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FÜR PLASMAPHYSIK

Towards a Stellarator Fusion Reactor: Achievements of the European Stellarator Program

Felix Warmer for SPPS Team & Colleagues

IAEA FEC, October 2025

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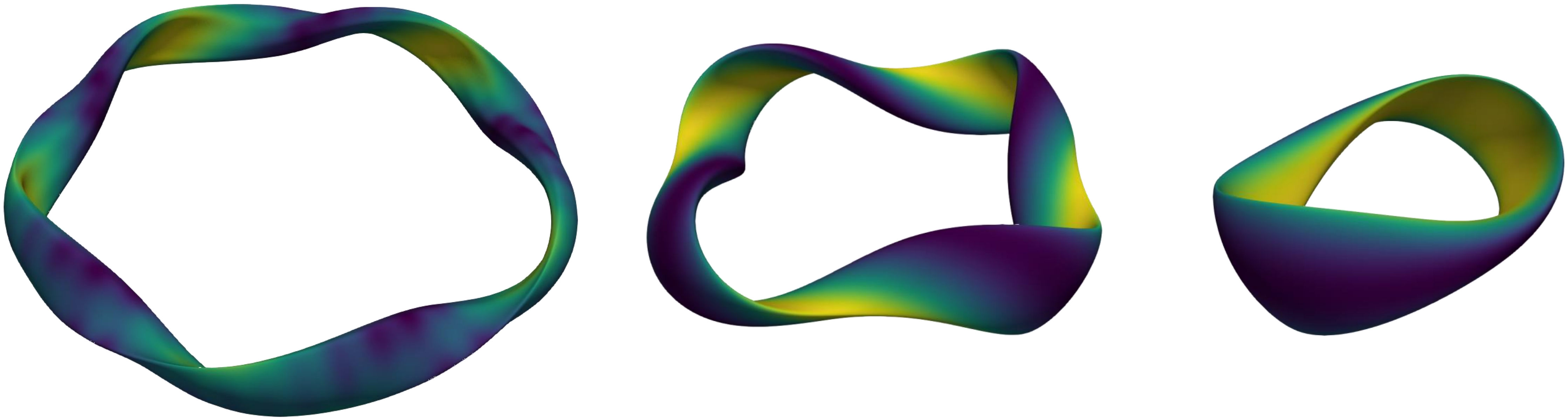
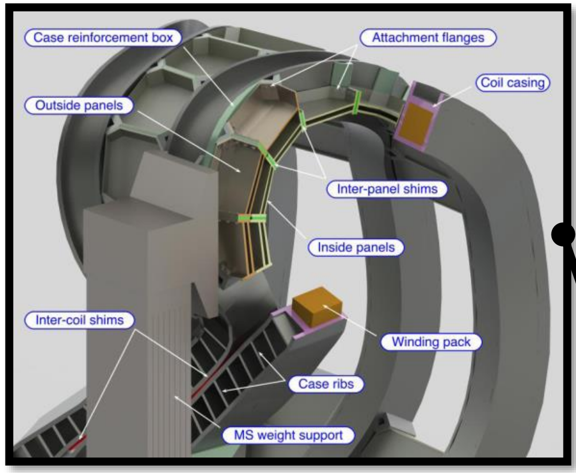
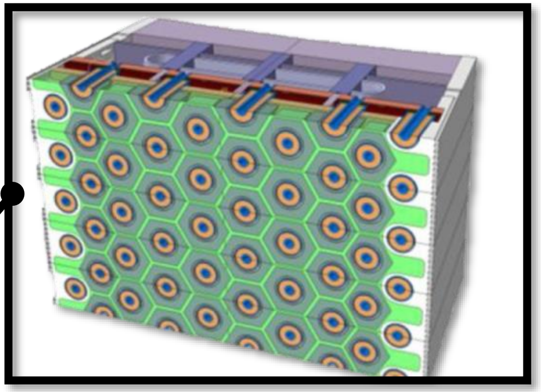
Advance in Stellarator Optimisation

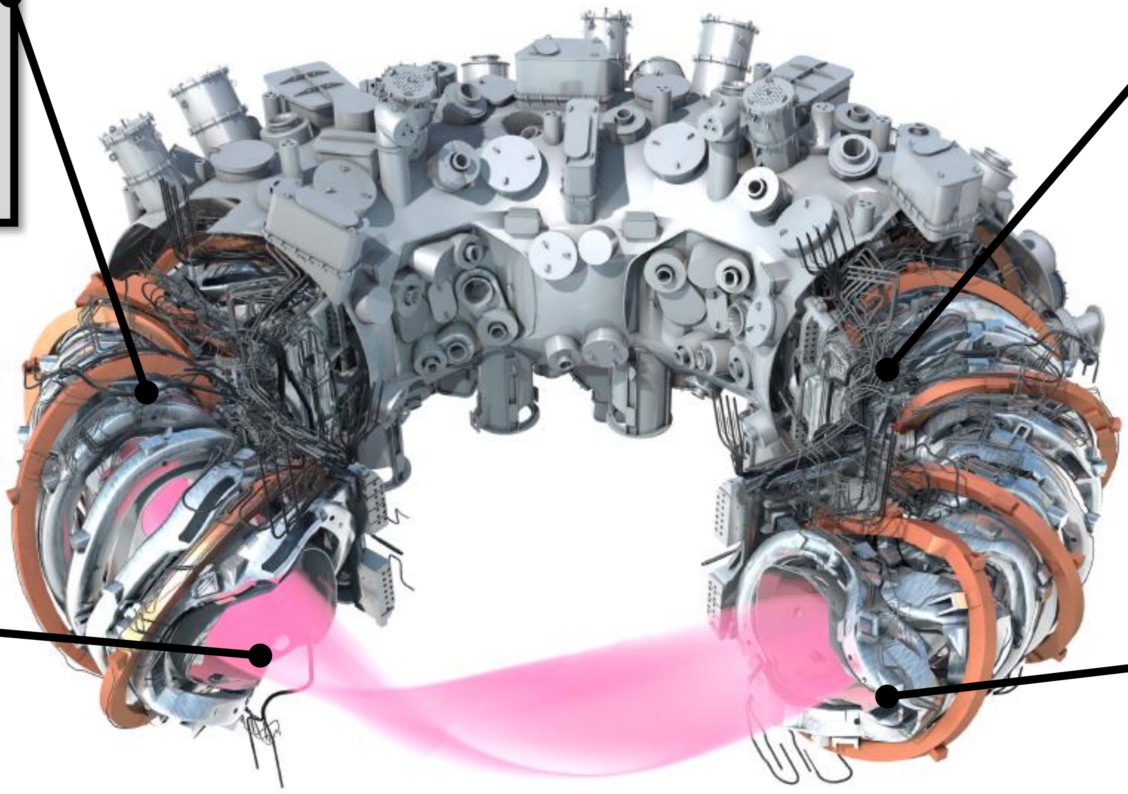


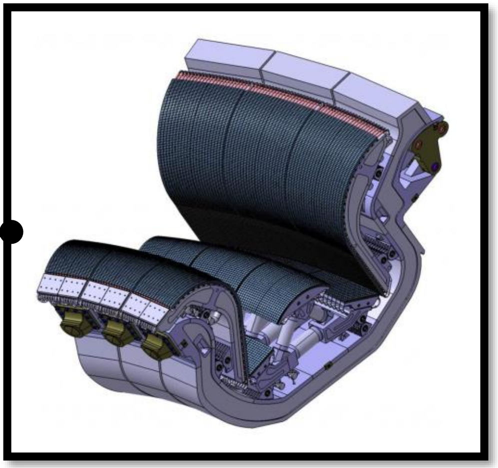
Big steps in Stellarator Optimisation with new configurations

Reactor Engineering









Various technology options & integration

Goal: Automating the Assessment of new Stell. Configurations

- **Potentially countless Stellarator shape variations**
- **Different technology options (HTS vs. LTS, blanket materials, etc.)**
- **High entanglement between components (& plasma) – challenge of integration**

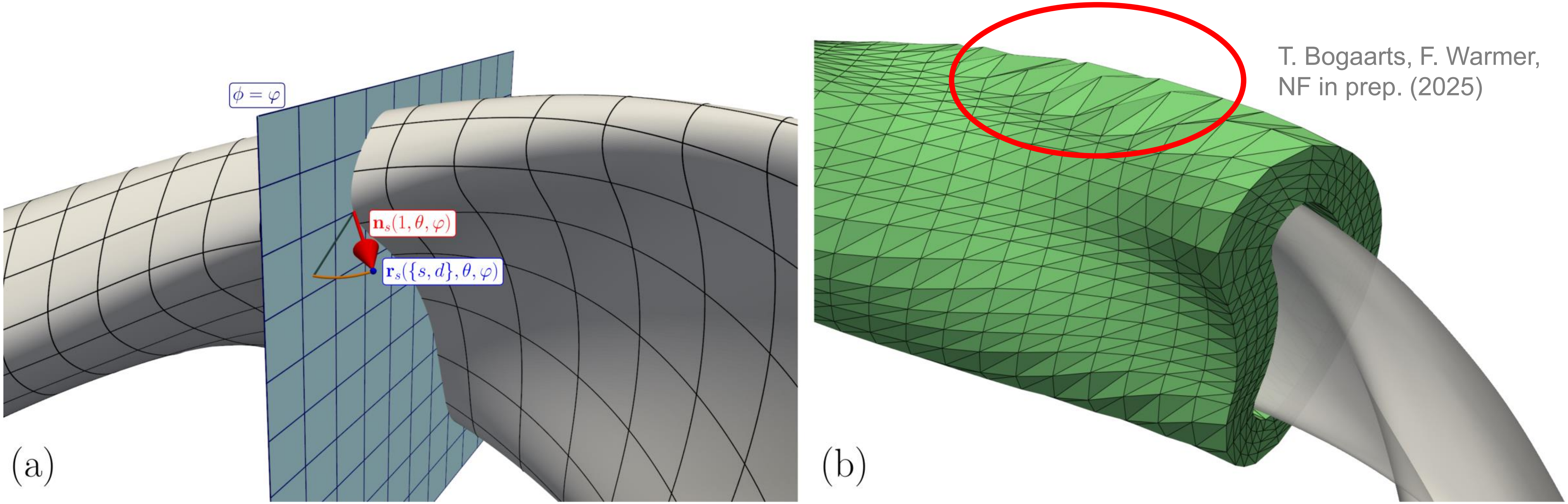
Importance of having an (automated) workflow for design assessment
(while working with limited resources)

Content

- Tools for the Geometry description
- Parametric workflow for neutronic analysis
- Parametric workflow for magnet assessment
- Summary

Tools for the Geometry Description

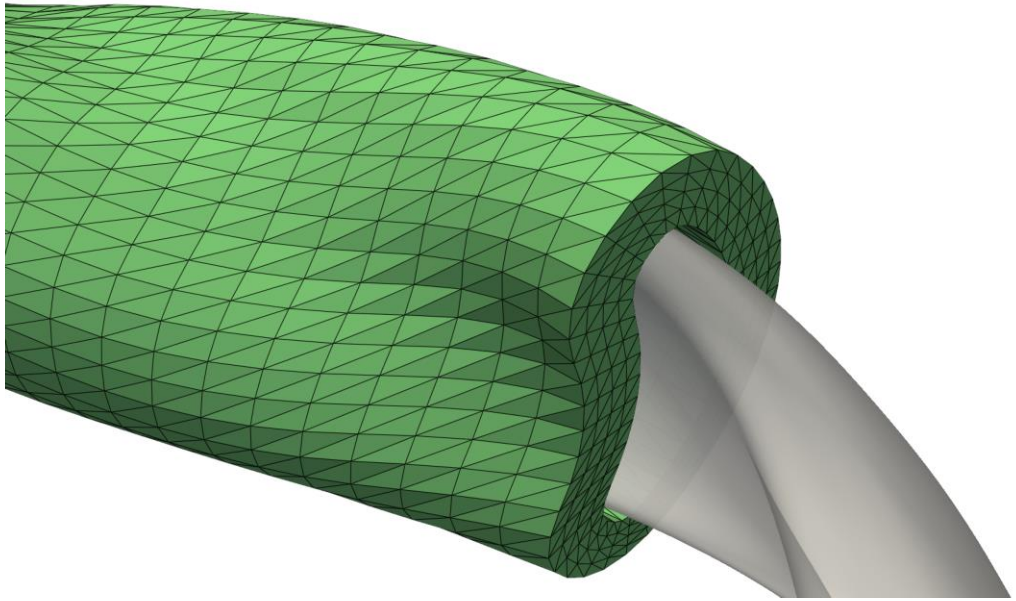
Creating a 3D (equidistant) wall surface / blanket layers

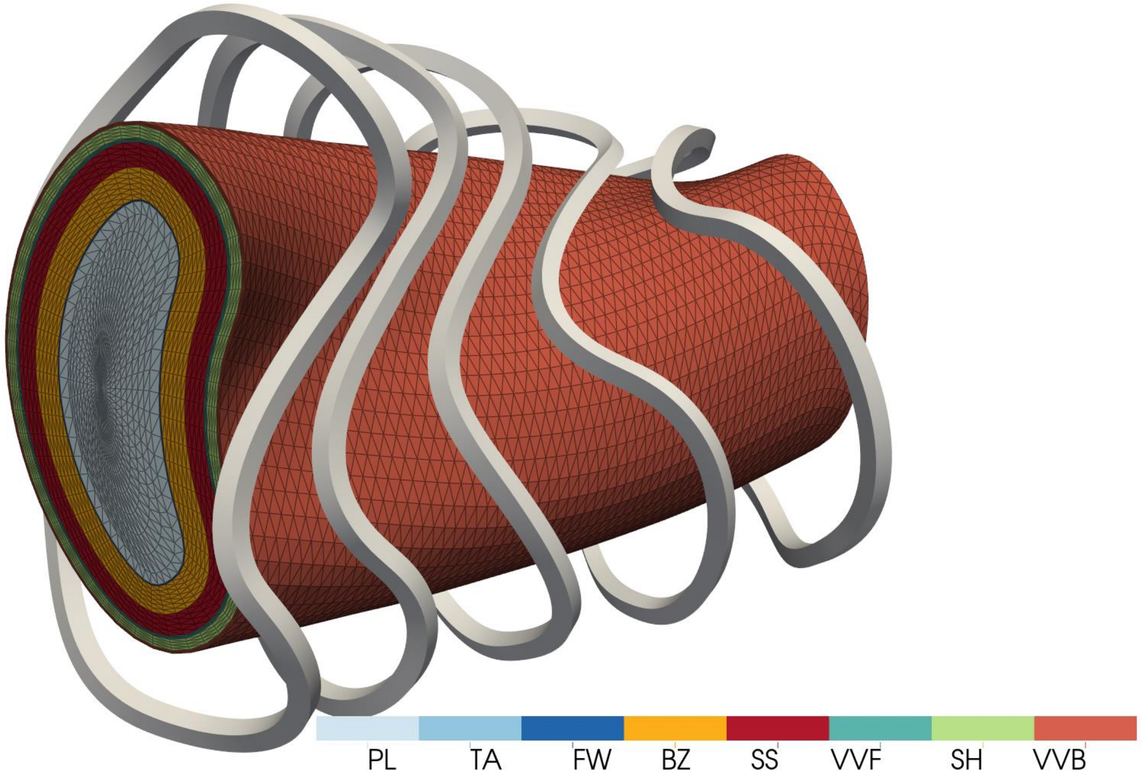


T. Bogaarts, F. Warmer, NF in prep. (2025)

- Normal vectors have a toroidal component → elements no longer lie on a poloidal cut
- Curvature leads to unequally-spaced elements

Solution: Fourier Transform of wall & blanket surfaces



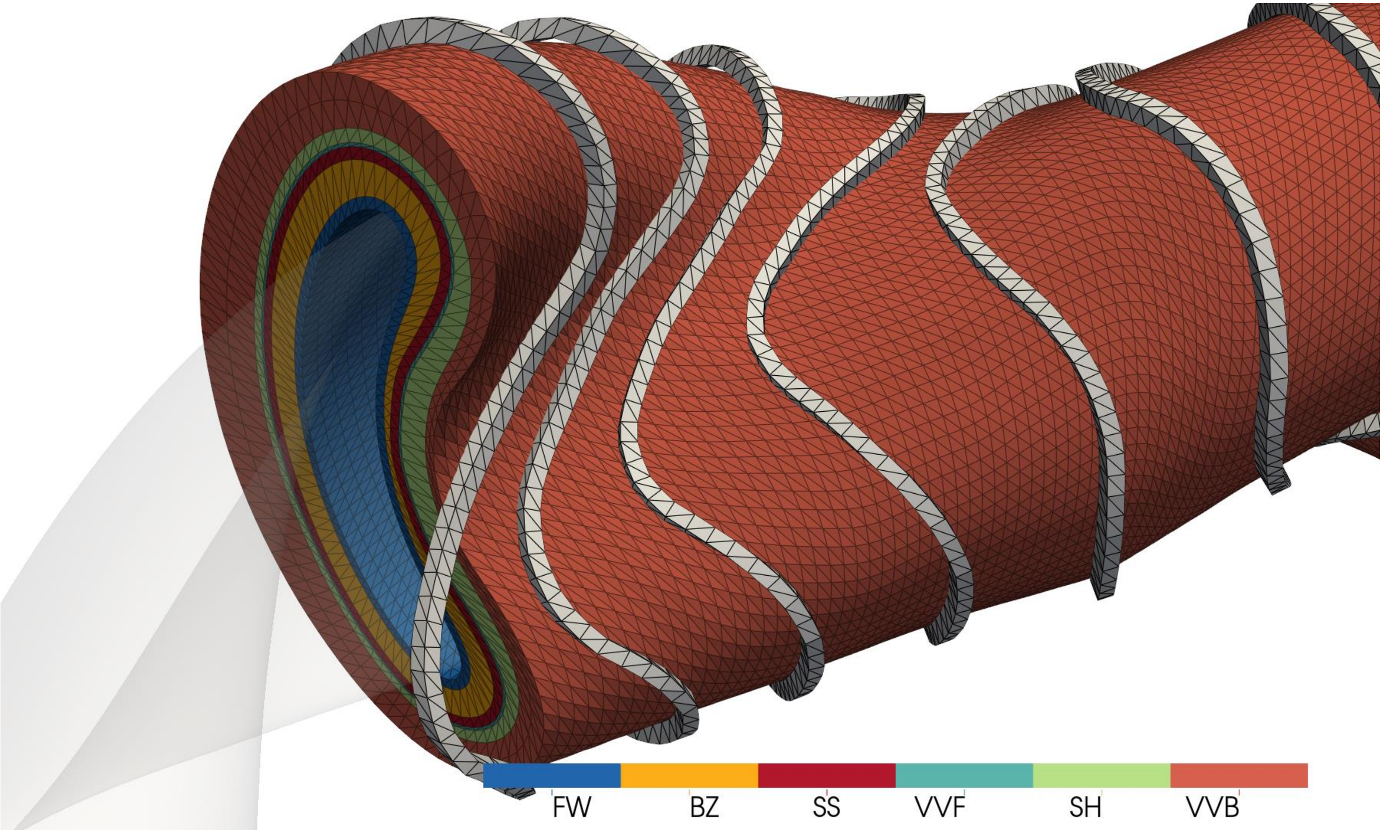


- Apply Fourier Transform and re-order poloidal coordinate for a constant poloidal arc length

→ better mesh (also reduces Fourier harmonics)

- Multiple surfaces can be combined resulting in layered blanket

Fitting "arbitrary" surfaces, i.e. coil surface



- Find 'distances' and 'angles' from arbitrary points using a combination of a grid search and Newton iterations
- Apply Fourier Transform
- Particularly useful for the 'coil surface'

Coil Geometry

Typical input:

- Discrete filaments OR Fourier-based filaments

Several ways to define a coordinate system along a coil to get finite size coils:

- *The Frenet-Serret frame* (leads to irregular shapes)
- *The centroid frame* (vector to its center of mass)
- *The rotation-minimized frame* (reduces twisting)

- (any user-defined normal’s)

Likely to be custom defined depending on detailed engineering requirements (e.g. HTS tape orientation)

Parametric workflow for neutronic analysis

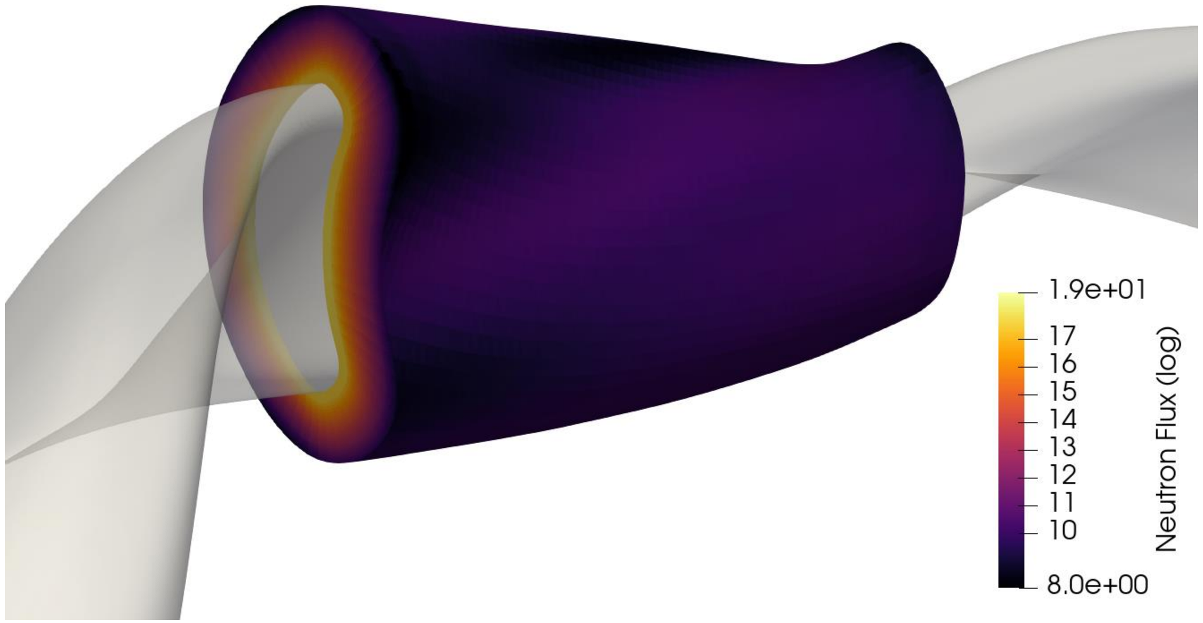
Neutron Transport & Blanket

<u>Neutrons are a key aspect that separates experiments from a Fusion Reactor</u>

Desired quantities:

- Tritium breeding
- Nuclear heating
- Neutron damage
- Shielding / Safety

→ **Solve neutron transport**



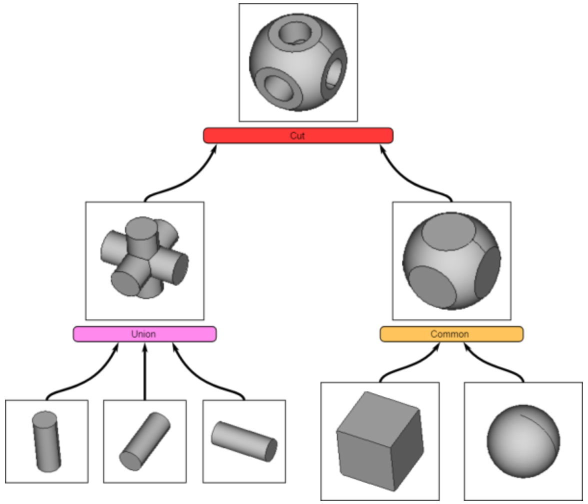
$$\underbrace{\hat{\mathbf{\Omega}} \cdot \nabla \psi(\mathbf{r}, \hat{\mathbf{\Omega}}, E)}_{\text{Streaming}} + \underbrace{\sigma(\mathbf{r}, E)\, \psi(\mathbf{r}, \hat{\mathbf{\Omega}}, E)}_{\text{Collisions}} = \underbrace{q(\mathbf{r}, \hat{\mathbf{\Omega}}, E)}_{\text{Sources}}$$

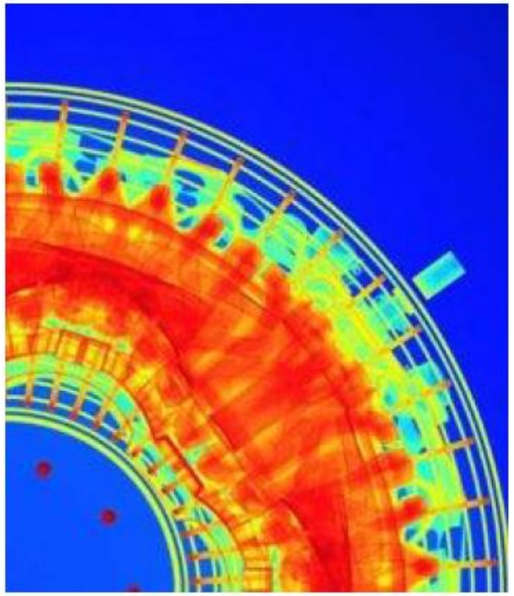
Neutron Transport: Traditional MC approach

- Monte Carlo method
- Requires 10^9 samples
- Poor statistics far from source
- Not suited for complex shapes (CSG format)

→ Has been successfully applied to stellarators in EUROfusion: MCNP5/6, Serpent2, OpenMC

→ But impractical for design exploration



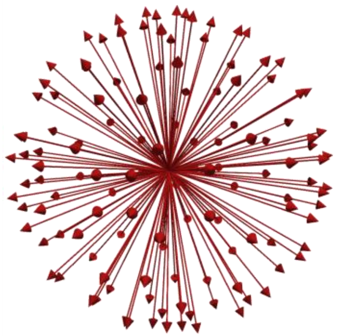


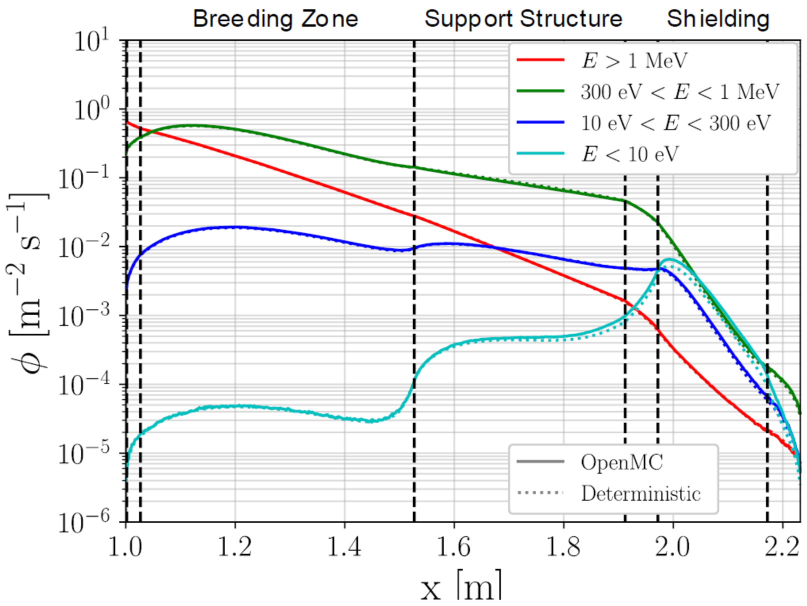
A. Häussler, et al. FED 136 (2018)
I. Palermo, et al. NF 61 (2021)
T. Lyytinen, et al. NF 64 (2024)
etc.

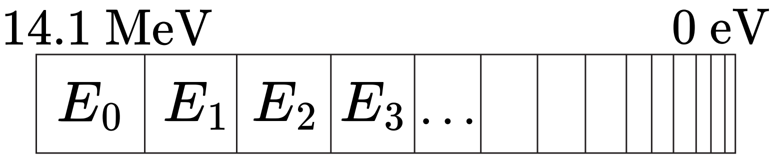
I. Palermo, this IAEA FEC, Friday, 14:40, TEC/4-3

Modelling Innovations: Deterministic Neutronics

- Directly solve neutron transport equation
- E: Multigroup, $\widehat{\Omega}$: discrete ordinates, **Tetrahedral mesh**
- **Discontinuous Galerkin,** sweep algorithm
- Exact neutron conservation

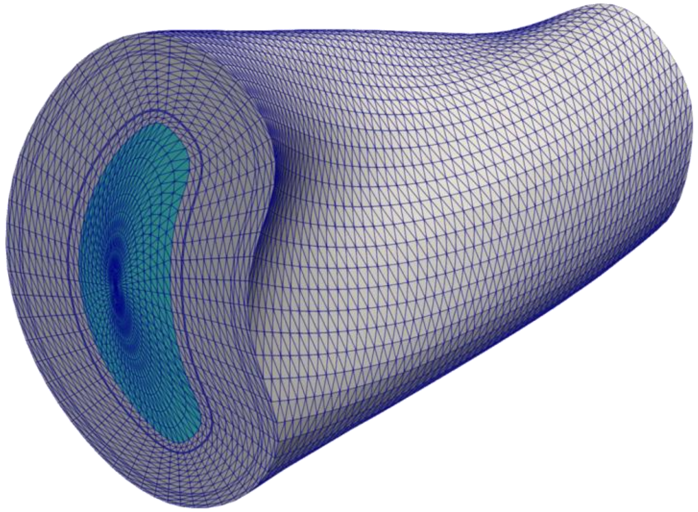




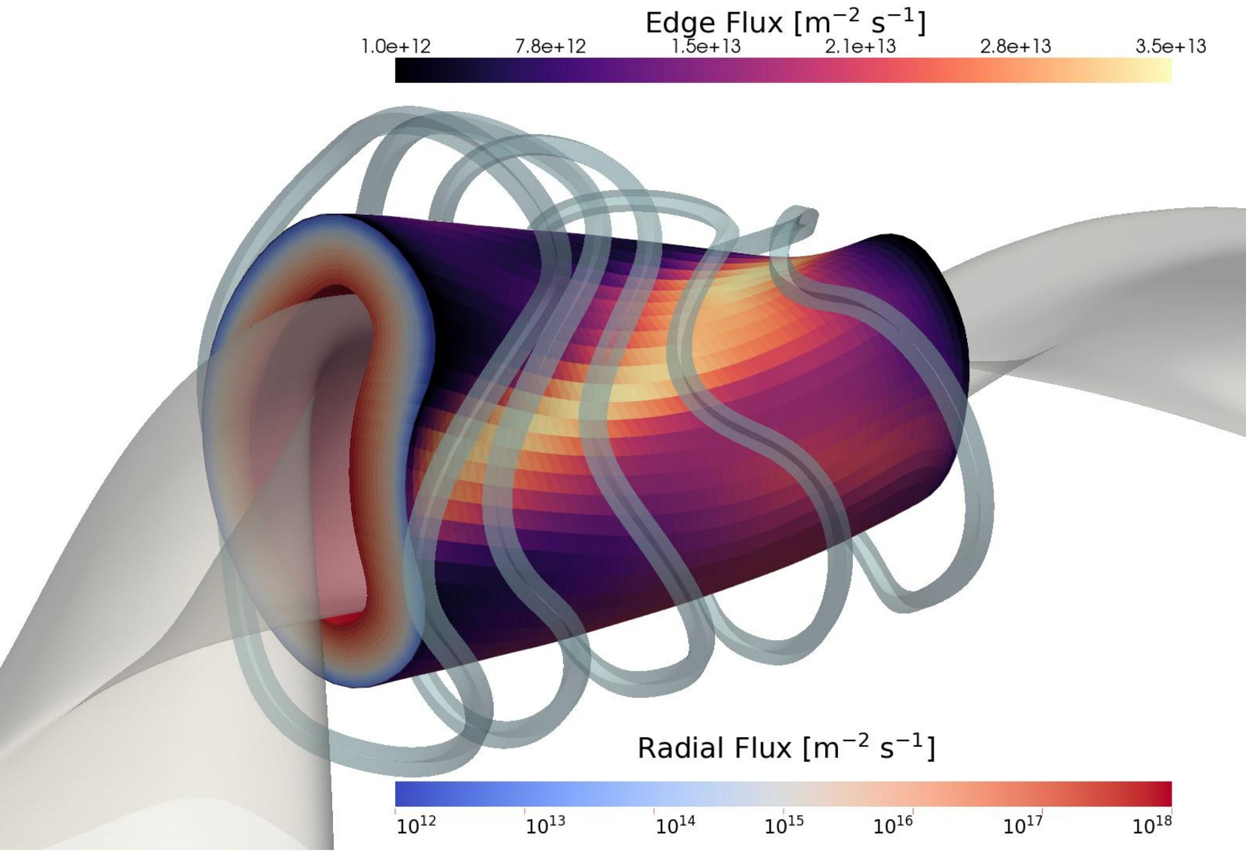


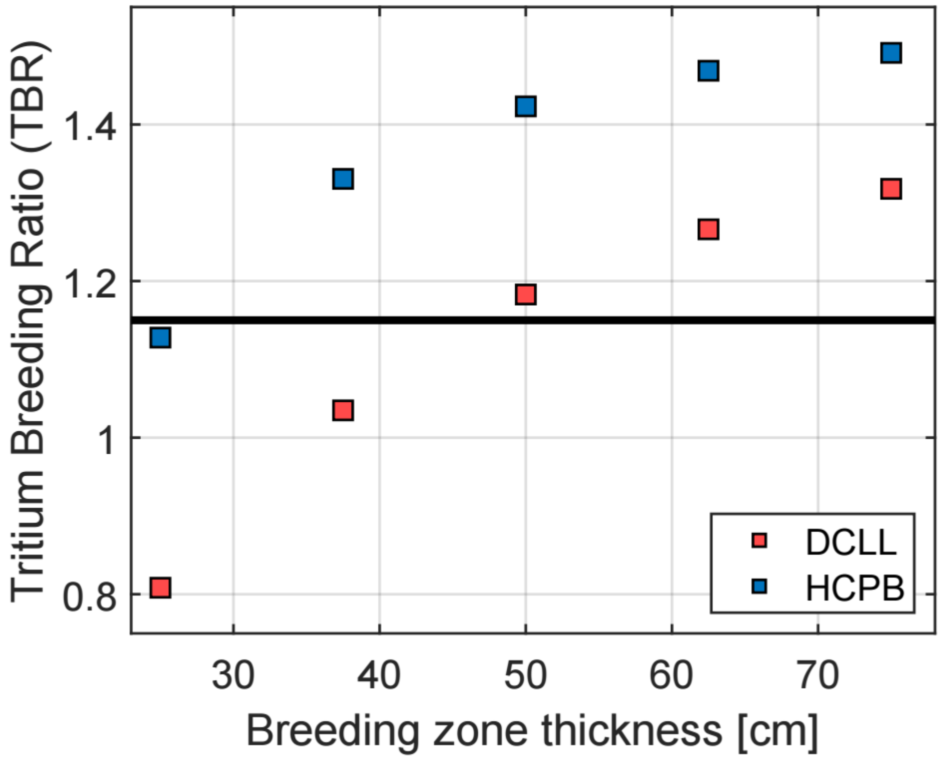
- Finished development
- Fully 3D capable
- Benchmarked
- 10^5 faster than MC

T. Bogaarts, F. Warmer, NF 65 (2025)



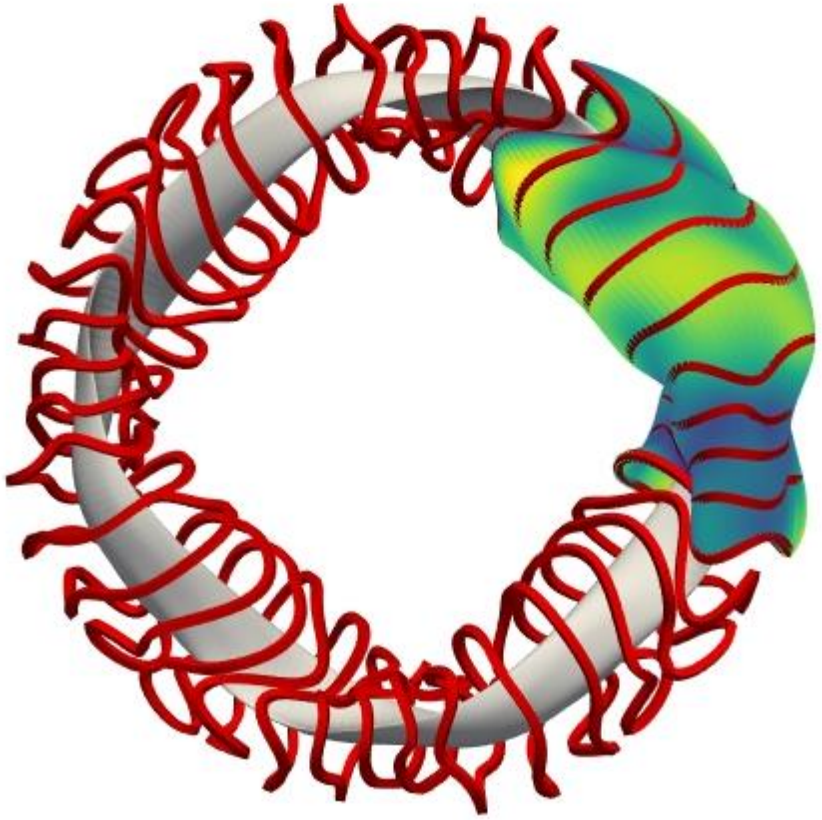
Deterministic Neutronics: 3D solution & optimisation



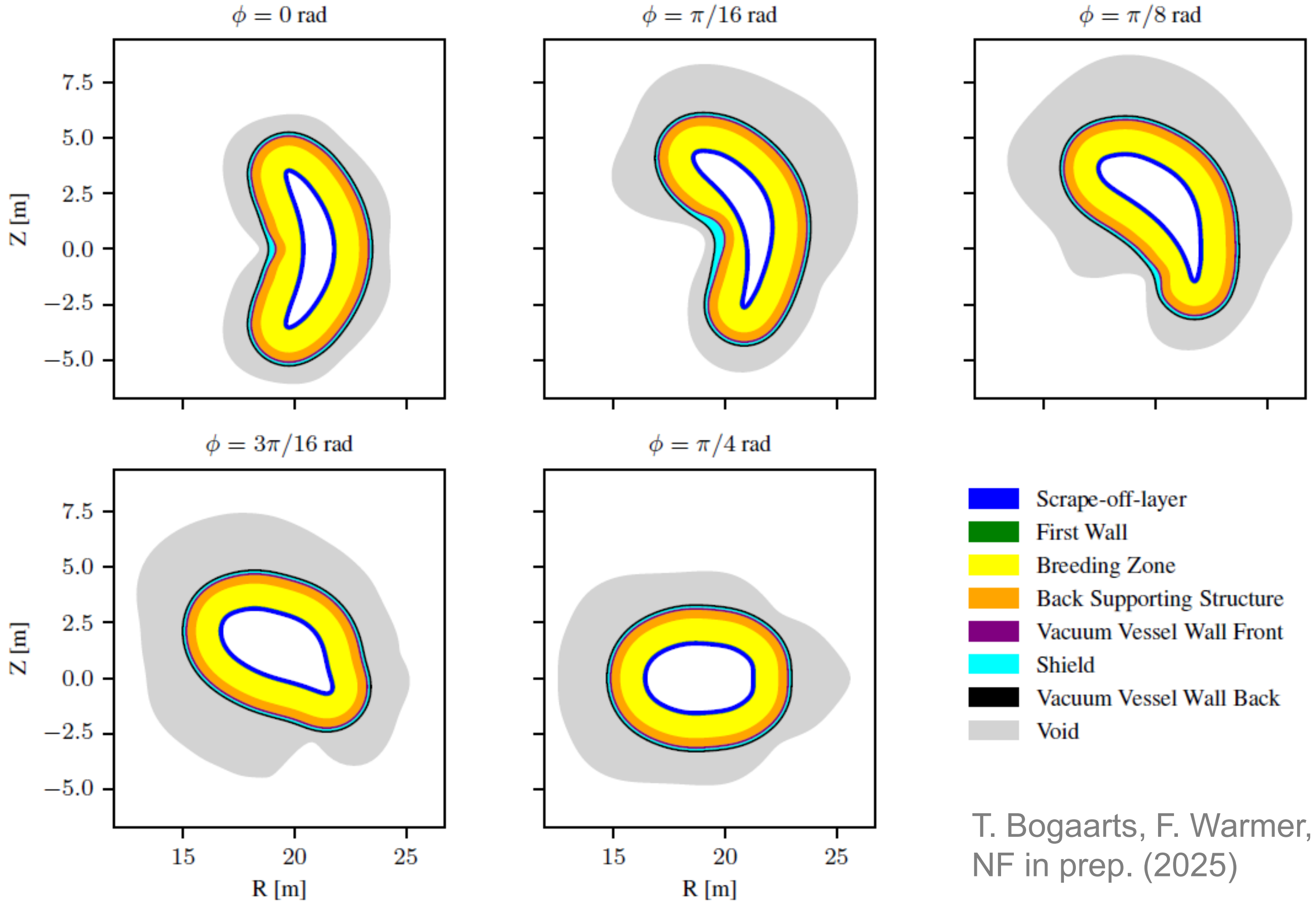


- **Neutrons are a key design driver → new tool allows fast design iteration and optimisation**

Method Application to a New Configuration

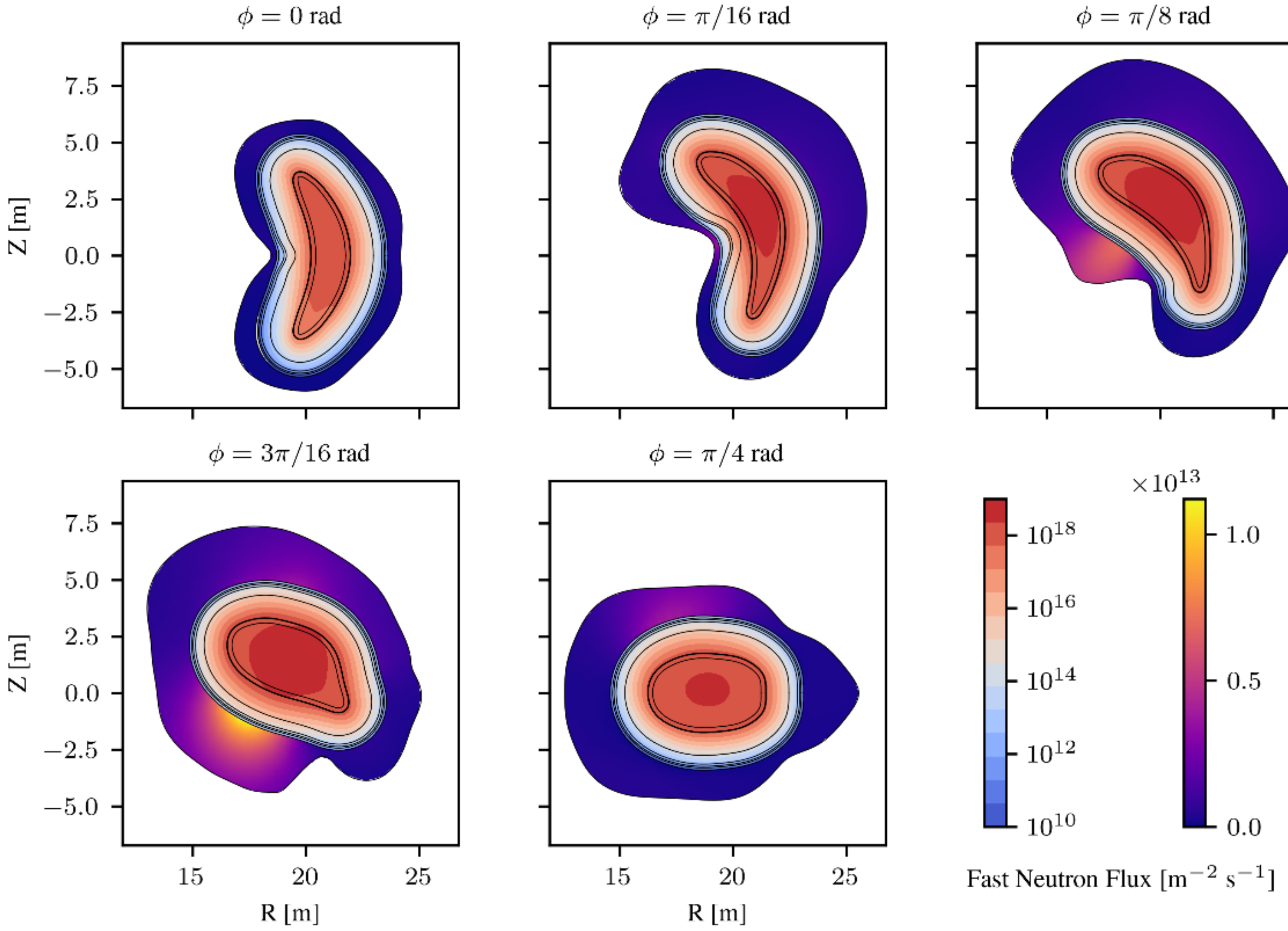


A. Goodman, et al., PRX Energy 3.2 (2024)
A. Goodman, et al., JPP, in prep. (2025)



T. Bogaarts, F. Warmer, NF in prep. (2025)

Insights from the New Configuration + Coil set



- Highly varying coil-plasma distance
- Typical narrow regions on the inboard side
- Shielding needed to be adjusted to satisfy the fast flux constraint on the coils ($< 10^{13}$ $m^{-2}s^{-1}$)
- **Conclusion**: coils need iteration, but new method key for quick assessment

T. Bogaarts, F. Warmer, NF in prep. (2025)

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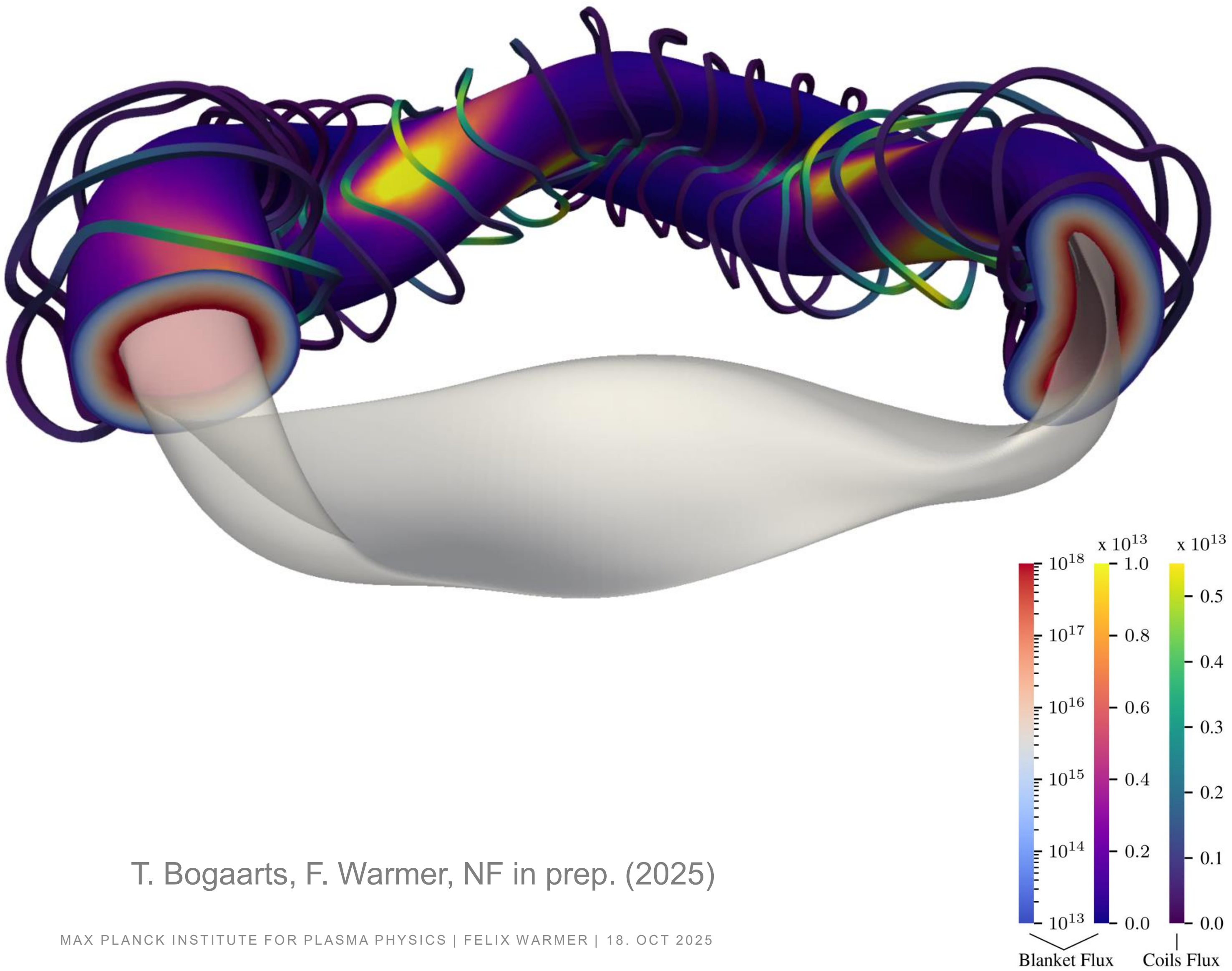

T. Bogaarts, F. Warmer, NF in prep. (2025)

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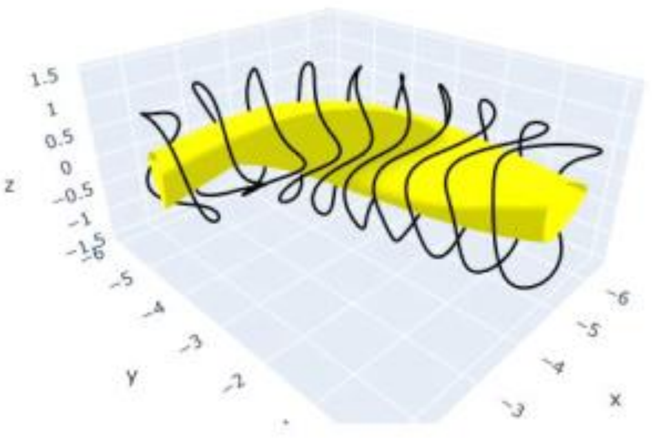
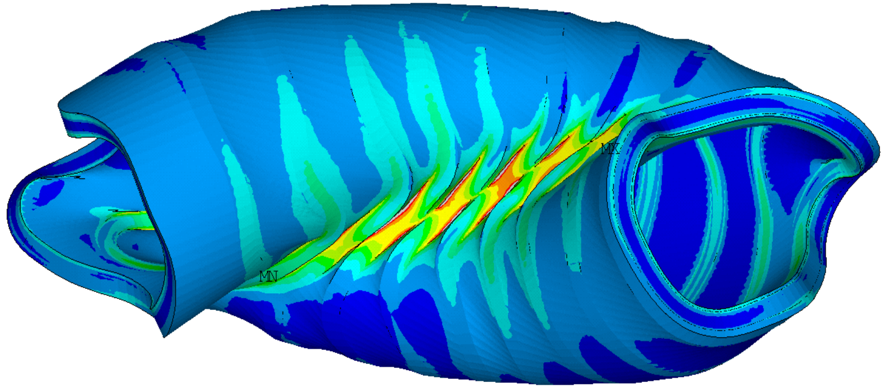
Parametric workflow for magnet assessment

Towards a realistic & feasible coil set





Coil optimisation:

- Finding optimal shape
- Reproduce configuration
- Some engineering constraints

Winding Pack:

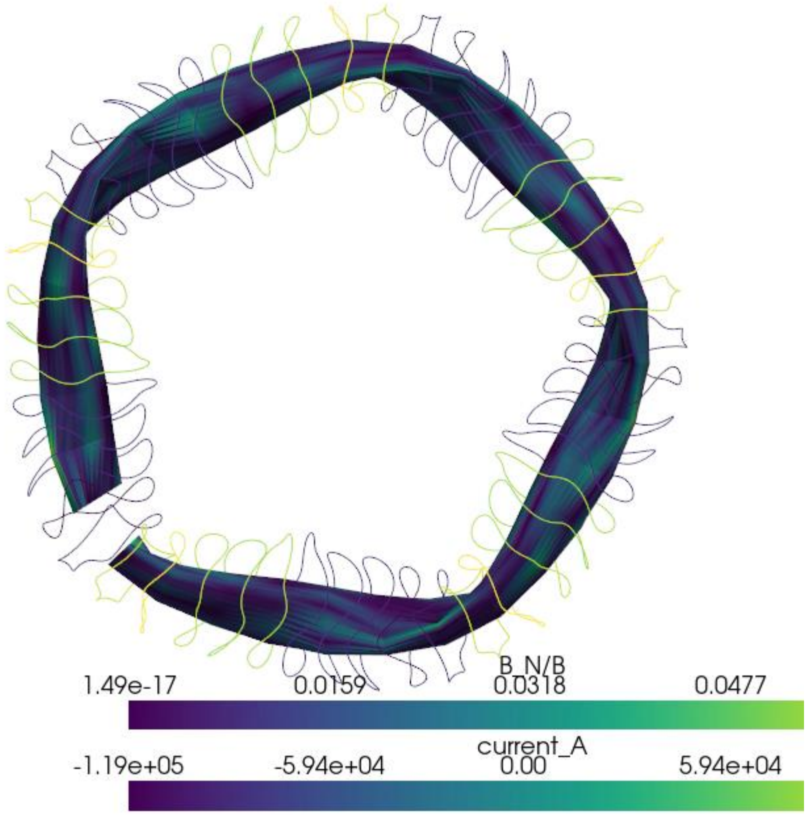
- SC choice (HTS vs LTS)
- Cable concept
- Max B-field
- Quench protection

Mechanical Analysis:

- Add support structure
- FEM simulations
- Iteration

1) Bayesian Optimisation of Stellarator Coils

Coil design is a heavily constrained optimisation problem that needs modern solutions



Automated and intelligent design space exploration:

- Many engineering constraints → many weights
- Typically requires manual adjustment or studies
- Reformulate as a Bayesian optimization problem
- Prototype optimization implemented

Ongoing improvements:

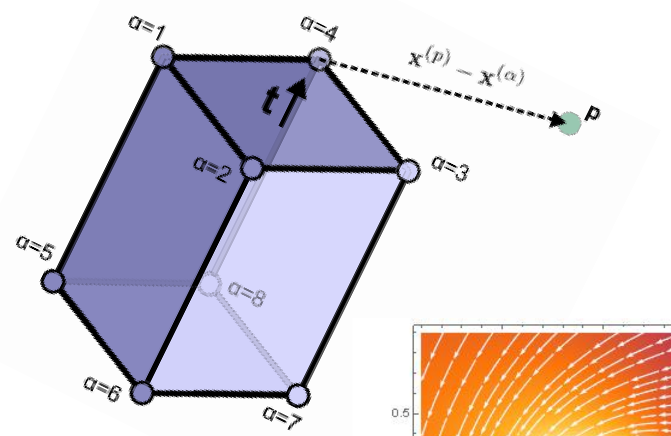
- more effective initial guesses
- employ Gaussian processes to model the coils
- …

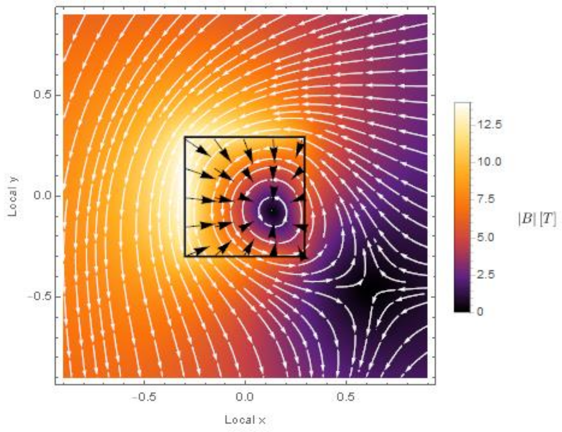
Quantity	W7-X	Bayesian
$\langle B \cdot n \rangle / \langle B \rangle \times 10^{-3}$	29	14
$\max \langle B \cdot n \rangle / \langle B \rangle \times 10^{-2}$	11	6.4

2) Winding Pack modelling

J. Lion, F. Warmer, et al NF 61 (2021)

- **Flexible model that considers engineering constraints self-consistently:**
  - Superconductor properties (j_{crit}, B_{max}, T_c)
  - B-Field inside the coils (Biot-Savart)
  - Coil quench protection (Cu fraction)
  - Coil-coil and coil-plasma distance
  - Lateral and radial forces
  - Bending radius





- **Under development:**
  - superconductor strain limits
  - structure stress
  - explore alternative approaches

- Coils approximated by cuboids with constant current density
- Analytic solution to Biot-Savart

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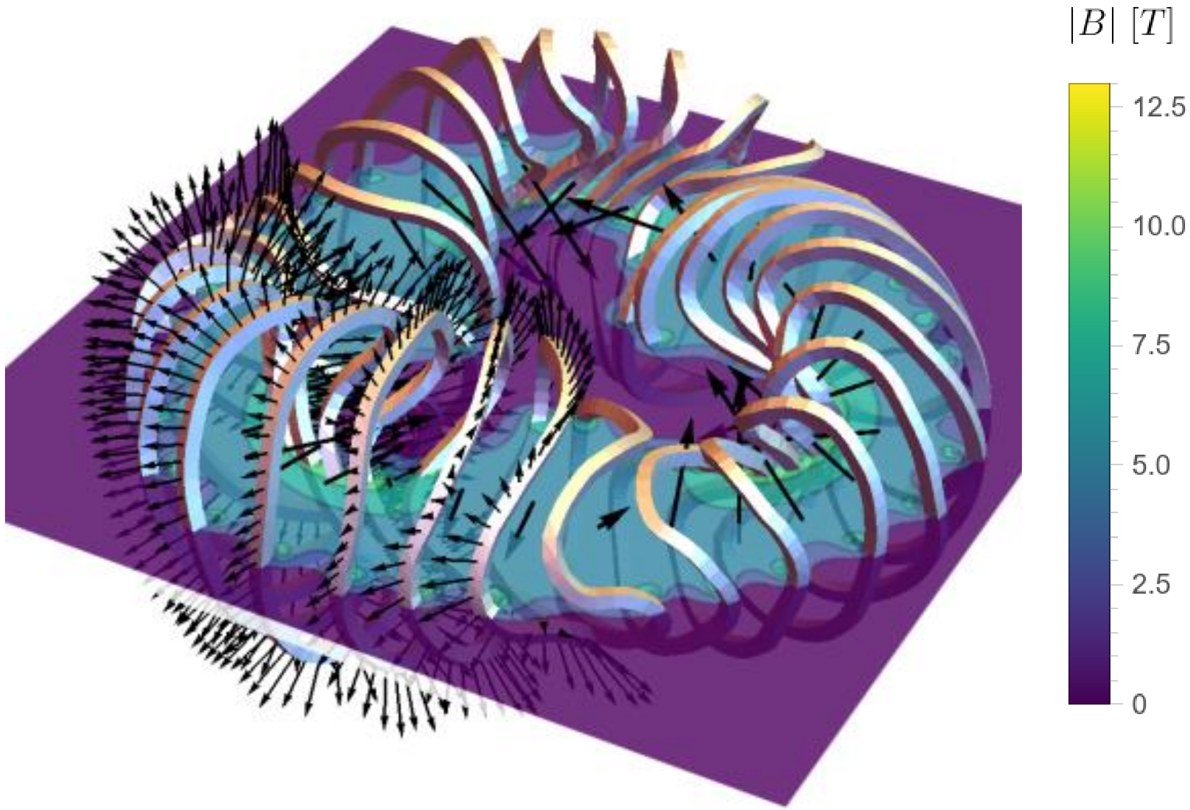
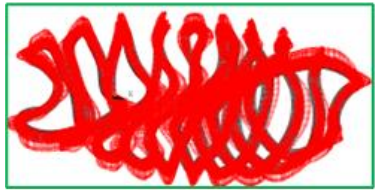


J. Lion, F. Warmer, et al NF 61 (2021)

3) Mechanical Analysis workflow



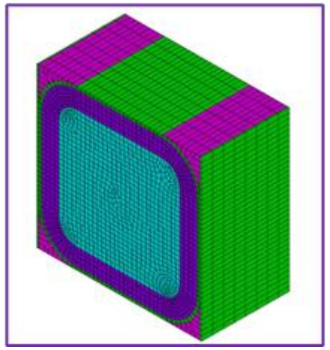
Fully bonded or Frictionless btw. Case and Coil

Lorentz Force from EM simulation

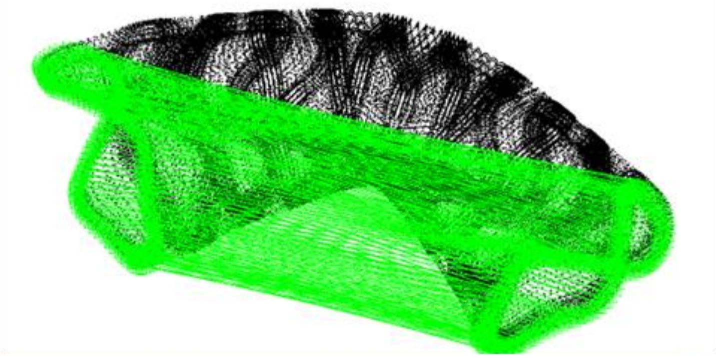
Mechanical Analysis: Coil Cases and Intercoil structure

1. Cool-down to 4.2K
2. EM load during operation

Smeared mechanical properties

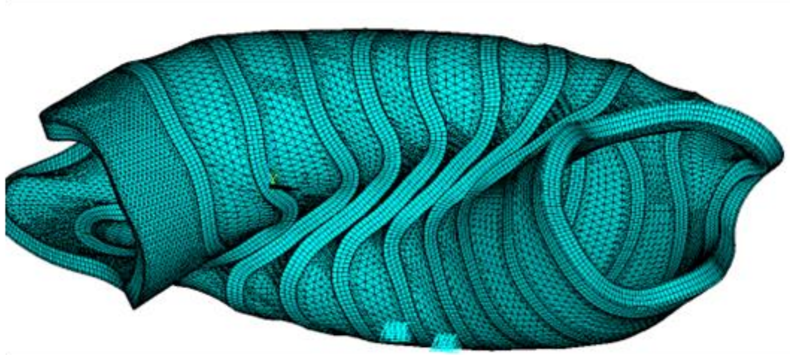


Intercoil Structure: Space filled between coils



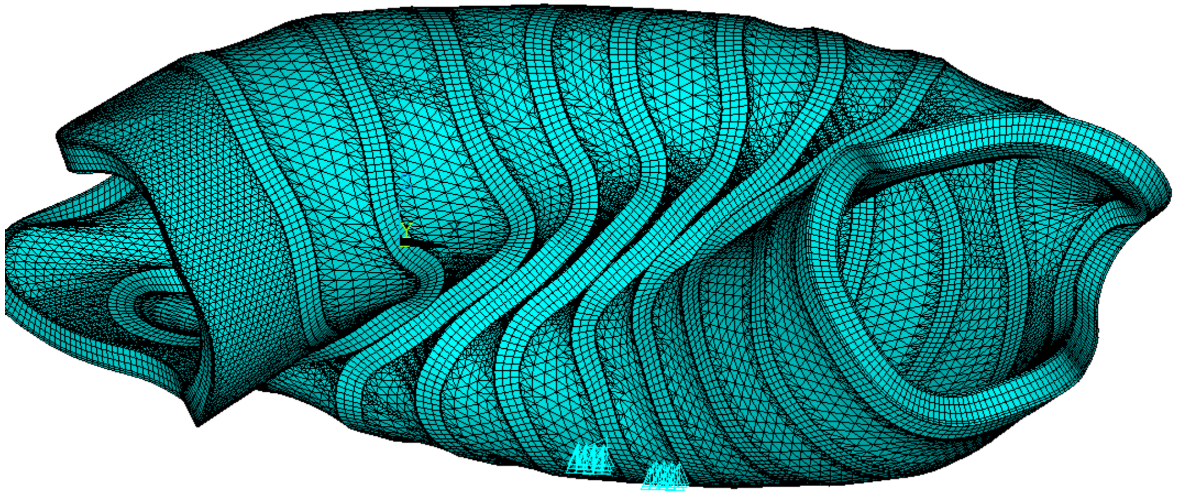
Boundary Conditions:

1. Gravity support: Sliding contact
2. Periodic boundary conditions



D. Biek, et al, IEEE Transactions on Applied Superconductivity, submitted (2025)

3) Mechanical Analysis



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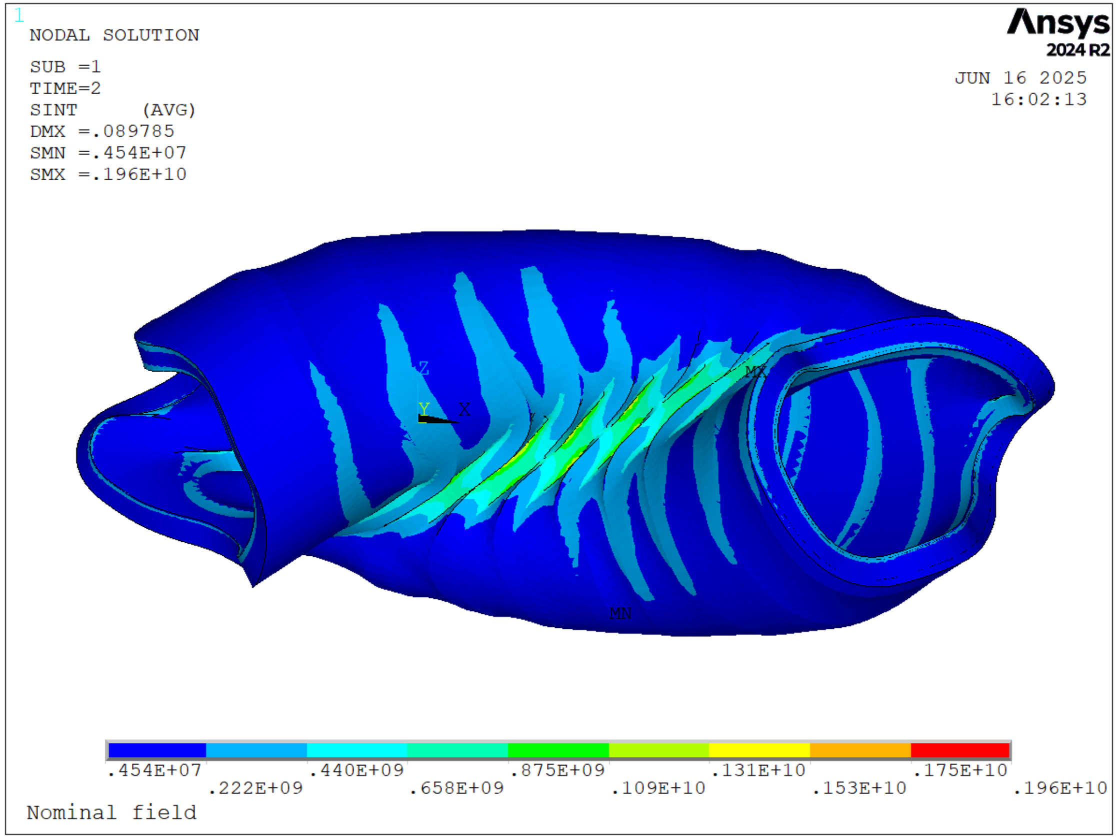


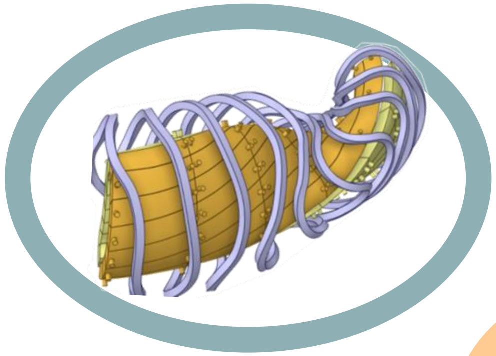
- First prototype workflow (old config.)
- Automate, apply to new configurations
- Include ports / access / inner ring(?)

Coherent Blanket design for Stellarators

More detailed engineering activities within EUROfusion

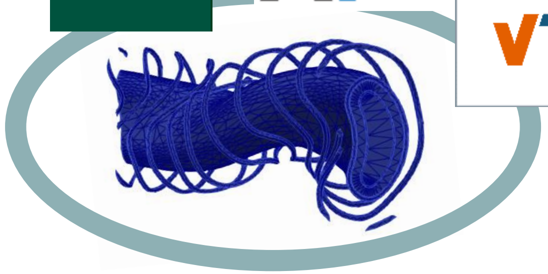
I. Palermo, this IAEA FEC,
Friday, 14:40, TEC/4-3

Laboratorio Nacional de Fusión
Ciemat



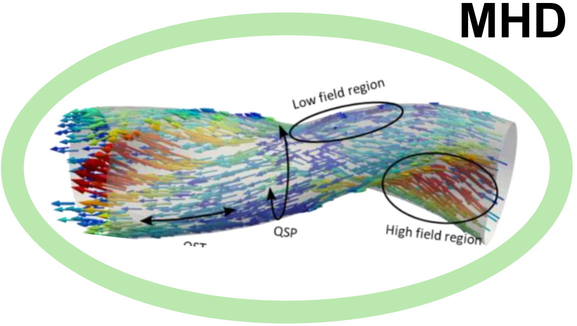
Segmentation

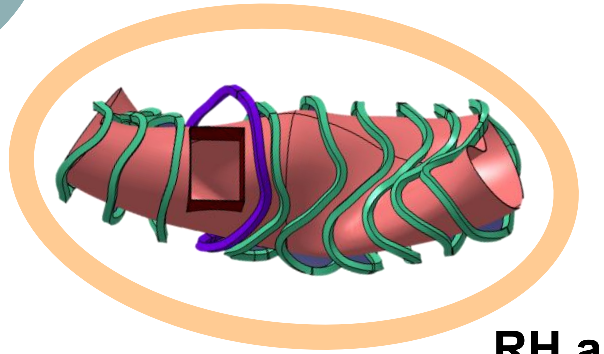
UNED
Aalto University
VTT



Neutronics tolos for MC

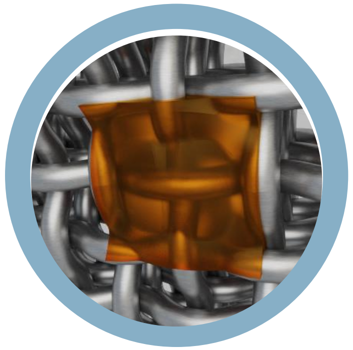
MHD tools



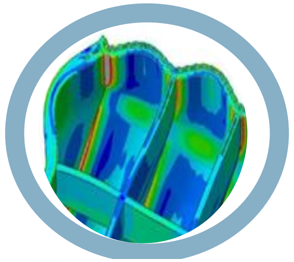


RH approaches

UK Atomic Energy Authority



FW design



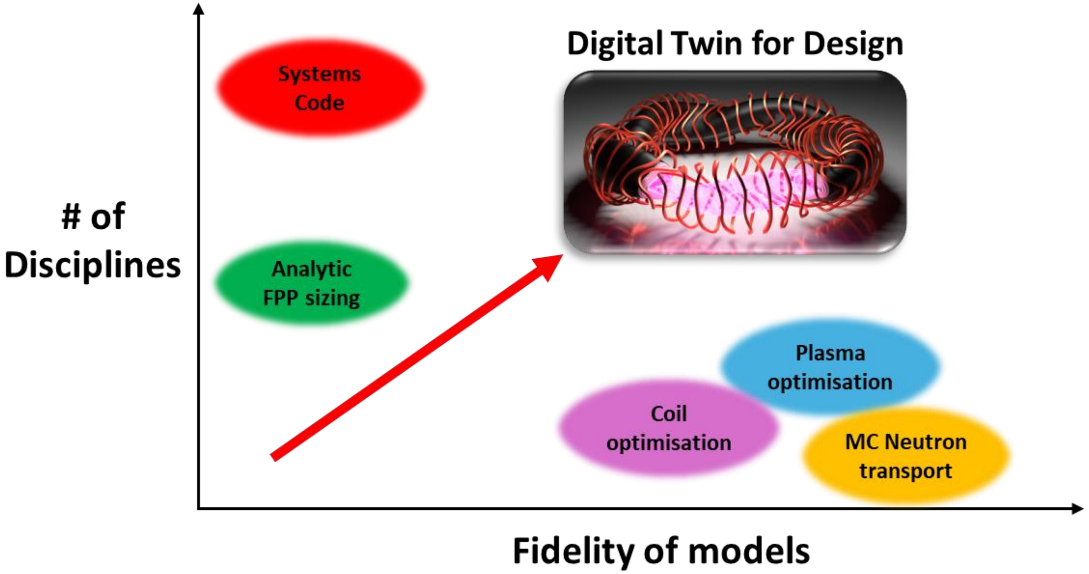
Thermal-hydraulics +
Thermo-mechanics
Multi-scale approach

UNIVERSITÀ DEGLI STUDI DI PALERMO

Dedicated Stellarator Reactor group founded at IPP Greifswald

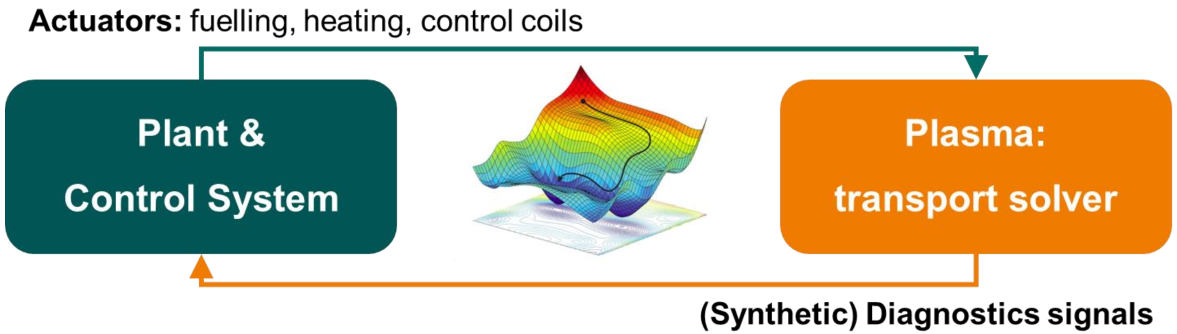
‘Digital Twin’ for Stellarator Design

- innovative modelling
- model integration
- intrinsic multidisciplinary



‘Flight Simulator’ for Stellarator Operation

- reactor operation & control
- model predictive control
- diagnostic requirements



Summary

Acknowledgements

C. Albert[7], J. Alguacil[1], D. Biek[2], T. Bogaarts[3], G. Bongiovi[4], V. Bykov[5], J.P. Catalán[1], R. Duligal[3], I. Fernandez[6], S. Giambrone[4], C. Hume[10], M. Hrecinuc[10], J. Lion[5], T. Lyytinen[8/9], J.A. Nogueron[6], I. Palermo[6], V. Queral[6], D. Rapisarda[6], L. Sanchis[8], X. Sarasola[2], K. Sedlak[2], A. Snicker[8/9], D. Sosa[6], F.R. Urgorri[6], F. Warmer[3]

3-4ppy/y

[1]Universidad Nacional de Educación a Distancia
[2]École Polytechnique Fédérale de Lausanne, Swiss Plasma Center
[3]Eindhoven University of Technology
[4]Università degli Studi di Palermo
[5]Max Planck Institute for Plasma Physics
[6]Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
[7]Technical University Graz
[8]Aalto University
[9]VTT Finland
[10]UK Atomic Energy Authority

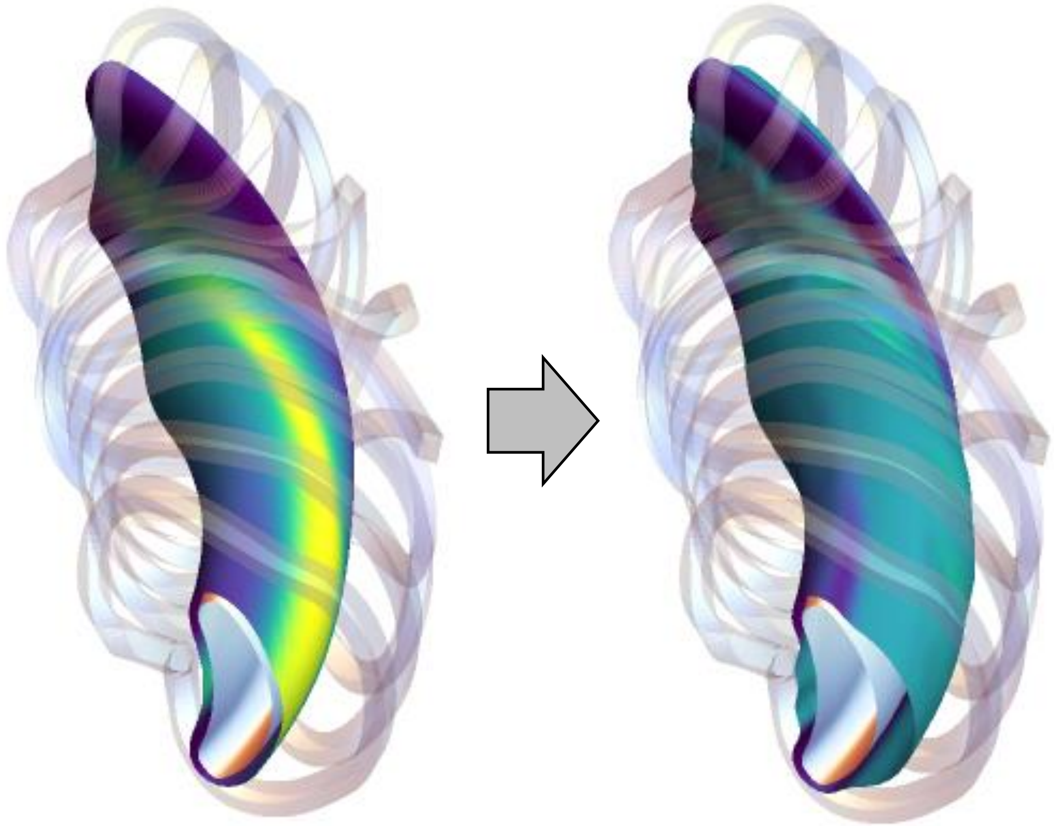
Summary

- Geometry tools developed for blanket & coil representation (tetrahedral mesh)
- New, fast deterministic neutronics method that works directly on this geometry
- Application to a new promising configuration reveals the importance of coil design
- Consequently, advances are made in automating magnet system design workflow
- New methods for coil optimisation emerging (+ adding engineering constraints)
- First steps towards FEM structural mechanical analysis
- EU filling gaps in Stellarator engineering that were desperately needed

- **contact:** felix.warmer@ipp.mpg.de

Backup slides

Such Models allow unprecedented Design Optimisation

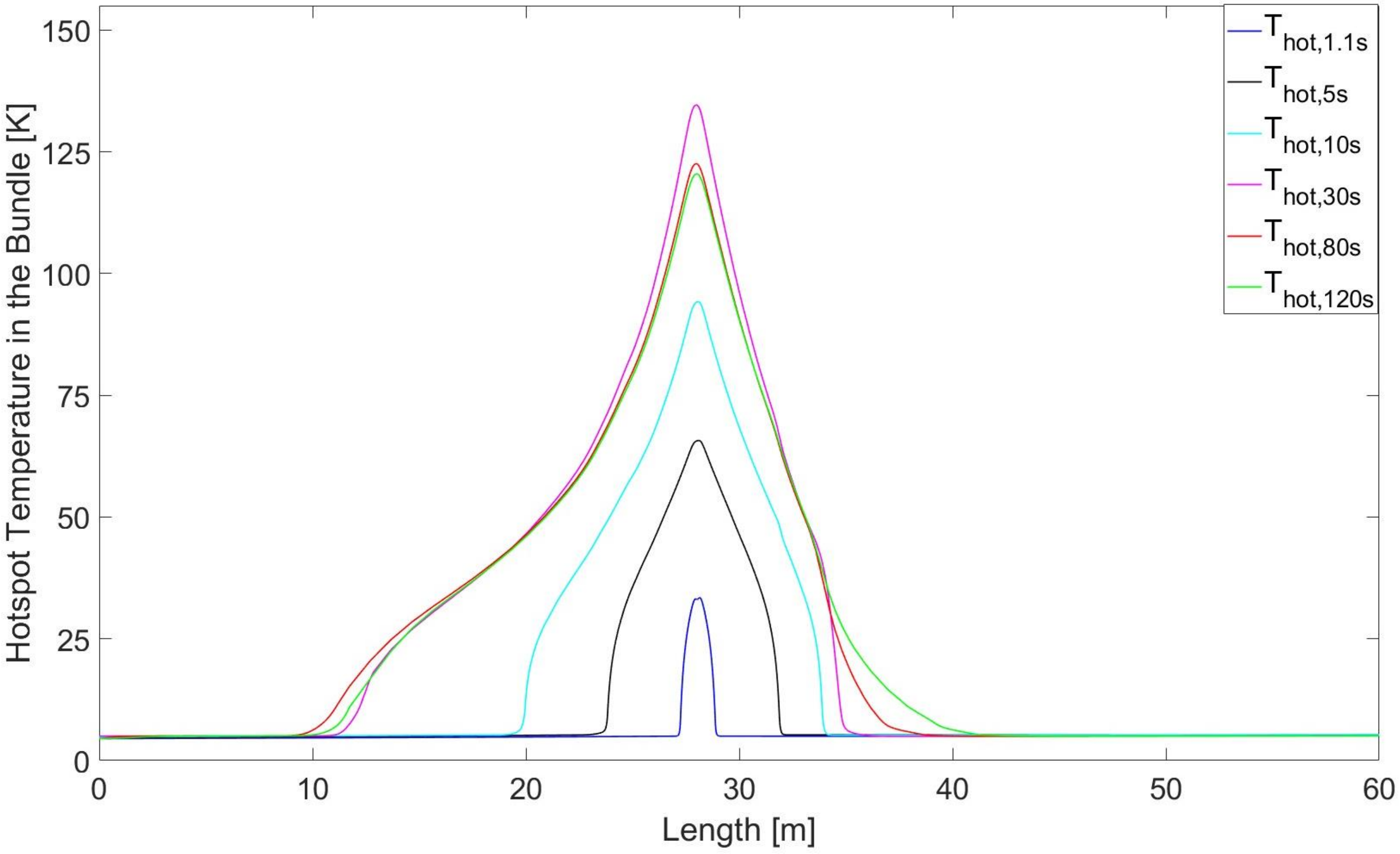


- <u>Allows 3D blanket optimisation</u>
- Potentially increased life-time
- **Next step: integrate with coil optimization**

Virtually impossible with previous methods

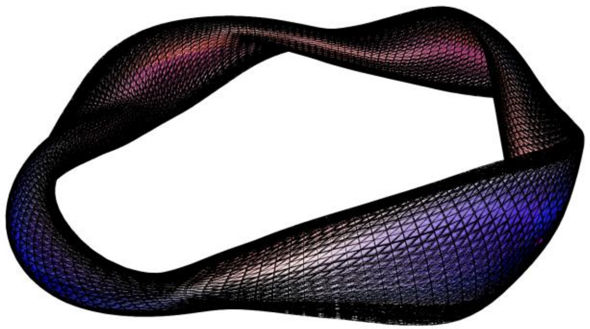
J. Lion, F. Warmer, et al NF 62 (2022)

3) Quench Modelling



Neutron Transport: Traditional MC approach applied to Stellarators

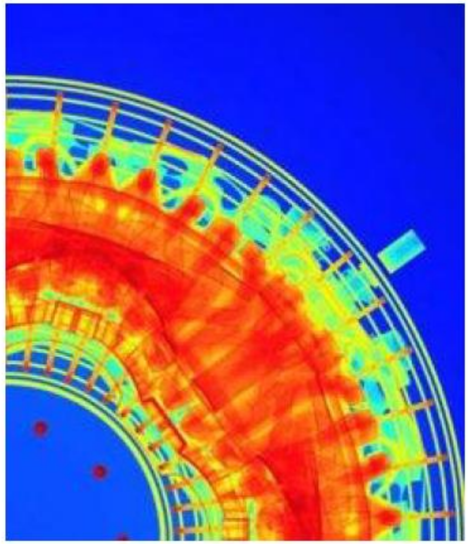
automatic CAD model



Tetrahedral / Meshed

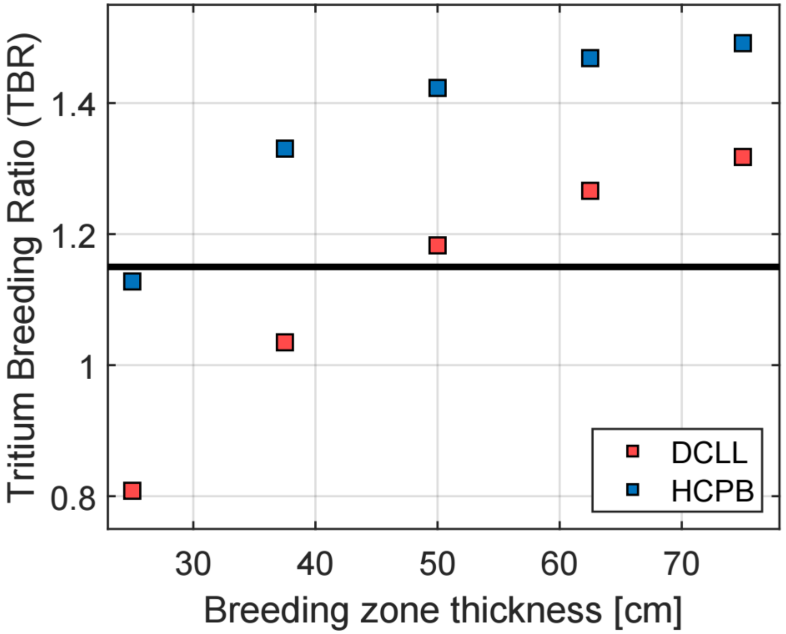
Conversion tools / directly on mesh

3D nuclear response



e.g. MCNP6, Serpent2

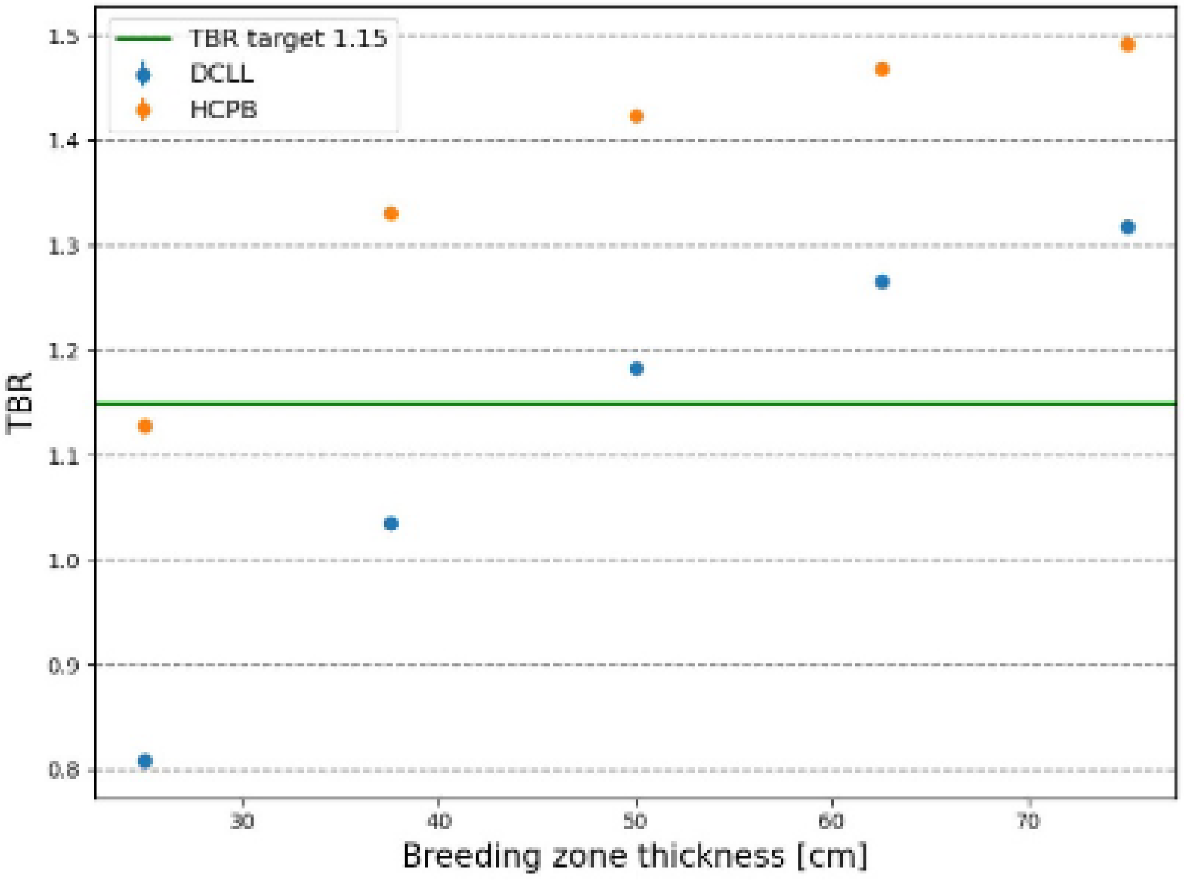
Parametric Studies



Full 3D Stellarator geometry

EUROfusion collaboration

TBR deterministic neutronics



(a)

State-of-the-art: Systems Codes such as “PROCESS”

Simplified, yet comprehensive model of an entire fusion reactor (0D or 1D!)

- **Holistic framework**
- **Modular(?), multidisciplinary**
- **Fast for Design Point exploration**

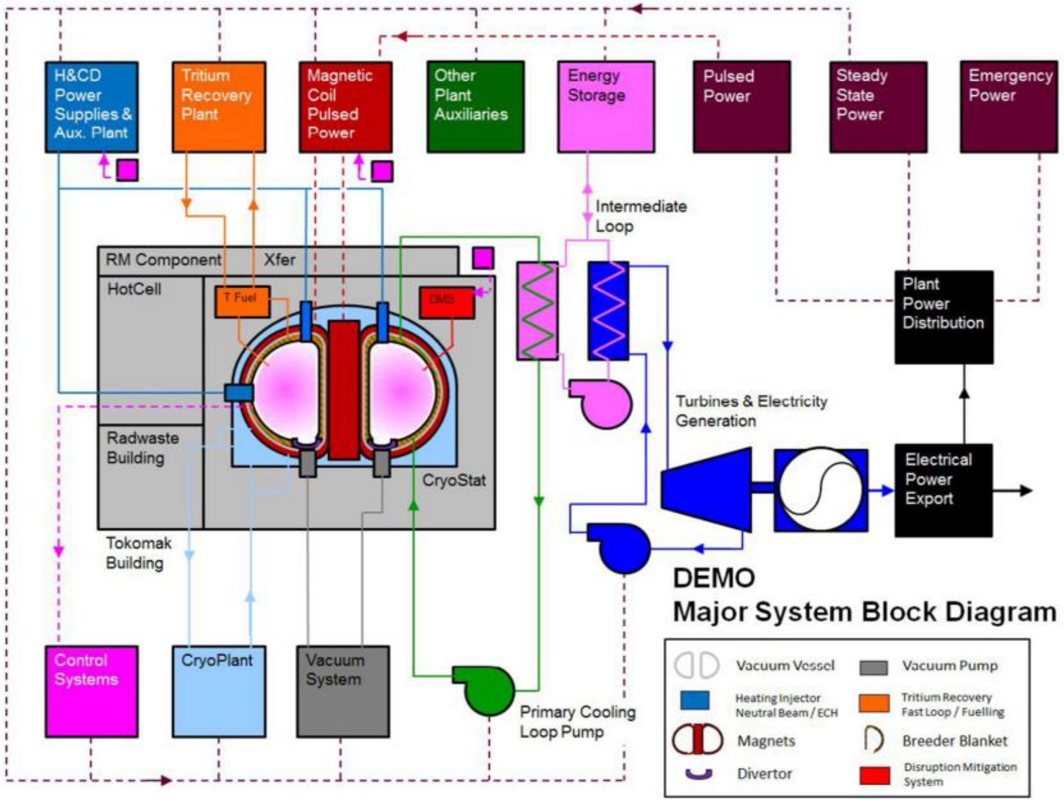
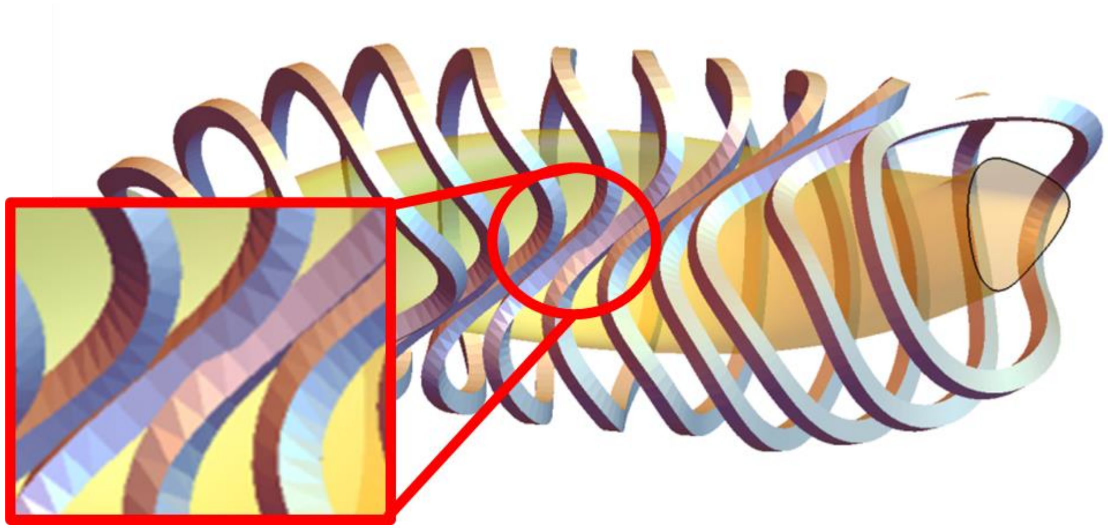
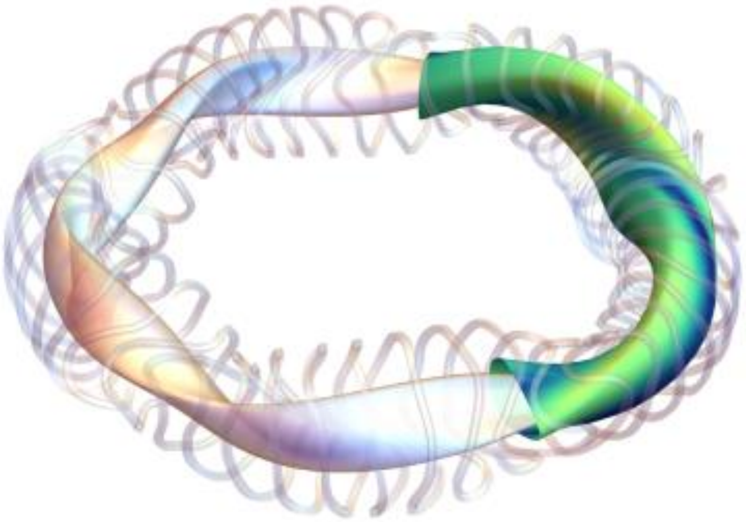


Figure 1. Schematic of a DEMO power plant.

Limits of Systems Codes





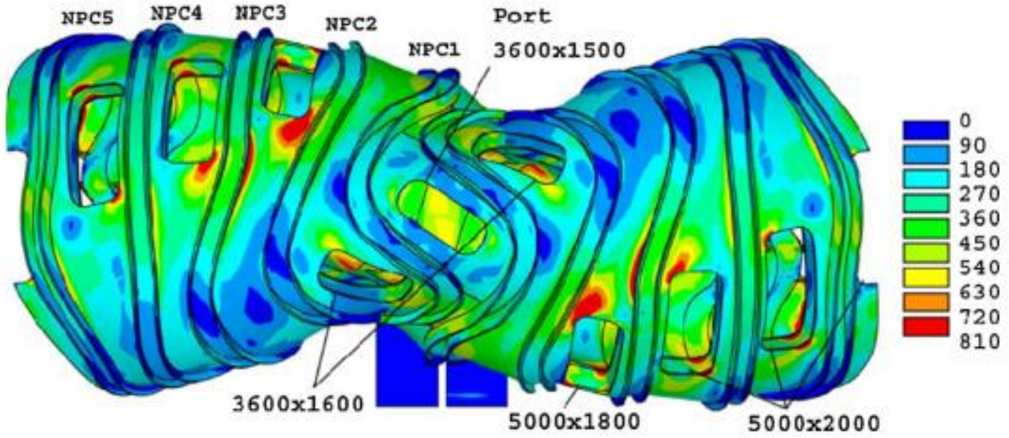
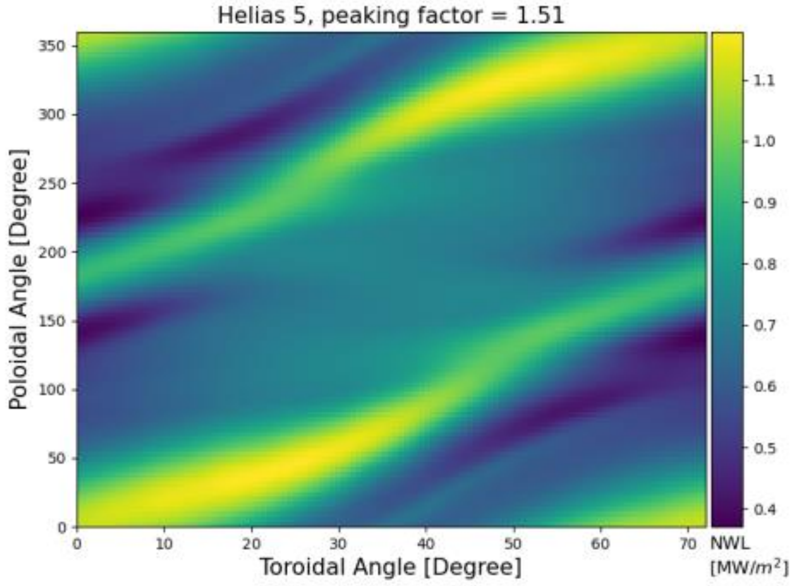


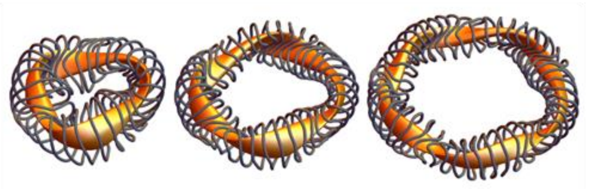
Fig. 4. Stress intensity (MPa) in magnet system and maximally possible port windows (mm); structure not yet optimized.



State-of-the-art: Systems Codes such as “PROCESS”

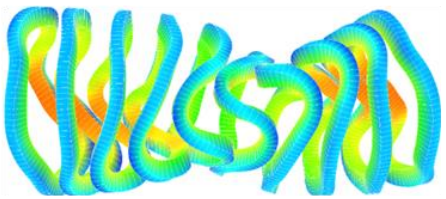
Stellarator Optimisation

- **Coil filaments**
- Magnetic configuration



Pre-Processing

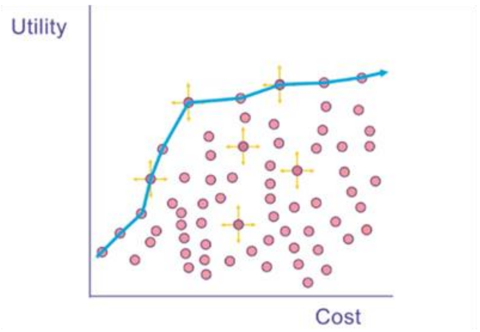
- **Reduce dimensionality** by pre-calculation of effective parameters



e.g. B_{max} w/ Biot-Savart

Systems Code PROCESS

- **Constrained optimization** within a wider design space

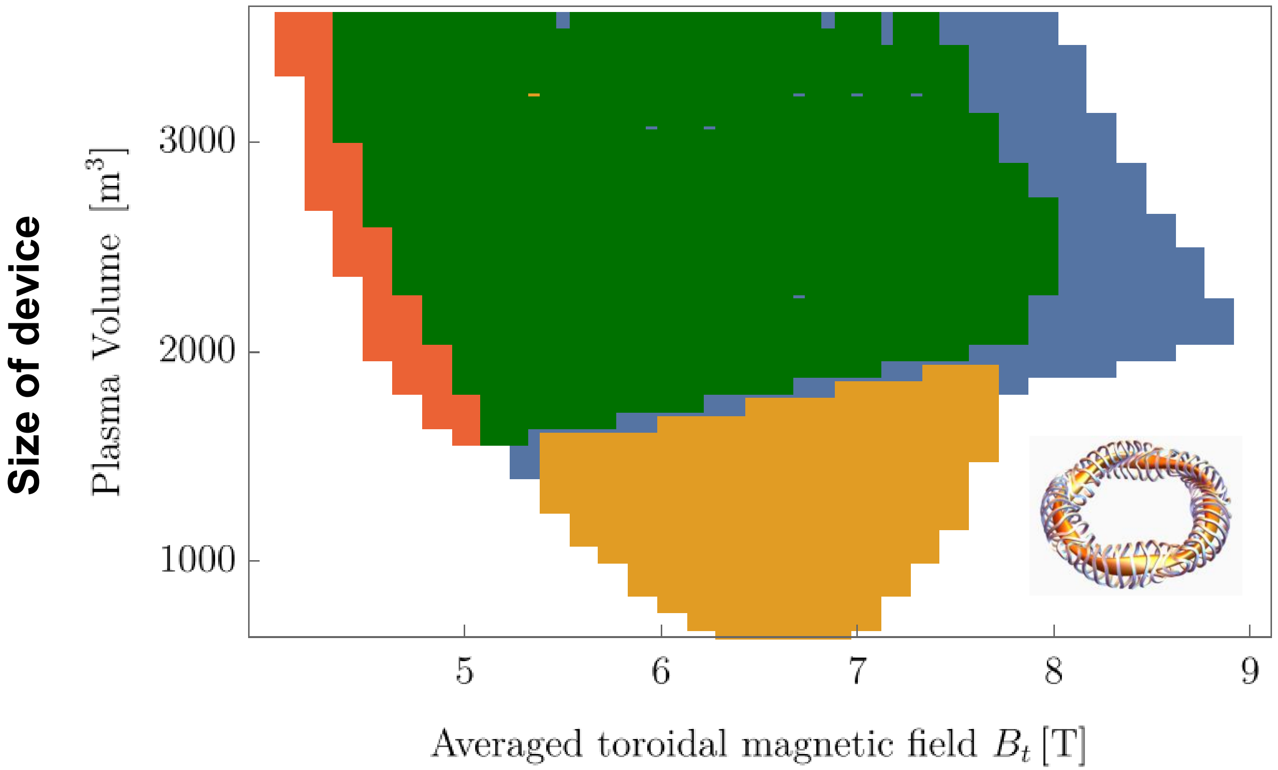


Future work: systems design feedback (e.g. engineering constraints)

Design Point

- **Engineering feasibility**
- **Attractiveness**
- Impact of **new technologies** (e.g. HTS)

State-of-the-art: Systems Codes such as “PROCESS”



Successfully used in the past

- **Identify design space boundaries**
- **Assess engineering limits**
- **Study impact of new technologies**

ECRH design for new reactor-relevant Stellarator configurations

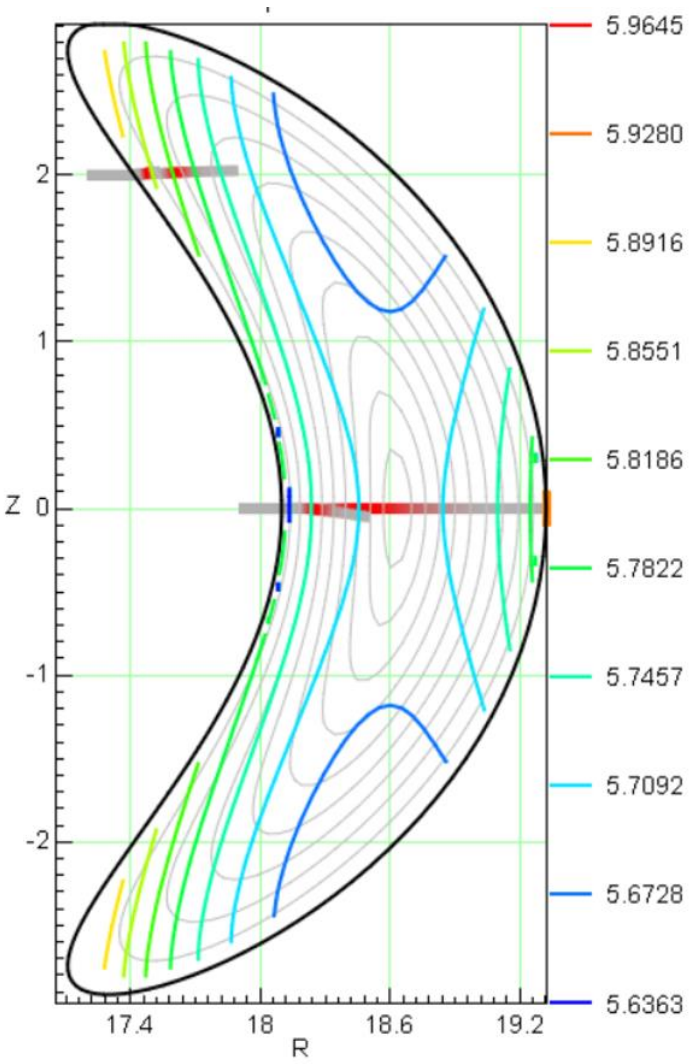
Experiments today use X2 or O2, but high field & density requires X1 or O1

Extensive TRAVIS simulations done:

- SQUID: High mirror ratio / saddle-points
- Injection location (pol./tor.) & angle
- Scenario depends on freq. and density
- Several solutions found for a combination of O1 (startup) and X1 (overtake)

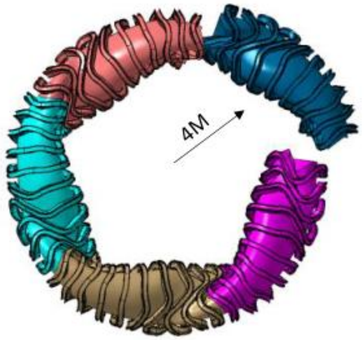
Complexities identified:

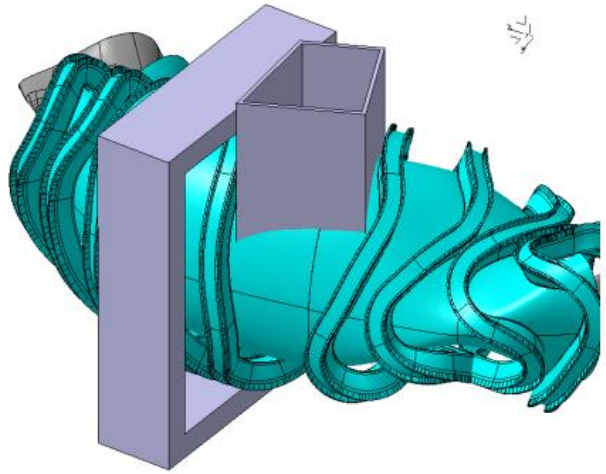
- Sensitive to magnetic geometry
- Heating of trapped electrons
- Relativistic effects



Remote Maintenance

1) Vertical Ports only
2) Vertical + Horizontal Ports
3) Enlarged Vertical Ports
4) Sector Splitting



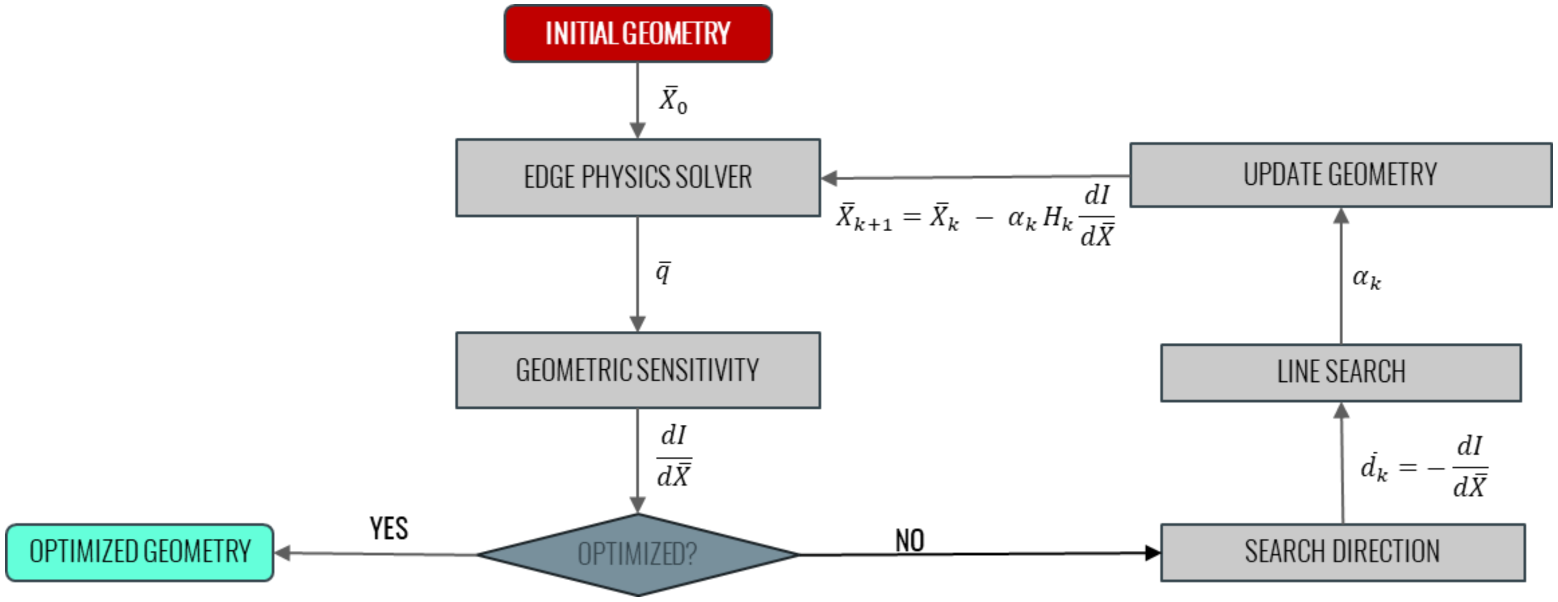


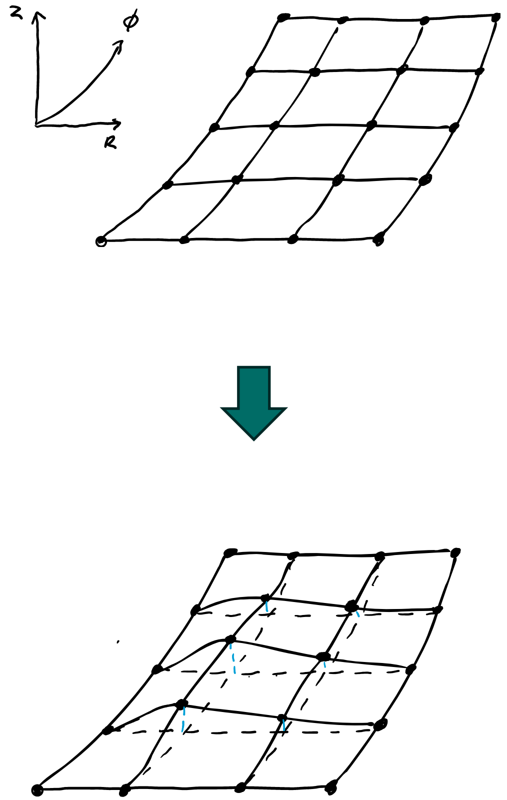
(Baseline)

Consideration	Approach 1	Approach 2	Approach 3	Approach 4
Blanket handling	0	+1	+1	+2
Divertor handling	0	-1	0	+1*
Failure scenarios	0	+1	+1	+1
Inspectability	0	+1	+1	+1**
Hardware costs	0	0	0	-2
Radiation & CC	0	-1	-1	-1
RM Durations	0	0	0	0
Wider plant implications	0	-1	-1	-2
Total:	**0**	**0**	**+1**	**0**

+2 Much better than
+1 Better than
0 Same as baseline
-1 Worse than
-2 Much worse than

Divertor Development: a) Automatic Target Optimisation

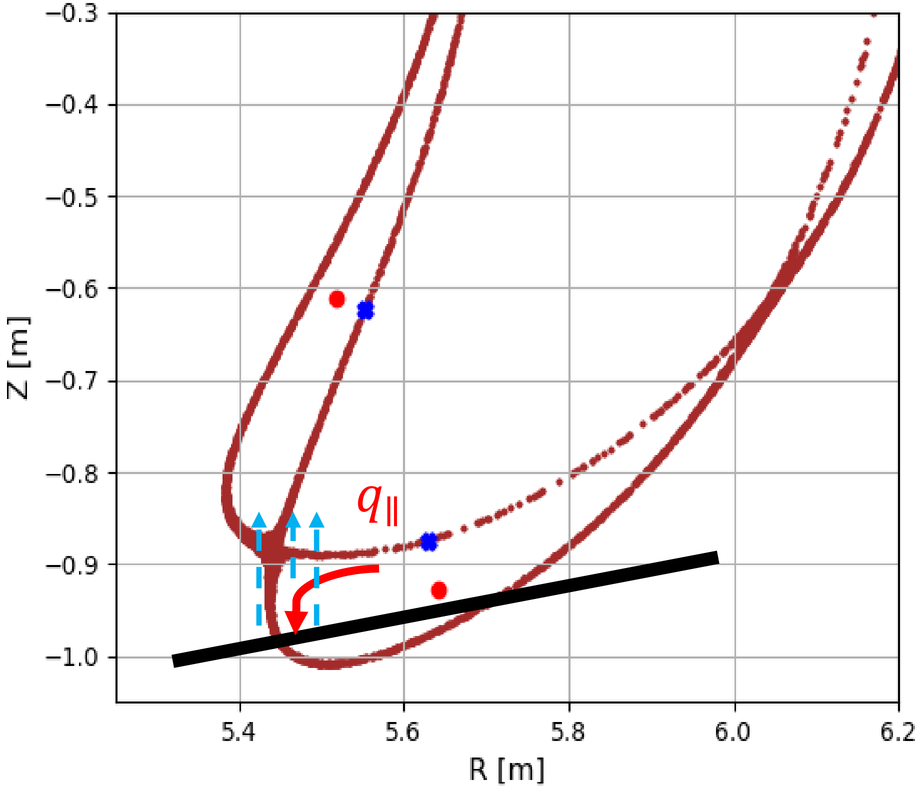




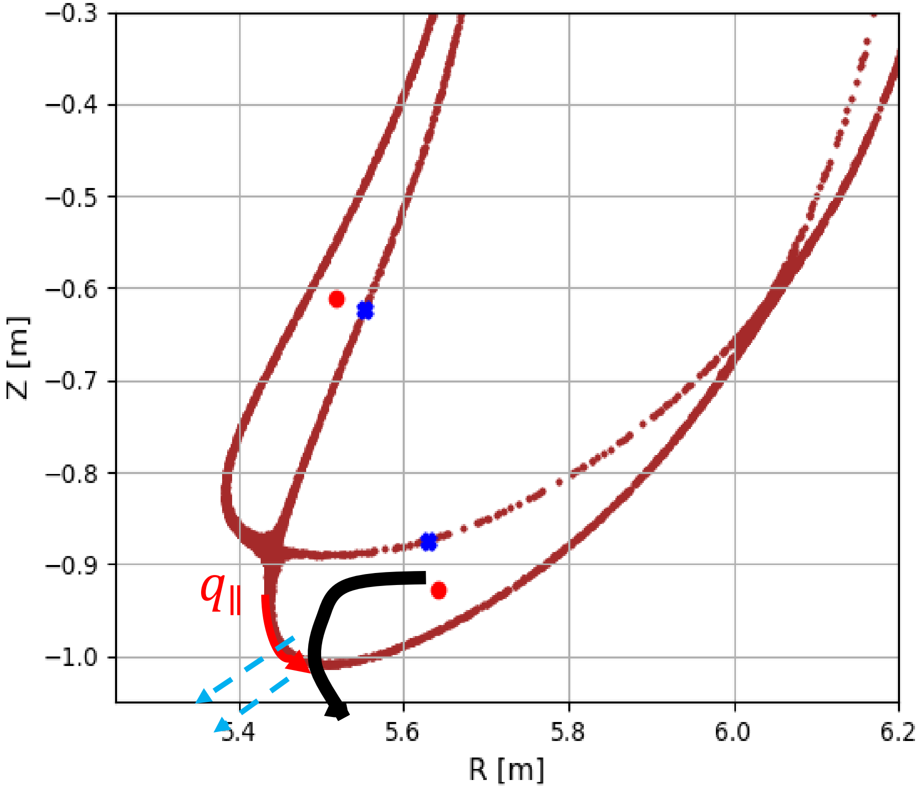
see Poster Nr. 28 by Reeve K. Duligal

Divertor Development: b) Closed Divertor

Open (W7-X now)



Closed (LHD/Tokamaks)



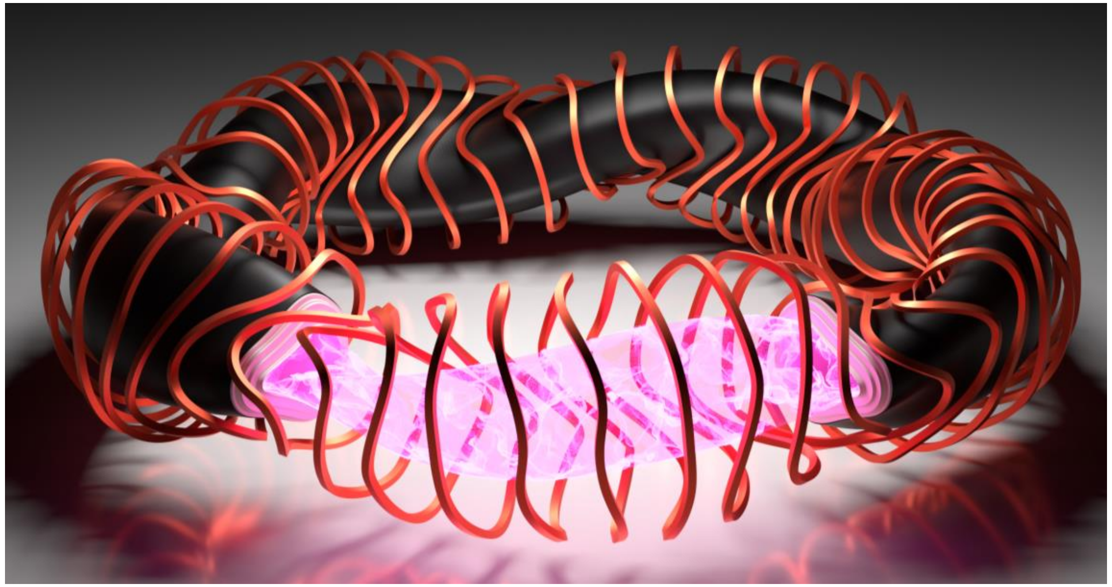
see also presentation N. Maaziz

Limits of Systems Codes

- Naturally evolved over years: old code, no standardised interfaces
- not as modular as required, difficult to make changes
- Mostly 0D or 1D models
- Addressing 3D features important
- **Stellarator version is diverging from main PROCESS**

→ Develop new stellarator design platform: a Digital Twin

New Project: an integrated 3D design platform



A virtual stellarator reactor

- Configuration flexibility
- 3D engineering models
- Enables fast design iteration
- Allows data-driven decisions
- Link to stellarator optimization

But: What do we actually need to model?

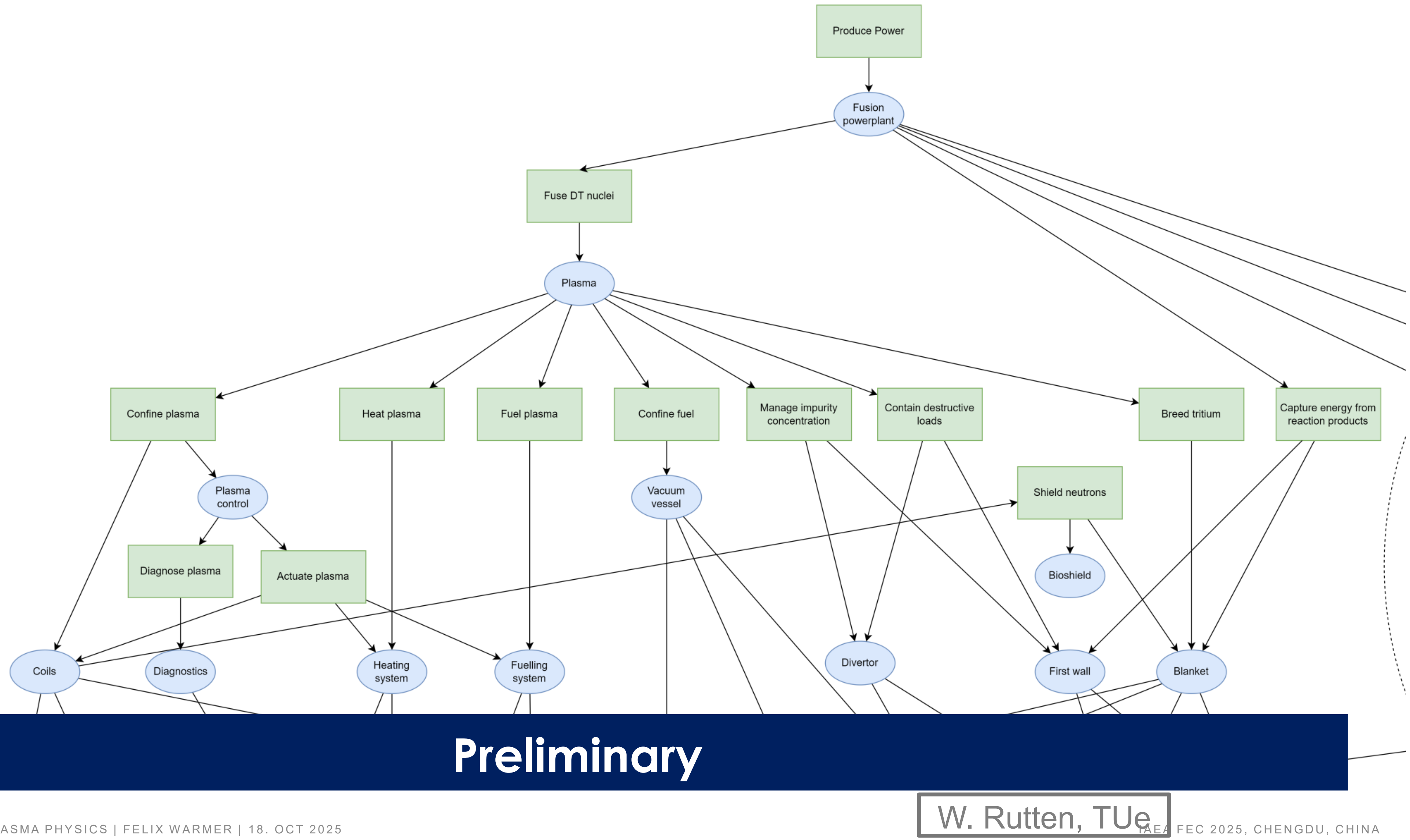
Structured System / Functional Decomposition

Level 0

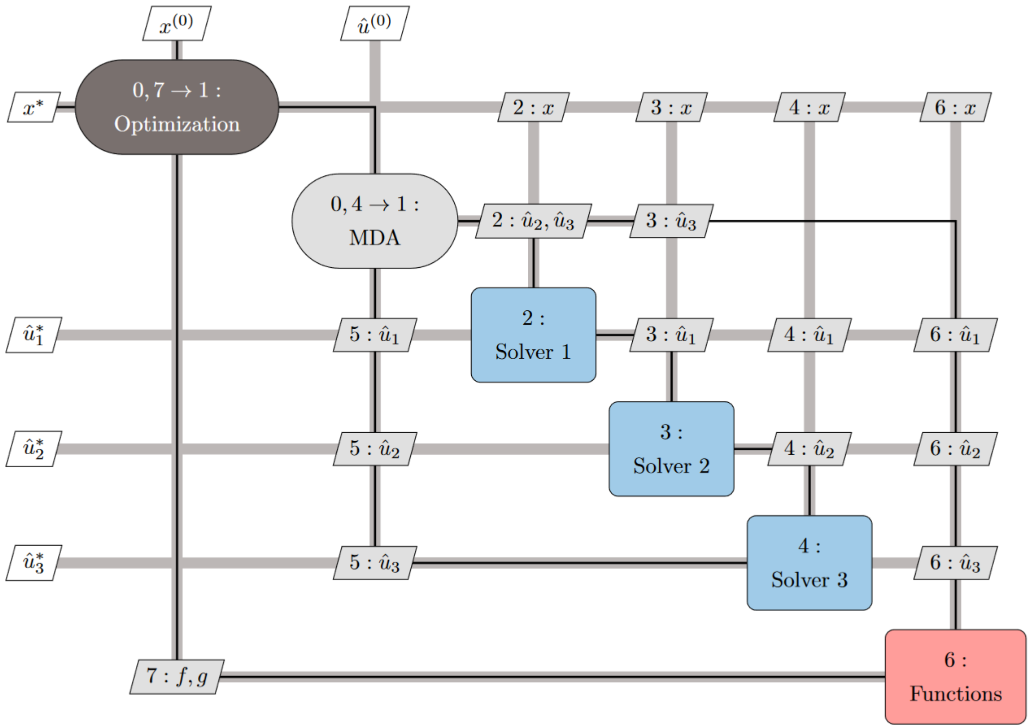
Level 1

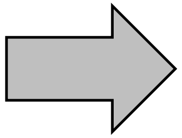
Level 2

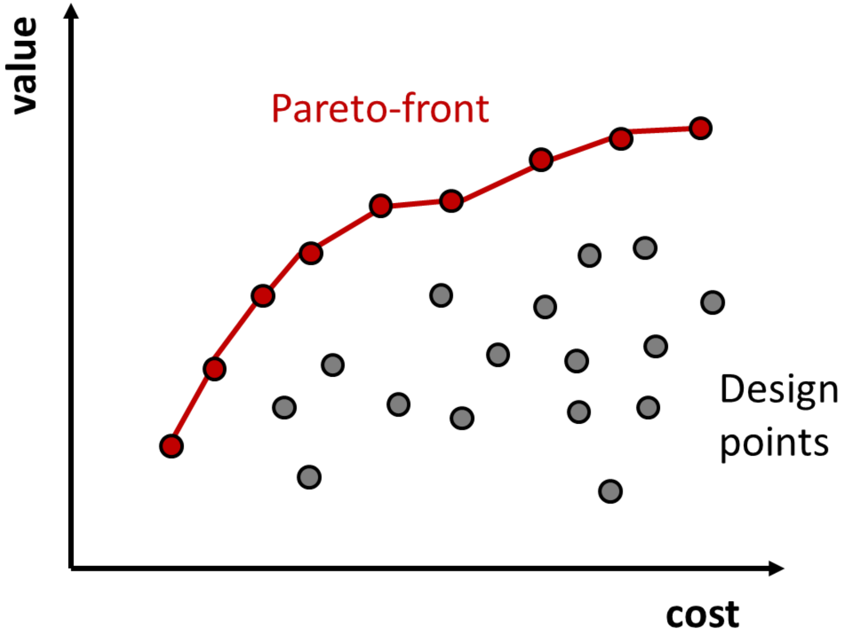
...



Optimisation Architecture in a multidisciplinary setting







Quantifying trade-offs for data-driven design decisions