European efforts and advances in Stellarator power plant studies

Felix Warmer for the SPPS Team
Task Leader for Stellarator Power Plant Studies in EUROfusion
January 27, 2023

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EUROfusion Roadmap

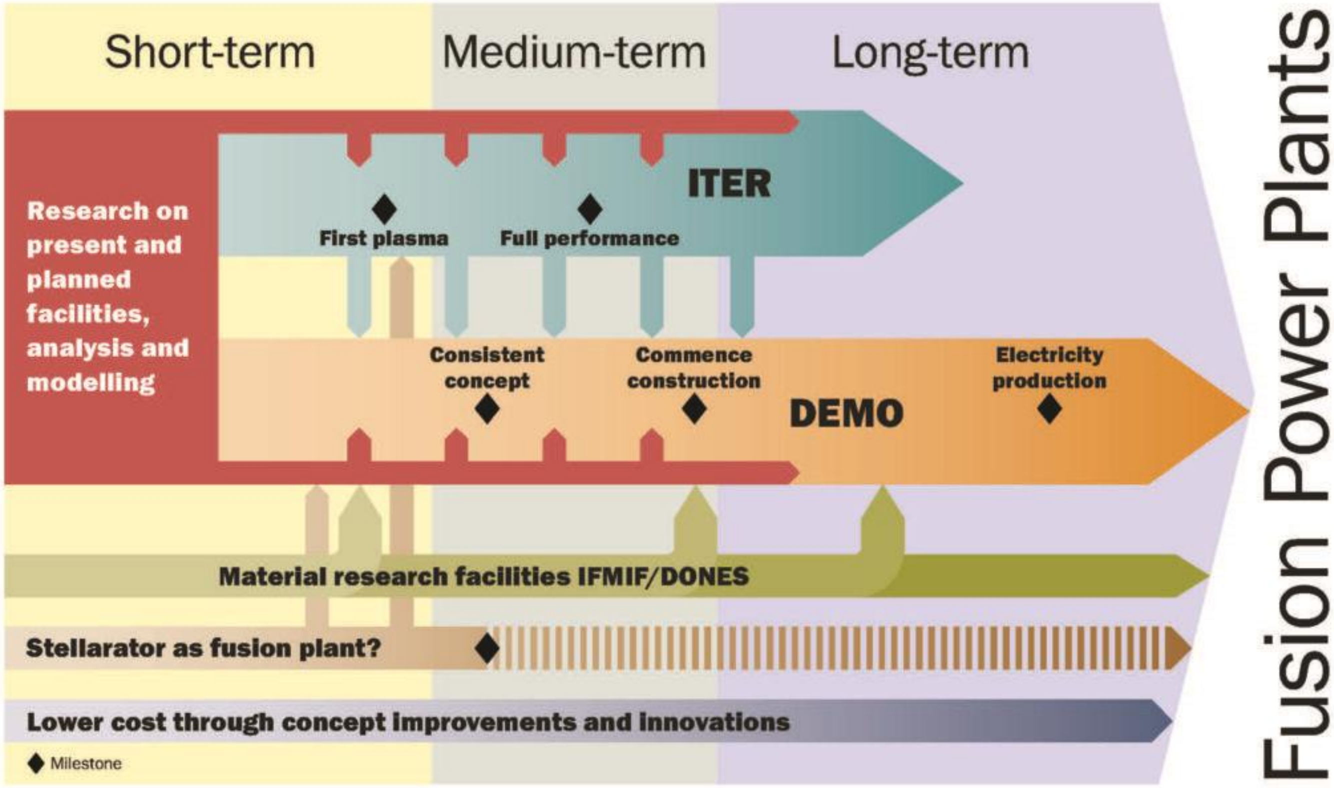
National institutes

form ↓

EUROfusion consortium →

$$$ ↑

European Union



SPPS Team List

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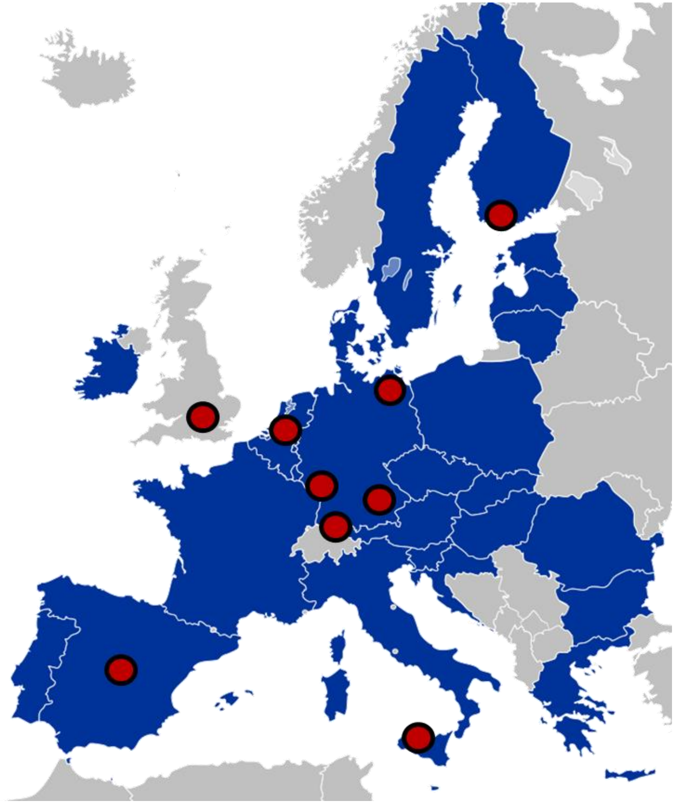
[7]Karlsruhe Institute for Technology
[8]Aalto University
[9]UK Atomic Energy Authority

Organisation & Team



Stellarator Power Plant Studies in WP-PRD

TU/e providing Task Leader

- **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)

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

1) Objectives, Strategy, Team

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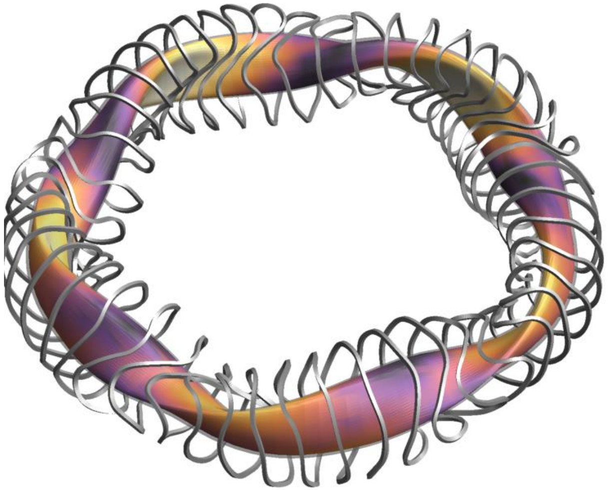
Objectives

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

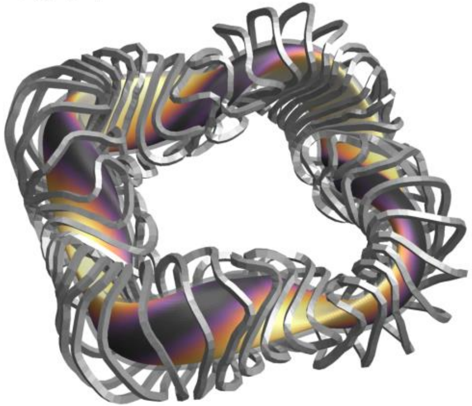
- **Identify Stellarator-specific key design drivers & issues and address them**
- **Open mind to new technologies and their impact on design aspects**
- **Integrated systems view of physics, engineering, and economics aspects; capitalise on computational and modelling advancements**
- **Leverage existing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

Stellarator is not a single configuration



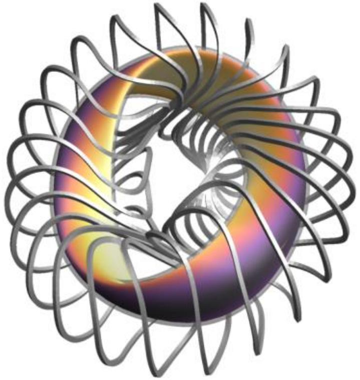
HSR-5/22

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

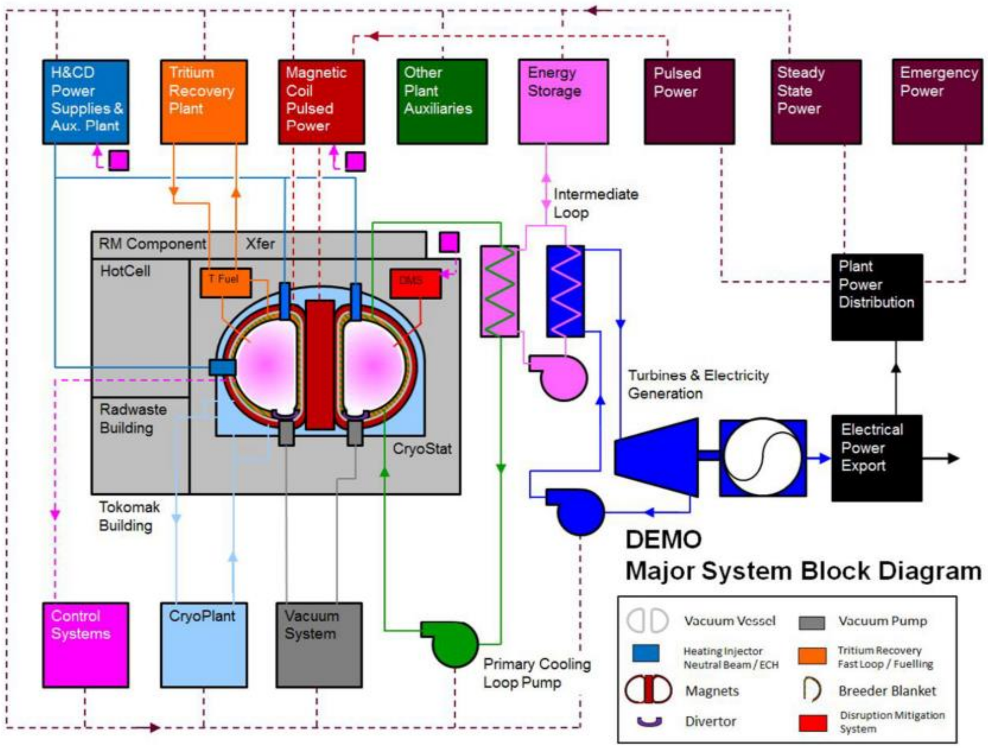


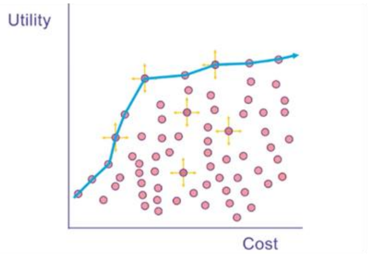
Figure 1. Schematic of a DEMO power plant.

- **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

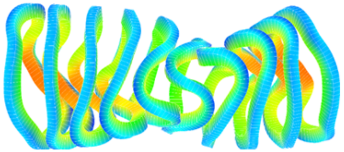
- **Constrained optimization** within a wider design space



Workflow for the Stellarator Systems Code Activities

Pre-Processing

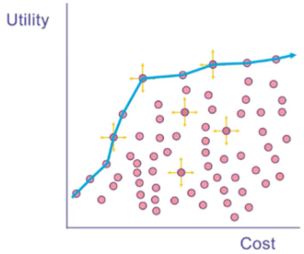
- **Reduce dimensionality** by pre-calculation of effective parameters



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

Systems Code PROCESS

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



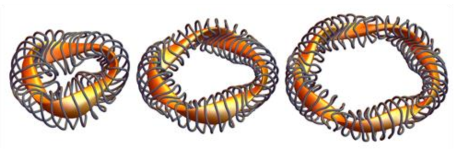
Design Point

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

Workflow for the Stellarator Systems Code Activities

Stellarator Optimisation

- **Coil filaments**
- Magnetic configuration



Pre-Processing

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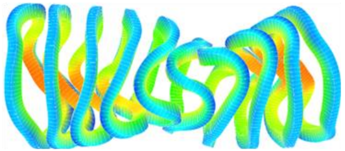

e.g. B_{max} w/ Biot-Savart

Systems Code PROCESS

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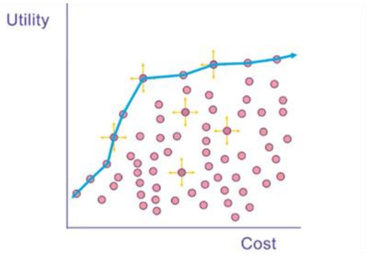


Design Point

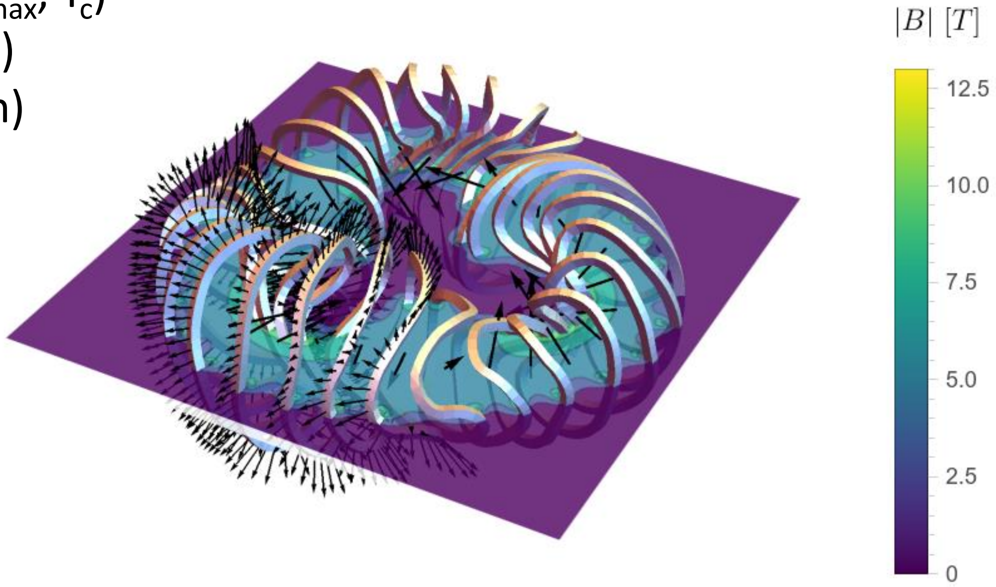
- **Engineering feasibility**
- **Attractiveness**
- Impact of **new technologies** (e.g. HTS)

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

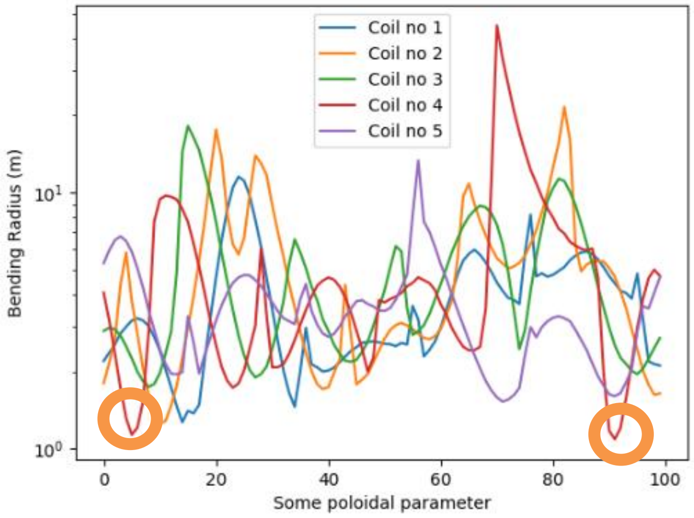


J. Lion, F. Warmer, et. al, NF 61 (2021)

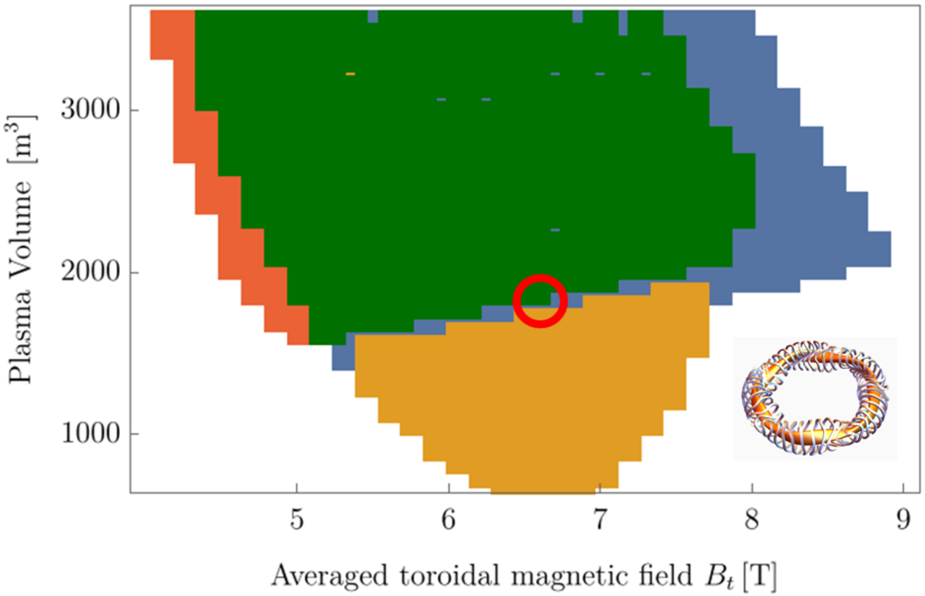
Realistic Winding Pack Design for Stellarators

- 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

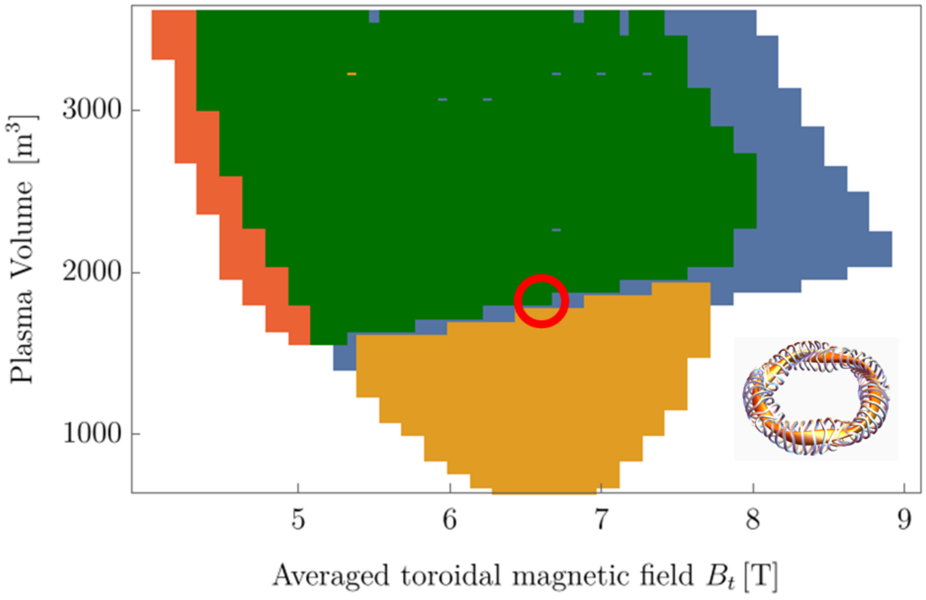


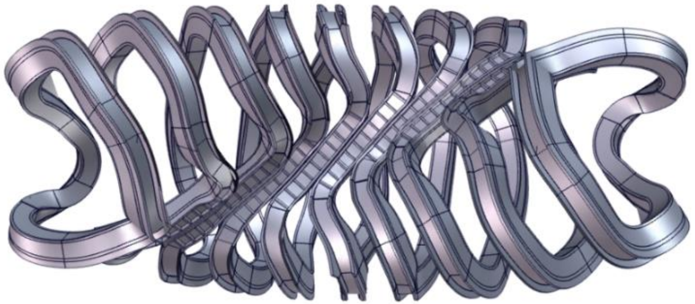
Stellarator Design Space Exploration



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

Stellarator Design Space Exploration

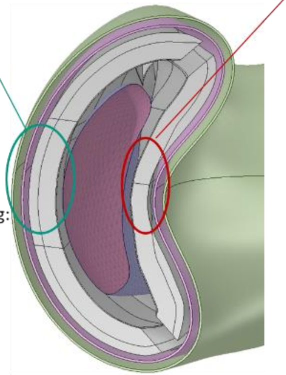




Maximum available space

- 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**

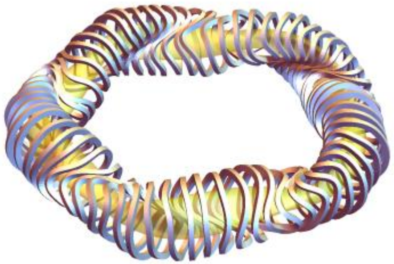
- ➢ Identify design space boundaries
- ➢ Assess technological & **engineering limits**
- ➢ Study impact of new technologies (e.g. HTS, liquid metals)

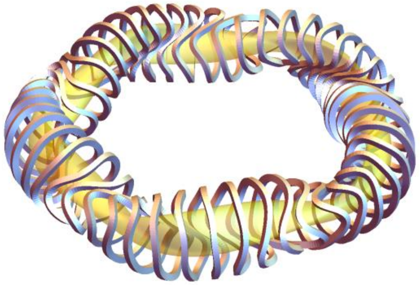
Parametric Modelling for Fast Design Iteration

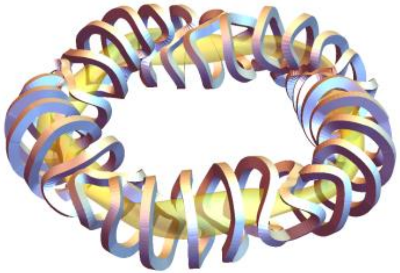
Example: Varying the number of coils

Target: Finding the optimal compromise between plasma and engineering goals

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



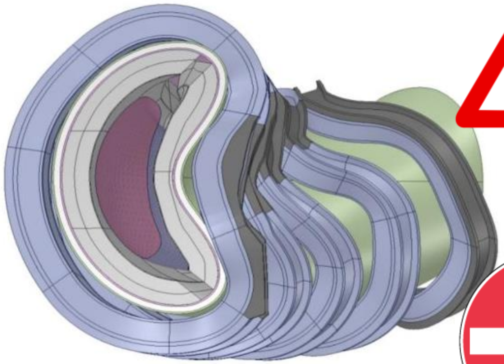




Content

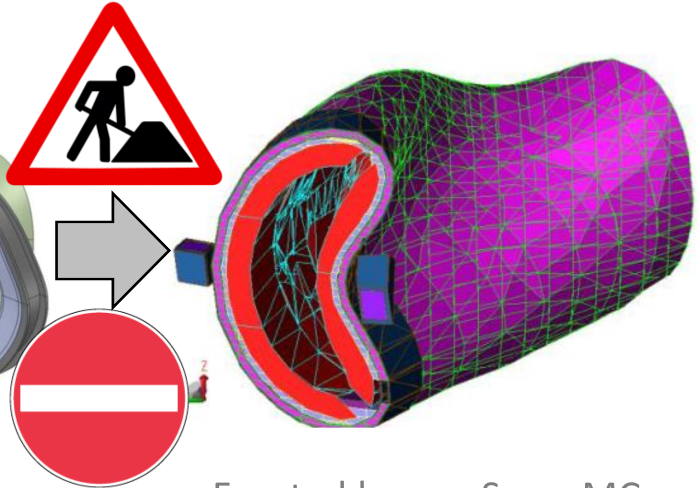
Stellarator Neutronics: cumbersome CAD conversion

CAD model



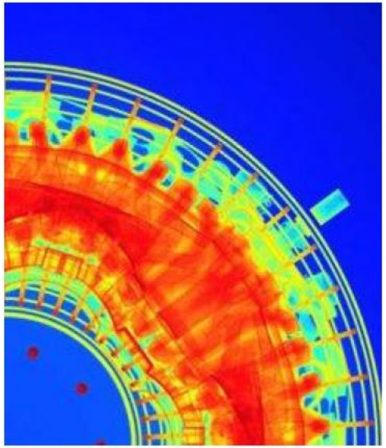
Smooth Splines

MCNP neutronic model



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

3D nuclear response

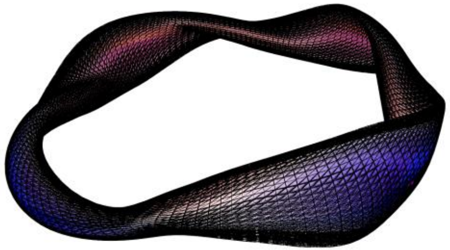


e.g. MCNP5

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

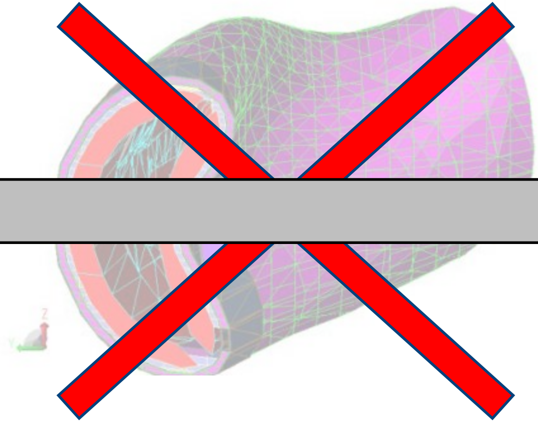
Stellarator Neutronics: direct analysis on geometry

CAD model



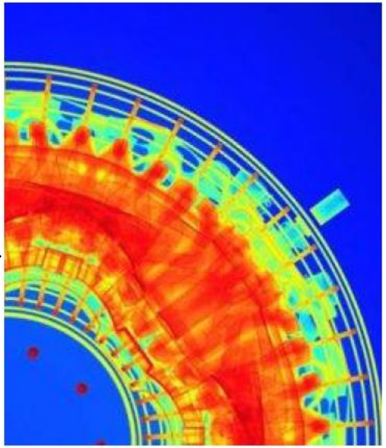
~~Smooth Splines~~
Tetrahedral / Meshed

MCNP neutronic model



Faceted by e.g. SuperMC

3D nuclear response

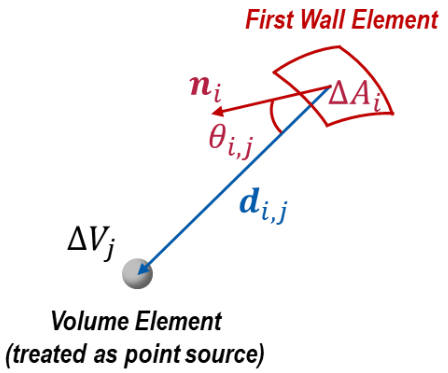


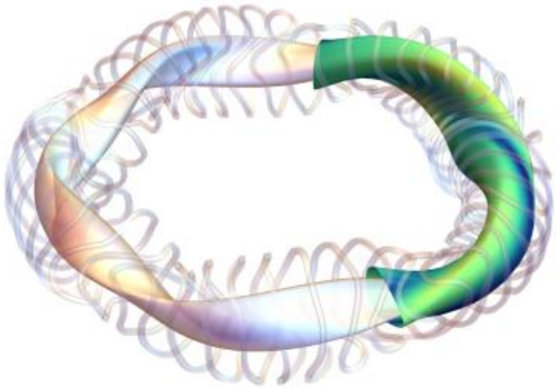
~~e.g. MCNP5~~
e.g. MCNP6, Serpent2

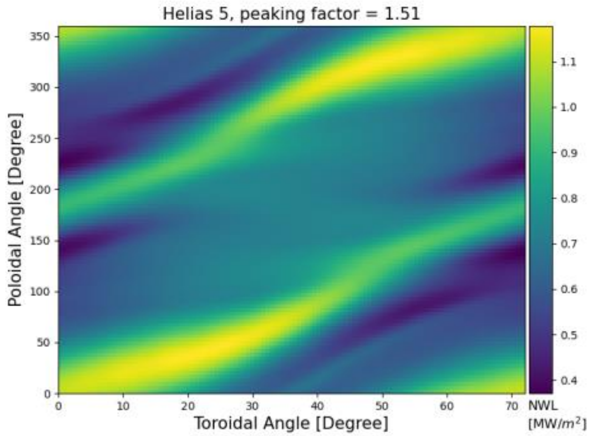
- **Exploration of methods to do neutronics analysis directly on CAD geometry**
- **Direct (parametric) generation of CAD models from magnetic geometry**
- High fidelity → high computational cost – 10^9 Monte Carlo samples

Deterministic Neutronics Model for Design Optimisation

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



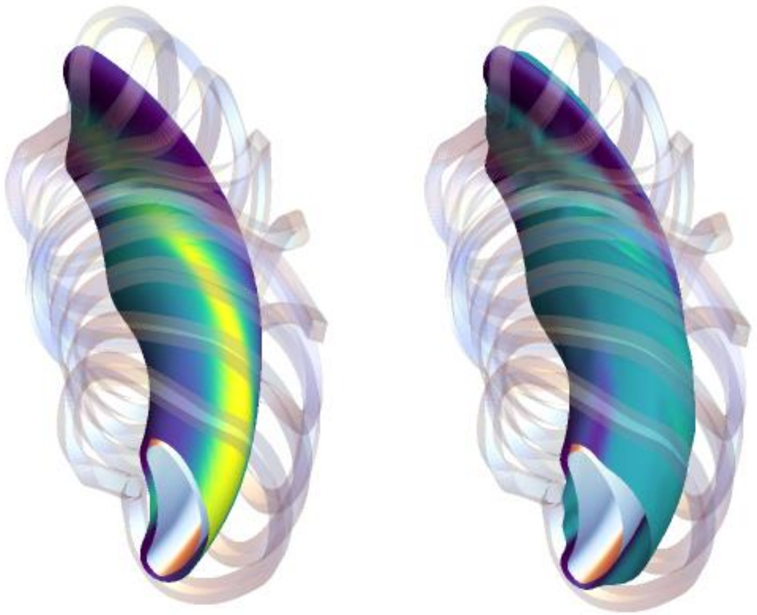




$$NWL_i = \sum_j \frac{\Phi_j \cdot E_N}{4\pi \left|\boldsymbol{d}_{i,j}\right|^2} \left(\widehat{\boldsymbol{n}}_i \cdot \widehat{\boldsymbol{d}}_{i,j}\right)$$

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

Optimising the Wall for Neutron Loads



- <u>Can be used to optimise the 3D wall</u>
- Potentially increased life-time by reducing peak loads
- optimization strong design driver for coil optimization
- allows fast design iteration
- **Extension to 3D blanket space ongoing for TBR, shielding, etc.**

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

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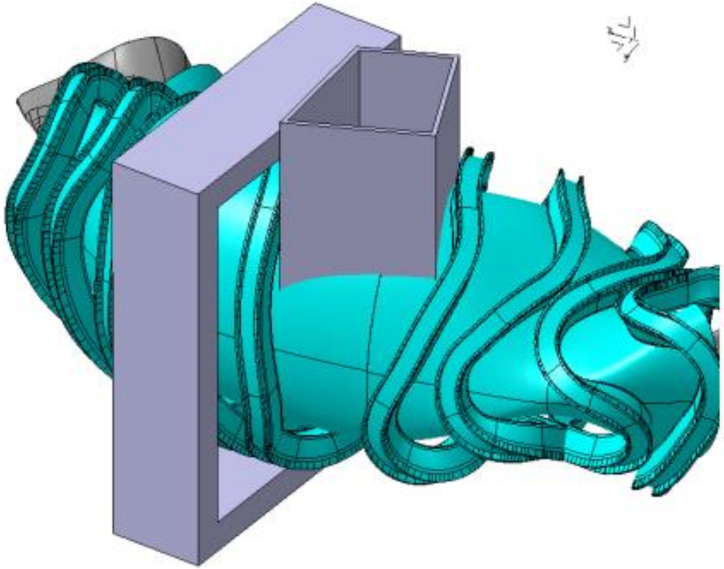
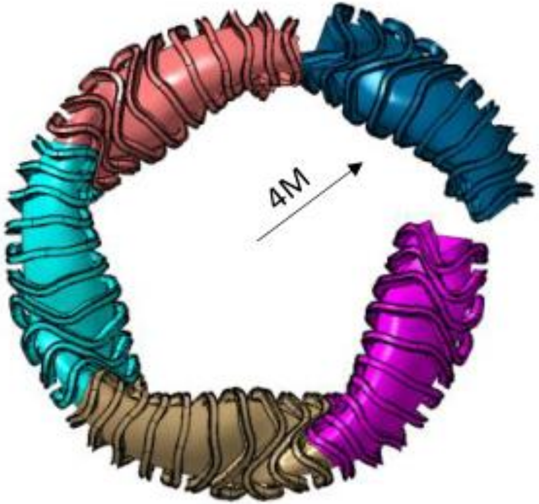
Stellarator Remote Maintenance

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





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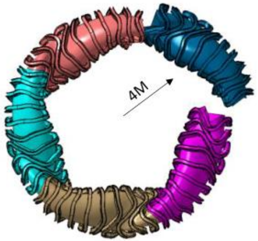

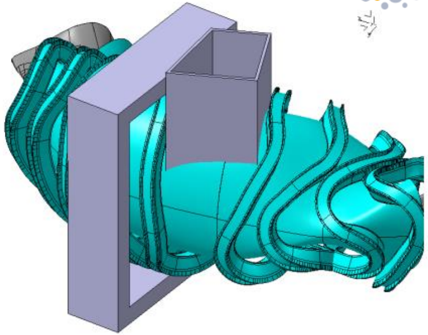

(Baseline)

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

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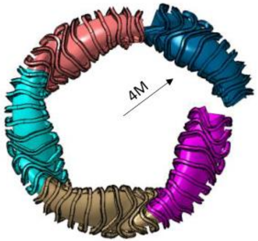

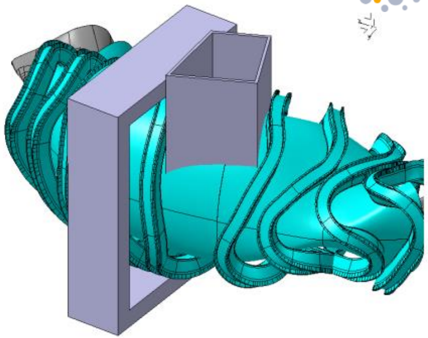

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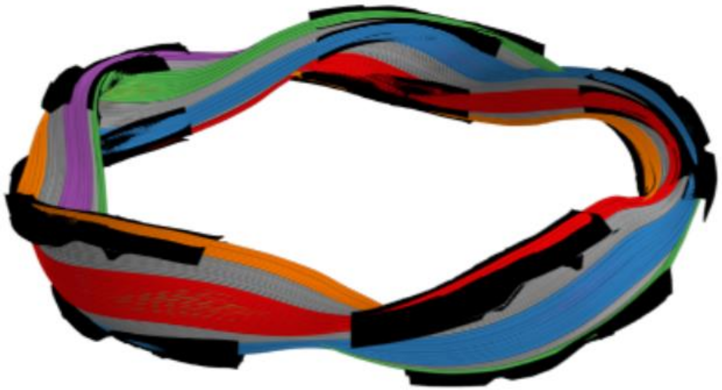
Wider plant implications	0	-1	-1	-2
Total:	**0**	**0**	**+1**	**0**

The general problem with Remote Maintenance or Systems Integration

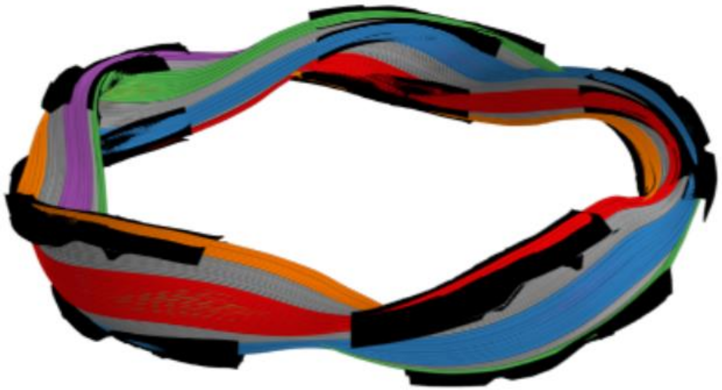
Island Divertor for a Stellarator reactor

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



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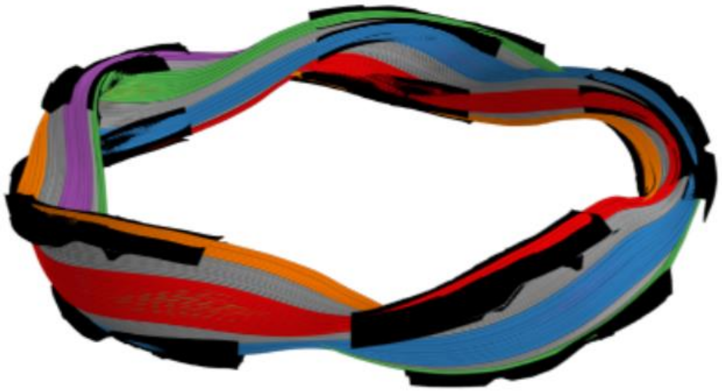
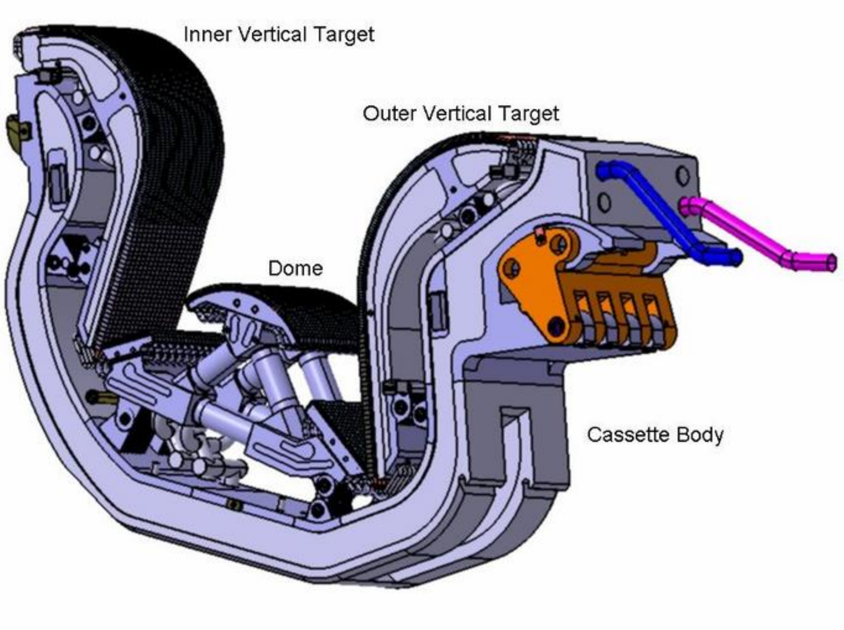
- **Open geometry, designed for maximum flexibility (magnetic config.)**

Island Divertor for a Stellarator reactor





- 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
- What to expect from the EUROfusion review point on Stellarators in 2030ish?