European efforts and advances in Stellarator power plant studies

Felix Warmer for the SPPS Team
Task Leader for Stellarator Power Plant Studies in EUROfusion
September 12, 2023

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Objectives of Stellarator Power Plant Studies (SPPS)

Bring the Stellarator concept to maturity

– i.e. catch-up with Tokamak developments; – demonstrate the viability of the stellarator concept; – deliver attractive options for a next-step device

- **Identify Stellarator-specific key design drivers & issues and address them**
- **Open mind to new technologies and their impact on design aspects**
- **Integrated systems view of physics, engineering, and economics aspects; capitalise on computational and modelling advancements**
- **Leverage existing Stellarator expertise to develop more competences in the EU**

SPPS Team List

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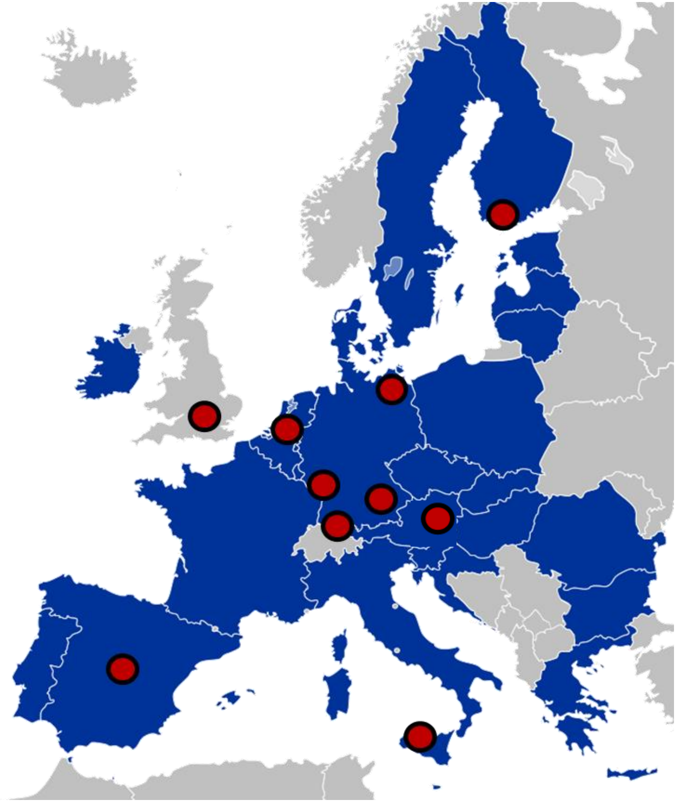
[7] Karlsruhe Institute for Technology
[8] Aalto University
[9] UK Atomic Energy Authority
[10] Technical University Graz

Organisation & Team



Stellarator Power Plant Studies in WP-PRD

- **TU/e** – Stellarator Systems studies
- **IPP** – Physics scenarios & modelling
- **CIEMAT/UNED** – Blanket Design
- **CIEMAT/Aalto** – Neutronics (+KIT?)
- **EPFL** – Magnets
- **UniPa** – 3D Multi-Physics
- **CCFE** – Remote Maintenance (small)
- **TU Graz** – Alpha loss patterns

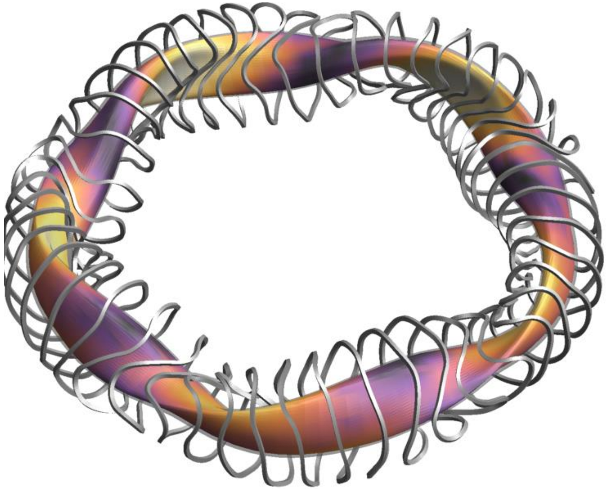
EUROfusion funding ~3-4ppy/y (was cut twice by 50%)

Content

1) Objectives, Strategy, Team
2) New Developments for Systems Studies
3) Neutronics approach (+ α Wall Loads)
4) Remote Maintenance & Blanket
5) Outlook & Summary

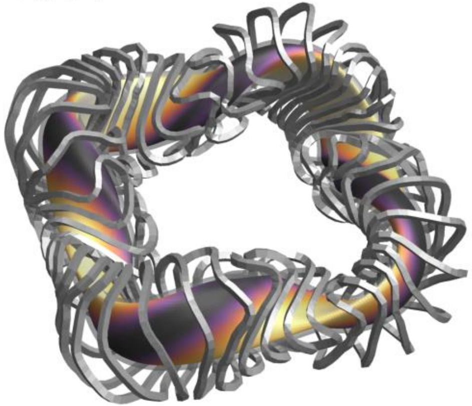
Content

Stellarator is not a single configuration



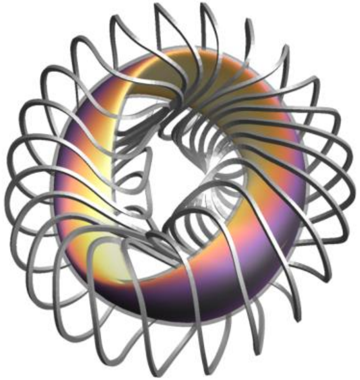
HSR-5/22

Beidler, C.D. et al (1996)



WISTELL-A

Bader, A. J. Plasma Phys. (2020)



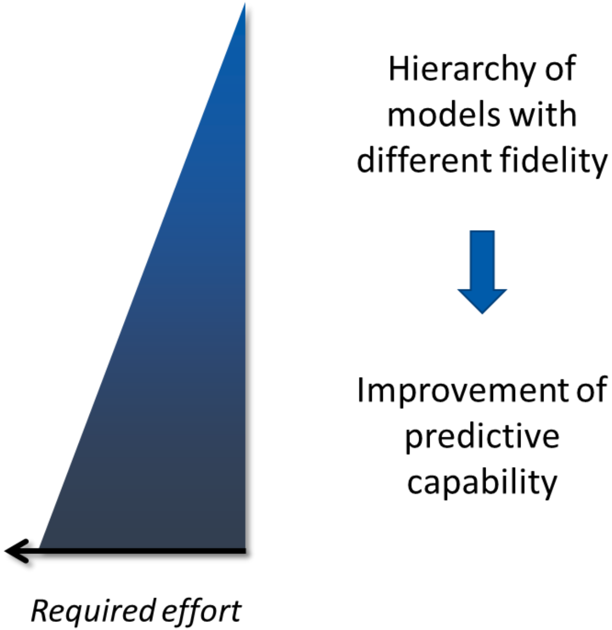
SIMSOPT-QA

Landreman, M., Paul, E.
preprint (2021) + ind. coils

- Drastically improved fast-ion confinement
- Turbulence optimization promising

Strategy: A bit more Tangible

1) **Systems Studies for design space exploration**
2) **Parametric (CAD) modelling for fast design iteration**
3) **3D Multi-physics assessment to solve stellarator-specific engineering challenges**



Hierarchy of models with different fidelity

Improvement of predictive capability

Fast design iteration and optimisation within minimal time & resources

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Systems Codes: Systemic View of a Fusion Power Plant

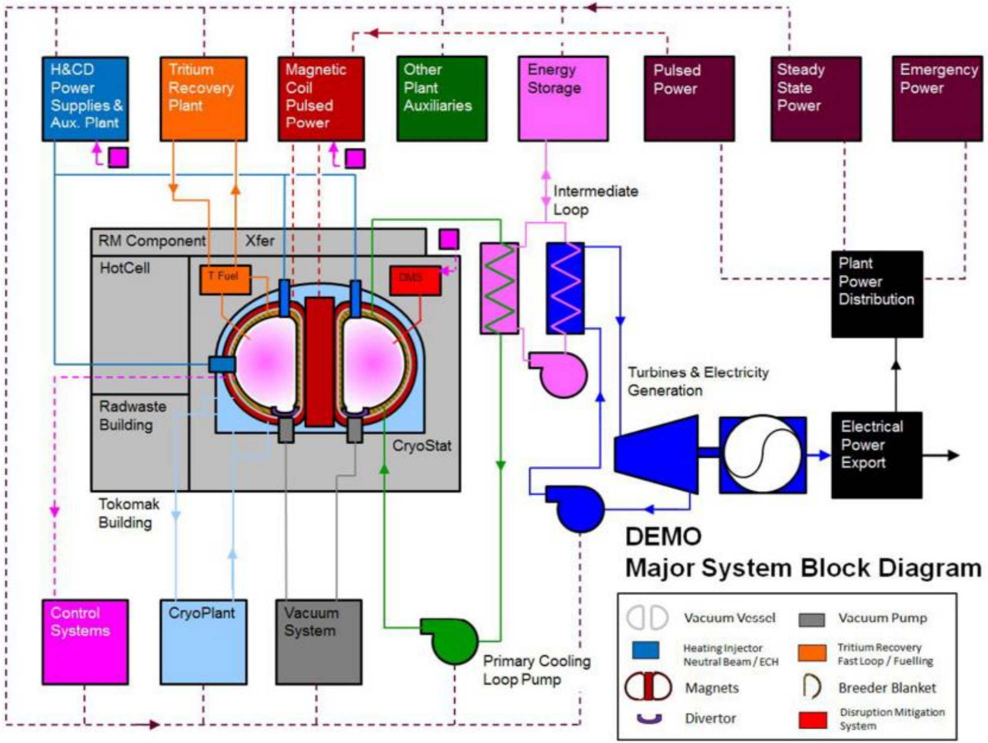


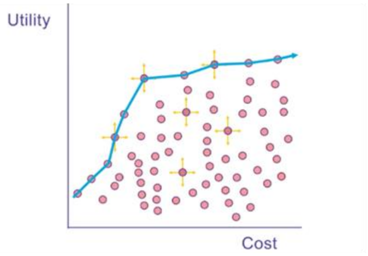
Figure 1. Schematic of a DEMO power plant.

- **Comprehensive** model of an entire fusion power plant
- **Multidisciplinary** (physics, engineering, economics)
- **Fast** (design space exploration)
- **Modular** (easily adoptable to new developments)

Workflow for the Stellarator Systems Code Activities

Systems Code PROCESS

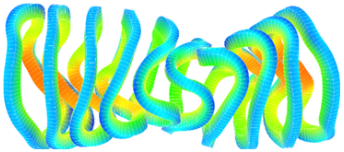
- **Constrained optimization** within a wider design space



Workflow for the Stellarator Systems Code Activities

Pre-Processing

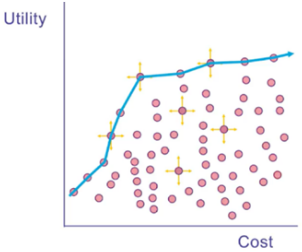
- **Reduce dimensionality** by pre-calculation of effective parameters



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

Systems Code PROCESS

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



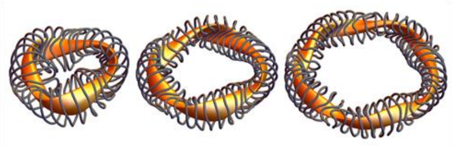
Design Point

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

Workflow for the Stellarator Systems Code Activities

Stellarator Optimisation

- **Coil filaments**
- Magnetic configuration



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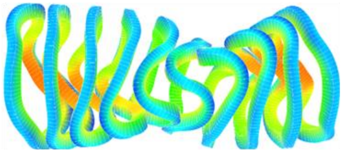

e.g. B_{max} w/ Biot-Savart

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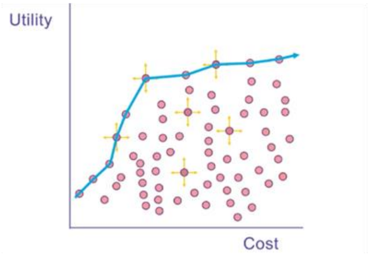

Design Point

- **Engineering feasibility**
- **Attractiveness**
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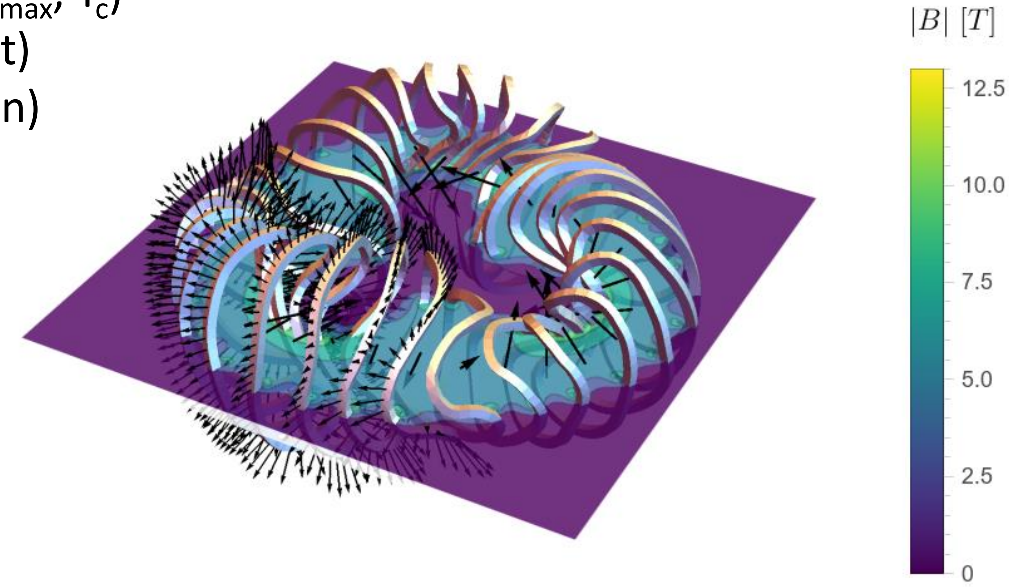
Future work: systems design feedback (e.g. engineering constraints)

Example: The New Magnet System Model

- **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

- **Still missing:**
    - Superconductor strain limits
    - structure stress limits



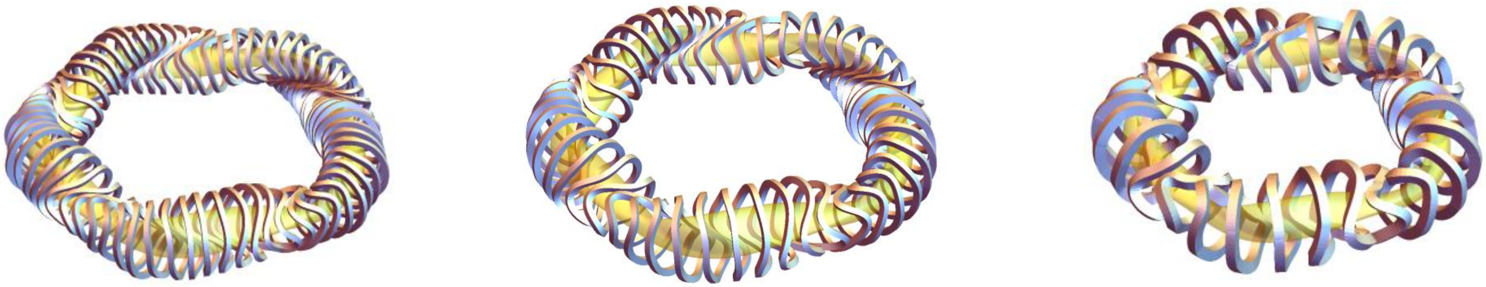
J. Lion, F. Warmer, et. al, NF 61 (2021)

Parametric Modelling for Fast Design Iteration

Example: Varying the number of coils

Target: Finding the optimal compromise between plasma and engineering goals

- Retaining magnetic field accuracy
- Space between coils for maintenance
- Minimising cost



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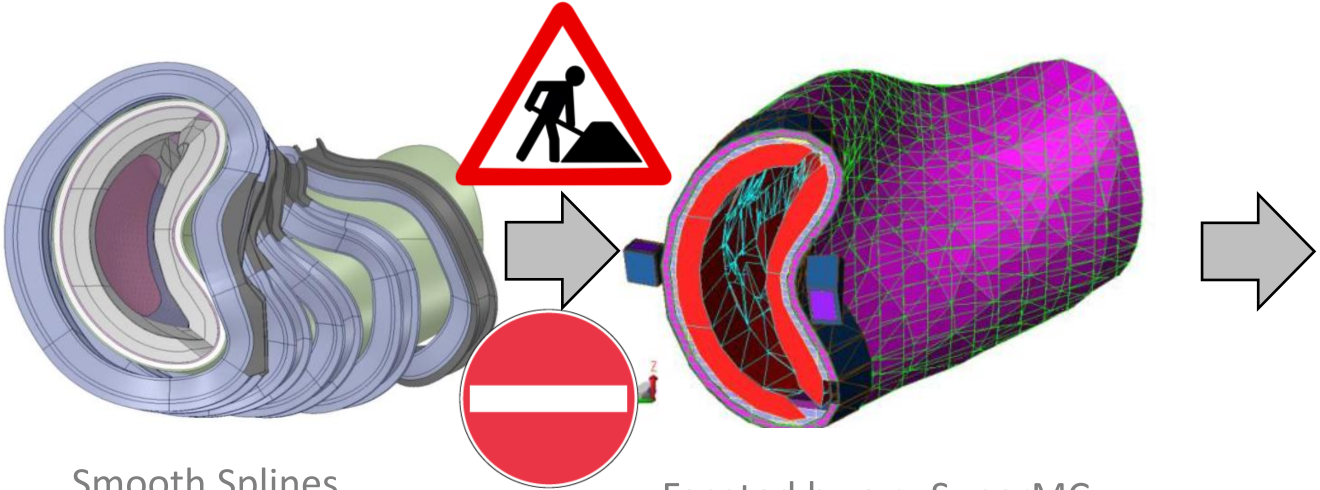
Stellarator Neutronics: cumbersome CAD conversion

old hand-crafted CAD model

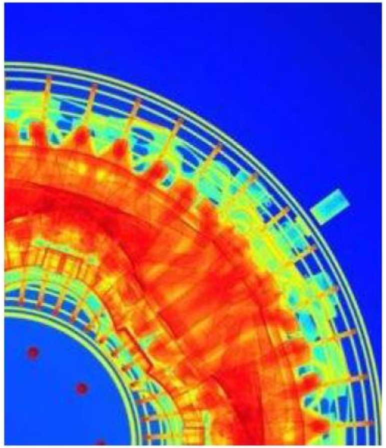
MCNP neutronic model

3D nuclear response



Smooth Splines

Faceted by e.g. SuperMC, DAGMC, etc.



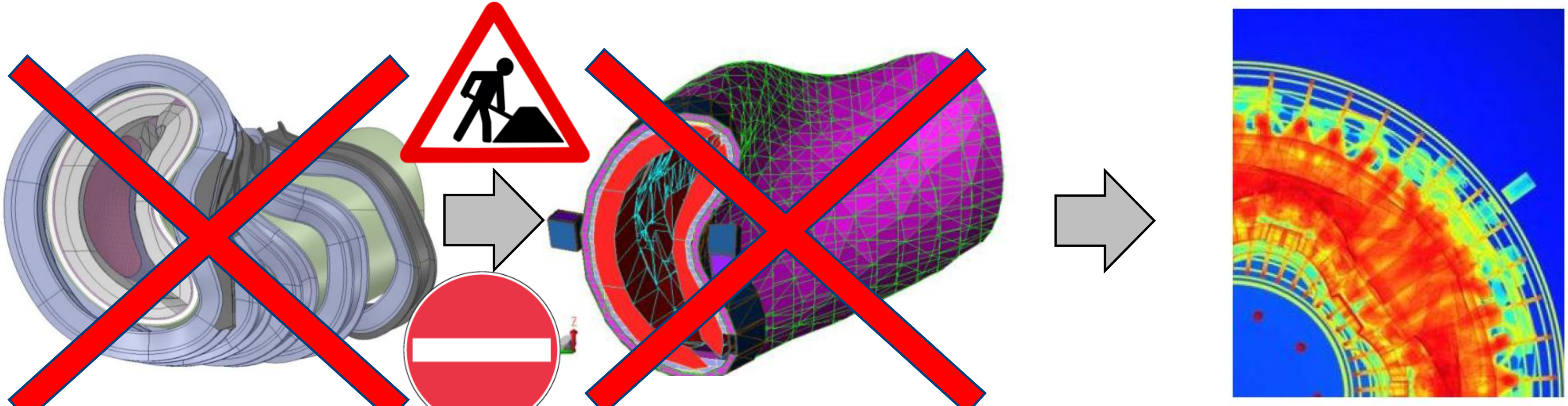
e.g. MCNP5

- **Time consuming manual work – slow & limited variability – address issues**

A. Häußler, F. Warmer, et al., FED 136 (2018)
I. Palermo, F. Warmer, et al., NF 61 (2021)

Stellarator Neutronics: cumbersome CAD conversion

old hand-crafted CAD model **MCNP neutronic model** **3D nuclear response**



Smooth Splines

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A. Häußler, F. Warmer, et al., FED 136 (2018)
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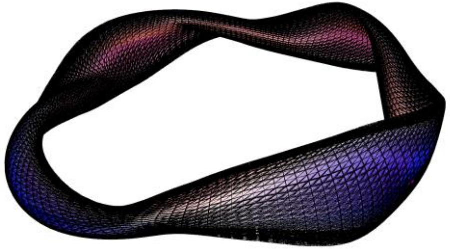
Stellarator Neutronics: direct analysis on geometry

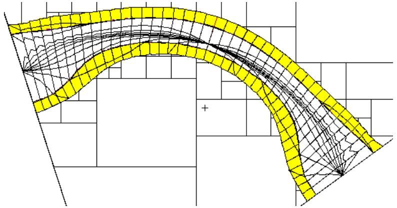
automatic CAD model



~~Smooth Splines~~
Tetrahedral / Meshed

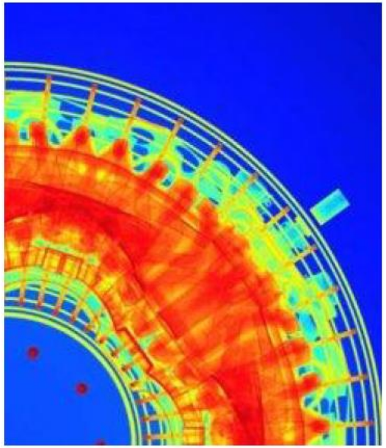
P1A2: Iole Palermo

automatic MCNP model



or directly on mesh

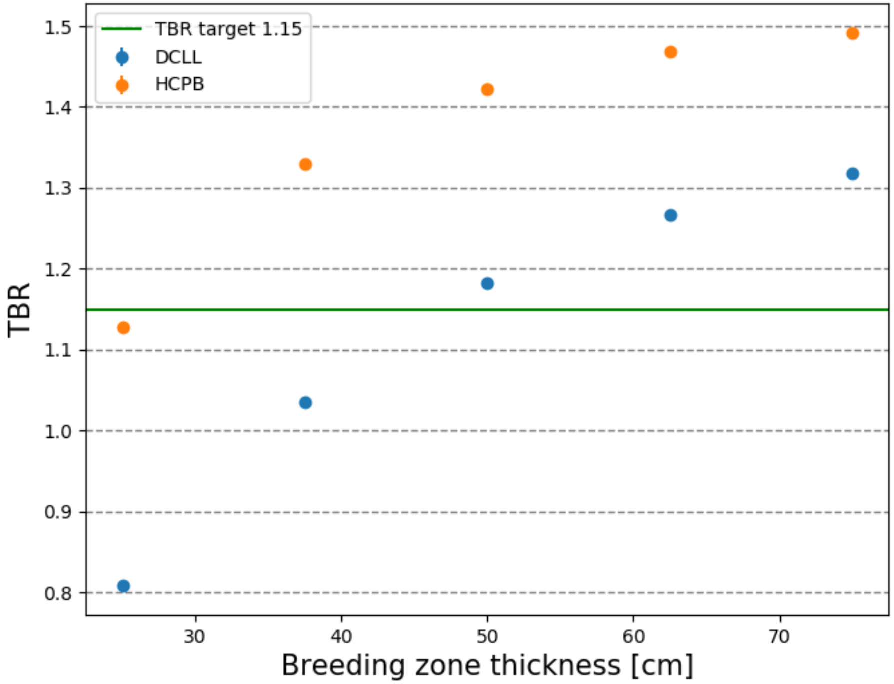
3D nuclear response



~~e.g. MCNP5~~
e.g. MCNP6, Serpent2

- **Direct (parametric) generation of CAD/neutronics models from magnetic geometry**
- High fidelity → high computational cost – 10^9 Monte Carlo samples

Stellarator Neutronics: direct analysis on geometry



Laboratorio Nacional de Fusión Ciemat

UNED

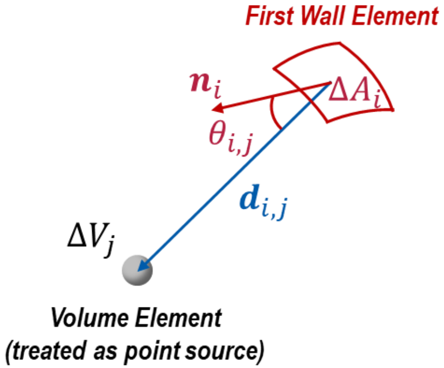
Aalto University

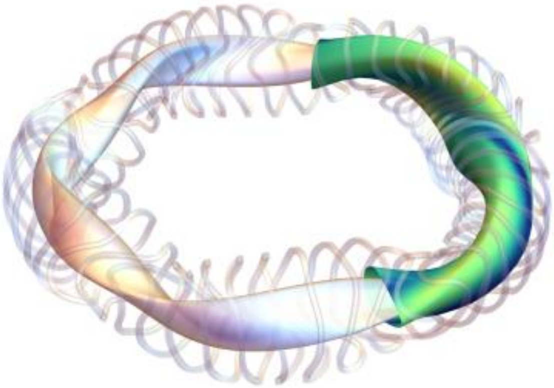
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

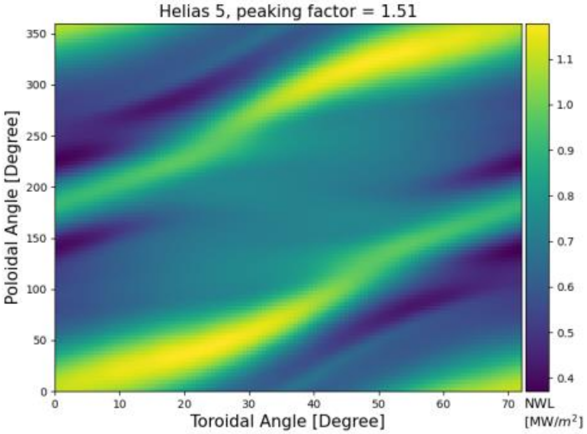
- **Example: Quick variation of BB thickness in 3D geometry**
- **Preliminary, unpublished**

Deterministic Neutronics Model for Design Optimisation

- Necessary to rethink the problem and find innovative solution: **Matrix description**



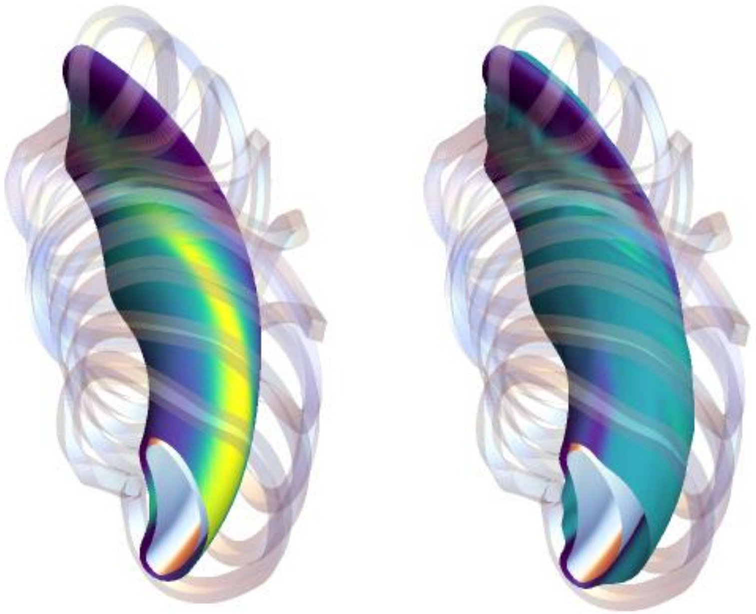




$$NWL_i = \sum_j \frac{\Phi_j \cdot E_N}{4\,\pi\,\left|\boldsymbol{d}_{i,j}\right|^2}\,(\hat{\boldsymbol{n}}_i \cdot \hat{\boldsymbol{d}}_{i,j})$$

- **Allows fast estimation of neutron wall loads**
- **Reduction of computational time by orders of magnitude (now ~1s)**

Optimising the Wall for Neutron Loads



J. Lion, F. Warmer, H. Wang, NF 62 (2022)

- <u>Can be used to optimise the 3D wall</u>
- Potentially increased life-time by reducing peak loads
- strong design driver for coil optimization
- allows fast design iteration → will become Systems code model

Deterministic method for full 3D blanket see Poster PS4-88 Timo Bogaarts, Friday 10:35

Content

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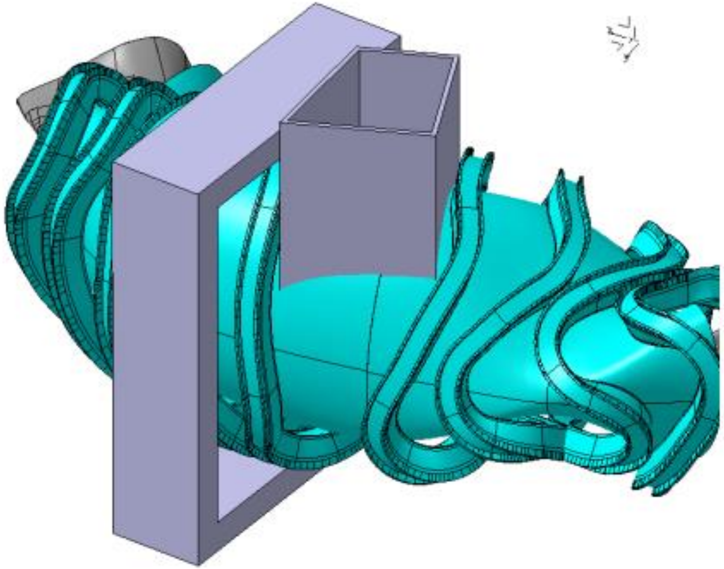
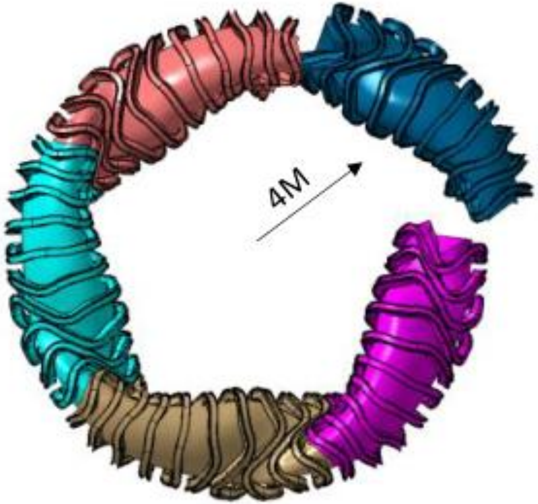
Stellarator Remote Maintenance

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





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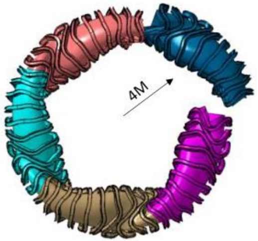
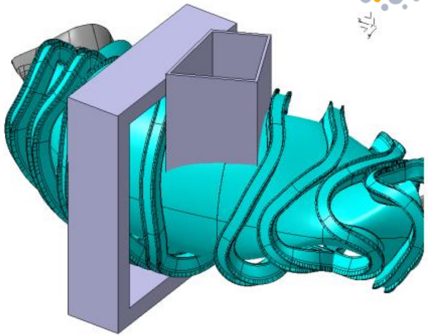




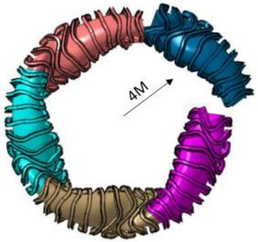
(Baseline)

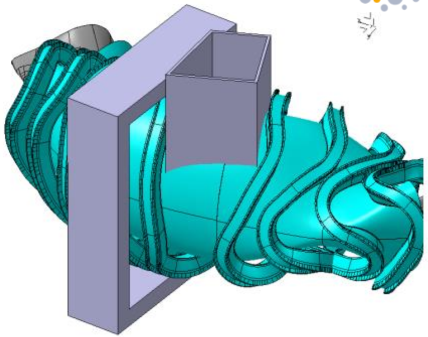
Consideration	Approach 1	Approach 2	Approach 3	Approach 4
Blanket handling	0	+1	+1	+2
Divertor handling	0	-1	0	+1*
Failure scenarios	0	+1	+1	+1
Inspectability	0	+1	+1	+1**
Hardware costs	0	0	0	-2
Radiation & CC	0	-1	-1	-1
RM Durations	0	0	0	0
Wider plant implications	0	-1	-1	-2
Total:	**0**	**0**	**+1**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

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

Stellarator Remote Maintenance

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





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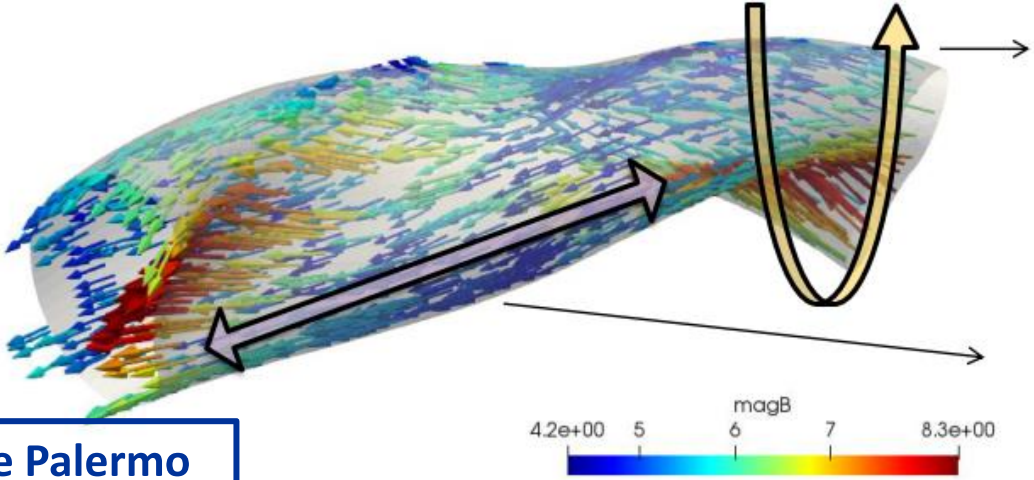
RM Durations	0	0	0	0
Wider plant implications	0	-1	-1	-2
Total:	**0**	**0**	**+1**	**0**

The general problem with Remote Maintenance or Systems Integration

DCLL: Blanket Choice and Segmentation

- **Many different Blanket concepts exist in the world – each with its own advantages and disadvantages**
- For example: What would DCLL mean for a Stellarator?



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

- Complete insulation is necessary

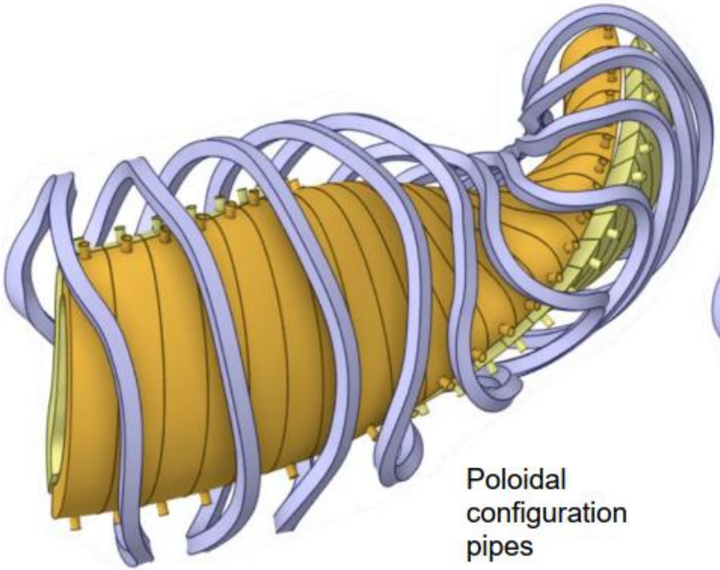
"Toroidal" circulation would imply a less contribution to the MHD pressure drop

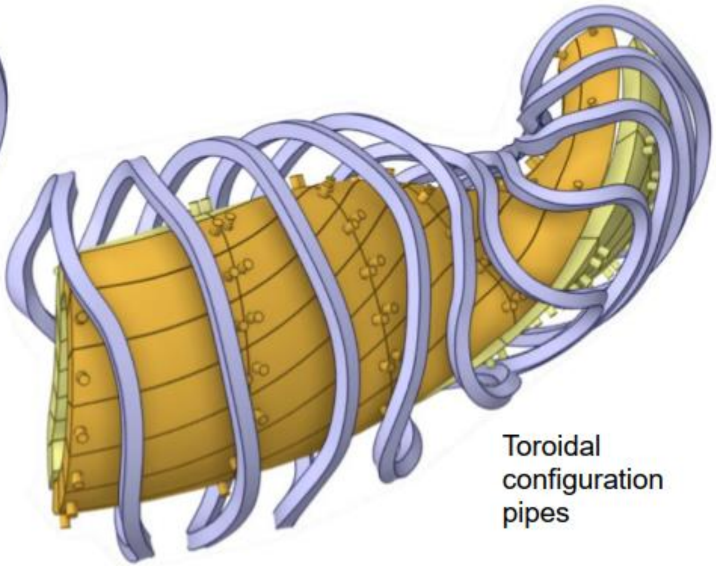
- Partial insulation could be sufficient

P1A2: Iole Palermo

Preliminary, unpublished

DCLL: Blanket Choice and Segmentation



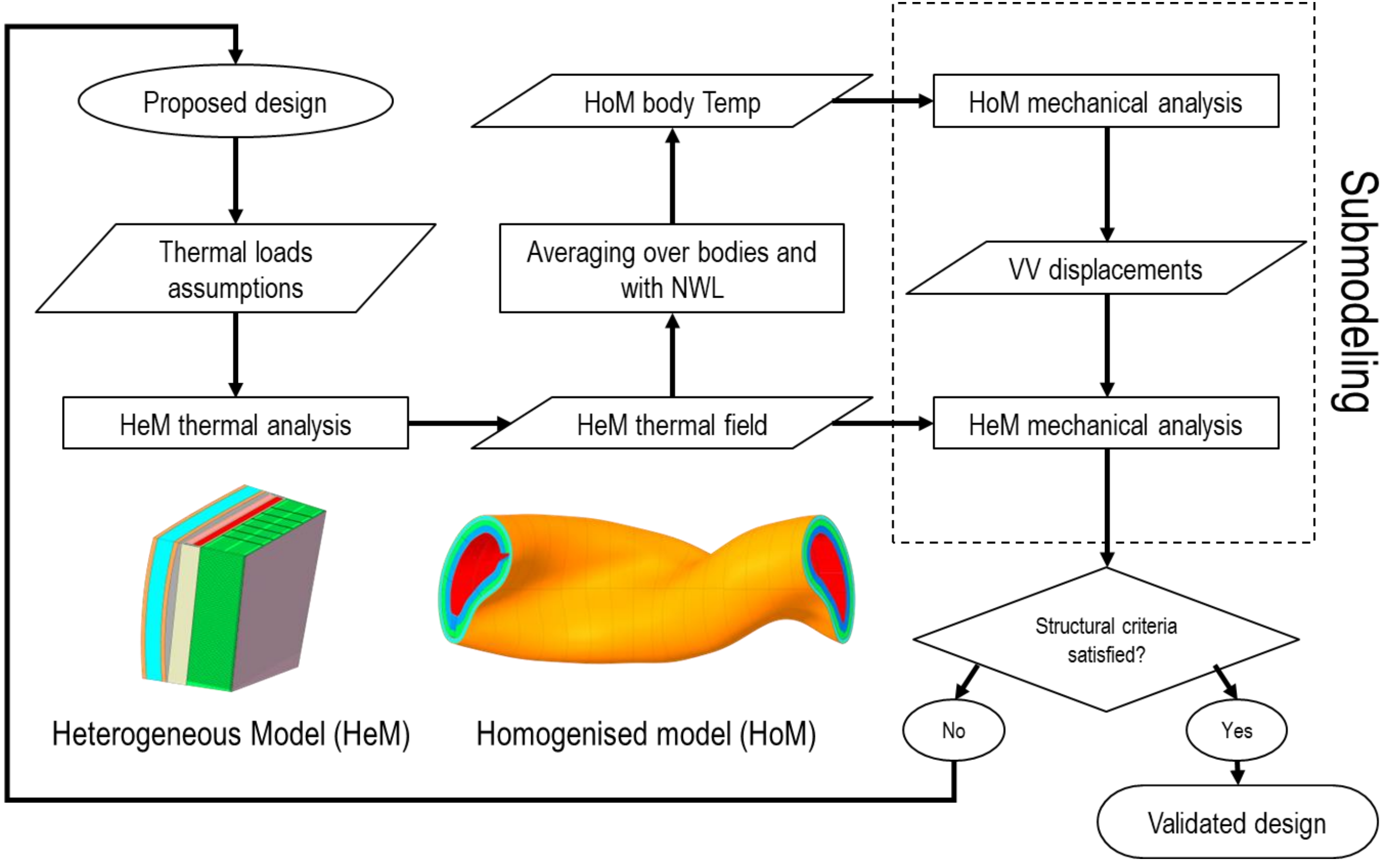


- **Requires complete insulation (FCI)**

- **Only U- and L-Turns require insulation**

Preliminary, unpublished

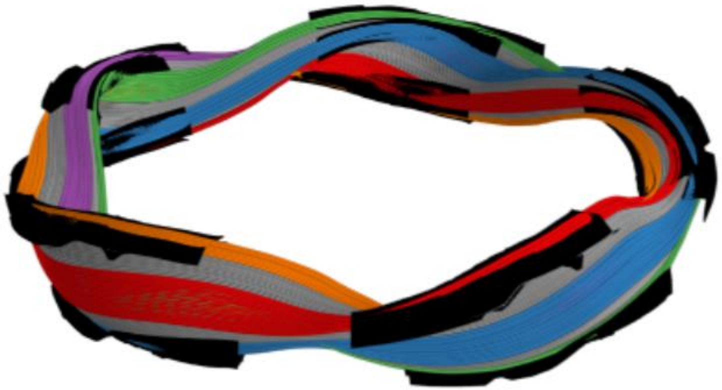
Thermo-mechanics towards “multi-physics”



- **Hybrid approach**
- **Preliminary, unpublished**

Island Divertor for a Stellarator reactor

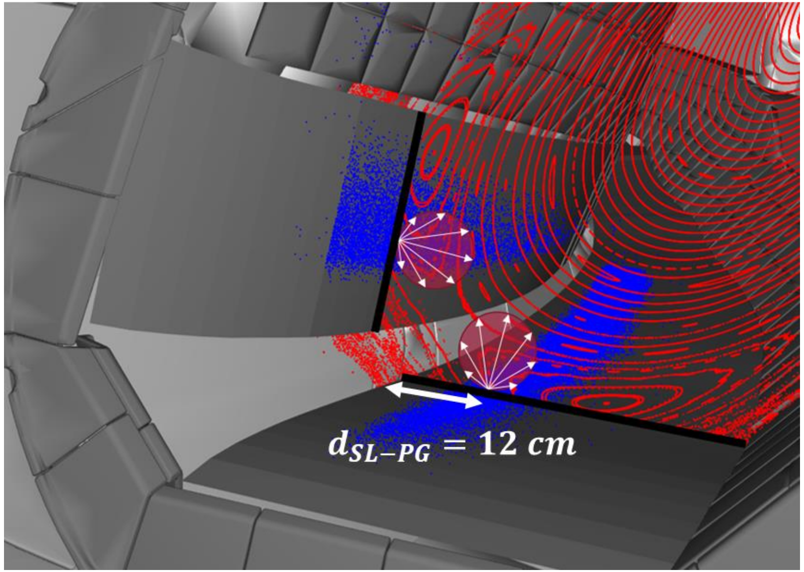
W7-X Island Divertor



- **So far good energy exhaust (detachment), but <u>not</u> good particle exhaust (W7-X)**

Island Divertor for a Stellarator reactor

T. Kremeyer (IPP)



- So far good energy exhaust (detachment), but <u>not</u> good particle exhaust (W7-X)
- Open geometry, designed for maximum flexibility (magnetic config.)

Island Divertor for a Stellarator reactor

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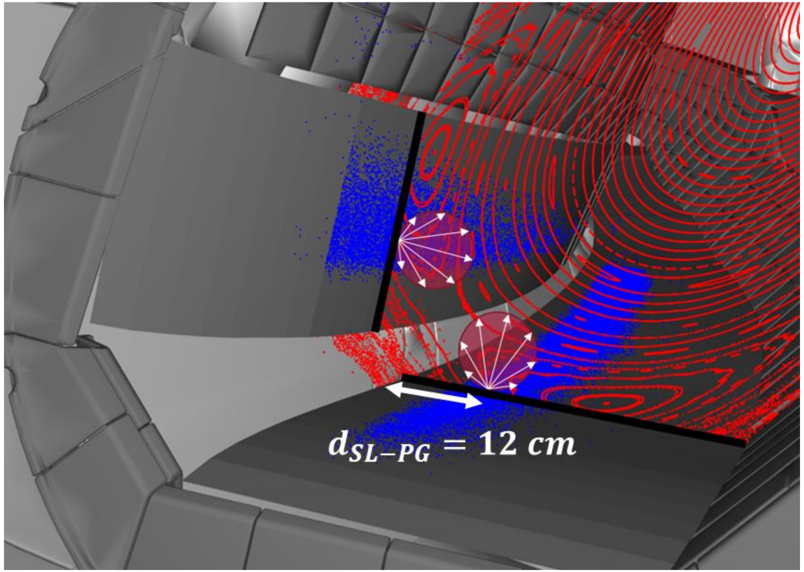
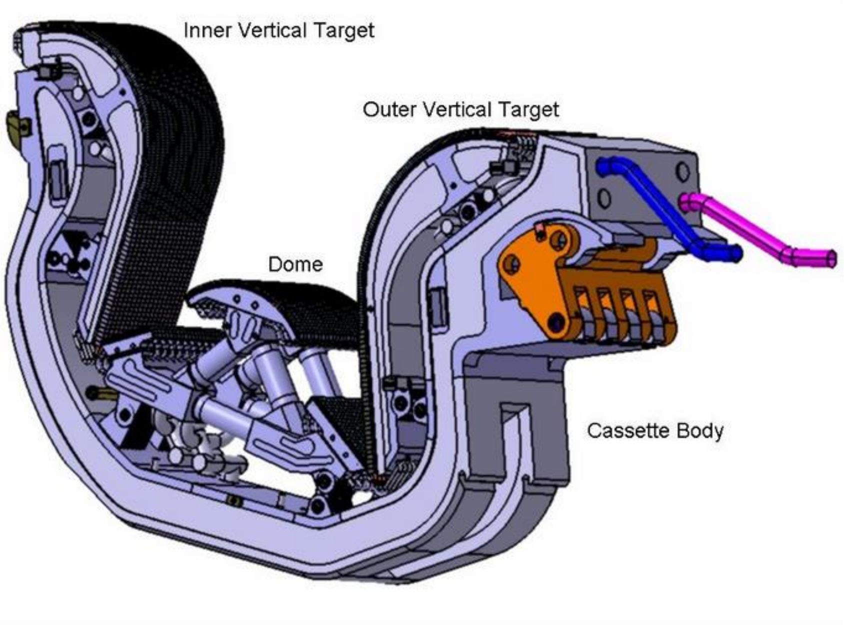




- **So far good energy exhaust (detachment), but <u>not</u> good particle exhaust (W7-X)**
- **Open geometry, designed for maximum flexibility (magnetic config.)**
- **<u>New geometry needed for stellarator reactor?</u> (e.g. dome?)**

Content

Summary

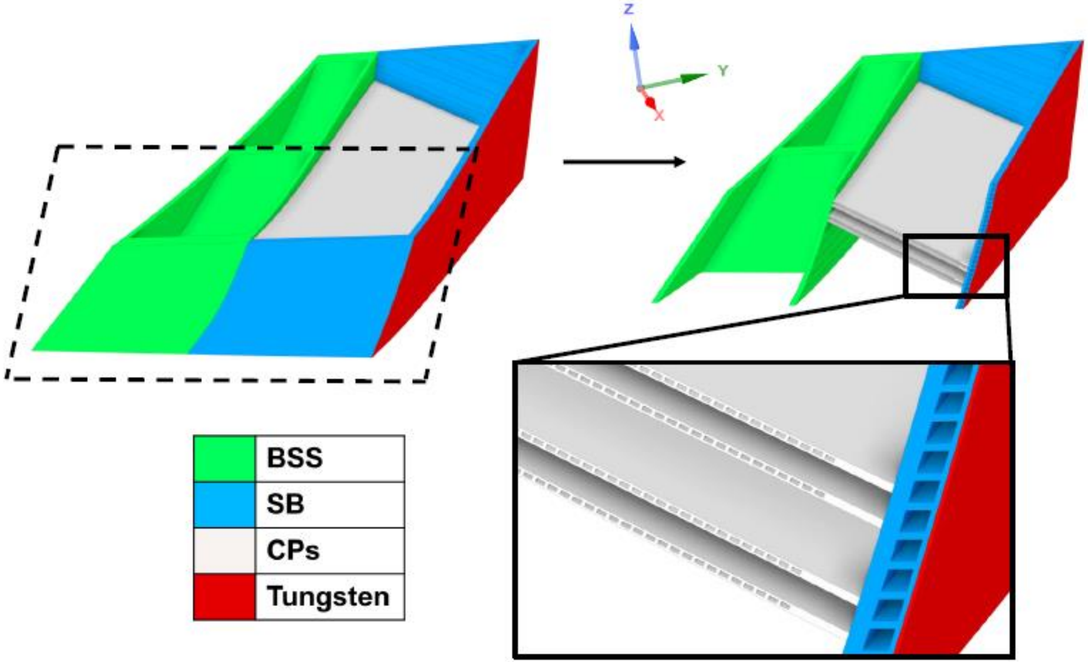
- SPPS has been successfully started (2021, lowish resources)
- 3D geometry is a challenge everywhere (blanket, magnets, divertor, …)
- High focus on parametric / computational models
- Training (PhDs, PDeng) important to bring new talents into the team
- New updated EUROfusion roadmap emphasizes the stellarator as a serious alternative that should be fully pursued in parallel

Some references

- J. Lion, F. Warmer, et al., NF 61, 2021
- J. Lion, F. Warmer, H. Wang, NF, 2022
- A. Häußler, F. Warmer, et al., FED 136, 2018
- I. Palermo, F. Warmer, et al., NF 61, 2021
- S.A. Lazerson, et al., NF 61, 2021/22
- M. Landreman, E. Paul, PRL 128, 2022
- S. Äkäslompolo, et al., FED 167, 2021
- PRD-8.MOD.01-T002-D001 DCLL BB development for SPPS, EFDA_D_2NQ8A7, Jan 2022

3D Multi-Physics (Thermo- mechanics + hydraulics)

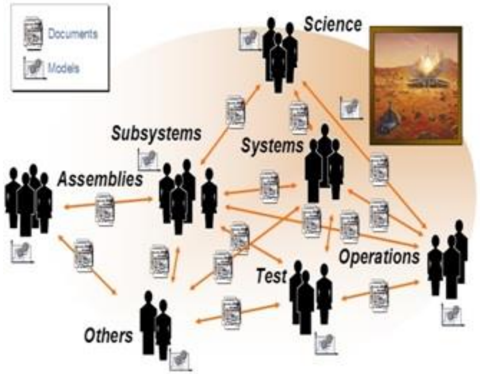
Homogenous blanket → automatic generation of details



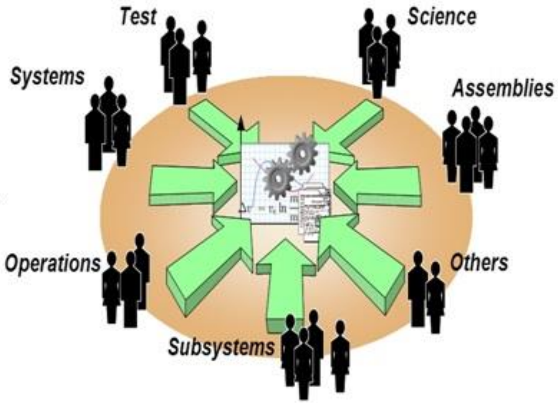
- 3D complex geometry a big challenge
- Investigations underway to automate CAD work

Preliminary, unpublished

Systems Engineering Culture: A Single Source of Truth



Today: Standalone models related through documents

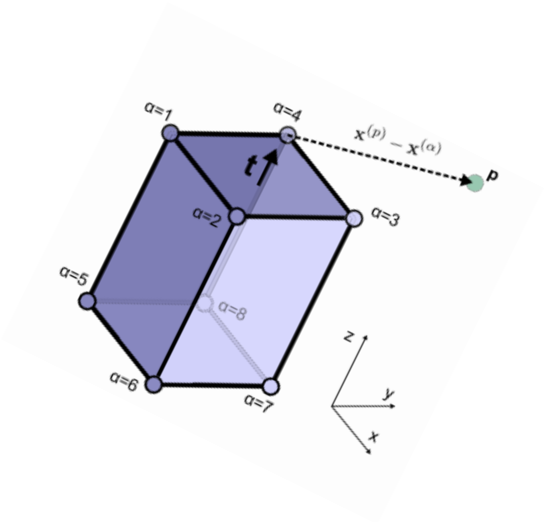


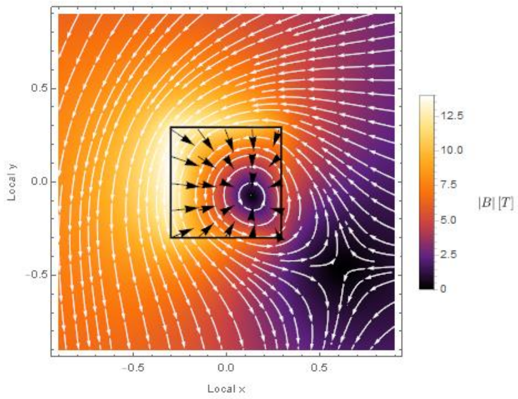
Future: Shared system model with multiple views, and connected to discipline models. Reusable, model based engineering with virtual product development and simulation capability

BUT:

- A corresponding “culture” must be adopted and lived
- Resource intensive development requiring appropriate tools
- Team spirit
- Permanent Experts (not only PhD)

Magnet System Model: Construct Cuboids

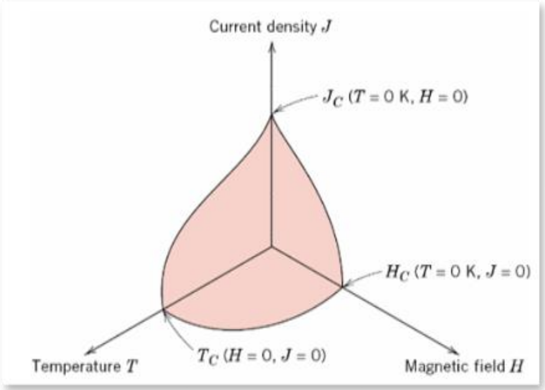




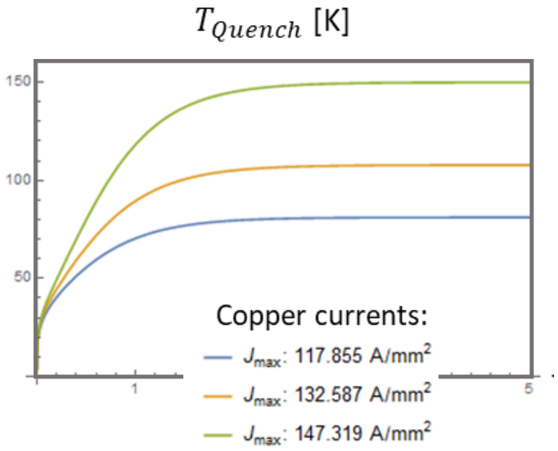
1st step: B_{max} on coil to determine possible SC current density

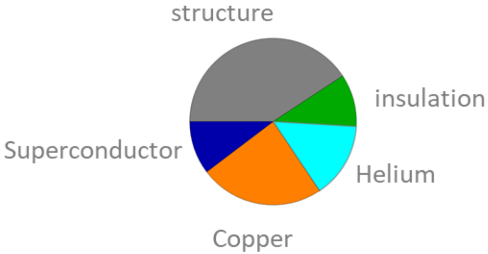
- Coils approximated by O(100) cuboids with constant current density
- Analytic solution to Biot-Savart (EFFI method)

Magnet System Model: Determine Current Density



C. Donnelly, PhD Thesis (2007)



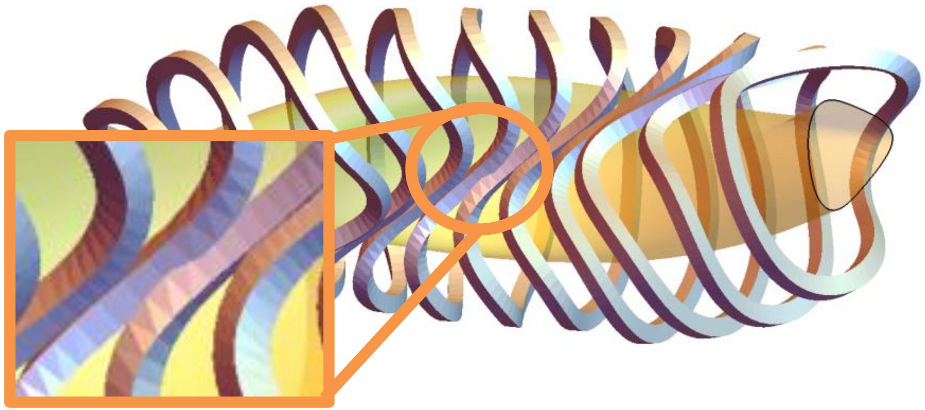


2nd step: self-consistent solution of current density

- Current density derived from Superconductor parametrisation (NbTi, Nb$_3$Sn, HTS)
- Check quench protection and adjust copper fraction
- Allows to derive the Winding Pack dimensions self-consistently

Magnet System Model: Forces and Build Consistency

Build consistency

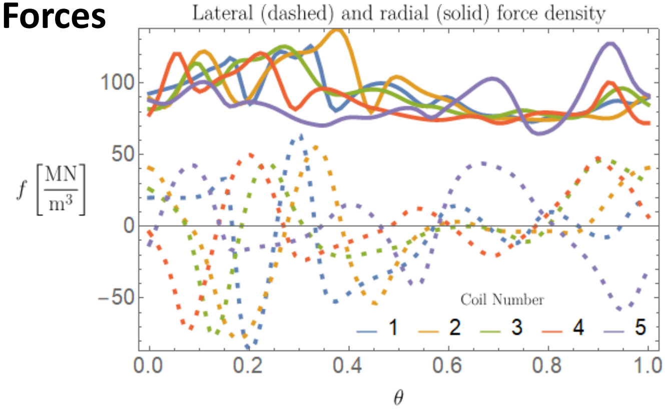


3rd step: check further engineering constraints

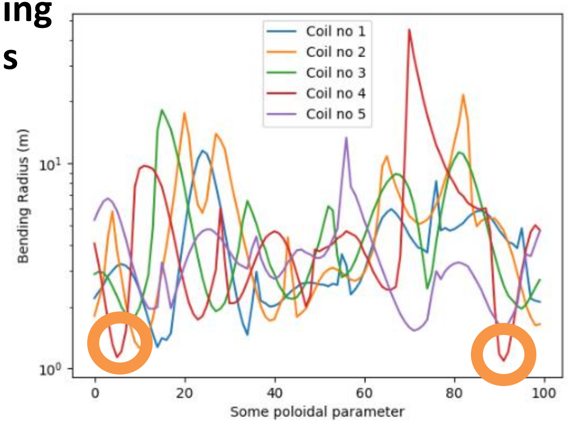
- Build consistency (coil-coil; coil-plasma distances)
- maximum force density and bending radius

→ **Iteration and optimisation**

Forces



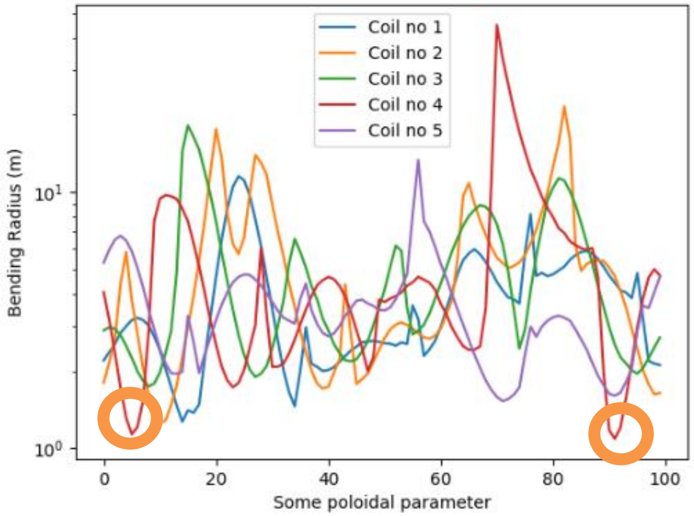
Bending radius



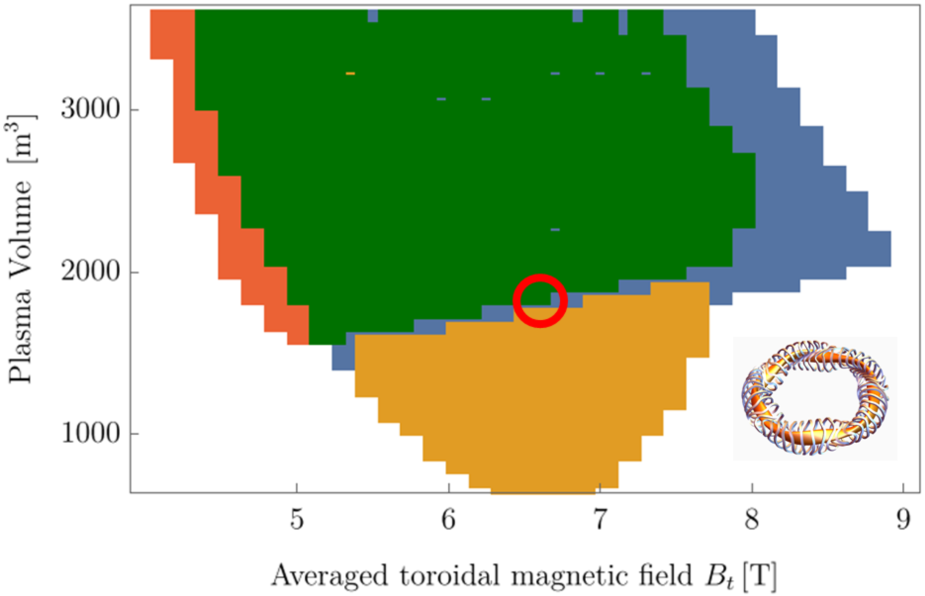
Realistic Winding Pack Design for Stellarators

- stress and strain needs to be appropriately addressed
- What is the minimum allowable bending radius?
- Need for radial plates?
- Non-insulated HTS coils?
- Development of detailed winding pack design
- EPFL-SPC started

Bending radius

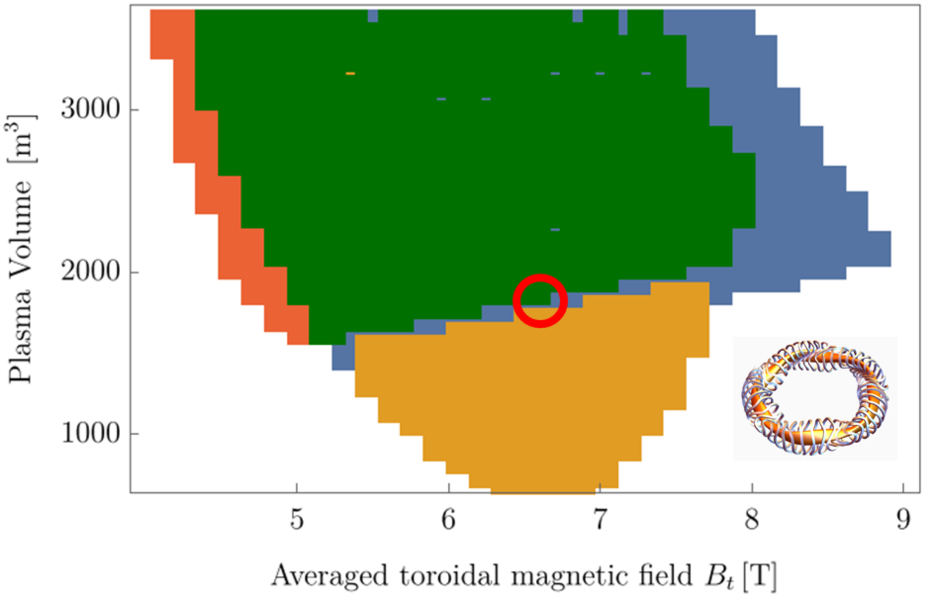


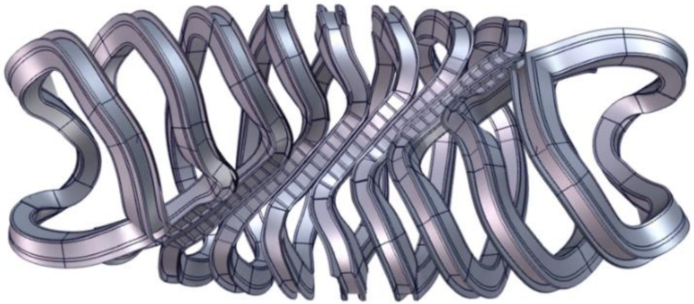
Stellarator Design Space Exploration



- Identify design space boundaries
- Assess technological & **engineering limits**
- Study impact of new technologies (e.g. HTS, liquid metals)

Stellarator Design Space Exploration

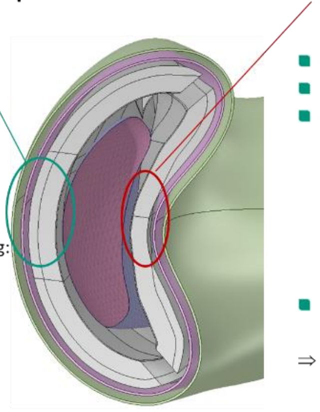




Maximum available space

- FW + armor: 27 mm
- Breeding zone: 500mm
- Space for shielding:
  - Blanket back ~250 mm
  - Void gap : ~100mm
  - VV walls: 2 x 58mm
  - VV interior: ~200mm
  - Total space for shielding: ~ 666mm
- <u>**Total thickness: ~ 1190 mm**</u>

⇒ **Presumably sufficient for satisfying breeding and shielding requirements**



Minimum available space

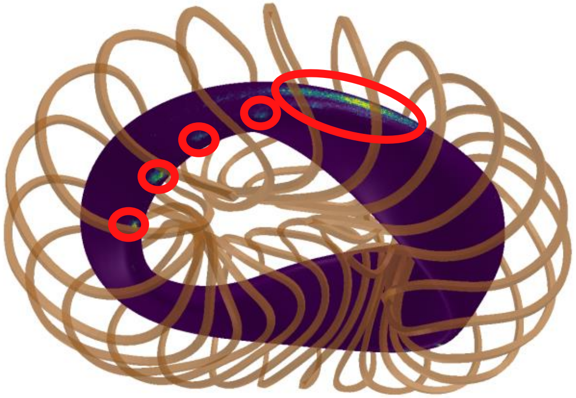
- FW + armor: 27 mm
- Breeding zone: 460mm
- Space for shielding:
  - Blanket back ~ 0 mm
  - Void gap : ~100mm
  - VV walls: 2 x 58mm
  - VV interior: ~200mm
  - Total space for shielding: ~ 416mm
- <u>**Total thickness: ~ 900 mm**</u>

⇒ **In such areas breeding zone must be reduced/minimized and/or efficient shielding materials must be utilized**

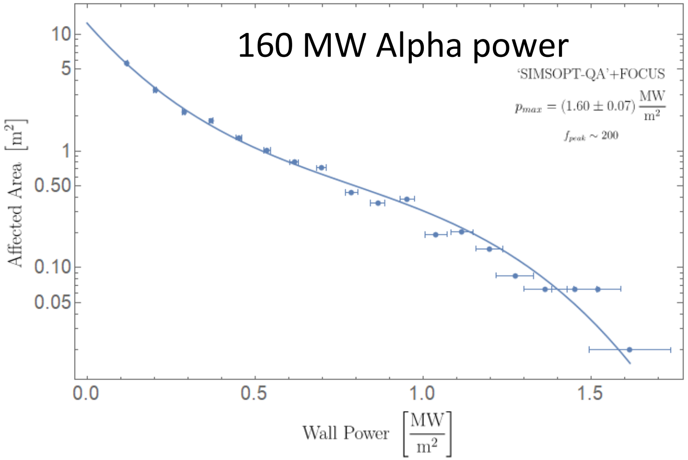
- ➢ Identify design space boundaries
- ➢ Assess technological & **engineering limits**
- ➢ Study impact of new technologies (e.g. HTS, liquid metals)

Alpha Particle Losses on the Wall

- Fast-particle confinement has historically been an issue of Stellarators
- **How dangerous are these losses for the wall in a reactor?**
- BEAMS3D (gyro-centre Monte Carlo with slowing down)
- Somewhat expensive, 10^3-10^4 CPU hours



SIMSOPT-QA



J. Lion, et al., unpublished