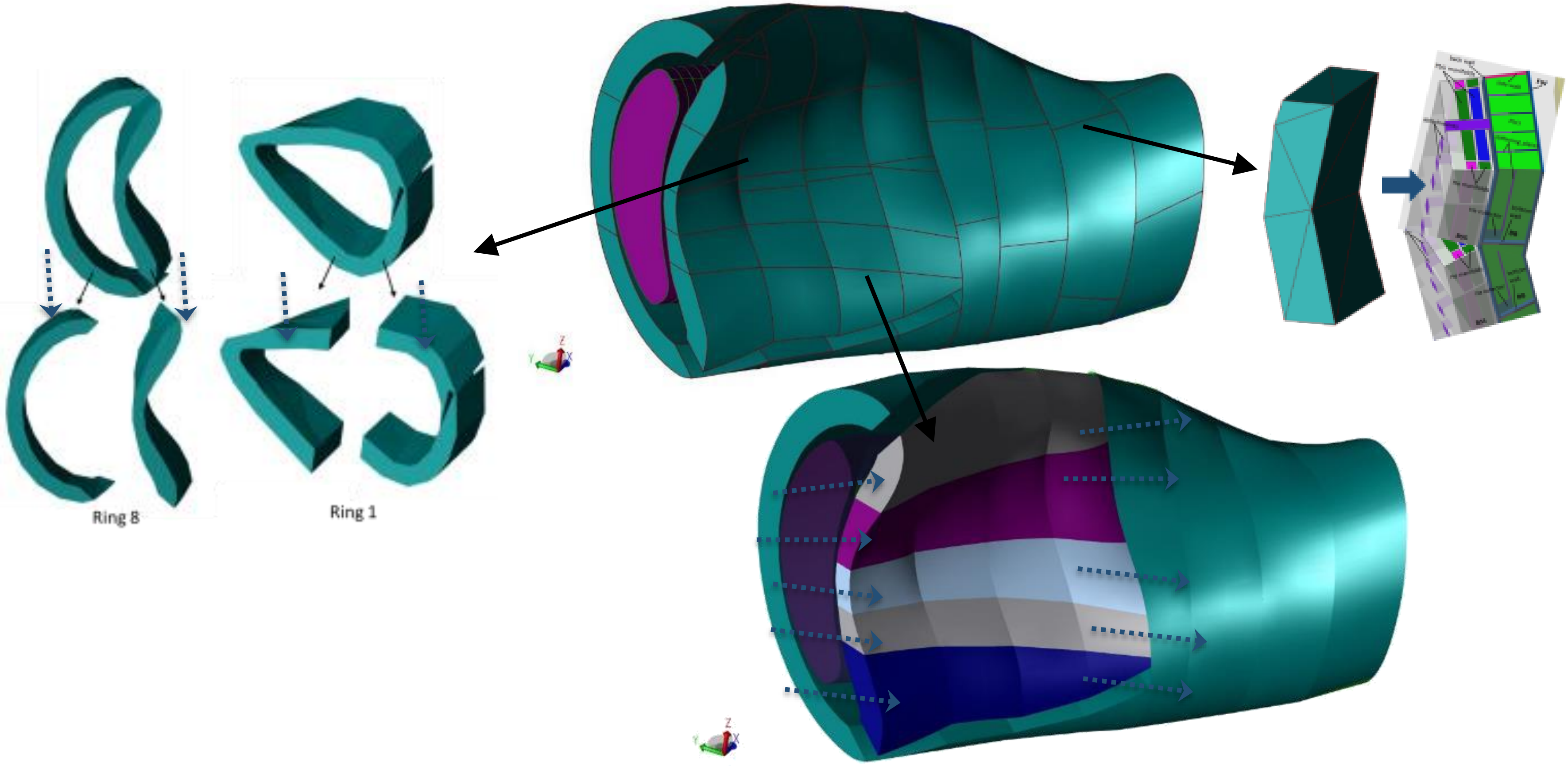
Other requirements								Technology readiness	
Power conversion efficiency	RAMI		Cost					Critical issues	R&D needs
Coolant temperatures	RH, maintenance time	Reliability (corrosion, weldings…)	Plant size	Materials	Fabrication	Balance of Plant			

DCLL segmentation

Develop a brand-new pre-conceptual design of DCLL for HELIAS without the specific DEMO constraints (i.e. limited space due to central solenoid, vertical RH from Upper Port), exploiting the flexibility and freshness of a reactor design still open.

Number/weight: Multi/ Single/ Few Modules Segment (MMS, SMS, FMS)

Direction: Poloidal /Toroidal/ mixed

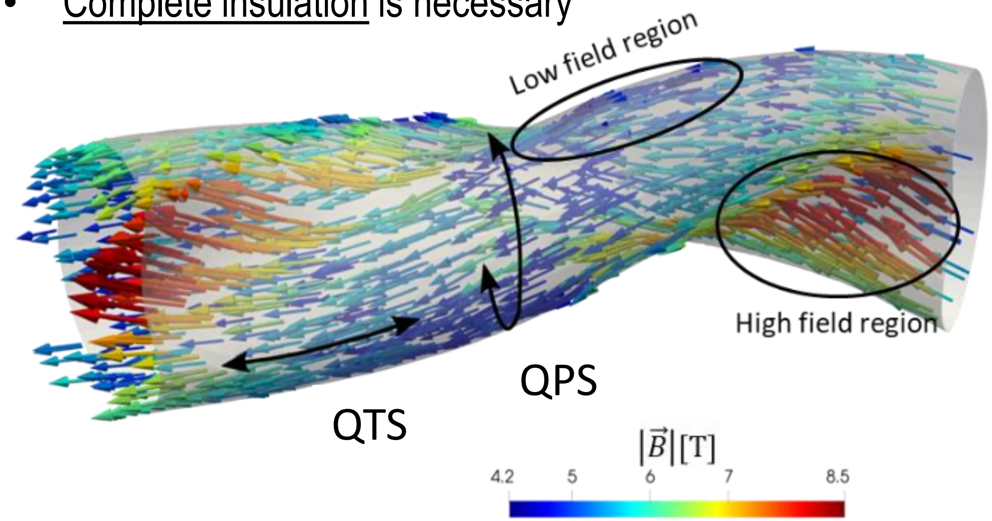


MHD studies and proposed segmentations

HELIAS magnetic field presents peak values as high as the DEMO tokamak inboard field. A PbLi based blanket would exhibit unacceptable pressure drop in a classical segmentation. Since the component of the magnetic field parallel to the flow does not impact on the 2D pressure gradient a segmentation following the magnetic field is proposed as a measure for reducing the MHD pressure drop without introducing ceramic insulators components in the complex HELIAS geometry.

"Poloidal" circulation would be "equivalent" to the DEMO-DCLL

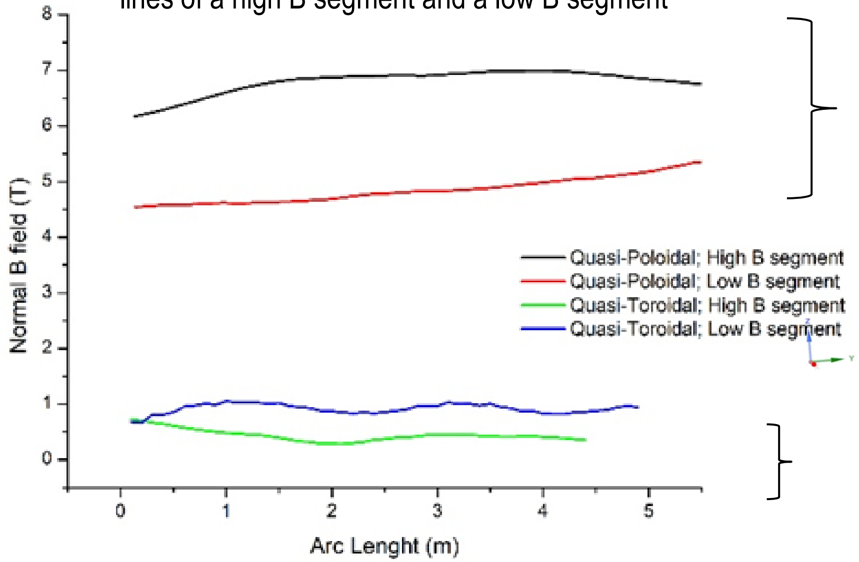
- <u>Complete insulation</u> is necessary

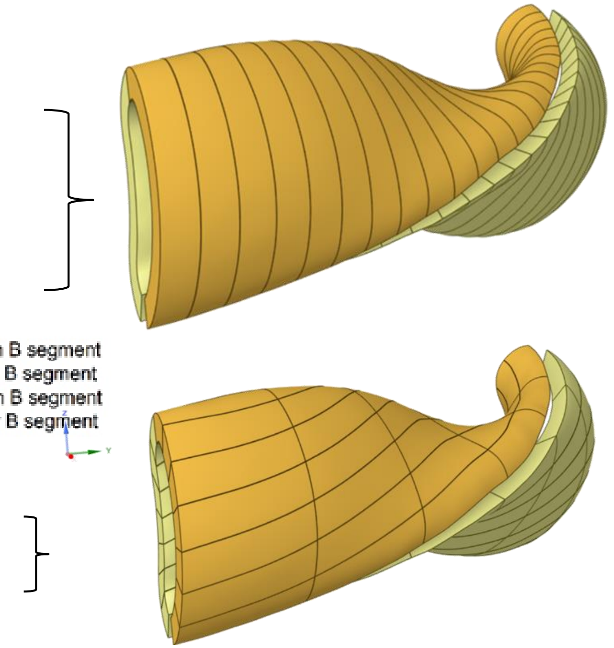


"Toroidal" circulation would imply a less contribution to the MHD pressure drop

- <u>Partial insulation</u> could be sufficient

Magnetic field normal component along the central lines of a high B segment and a low B segment

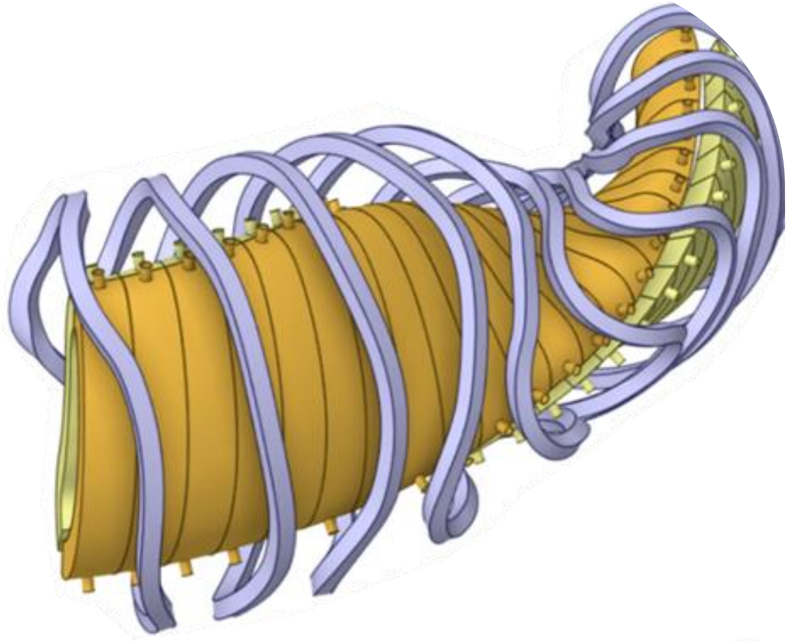


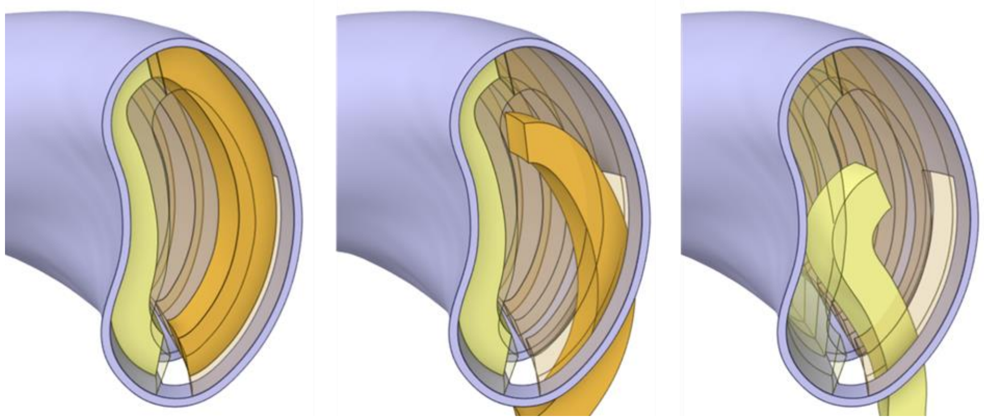


Iole Palermo at al., *Challenges towards an acceleration in stellarator reactors engineering: The Dual Coolant Lithium-Lead Breeding Blanket Helical-axis advanced stellarator case,* Energy (under review)

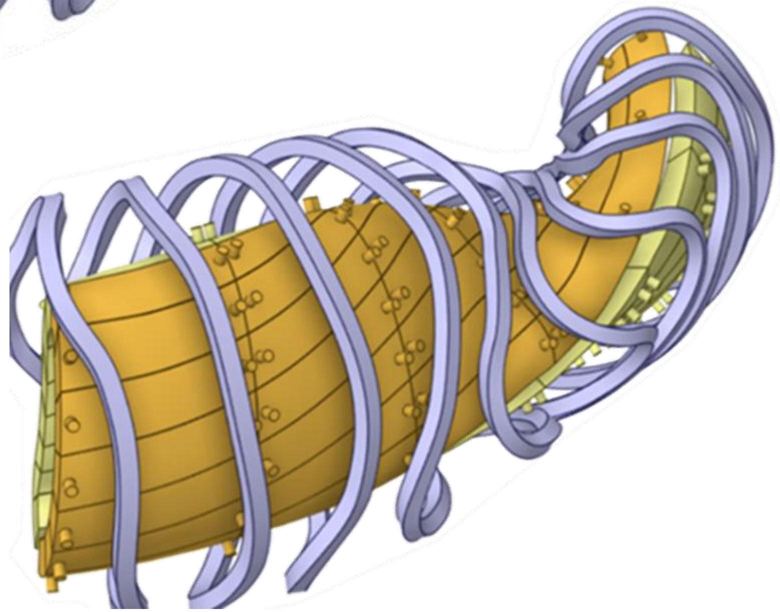
- Only the normal component of the B field contributes to the 2D MHD pressure drop.
- These are moderate even in the high field segment.

DCLL segmentation

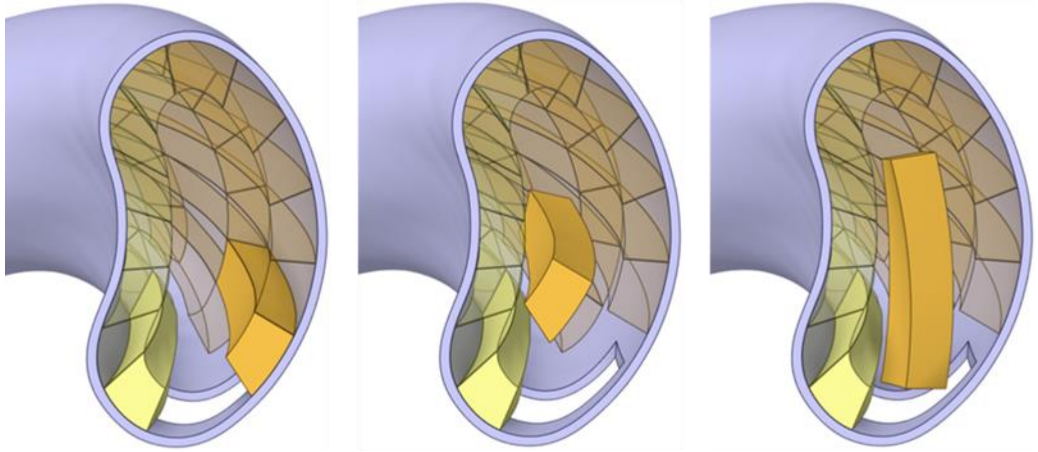




The traditional "quasi-poloidal" segmentation could be favorable for integration and RH through ports, but would generate higher PbLi pressure drop.



Alternatively, a "quasi-toroidal" configuration would produce **low MHD pressure drop**, inclusive in the zones with the highest field. To cope with the resultant RH issues other options are being investigated, such as using a decoupled FW to reduce most of the RH operation to smaller FW panels.



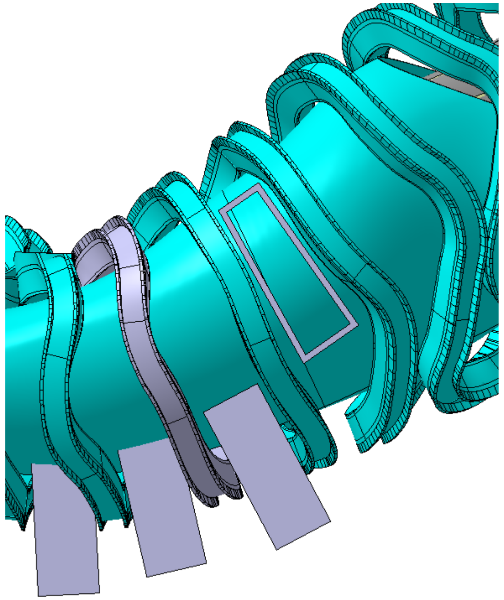
Integration activities: Remote Handling hypothesis

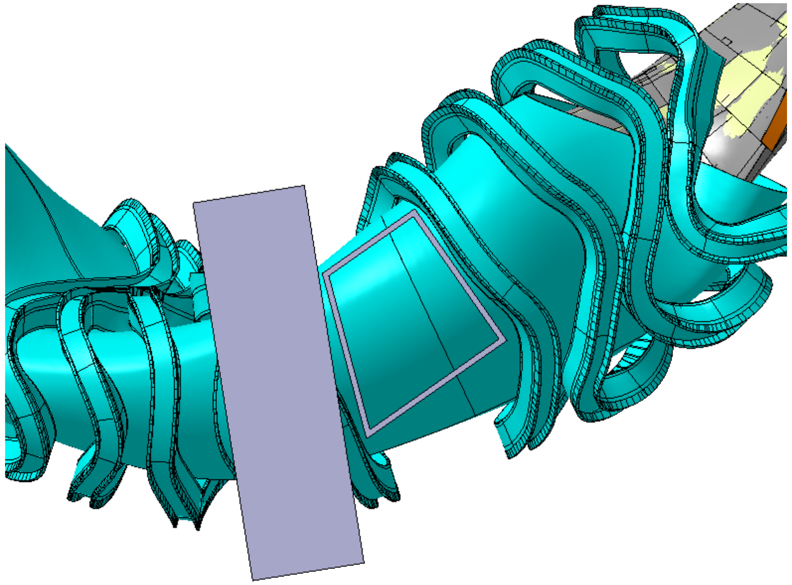
Alternative Approach 1:

Access blankets through **enlarged vertical ports**

Concepts proposed that could facilitate larger vertical ports to allow alternative blanket segmentation with fewer, but heavier, components.

- Rotating a coil or coils poloidally while simultaneously sliding it toroidally (to follow the contours) towards the adjacent coil, vacating space for a larger vertical port to be **temporarily attached**.
- Splittable magnets (as are being developed for STEP), so that a much larger vertical port could be temporarily attached.



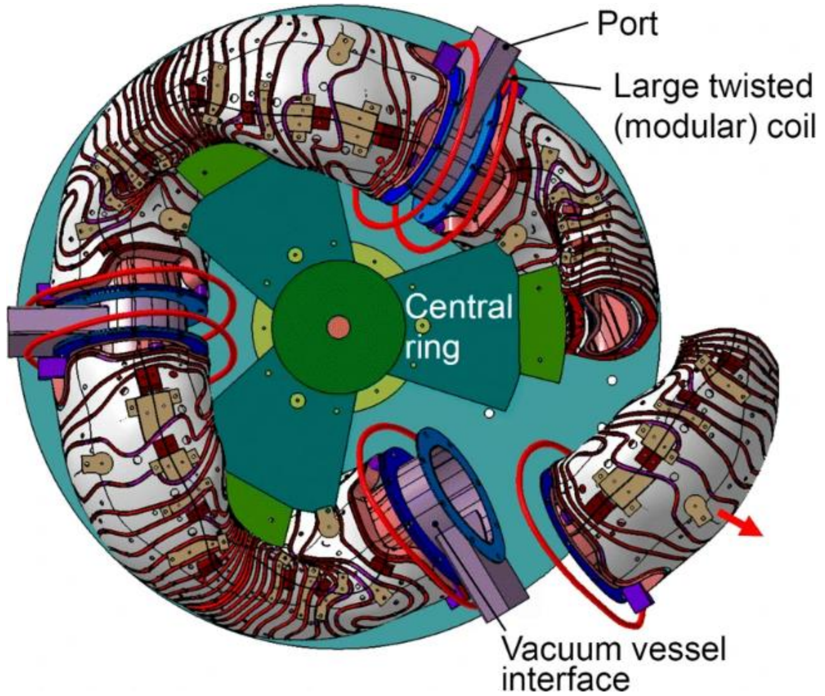


EFDA_D_ 2PNBXE, S2-WP19.2-T003-D002, *Remote Maintenance, safety and control (2020) (CCFE),* A. Wilde, J. Lilburne

Integration activities: Remote Handling hypothesis

Alternative Approach 2:

Detachable (haf) periods

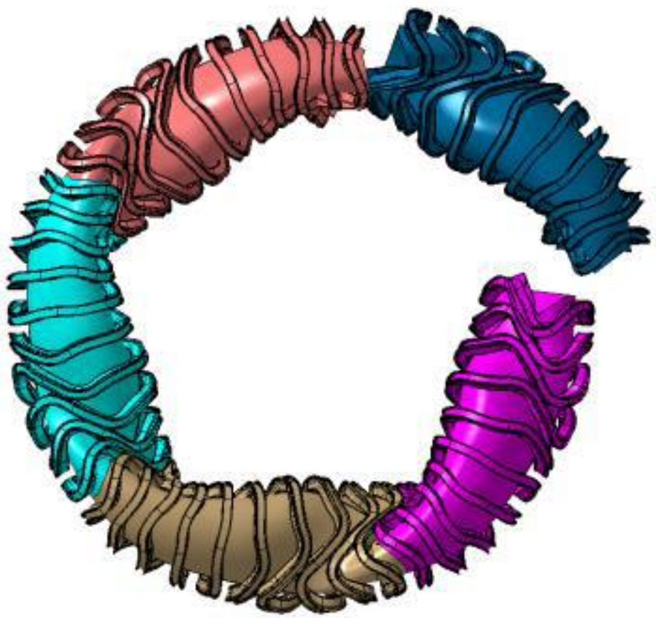


Vicente Queral, Seminar in Univ. Carlos III of Madrid about *high-field ignition stellarators and i-ASTER*, 19-11-2018

Initial Exploration of High-Field Pulsed Stellarator Approach to Ignition Experiments V. Queral, F. A. Volpe, D. Spong, S. Cabrera & F. Tabarés, Journal of Fusion Energy volume 37, p275–290 (2018)

X.R. Wang et al., *Maintenance approaches for ARIES-CS compact stellarator power core*. Fusion Sci. Technol. 47(4), 1074–1078 (2005)

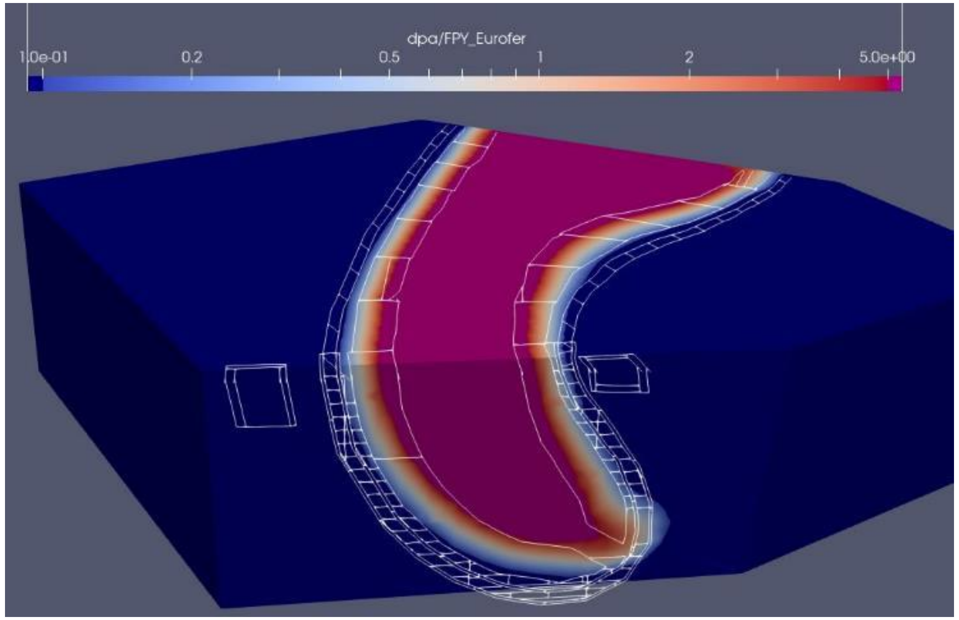
Access blankets by splitting the VV



EFDA_D_ 2PNBXE, S2-WP19.2-T003-D002, *Remote Maintenance, safety and control (2020) (CCFE),* Andrew Wilde, James Lilburne

Issues: Interfaces, safety, time

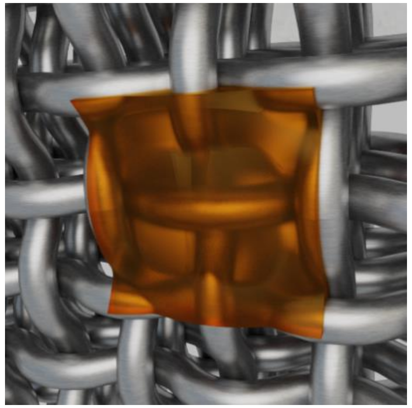
How to manage dpa to increase BB availability

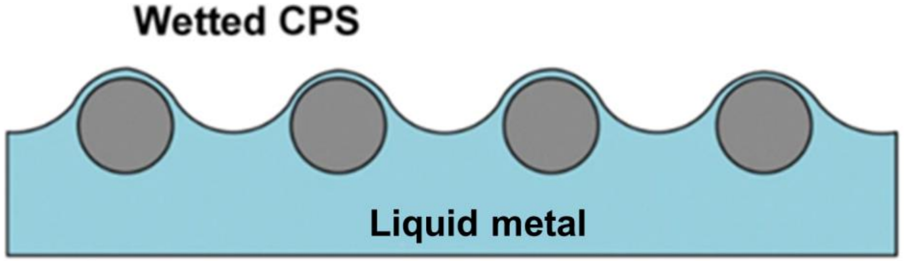


switch the blankets scheduled maintenance just to FW panels maintenance

If we get 5 dpa in SW → 4 FPY working continuously up to reach 20 dpa? Or 10 FPY up to 50 dpa?

In CPS concept a liquid metal pool is put into contact with a porous metallic mesh through which the LM can flow. The liquid layer can eliminate the degradation of wall materials produced by plasmas. Flowing liquids can remove the surface heat load and reduce gradients temperature and stress. Somewhat thicker liquid layers/substrate can reduce the nuclear damage of the BB.

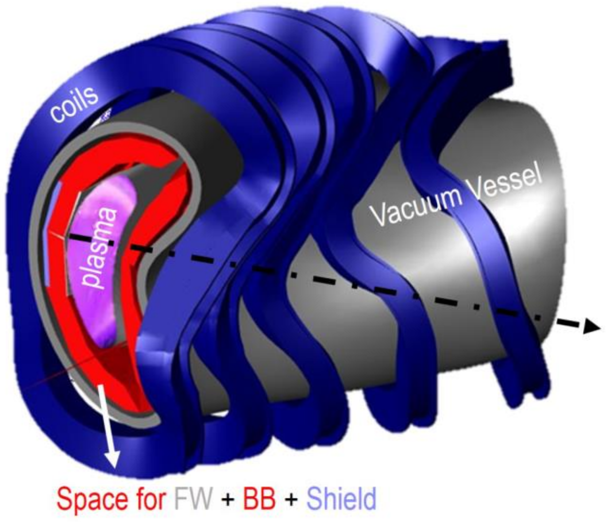


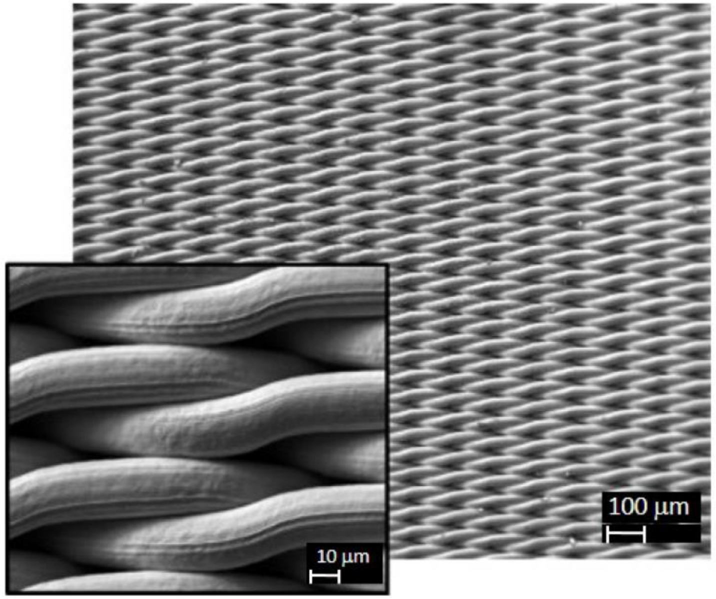


Source: Zong-Biao Ye et al., "Compatibility investigation of liquid tin and tungsten-based capillary porous system under high-density plasma environment", Tungsten, Springer, 2020

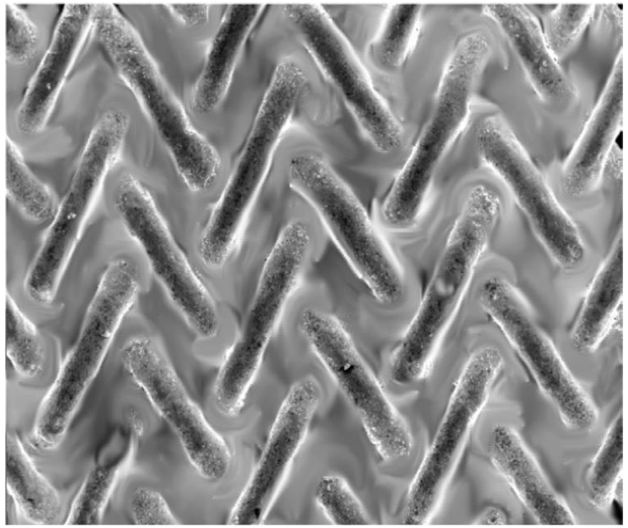
Integration activities: FW solutions for faster RM

Liquid (Li or Sn) Capillary Porous System (CPS) for decoupled and complex shaped First Wall





A.V. Vertkov, I.E. Lyublinski, F. Tabares, E. Ascasibar, *Status and prospect of the development of liquid lithium limiters for stellarator TJ-II.* Fusion Eng. Des. 87, 1755–1759 (2012)



SS mesh wetted by Li as in CPS for first LLL in the Frascati tokamak. Fig. courtesy of Efremov Institute.

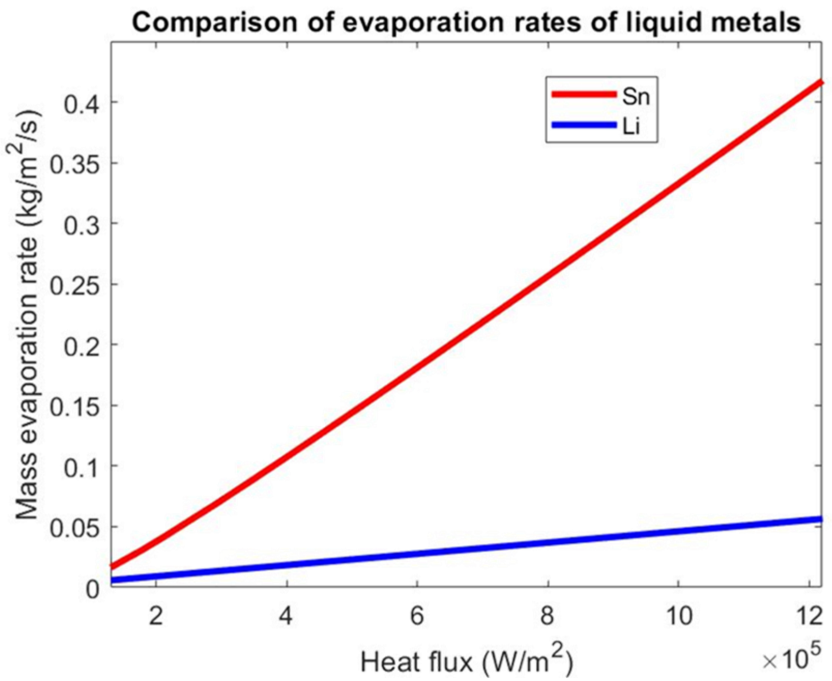
F.L. Tabarés et al., *Plasma performance and confinement in the TJ-II stellarator with lithium-coated walls*. Plasma Phys. Control. Fusion 50, 124051 (2008)
R.E. Nygren, F.L. Tabarés, *Liquid surfaces for fusion plasma facing components—A critical review. Part I: Physics and PSI,* Nuclear Mat. and En. 9 (2016) 6–21

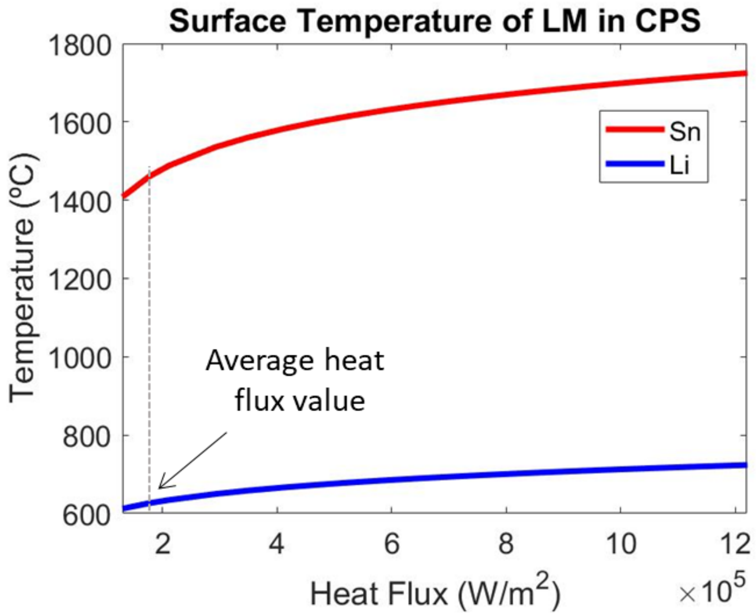
A first-wall almost entirely covered with liquid lithium could be realized by electrostatic/centrifugal spraying or by evaporation [Tabarés] of **lithium** on a CPS mesh [Verktov]. The mesh is locally heated during coating from inside the vacuum vessel for proper Li deposition in the capillary mesh. The CPS is located on a thick substrate (the first wall) coated with a thin protective film of a Li compatible material (i.e. W). The lithium in the CPS is solid before the plasma discharge, at room temperature or slightly higher, and it is liquefied after the pulse start.

A. de Castro et al., PS4-10, *Investigation of plasma plumes created during the exposition of a liquid-**tin** filled tungsten Capillary Porous System target to the OLMAT High-Heat Flux facility,* **FRIDAY 15TH**

FW CPS Thermal-hydraulic characterization

A Matlab code has been developed to address the equilibrium temperature reached by the LMs, the evaporation rates and the viability of a LM first wall without a cooling system. For an average heat flux of 0.18 MW/m^2 (extrapolated from DEMO) the equilibrium temperature would be around 1475 °C (Sn) and 630 °C (Li). At such heat flux value the **evaporation rate of Sn** is 3 times **higher** than for Li implying the need of a cooling system for Sn.

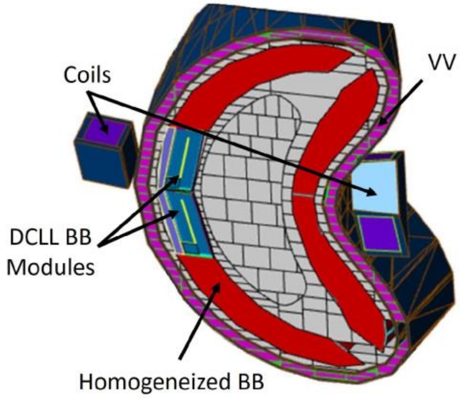


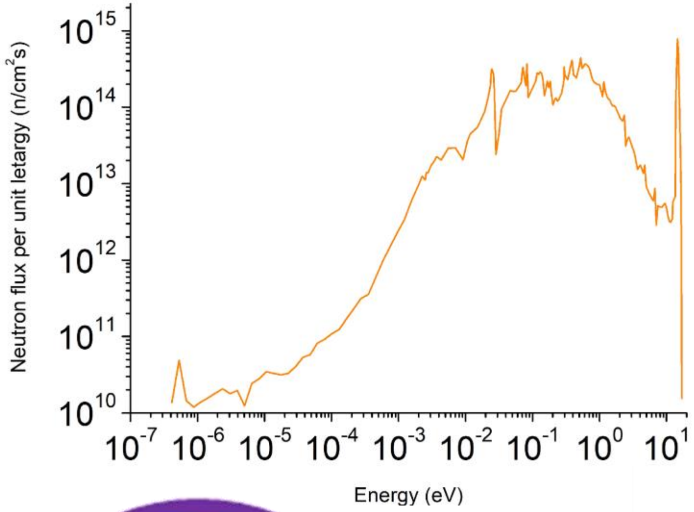


It would be important to find out the viability of using an **impurity extraction system** and establish an operation mode for HELIAS (**steady-state** in principle) in order to limit the **maximum impurity concentration** allowed for the normal operation of the reactor. Information about the transport of impurities inside the reactor to discover **where these particles are going to be deposited**, in which percentage are ionized and entering into the plasma

FW CPS Neutronic assessments on 1D geometry

Using, as source term, the FW spectrum of previous HELIAS DCLL BB neutronic semi-detailed model

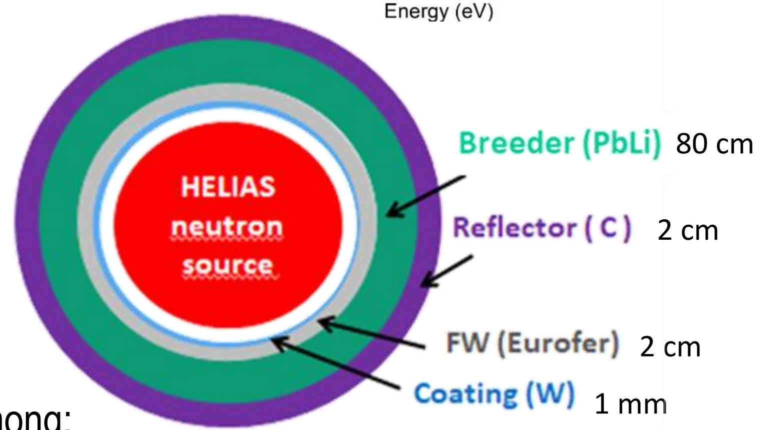




FW configurations	BB structure thickness	DPA/FPY in Eurofer of BB	Δ DPA/FPY (%)	TBR	Δ TBR (%)	Δ Refl. effect (%)
Baseline (coupled "traditional" FW integrated in BB) 1 mm W + 2 cm Eurofer	-	**7.99**		**1.05**		
Decoupled fingers FW 1 mm W + 3.5 cm Eurofer	2 cm Eurofer	6.58	-17.7%	1.02	-3.3%	
CPS 2.5 cm W (with Li/Sn) +1 cm Eurofer	2 cm Eurofer	5.59	-30.0%	0.831	-20.9%	
CPS 5 cm W	2 cm Eurofer	4.55	-43.0%	0.669	-36.3%	
CPS 4 cm C + 0.5 cm Eurofer (support)	1 cm Eurofer	5.04	-37.0%	0.964	-8.1%	
CPS Sn 3 cm C + 0.5 cm Eurofer (support)	1 cm Eurofer	5.67	**-29.0%**	0.999	**-4.9%**	
as previous[1] + additional 2 cm C back reflector (behind BB)	1 cm Eurofer			1	-4.7%	0.6%
as previous[1] + intermediate 2 cm C reflector (inside the BB)	1 cm Eurofer			1.006	-4.2%	1.1%
as previous[1] + back + intermediate 2 cm C x 2 reflectors	1 cm Eurofer			1.010	-3.8%	1.5%

[1] space of FW taken at the expense of the BB space while in the rest was taken at expense of the plasma space

David Sosa and Iole Palermo, *Neutronic Assessments towards a Novel First Wall Design for a Stellarator Fusion Reactor with Dual Coolant Lithium Lead Breeding Blanket*, Energies 2023, 16(11), 4430; https://doi.org/10.3390/en16114430

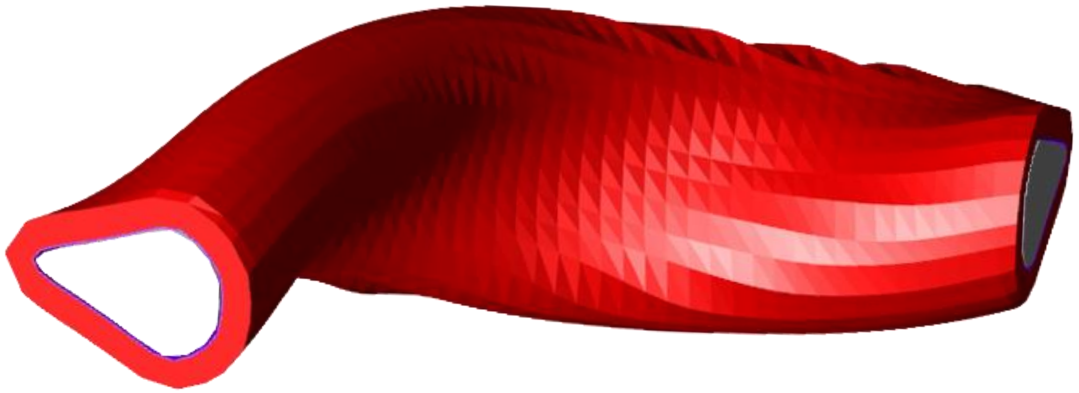


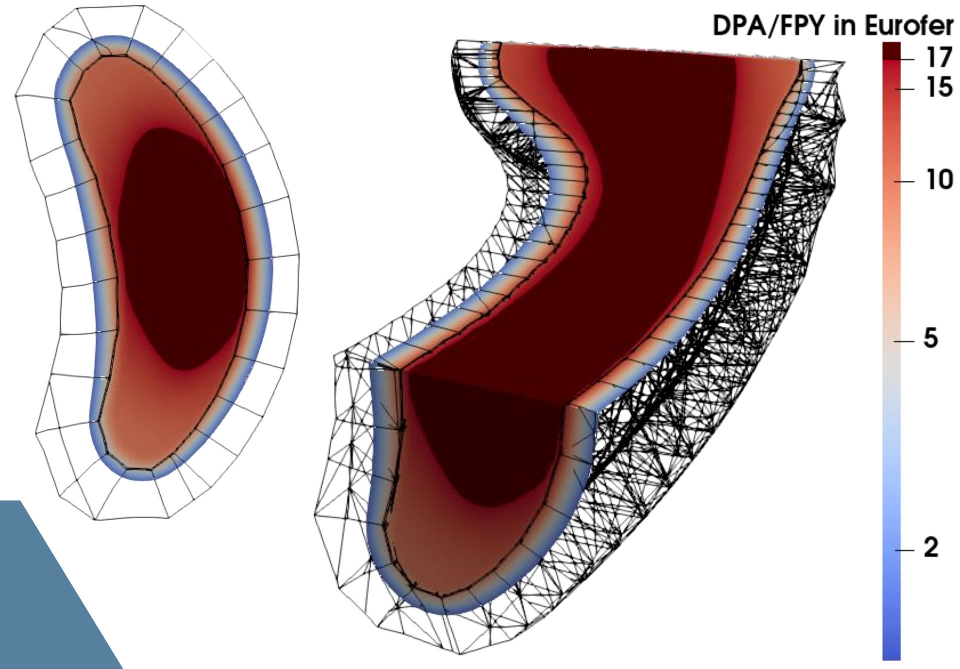
Compromise among:

- Reduce dpa to the BB (minimize BB frequency of substitution, avoid RH operations on big segments, etc.) → just substitution of detached FW panels → simplification of ports/RH
- Keep the TBR → reflectors

PS2-26 David Sosa et al., *Neutronic studies for the Dual Coolant Lithium Lead Breeding Blanket HELIAS design*, **Tuesday 12**

FW CPS Neutronic assessments on 3D geometry





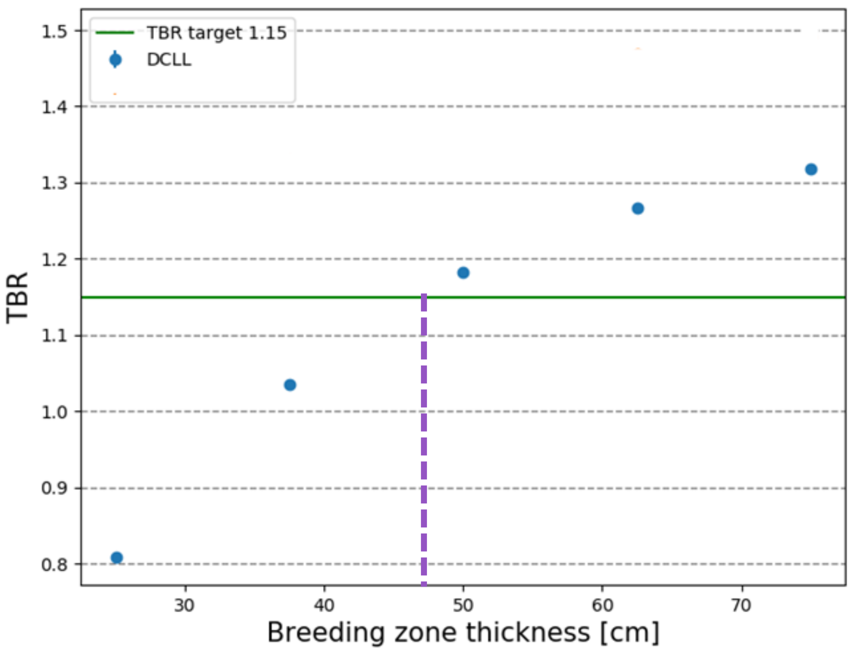
FW layers configurations (cm)		TBR	Δ TBR (%)	DPA/FPY in BB Eurofer (OB)	Δ DPA/FPY (%)
Baseline	0.1 W + 2 Eurofer	1.33		17.35	
*Decoupled FW	0.1 W +1.5 Eurofer	1.20	-9.7%	12.48	-28.1%
***CPS1**	**1 W + 2.5 Eurofer**	**1.22**	**-7.7%**	**11.78**	**-32.1%**
CPS1_v2	1 W + 2.5 Eurofer	1.21	-9.1%	12.75	-26.5%
*CPS2_inv	2.5 Eurofer + 1 C	1.17	-11.9%	13.42	-22.6%
CPS3_v2inv	**2.5 Eurofer + 1 Pb**	**1.24**	**-6.8%**	**14.03**	**-19.2%**
****CPS3_v2inv**	**2.5 Eurofer + 1 Pb**	**1.23**	**-7.7%**	**14.04**	**-19.1%**

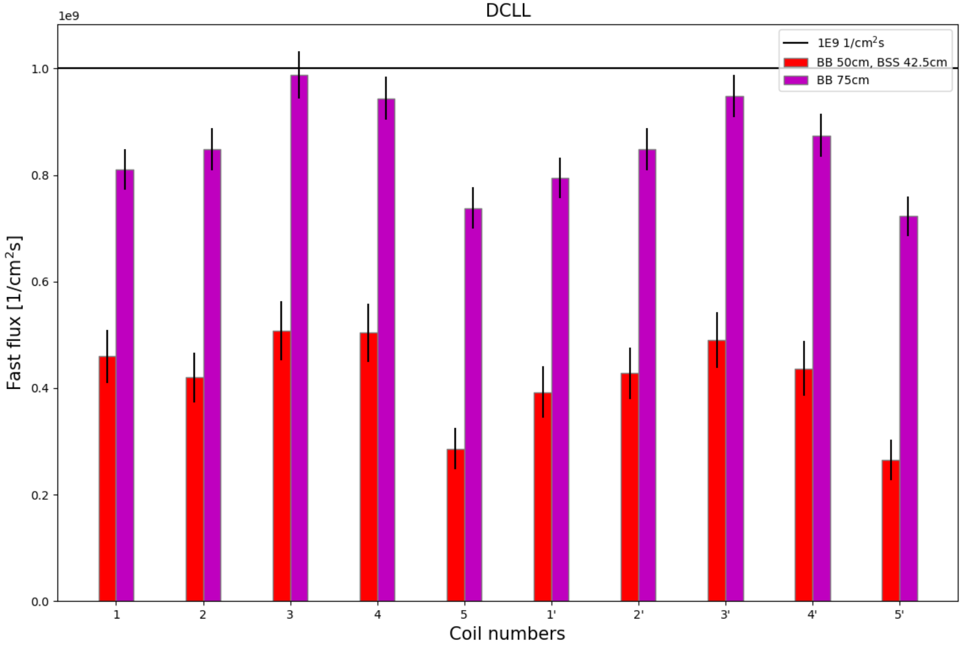
CPS with 1 mm W matrix with embedded Li/Sn; BB structure: 2 cm Eurofer; * Mixture of Eurofer steel and Helium (as coolant); while v2 means no He in Eurofer BB; ** 76.5 cm LiPb (SOL kept)

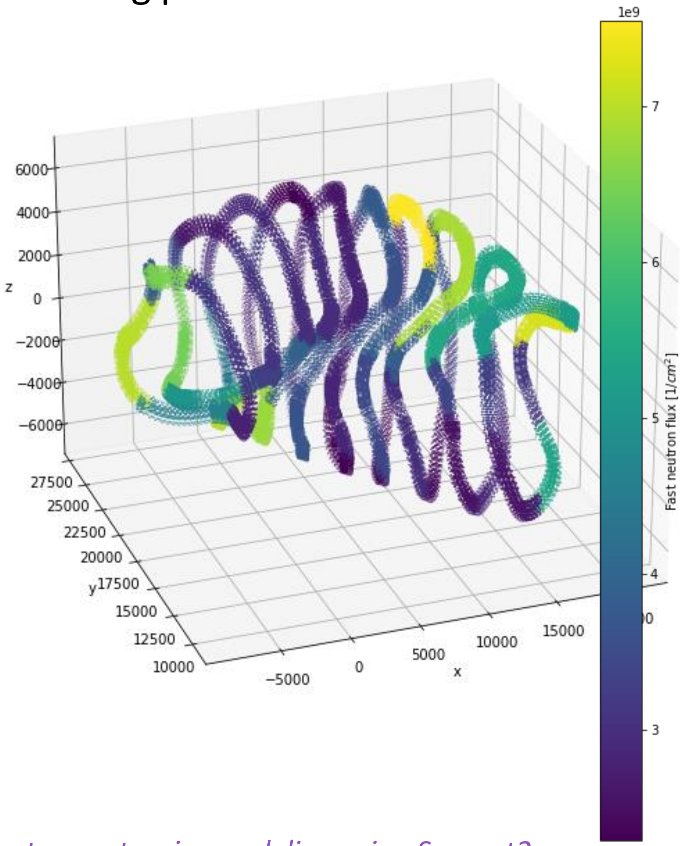
PS2-26 David Sosa et al., *Neutronic studies for the Dual Coolant Lithium Lead Breeding Blanket HELIAS design*, **Tuesday 12**

Parametric modeling – neutronic results with Serpent 2

- A wide scan of breeding zone thickness from 25 cm to 75 cm.
- 7 material layers: W armour, FW, Breeding Zone, Back Supporting Structure, 3 Vacuum Vessels (inner, shield, outer).
- Evaluation of TBR and neutron shielding of the coils.
- TBR target achieved with BZ thickness 45 cm.
- Neutron fast flux within the limit with the thickest configurations. DCLL resulted in a good shielding performance.







(Red: BZ = 50 cm, BSS = 42.5 cm)
(Purple: BZ = 75 cm, BSS = 12 cm)

A. Snicker et al., *Proof-of-principle of parametric stellarator neutronics modeling using Serpent2*, next 29th IAEA Fusion Energy Conference (FEC 2023), 16-21 October 2023, London, United Kingdom

Integration activities: Ports/Div/FW impact on TBR

loss of breeder area coverage + loss of breeder volume → impact on TBR

- Ports → 10% loss of FW Surface area with no breeding elements

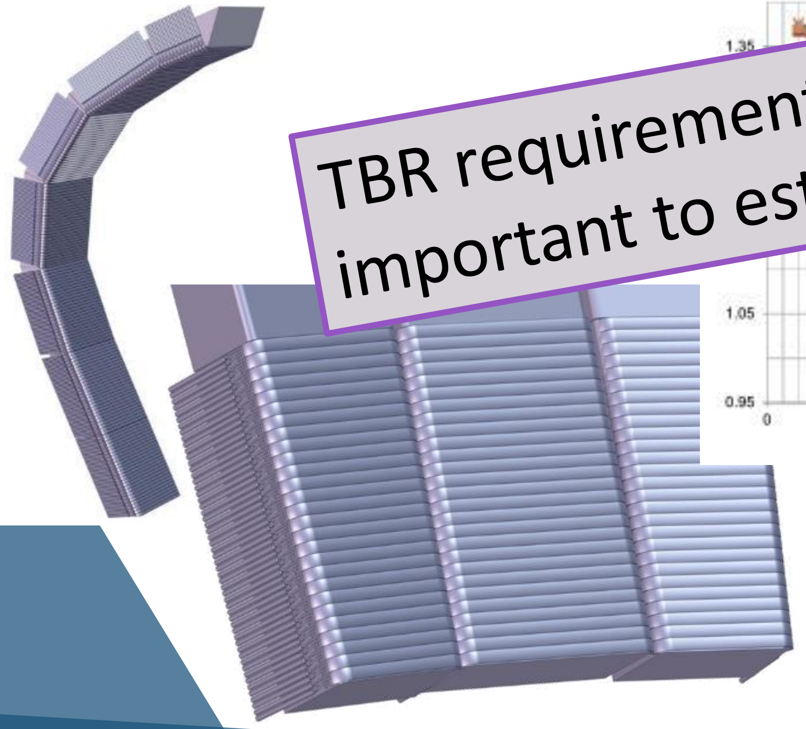
→ TBR target from 1.05 to 1.15)

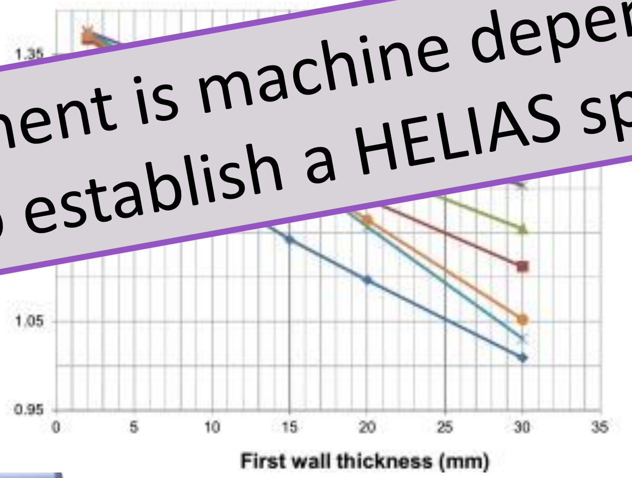
- Divertor → if double null it could increase the target another 10%!

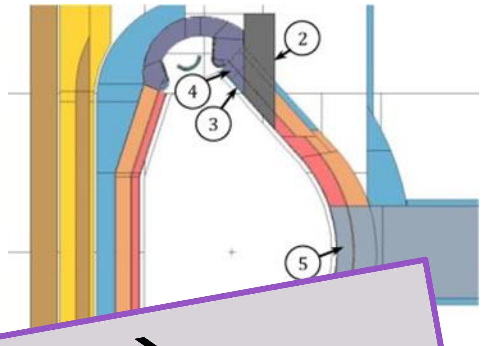
→ TBR target from 1.15 to 1.25

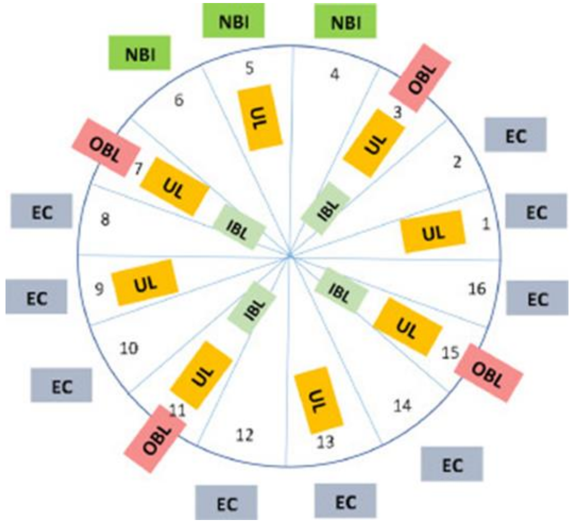
- Decoupled FW → 5% TBR reduction

→ TBR target from 1.25 to 1.30









TBR requirement is machine dependent → important to establish a HELIAS specific TBR target

[1] U.Fischer, Required, achievable and target TBR for the European DEMO, Fusion Engineering and Design, Volume 155, June 2020, 111553

[2] G.A.Spagnuolo, et al., Integrated design of breeding blanket and ancillary systems related to the use of helium or water as a coolant and impact on the overall plant design, Fusion Eng. Des., 173, 2021, 112933

[3] Shanliang Zheng, Study of impacts on tritium breeding ratio of a fusion DEMO reactor, Fusion Eng. Des. 98–99 (2015) 1915–1918.

[4] Iole Palermo et al., Neutronic assessments towards a comprehensive design of DEMO with DCLL breeding blanket, Fus.Eng.Des.138 (2019) 217–225

[5] Pavel Pereslavtsev, et al. Neutronic analyses of design issues affecting the tritium breeding performance in different DEMO blanket concepts, Fusion Eng. Des. 109–111 (November) (2016) 1207–1211.

[6] Iván Fernández, Iole Palermo, José López-Miralles, Final Report, Integration Studies for FW, WPBB-DEL-BB-4.2.1-T005-D003, EFDA_D_2NPD26

[7] Thomas Barrett, et al., Progress in the engineering design and assessment of the European DEMO first wall and divertor plasma facing components, Fusion Eng. Des. 109–111 (Part A, 1 November) (2016) 917–924.

Impact of smoothed PF surface on TBR

The possibility of using modified plasma-facing surfaces for smoothing the variations of the Neutron Wall Loading, has been also analyzed, addressing its impact on the TBR

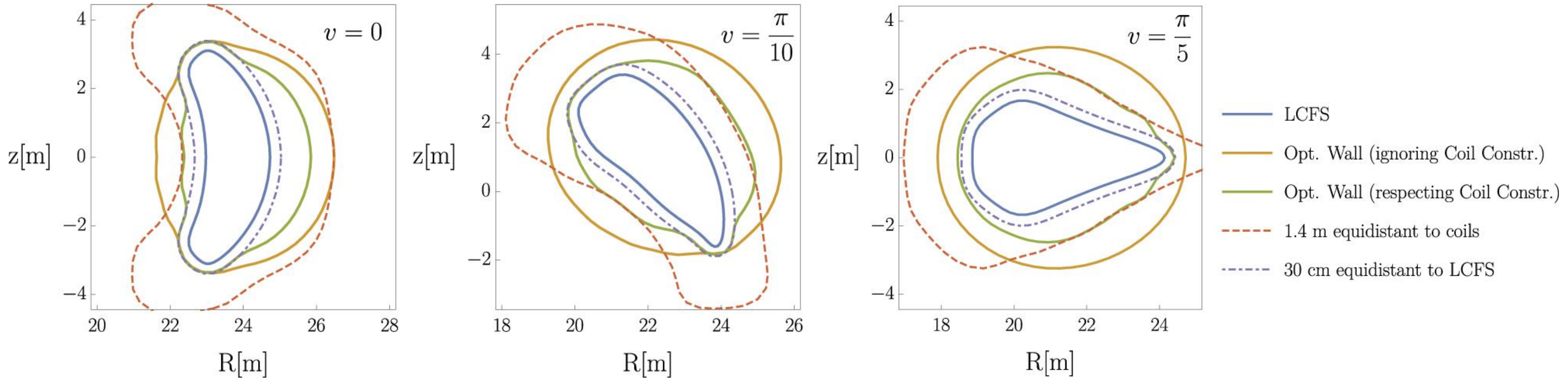
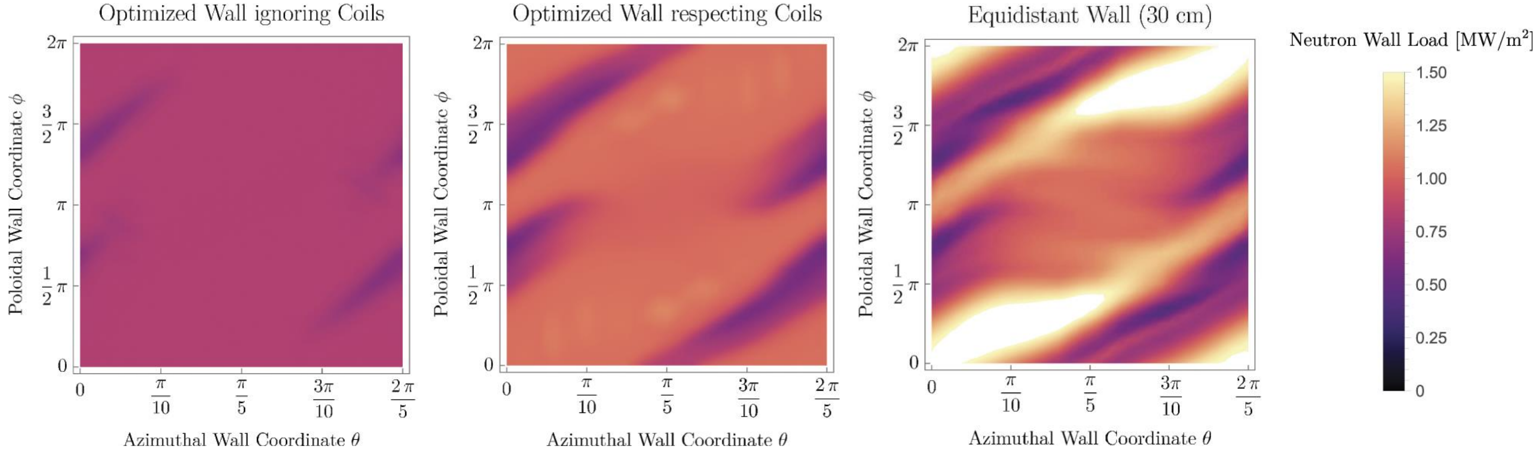


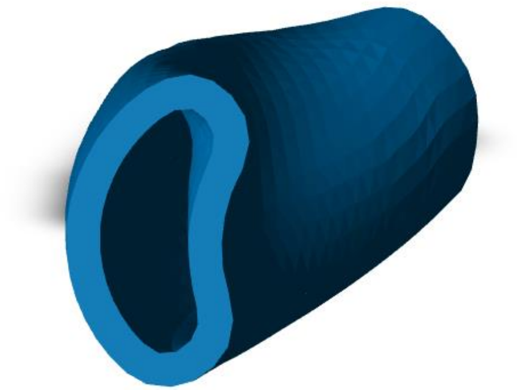
Figure 5. Optimized walls of a HELIAS-5 stellarator reactor FW using the algorithm in equation (20). The outermost dashed line (red) visualizes a surface of constant 1.4 m distance to the coils. The innermost dashed line (purple) is the 30 cm equidistant wall geometry. The yellow (light grey) solid line is the optimized wall which is allowed to violate the required minimum distance to the coils. The green (darker grey) solid line corresponds to a 'converged' wall, where the minimum distance to the coils is preserved. The resulting NWL of these walls are shown in figure 6.

Jorrit Lion et al 2022 Nucl. Fusion 62 076040



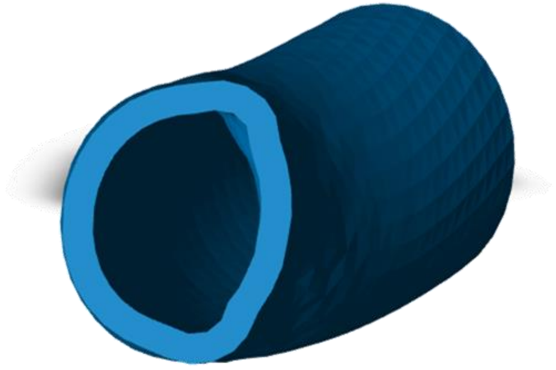
Impact of smoothed PF surface on TBR

coilset optimization



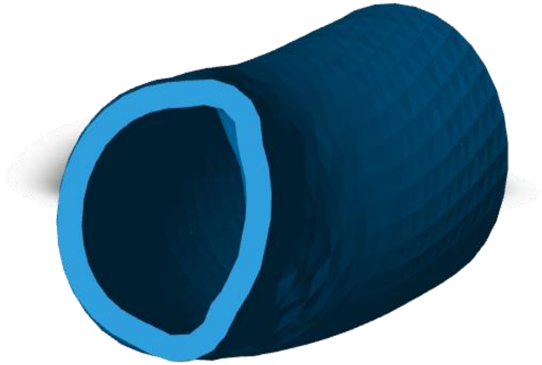
Equidistant (90 cm pure PbLi)

TBR = 1,70



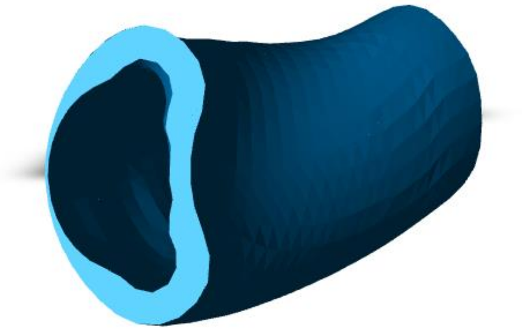
Ignoring Coils (thickness conserved)

TBR = 1,69



Ignoring Coils (volume conserved)

TBR = 1,59



Respecting coils constrains

TBR = 0,91

PS2-26 David Sosa at el.
Neutronic studies for the Dual Coolant Lithium Lead Breeding Blanket HELIAS design,
Tuesday 12

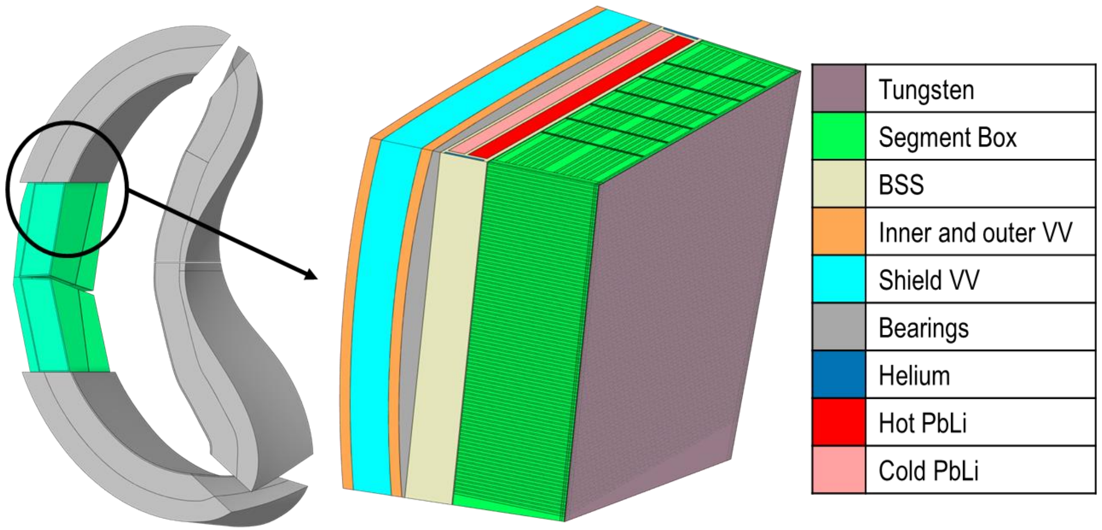
Iole Palermo et al.,
Neutronics activities in EU at CIEMAT, Satellite Meeting: IEA NTFR 2023 - International Workshop on Fusion Neutronics,
Tuesday 12

A multi-scale thermo-mechanical automatic procedure

The scope of the activity is to set a fully/partially automated workflow in order to study the HELIAS BB from the thermo-mechanical standpoint. To this purpose, a **back and forward multi-scale approach**, using the submodeling technique, is adopted properly developing Python scripts in view of the Ansys automation feature. The key aspect of the developed scripts is their adaptability to any kind of geometry, as long as it is identified by a specific label.

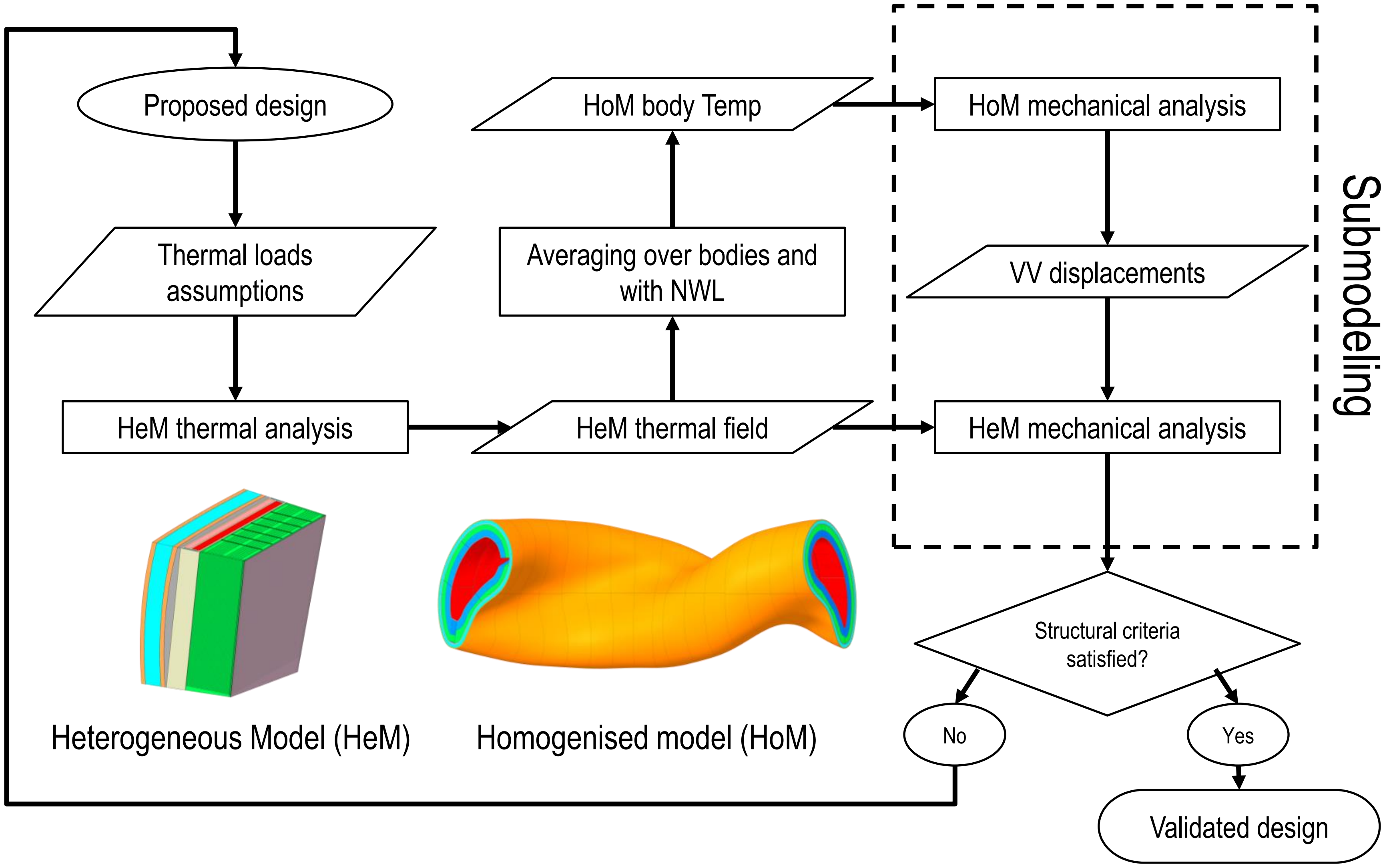
The following operations have been totally automated:

- assigning the **materials** and the constitutive models;
- imposing **mesh features** and modifying them if meshing operations fail;
- generating and verifying **contacts** between cooling fluids and structure;
- applying **loads** and boundary conditions for thermo-mechanical analysis;
- setting a simplified 1-D FEM approach for the fluid dynamics of the coolant;
- extracting, post-processing and evaluating results.



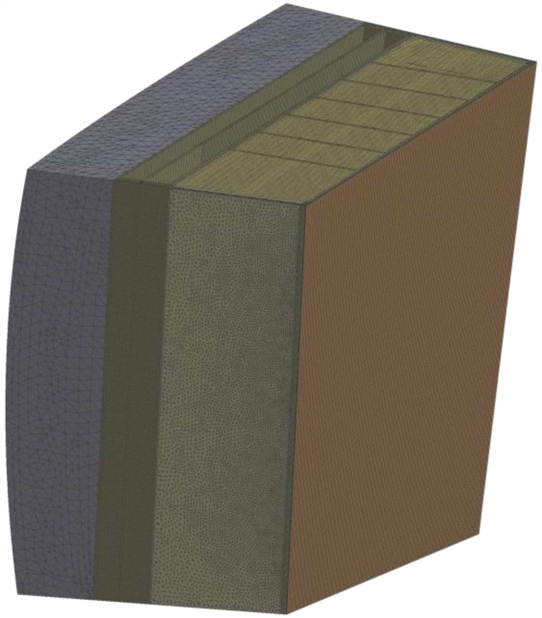
Neutronic model inside HoM   Heterogeneous Model

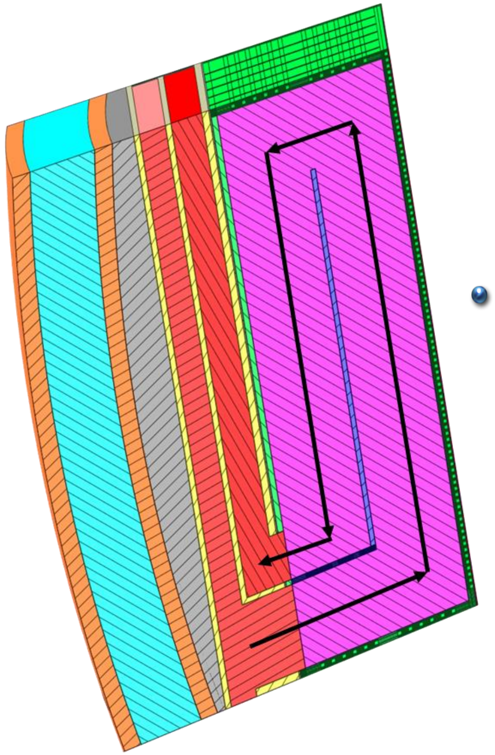
Thermo-mechanical analysis workflow



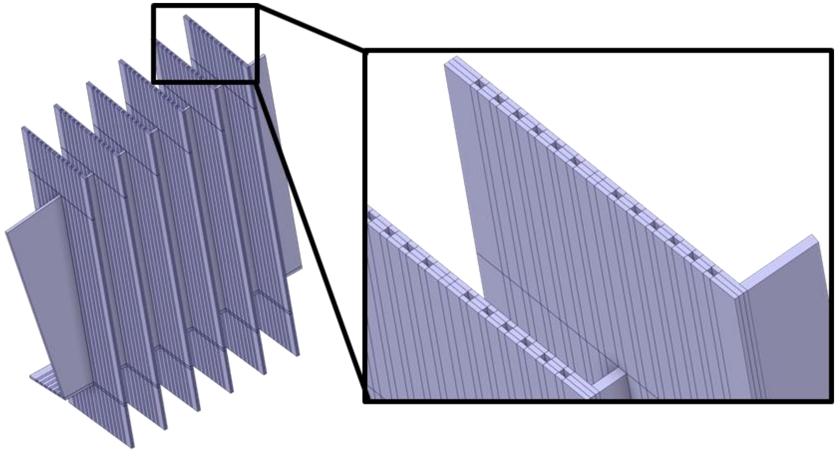
Fully heterogenous model and FEM model details

Both **homogeneous and fully heterogenous geometric layouts have been developed**, employed and combined to assess the thermo-mechanical performances of the DCLL BB for HELIAS. No intermediate model (i. e. semi or partially heterogeneous) should be necessary.





- 88 Segment box Helium channels;
- 12/12 Top/Bottom cap Helium manifolds;
- 6 Helium channels per 6 Cooling Plates;
- Detailed BSS with PbLi and Helium manifolds;
- 2 Bearings to simulate the attachment system between SB and BSS and between BSS and VV;
- 167 ''Thermal Fluids'' to properly set up a more realistic thermal analysis.



The **3D mesh of both the HoM and the HeM** has been generated. The relevant FEM models are going to be finalised.

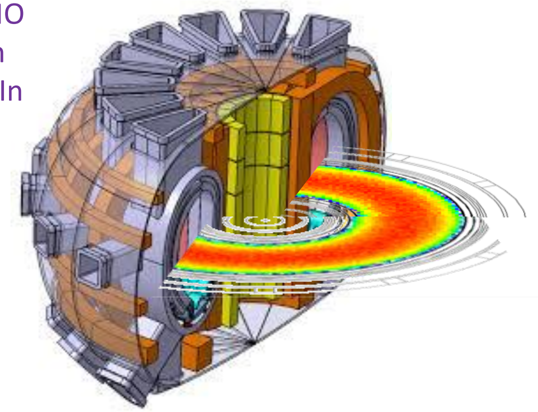
The workflow will continue with the HeM thermal analysis, useful to estimate the temperaures for the whole HoM that will be then assessed under the structural point of view to obtain the boundary conditions for the final structural analysis of the HeM

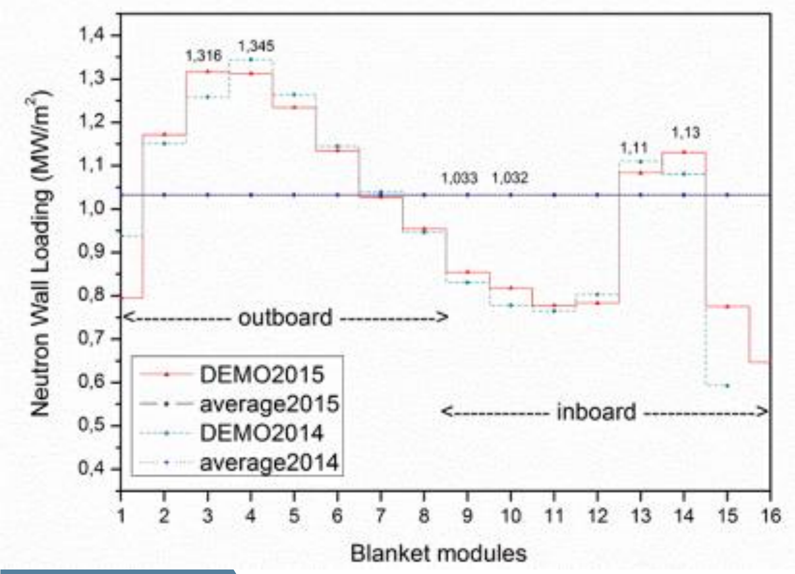
Content

- Introduction/context
  - Stellarators engineering in Eurofusion roadmap
- Strategy for the Conceptual Design of the DCLL BB HELIAS
  - DCLL BB evolution in DEMO
  - MHD studies and Segmentation proposals
  - Integration activities and Related problems
  - CPS FW: Neutronic and thermal-hydraulic assessments
  - Parametric assessments: TBR and n flux in coils
  - Multi-scale thermo-mechanical approach
- **Modelling tools developments and validations**
  - **DEMO tokamak vs. HELIAS stellarator: the modelling challenge**
  - **SHANE and HeliasGeom tools**
  - **Benchmarks MCNP / Serpent**
- Ongoing and future activities

DEMO tokamak vs. HELIAS stellarator

Boccaccini, L.V. DEMO blankets needs from ITER TBM program. In Proceedings of the 3rd IAEA DEMO Programme Workshop, Hefei, China, 11–14 May 2015.

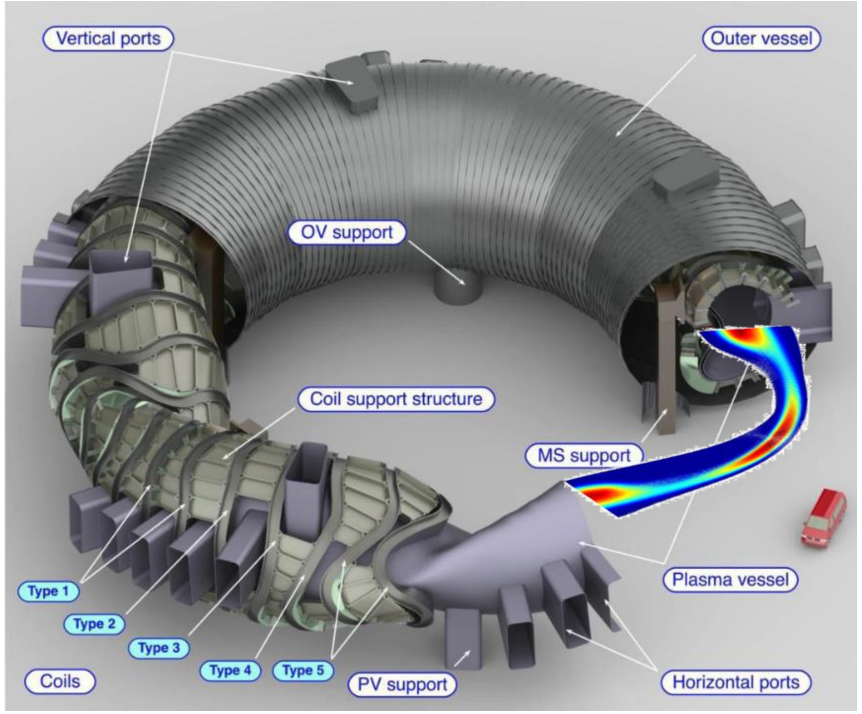




Complexity in Modeling and Analyses

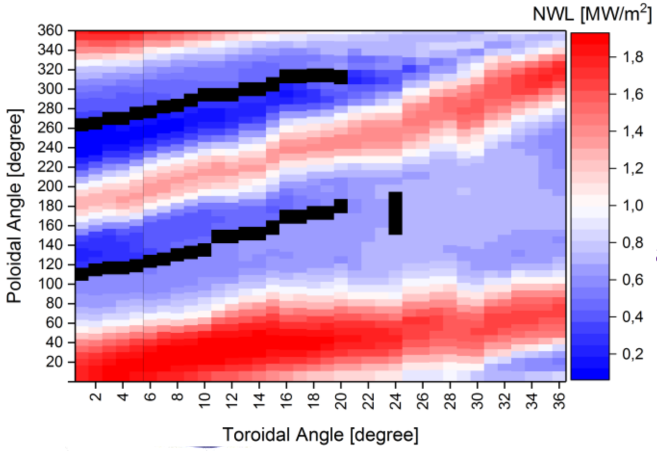
Axisymmetric regular DEMO CAD model

Complex 3D HELIAS CAD model with *splines*



MAX PLANCK INSTITUTE FOR PLASMA PHYSICS

Schauer, F.; Egorov, K.; Bykov, V. HELIAS 5-B magnet system structure and maintenance concept. Fusion Eng. Des. 2013, 88, 1619–1622.

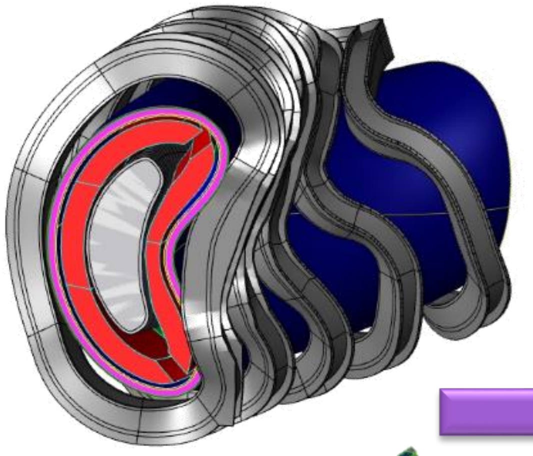


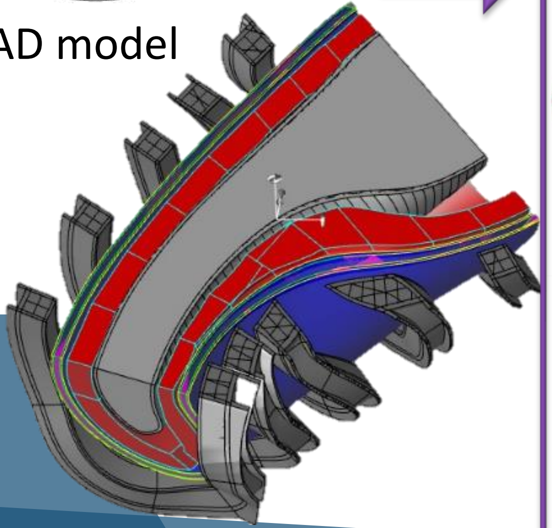
Häußler A. 2020 Computational approaches for nuclear design analyses of the stellarator power reactor HELIAS https://publikationen.bibliothek.kit.edu/1000124072

The modelling challenge

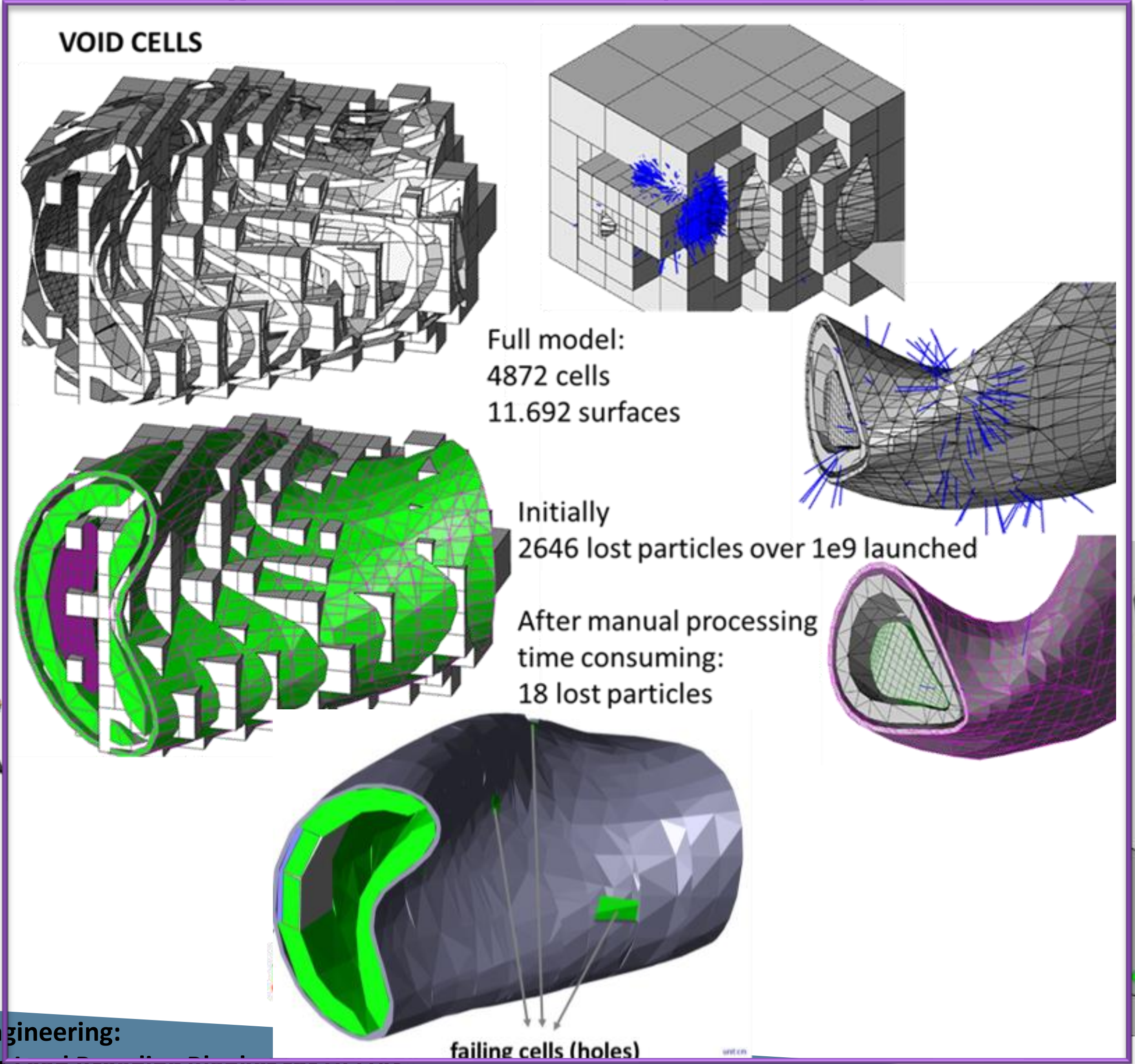
Neutronic model development Constructive solid geometry (CSG) with SuperMC → Faceted geometry

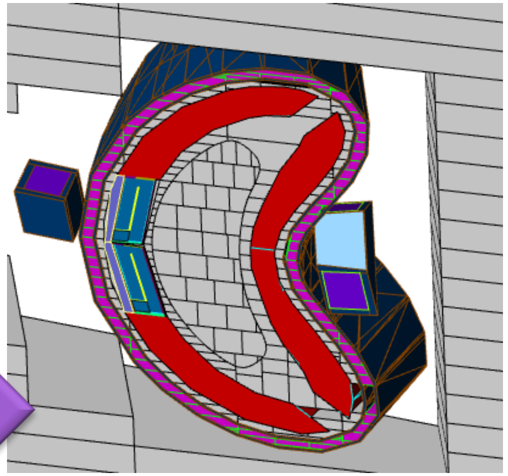
Different strategies and models according to the neutronic analyses to be performed with

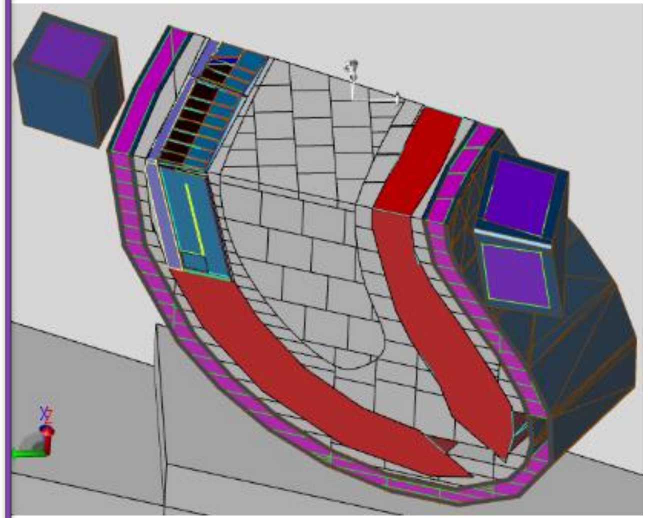




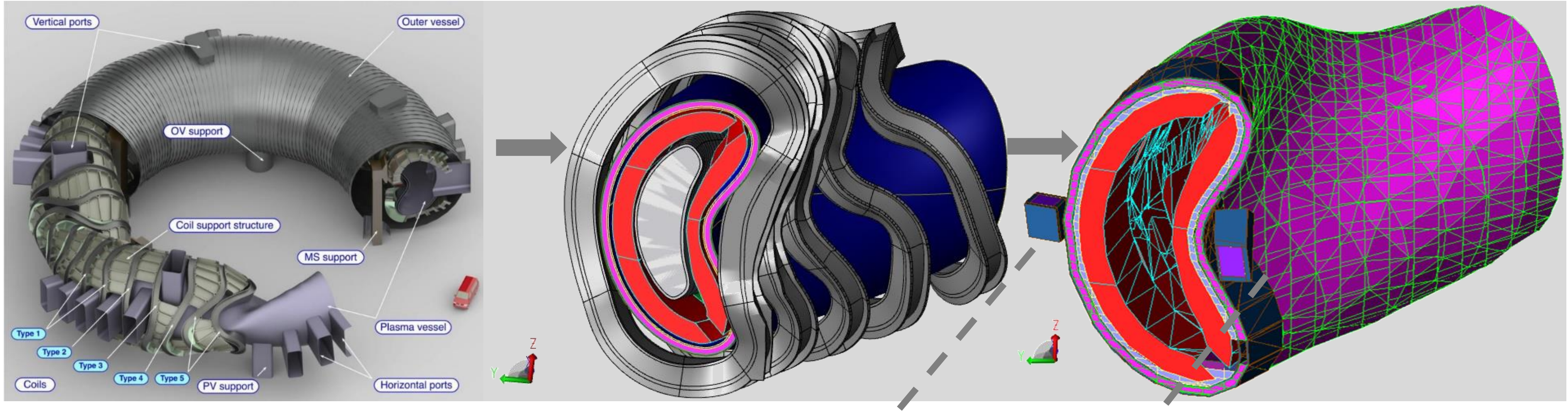
CAD model







The modelling challenge

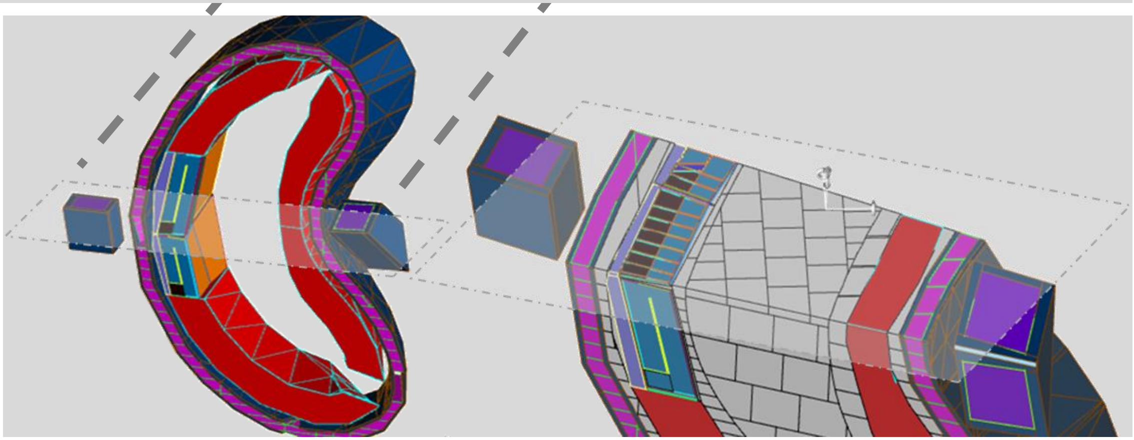


HELIAS 5-B CAD desing of the full torous, Source: F. Schauer et al., *HELIAS 5-B magnet system structure and maintenance concept*, Fus. Eng. Des. 88 (2013)

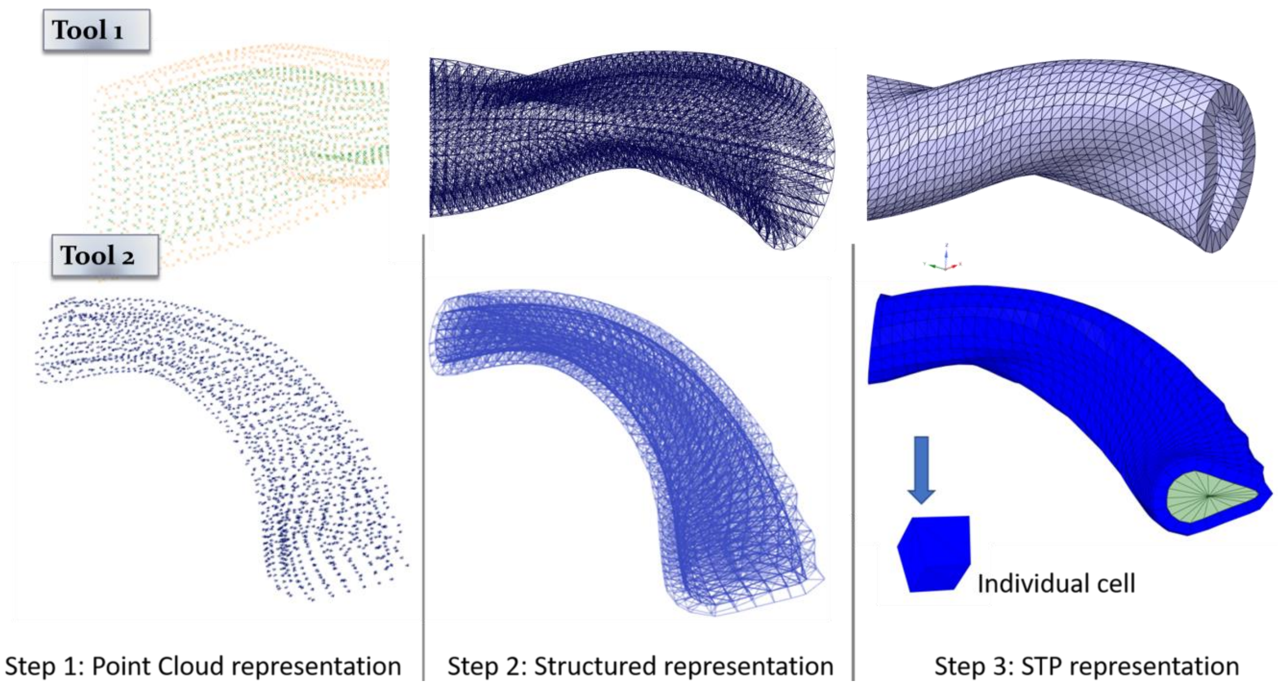
HELIAS 5-B simplified CAD with *splines*

HELIAS 5-B faceted neutronic model with medium degree of detail for Breeding Blanket, Vacuum Vessel and Coils
Source: I. Palermo et al., 2021 Nucl. Fusion 61 076019

The development of an apparently simple neutronic design of a stellarator is a very hard and time-consuming process. This is due to the inherent complexity of stellarators starting CAD models fully made by *splines*. This bottleneck has been tackled by developing *ad-hoc* tools, since nor Constructive Solid Geometry (CSG) nor DAGMC, nor Unstructured Mesh (UM) demonstrated to be procedures fully feasible/satisfactory.



Facing the challenge: *ad-hoc* tools development



for suitable and parametrized models to speed up the iteration process toward optimized design.

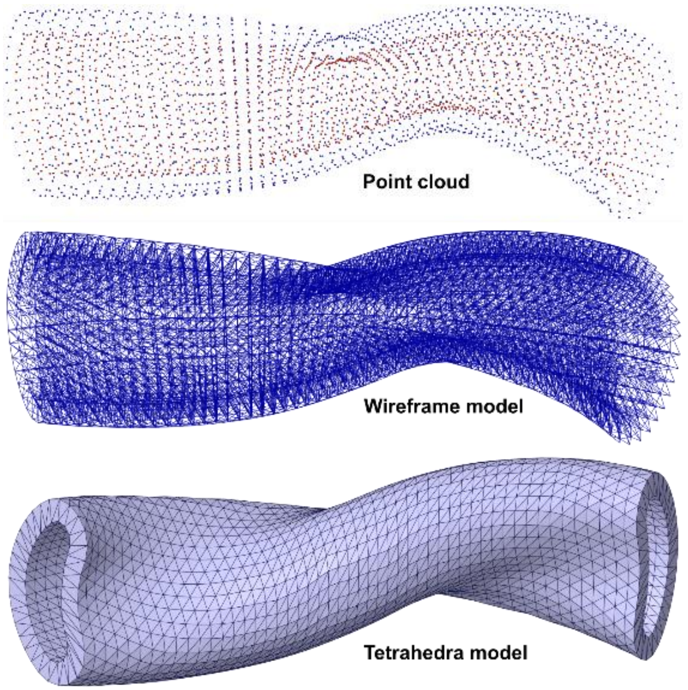
The two selected approaches consisted in the use of analytical expressions, such as **parametric equations/point clouds**, that are behind the plasma/SOL/BB/VV/coils configuration.

Tool 1- SHANE (SHape Adapter for Neutronics): based on tetrahedralization of complex shape volumes by means of VBA scripts is directly implemented within of CATIA. This allows the direct modification of the produced models with a graphical interface.

Tool 2 - HeliasGeom: is a python API based on pythonOCC for producing the CAD model. It has not a graphic interface. Otherwise, it allows modifying the geometry via scripting. Furthermore it allows to generate the surfaces in ABAQUS or VTK format. In addition, HeliasGeom can be easily coupled with GEOUNED API for the direct production of the parametric MCNP inputs.

Facing the challenge: *ad-hoc* tools development

SHANE (SHape Adapter for Neutronics)



1. creation of a point cloud with a certain resolution from surfaces defined by Fourier coefficients,
2. import of the point cloud into CATIA,
3. creation of a surface adjusted to that cloud by tetrahedralization with CATIA (tetrahedral adjusted to clouds of points),
4. obtaining a parallel surface,
5. obtaining a point cloud projected on that parallel surface,
6. import of the points of the internal surface and the external surface into CATIA + tetrahedralisation of that surface,
7. a wireframe structure (edges) is generated from a cloud of points.
8. finally, volumes are created from the wireframe structure and exported in STP format compatible with SuperMC interface used to create MCNP inputs.

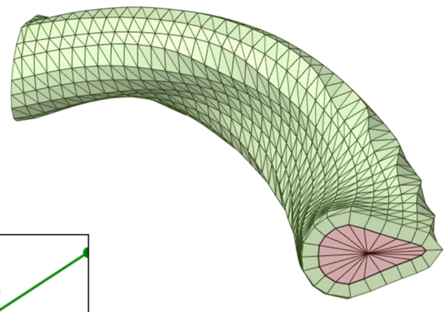
HeliasGeom

Javier Alguacil et al., *Computational scheme for fast production of parametric stellarator models suitable for neutronic analysis*, **Thursday 14th**, **PS3-104**

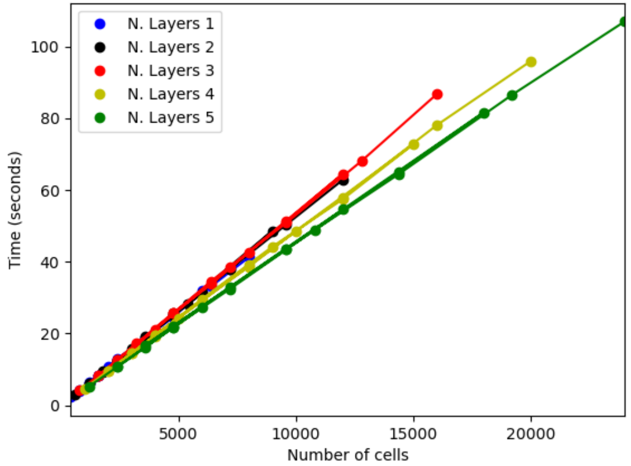
Iole Palermo at al., *Challenges towards an acceleration in stellarator reactors engineering: The Dual Coolant Lithium-Lead Breeding Blanket Helical-axis advanced stellarator case*, Energy (under review)

Coupling HeliasGeom and GEOUNED to get MCNP models

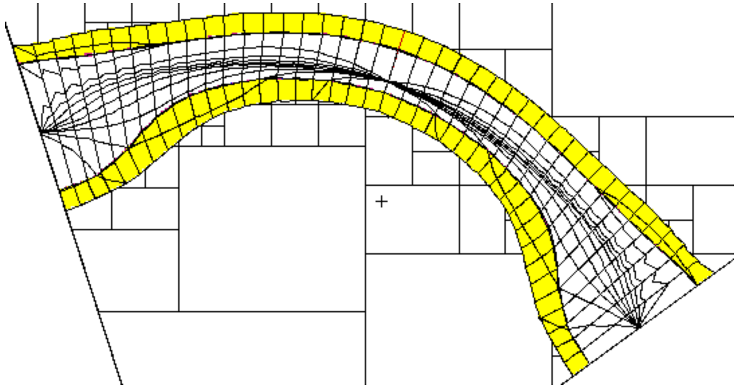
HELIAS GEOM



Time for model production



GEOUNED



- **Output formats**
  - **STP**
  - STL
  - VTK
- **Explicit definition for plasma and outer cell**
  - Required for MCNP transport
- **User defined**
  - Poloidal and toroidal discretization
  - Width and number of layers
- **No time consuming**

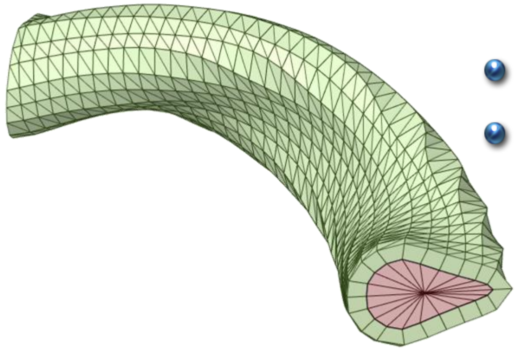
- MCNP Model production
  - <15 min human time
  - ~12 hours of computer time
    - HELIASGEOM only few minutes

- **Achievements of aims**
  - v Thinness control
  - v Almost no losing particles
    - v 0 particles in void (NPS 1e11)
    - v 2 particles with material (NPS 1e10)

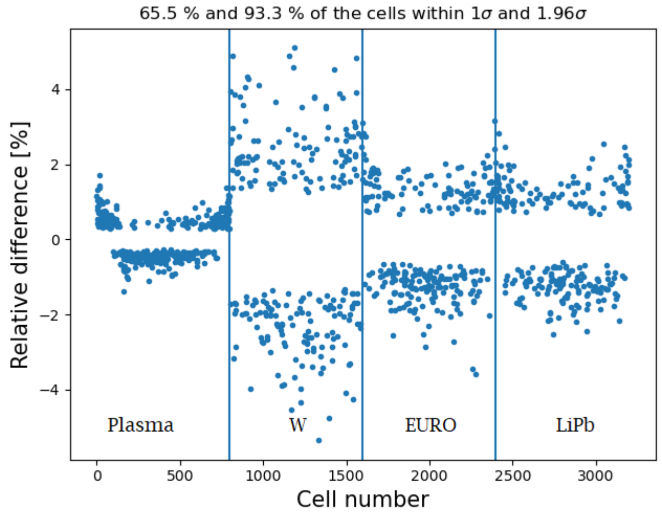
Time in Marconi(A3): (11520 cpu·h)

Benchmarking between MCNP and Serpent with HeliasGeom

- STL geometry in Serpent2 compared to CSG geometry in MCNP6.
- 72° model: 4 layers (plasma, W, EUROFER, LiPb), 800 cells in each layer, 3200 cells in total.
- 360° model: 5*3200 = 16000 cells.
- 360° model better match in terms of 1σ and 1.96σ confidence intervals.

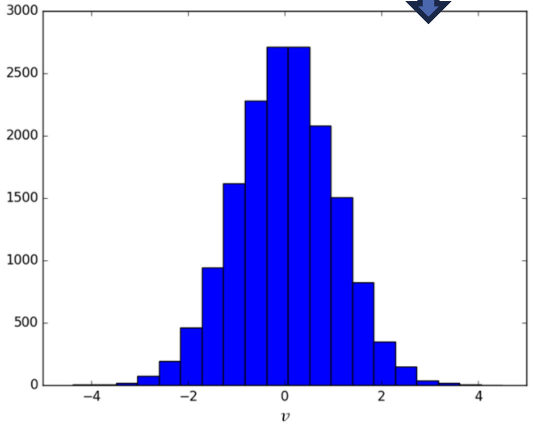


72° model + periodic conditions

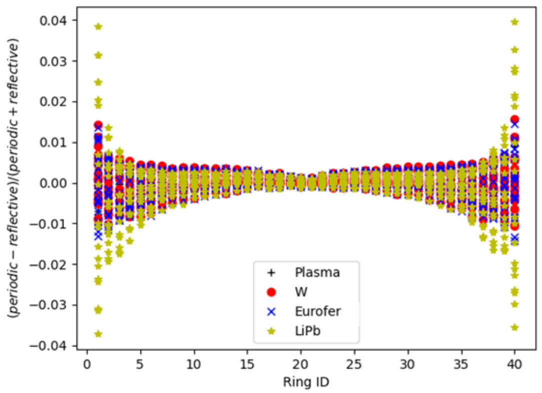


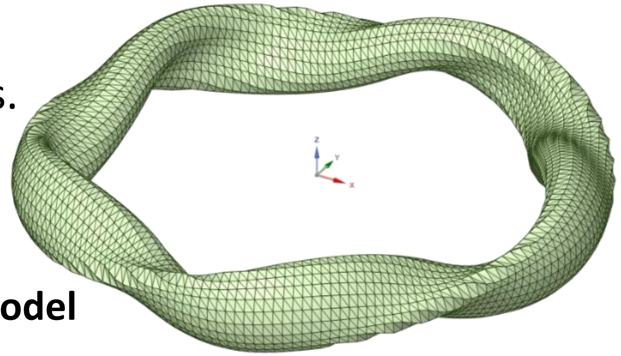
- **Comparison of the neutron flux in each cell**
- Distribution of $v = \frac{\phi_{MCNP} - \phi_{serpent}}{\sqrt{\sigma^2_{MCNP} + \sigma^2_{serpent}}}$

Standard normal distribution

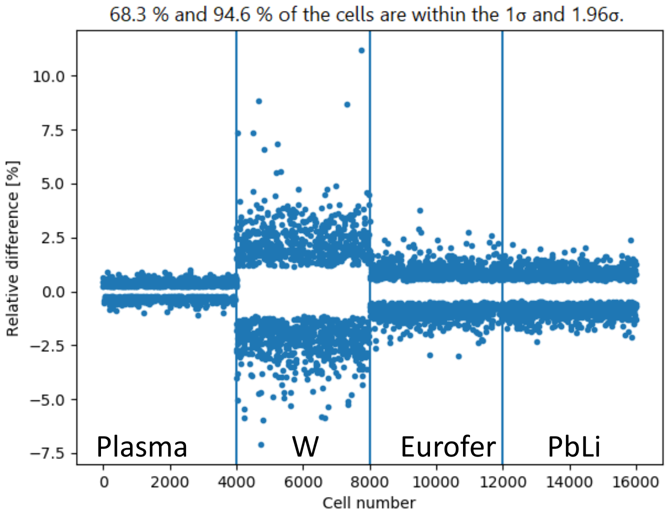


Comparison BC: Periodic vs Reflective





360° model



More details: LyytinenTommi. *Parametric studies of breeding blanket thickness of a HELIAS stellarator using Monte Carlo neutron transport code Serpent2* (2023). Master's Thesis http://urn.fi/URN:NBN:fi:jyu-202303062012

Content

- Introduction/context
  - Stellarators engineering in Eurofusion roadmap
- Strategy for the Conceptual Design of the DCLL BB HELIAS
  - DCLL BB evolution in DEMO
  - MHD studies and Segmentation proposals
  - Integration activities and Related problems
  - CPS FW: Neutronic and thermal-hydraulic assessments
  - Parametric assessments: TBR and n flux in coils
  - Multi-scale thermo-mechanical approach
- Modelling tools developments and validations
  - DEMO tokamak vs. HELIAS stellarator: the modelling challenge
  - SHANE and HeliasGeom tools
  - Benchmarks MCNP / Serpent
- **Ongoing and future activities**

ONGOING WORK

To progress in the conceptualization of a feasible and mature DCLL BB design for HELIAS, optimized under the neutronic, thermal and MHD points of view, **parametrized models** will be produced and analysed.

In the generic HELIAS design the **divertor and the magnets** will be included for neutronic calculations.

Afterwards, more detailed HELIAS DCLL BB models will be defined:

- modification of the BB segments shape in order to achieve an optimal orientation of the PbLi paths with respect to the magnetic field.
- Initial quantification of the MHD resistance factor of the toroidal and poloidal blanket configuration which allows a first estimation of the pressure drop and segment flow imbalance.
- dimensioning of the main components of the segments
- key operational parameters

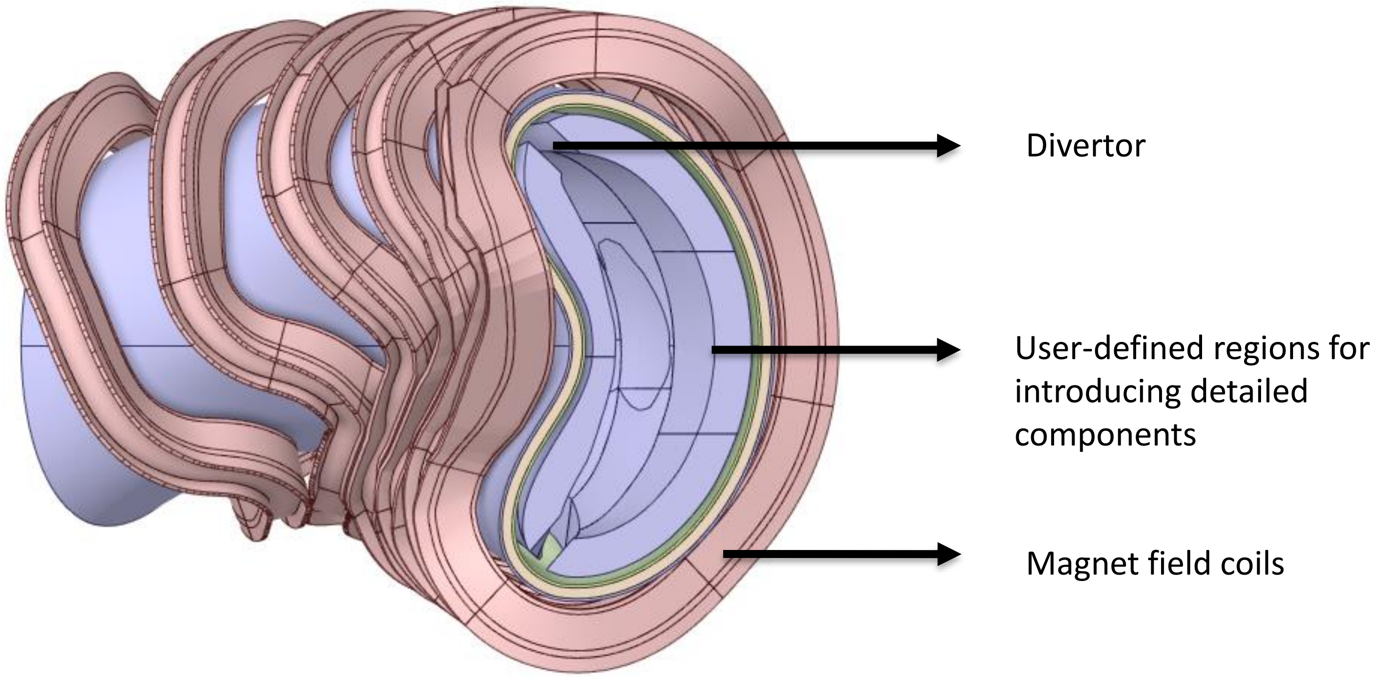
CPS FW concepts will be further explored as well as other integration solutions (RH activities will start).

The CPS integration challenge will be further addressed analysing different:

- arrangements of the mesh,
- the liquid metal supply,
- the cooling system and the substrate.

Multi-physic analyses performed to optimize the design by iterative modelling/analyses procedure

Future steps for modelling tools



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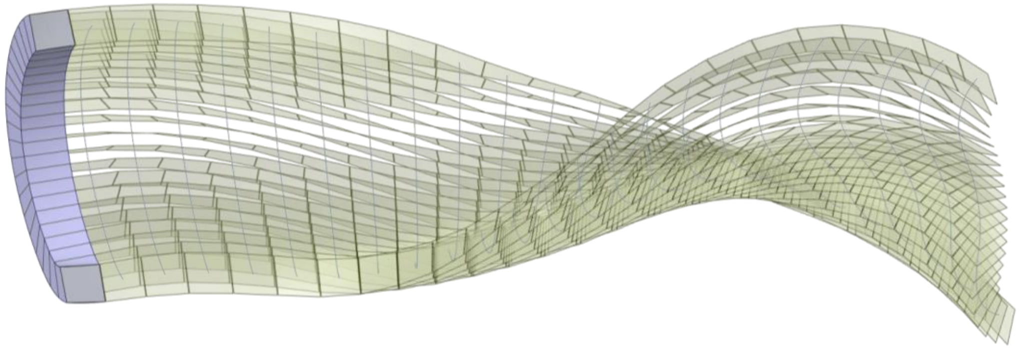
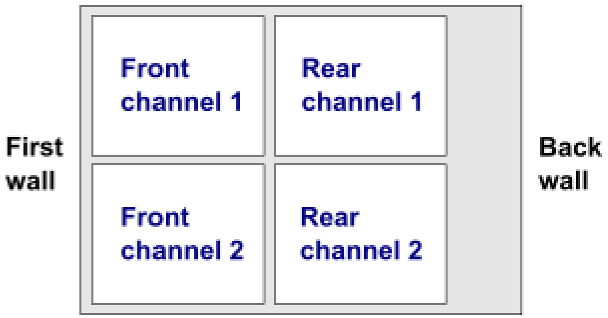
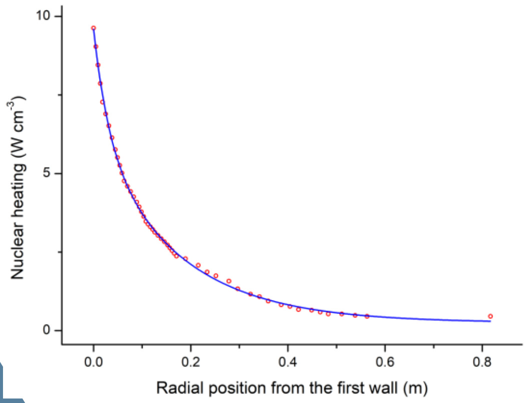
Analysis tool: PbLi flow characteristics

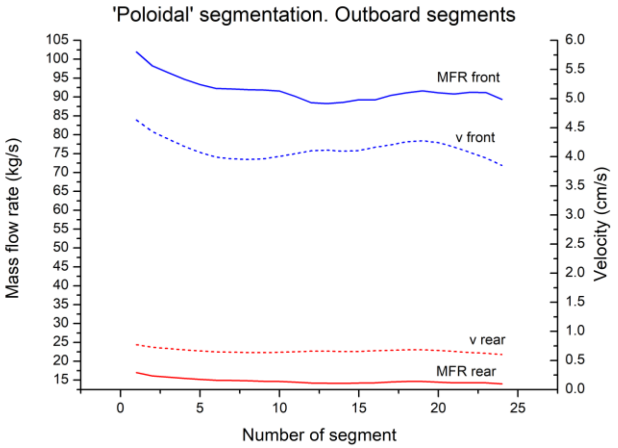


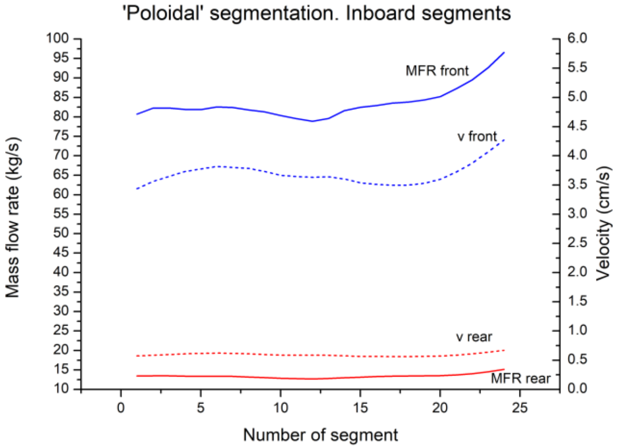


PS2-46, Jose Angel Noguerón Valiente et al., *Adaptation of the first wall cooling circuits to achieve an efficient distribution of the coolant flow in the SMS DCLL breeding blanket*, **Tuesday 12**

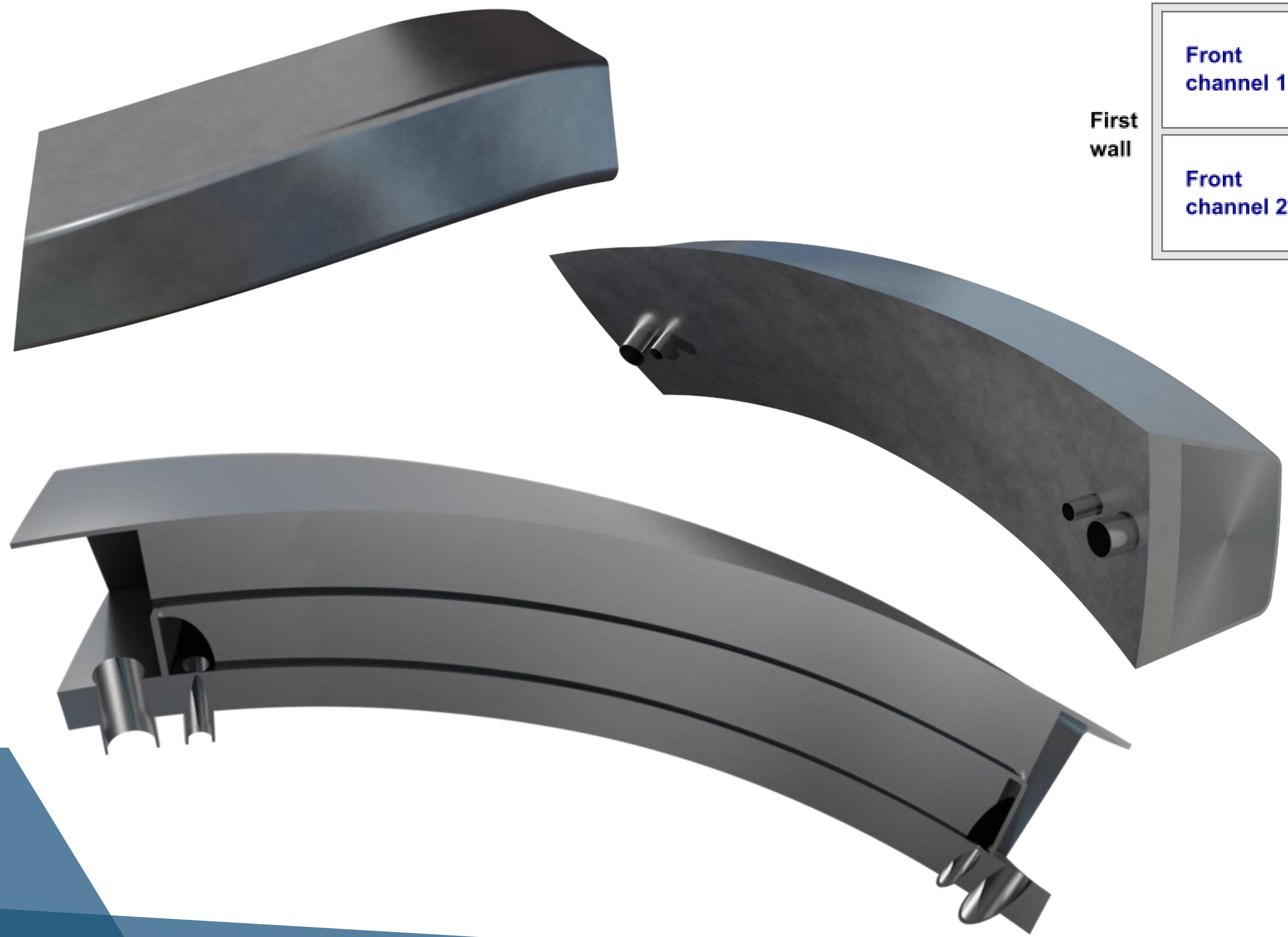
A new tool has been specifically developed to calculate some of the main parameters of the PbLi flows from the basic BB geometrical model. **The tool automatically extracts information from each segment of the CATIA model (volume, cross-section area, length, aspect ratio**) and transfers it to an Excel file. A cross-section with 4 parallel PbLi circuits (2 front and 2 rear) has been assumed. A radial profile of nuclear heating obtained from a previous heterogenized neutronic model of a DCLL BB has been used to estimate the power extracted by PbLi, and hence, the PbLi **mass flow rate** and **average velocity** in each segment.

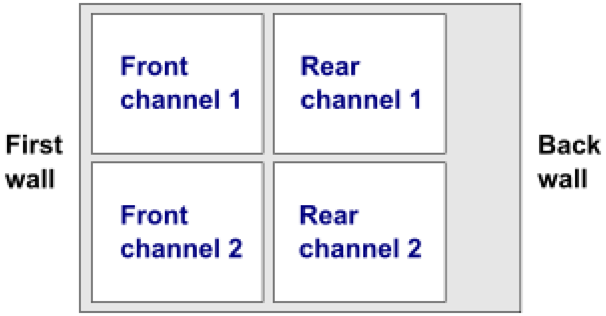






Preliminary design of a toroidal segment





Length	~4.9 m
Volume	1.878 m^3
Weight at room T without PbLi	14.54 t
Maximum width	~140 cm
Segment radial thickness	~99 cm
Breeding zone radial thickness	~75 cm

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Thank you for your attention

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