Advancing Neutronics Modeling of Stellarators Using Mesh-based Serpent2 workflow

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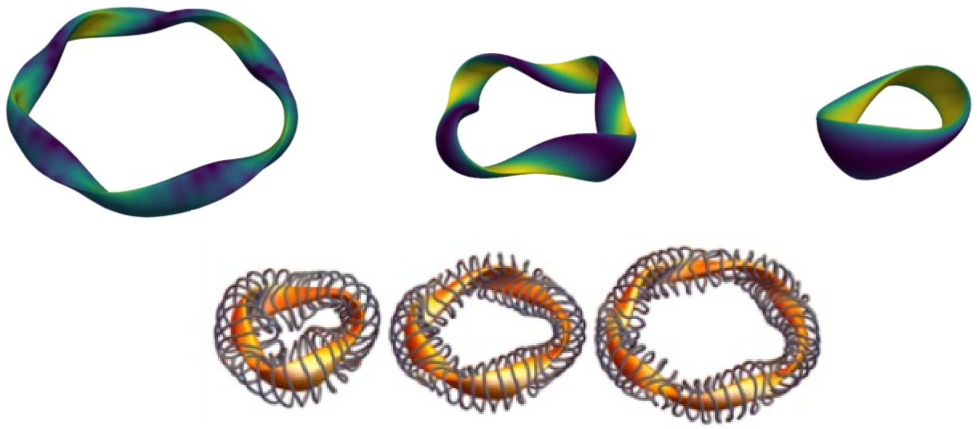
Topics

- Introduction: From stellarator optimization to neutronics
- Automated workflow for neutron transport simulations
- Balancing breeding and shielding volume to meet TBR and shielding design targets
- Effects of divertor on tritium breeding in HELIAS stellarator
- Conclusions and outlook

From stellarator optimization to neutronics

- Stellarator physics optimization has produced various stellarator configurations as shown in figure
  - Plasma shape (via Fourier coefficients) is varied so that target functions relating to e.g. turbulence and MHD stability are optimized [1]
  - Produces optimized plasma and coils geometries
- ➢ Stellarator neutronics modeling takes the boundary shape of the plasma (LCFS) and coil current curves as an input
- Neutronics models have not been directly included in physics optimization loop

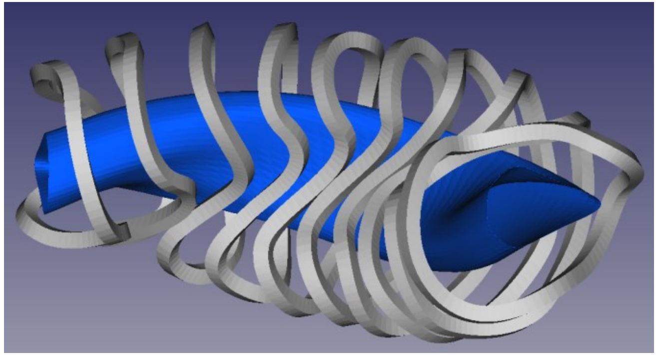


Examples of stellarator magnetic configurations with different symmetries, from left to right: quasi-isodnyamic, quasi-helical symmetric, and quasi-axisymmetric [F. Warmer et al. *Fus. Eng. Des.* **202** (2024)].

[1] A. Goodman et al. *Quasi-Isodynamic Stellarators with Low Turbulence as Fusion Reactor Candidates*, PRX Energy **3**, (2024) 023010

Generating a blanket model for stellarator

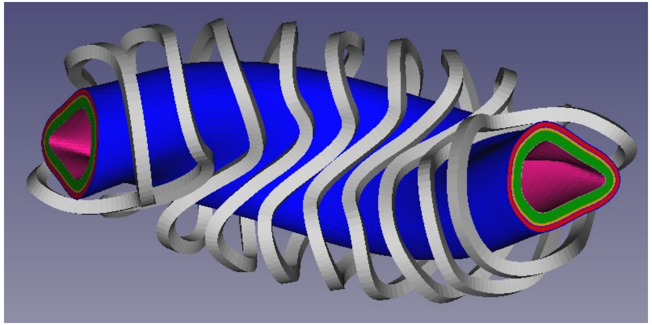
- How can we efficiently fit the breeding blanket into the limited space between the LCFS and the coils in stellarator configuration X?
- Extension of the LCFS in the normal direction with constant distance *d* to create plasma-shaped blanket layers



HELIAS 5B (R=22 m, 5 period, 72 deg.) LCFS and coils.

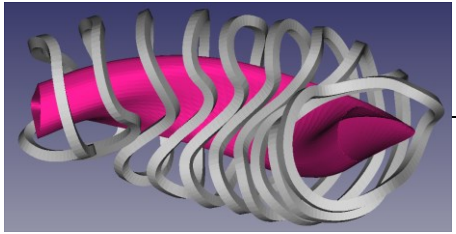
Generating a blanket model for stellarator

- How can we efficiently fit the breeding blanket into the limited space between the LCFS and the coils in stellarator configuration X?
- Extension of the LCFS in the normal direction with constant distance *d* to create plasma-shaped blanket layers
  - Blanket and VV cannot be fitted tightly within the coils
  - Not optimal for shielding and breeding volume
- Non-uniform blanket thickness d(u,v) is required



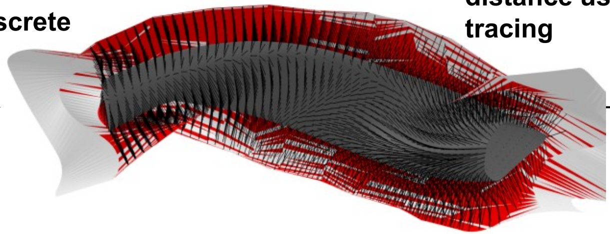
HELIAS 5B (R=22 m, 5 period, 72 deg.) LCFS and coils.

Workflow for fitting the blanket between the plasma and coils



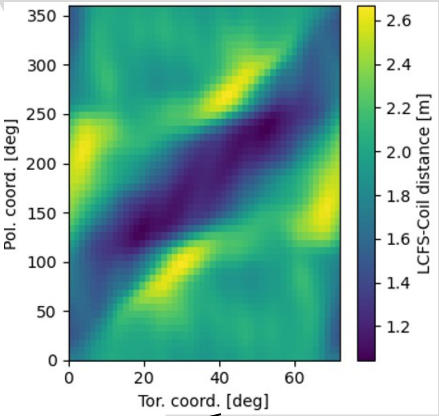
LCFS and coils as input

1) Coil surface from discrete coils

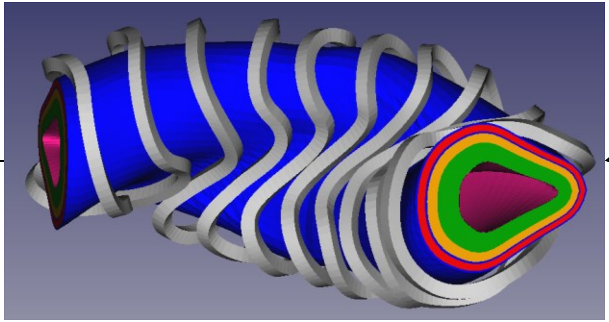


2) Solve LCFS-Coil distance using e.g. ray tracing

LCFS-Coils distance matrix



3) Generate the mesh geometry layers with the distance matrix information using *SBGeom* [1,2] tool

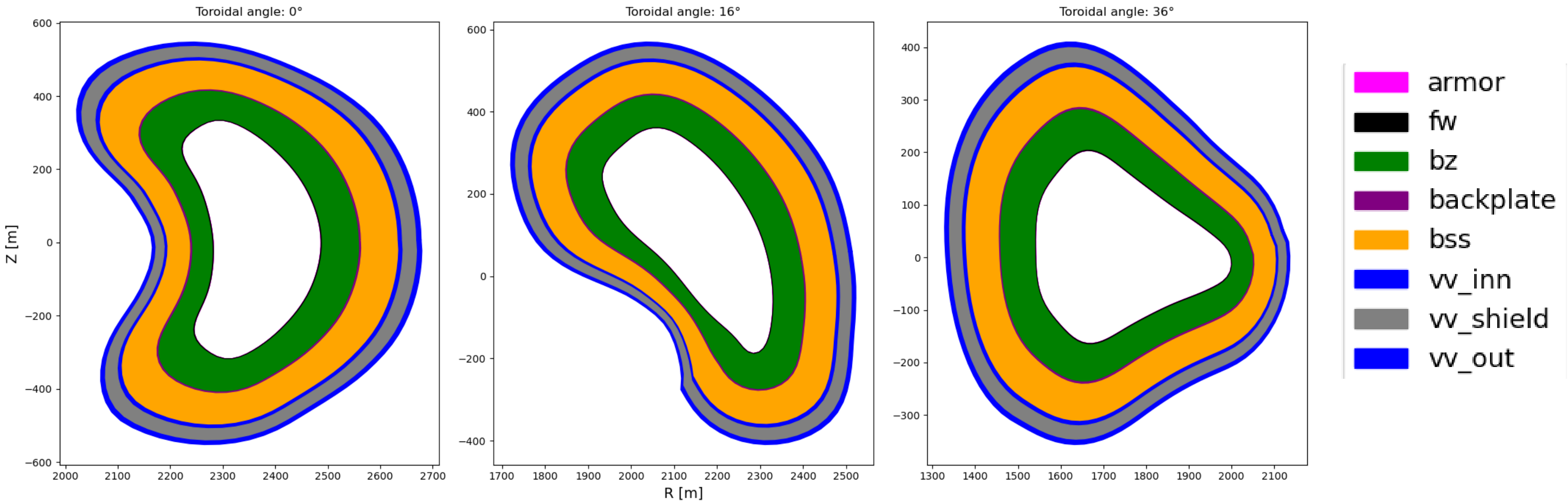


STL mesh geometry model ready for *Serpent* MC simulation

[1] T. Bogaarts, F. Warmer, ISFNT-15 (Poster), Spain (2023)

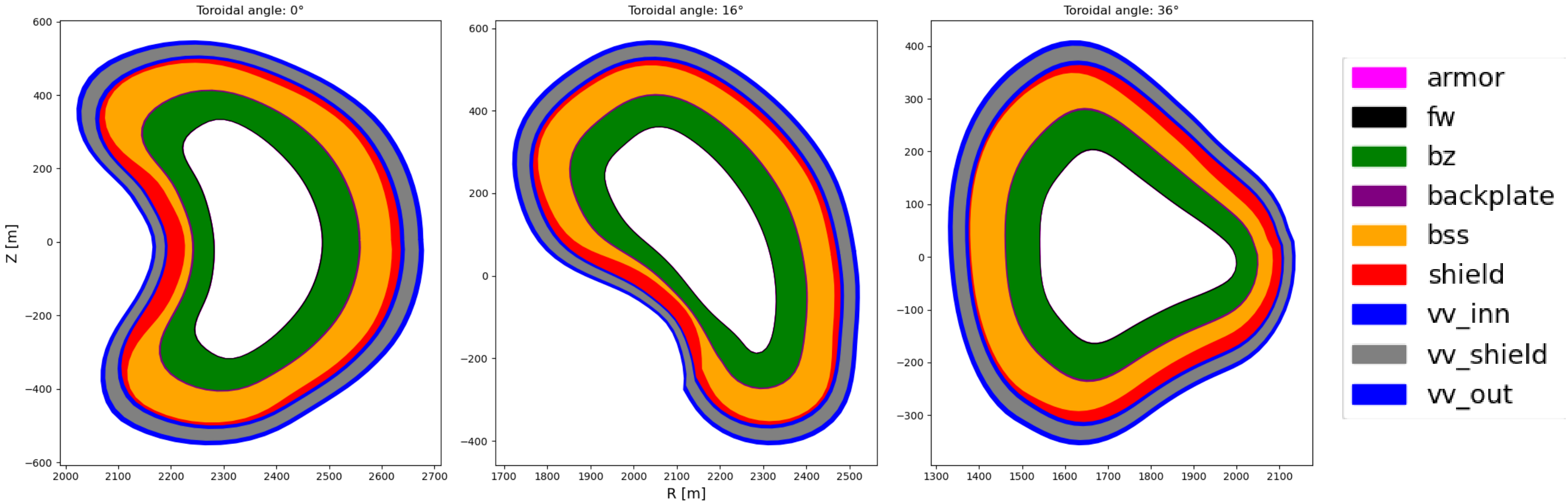
[2] Lyytien et al. Fus. Eng. Des. (2025), **216**, 115000

Blanket configuration with no extra shielding



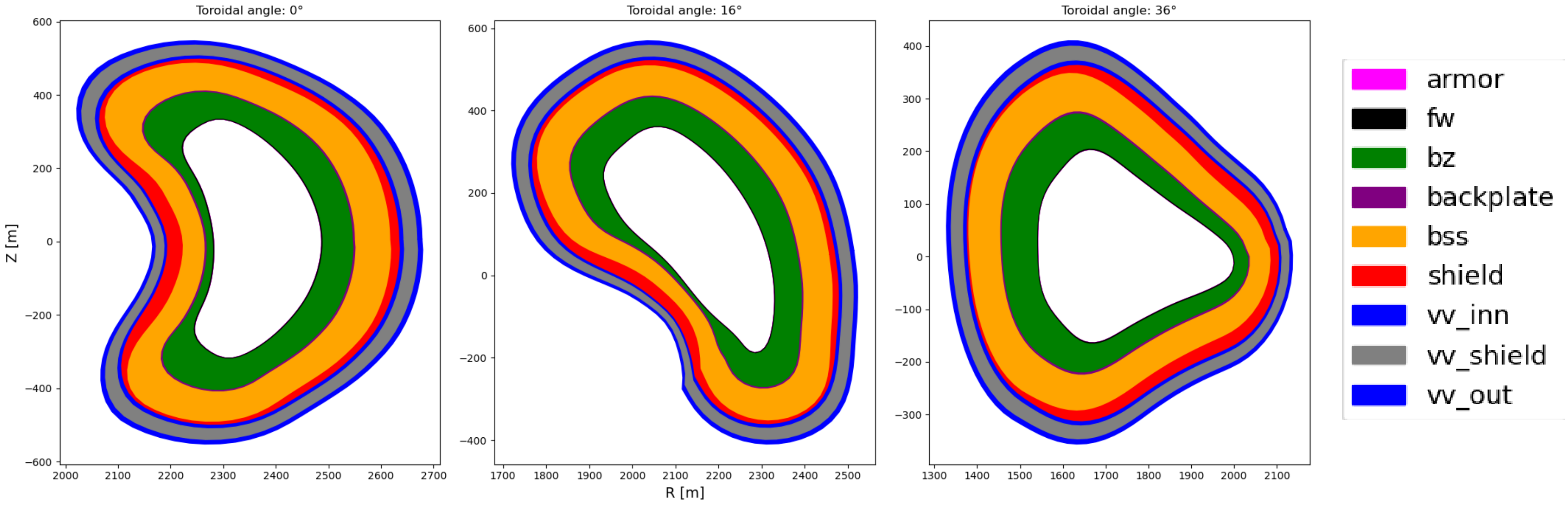
Reactor layer slices at toroidal angles 0, 16, and 36 degrees. (DCLL radial build)

Blanket geometry with a dedicated shield layer

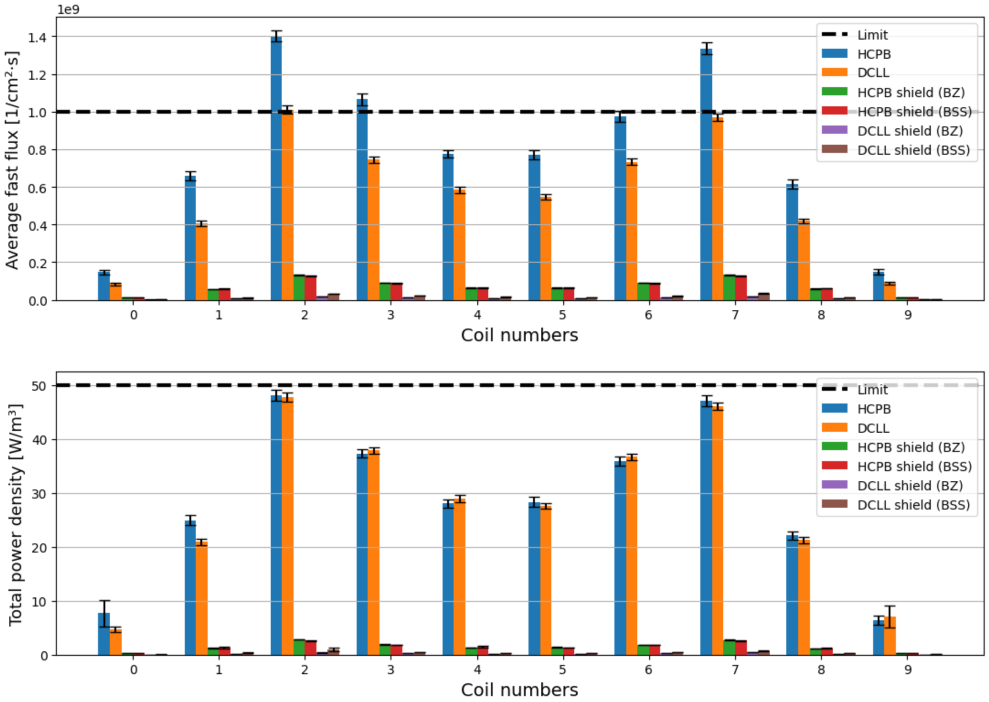


Reactor layer slices at toroidal angles 0, 16, and 36 degrees. BSS giving space for the shield (red).

Breeding zone giving space for the shield

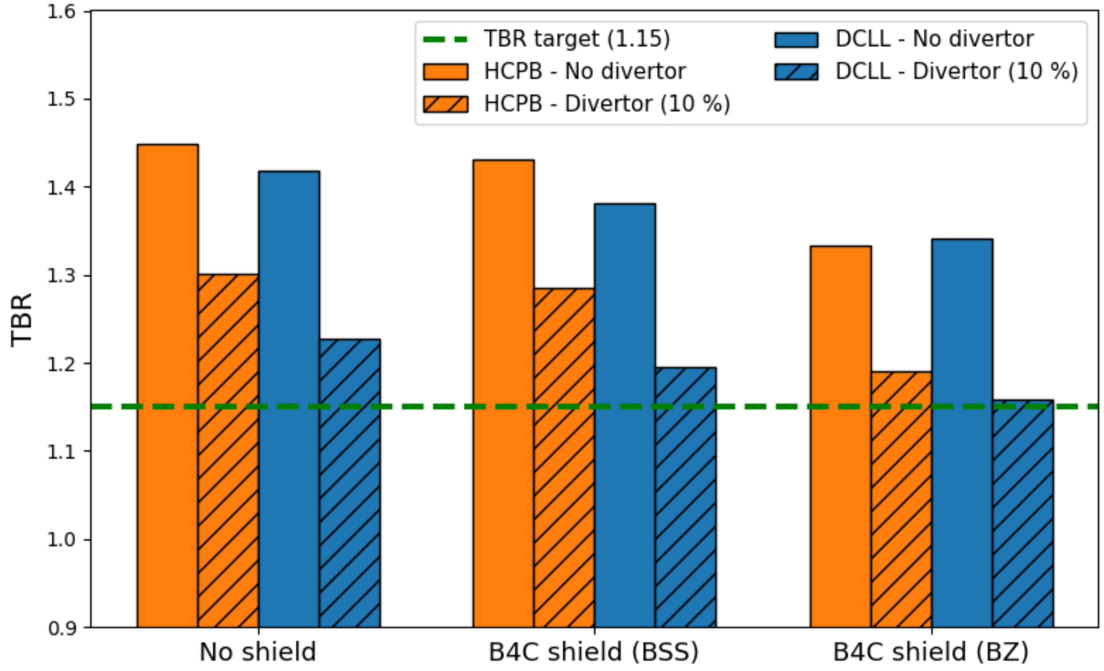


Demonstrating coil shielding improvement



Average fast flux and nuclear heating in each coil with DCLL and HCPB material compositions, and using boron-carbide (B4C) extra shield.

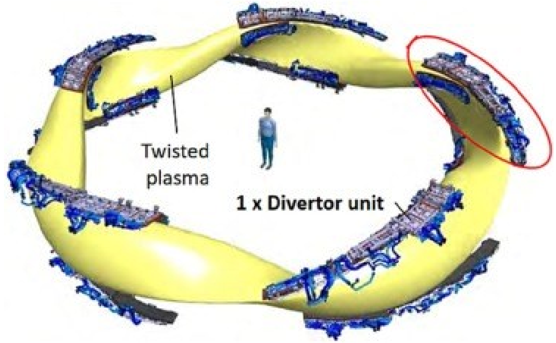
TBR comparison



Total TBR with no-shield and shield cases, including no-divertor and full blanket coverage cases. Water-cooled divertor with 10 % area fraction from the FW and replacing the breeding zone.

Including divertor into consideration

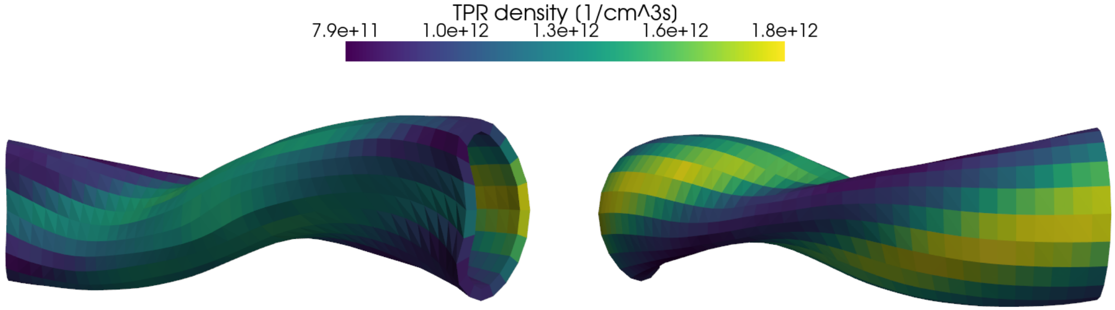
- Divertor is an essential component integrated into the blanket, which can take ~ 10 % of the first wall and also BZ volume in HELIAS 5B
  - Divertor components, especially the rear structures of the W armor (coolant pipes and steel components) take up space from the breeder material
- Island divertor is the driver candidate for stellarators
  - Placed on magnetic islands
  - Placement can be controlled by magnetic field configuration
  - Exact design highly open for stellarator pilot/power plants



W7-X divertor units. J. Fellinger et al. *Nuclear Materials and Energy* **37** (2023) 101506

Effect of divertor placement on TBR

- Possibility to control divertor position and variation observed in tritium production across the blanket
- ➢ Parameter study [2] for divertor placement and size, and also for coolant option, material composition

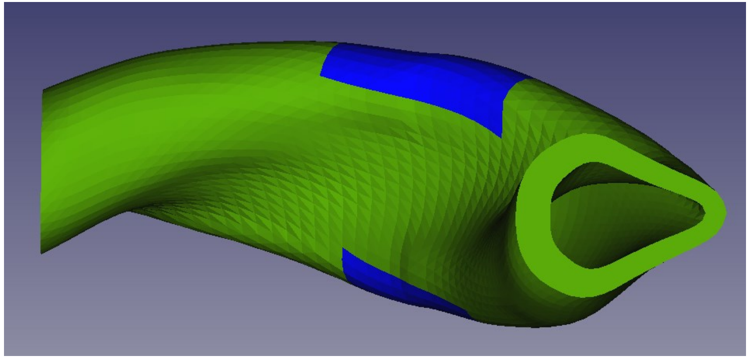


Tritium production density in breeding zone

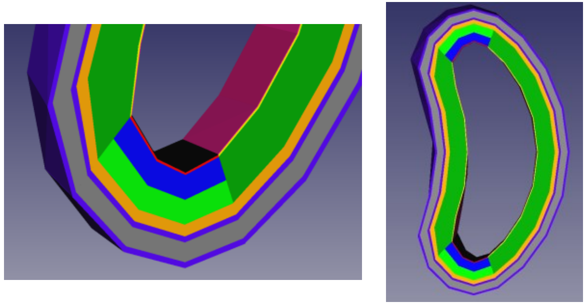
[2] Lyytinen et al. *Fus. Eng. Des.* 2025, **216,** 115000.

Divertor neutronics model

Comp	Armor	Heat Sink	Div. Body
Thickness [cm]	0.8 cm	2.3	25-50
Cu	-	13	-
Water/He [%]	-	25	43
CuCrZr [%]	-	62	-
Tungsten [%]	100	-	-
Steel	-	-	57



1. W armor (black)
2. CuCrZr heat sink (red)
3. Coolant-steel diveror body (blue)
4. Optional breeding manifold (light green)



Divertor geometry model

Effect of divertor placement

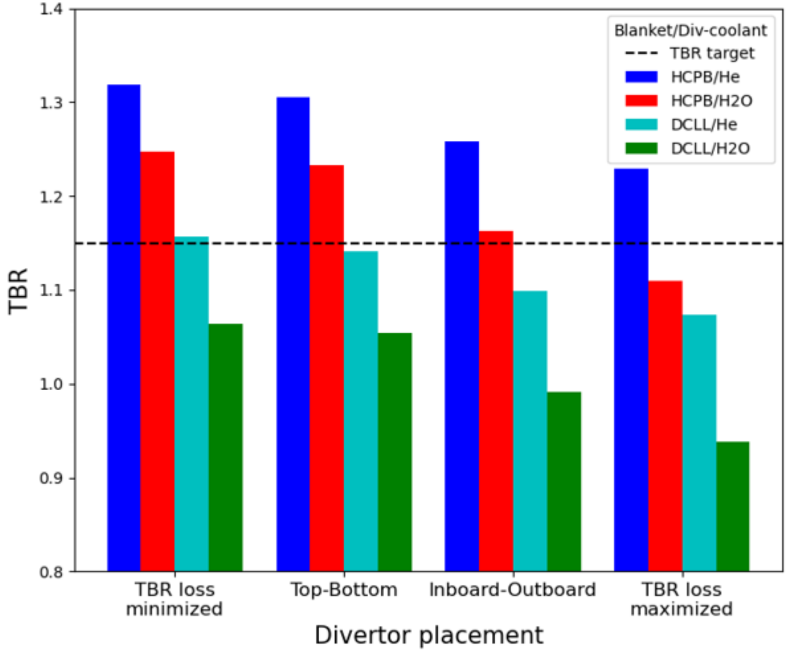
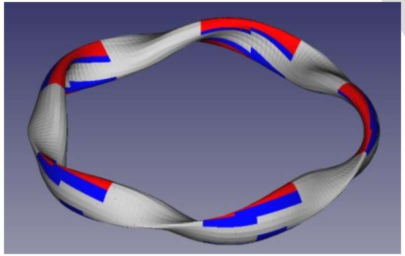
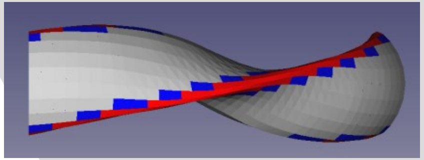


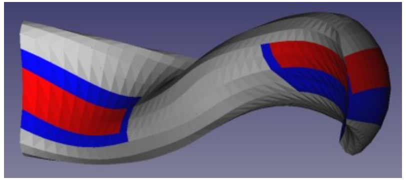
Fig 12: TBR with different divertor placement varying material options (divertor volume loss fixed 13 %).



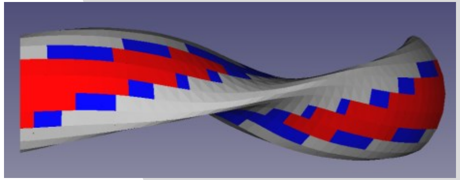
Top-Bottom



TBR loss minimised (ideal)



Inboard-outboard

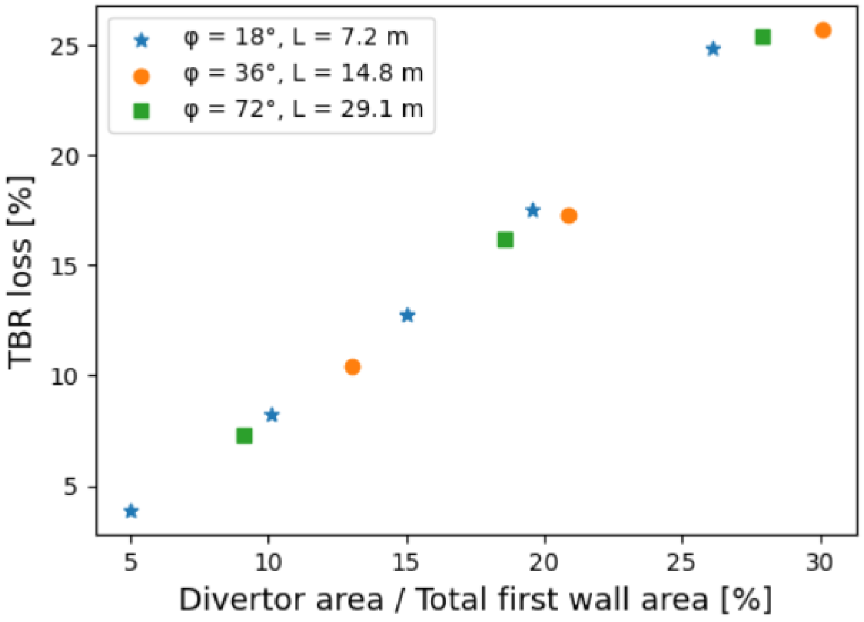


TBR loss maximised (worst case)

Divertor placement configurations

Effect of divertor area

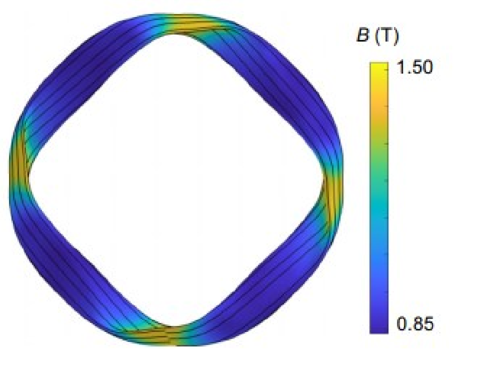
- Changing divertor length and width in the top-bottom configuration
- Linear behavior
- ➢ Total area fraction matters
- ➢ From TBR perspective, small divertor area and volume is preferred
- More factors e.g. coolant choice, divertor thickness are considered in Lyytinen et al. *Fus. Eng. Des.* 2025, **216,** 115000.



DCLL blanket and helium-cooled divertor with a 50 cm divertor body

Conclusions and outlook

- ✓ Automated parametric workflow for generating blankets and layered geometries for different stellarator configurations demonstrated
  - ✓ Can include simple divertor models, possible to make H&CD ports
  - – More heterogeneous blankets and structures are a challenge and future work
  - ➢ Currently applying this workflow for the new 4-period SQUID stellarator design
- ➢ Divertor area should be limited ~10 % of the first wall
- ➢ W7-X –like top-bottom divertor placement worked for HELIAS
- ➢ Advanced shielding materials must be allocated for coil shielding
  - ➢ Reduces available breeding blanket (BZ/BSS) space and impacts TBR
  - ➢ Necessitates targeted shield optimization in the most constrained regions



A. Goodman et al. *Quasi-Isodynamic Stellarators with Low Turbulence as Fusion Reactor Candidates*, PRX Energy **3**, (2024) 023010

Thank you! Questions?

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