Modeling neutronics for HELIAS stellarator using Serpent2

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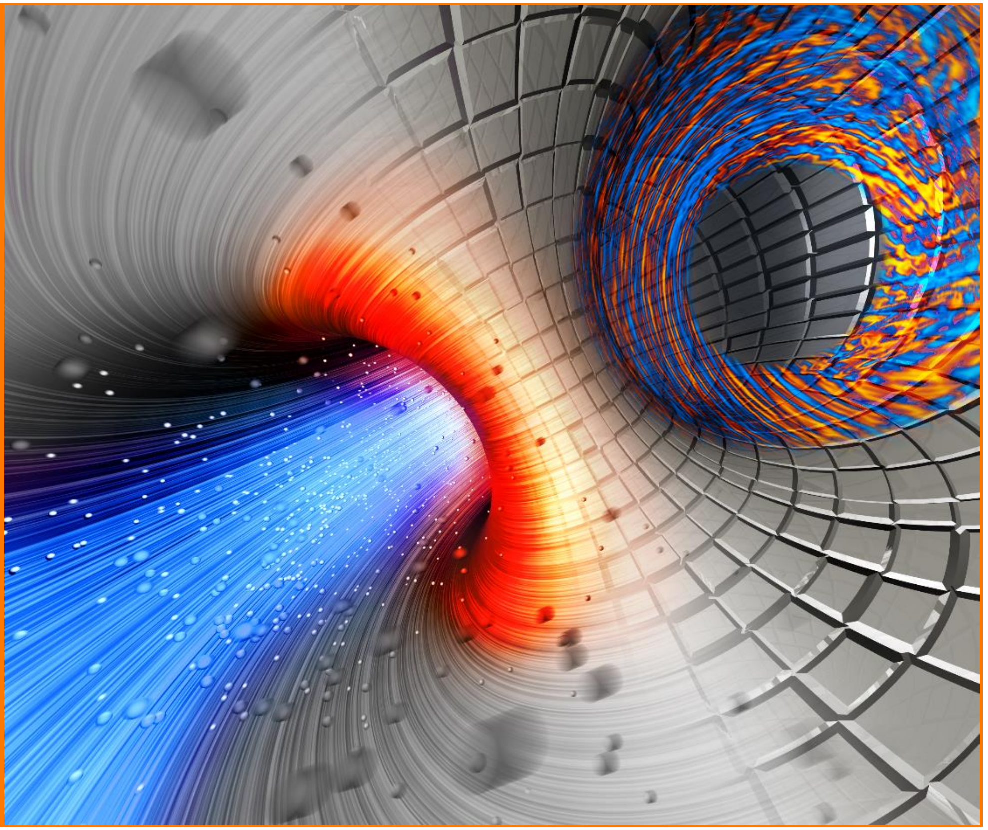


Outline

Introduction to fusion and stellarators

Benchmarking MCNP and Serpent2

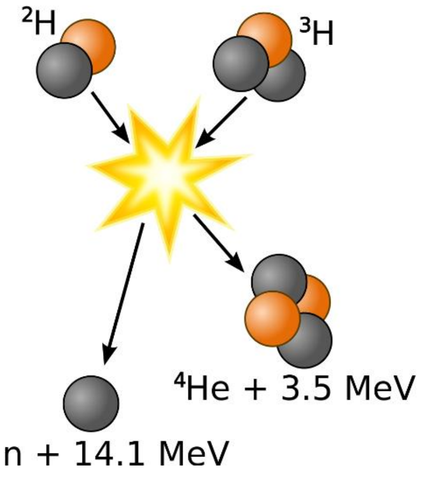
Breeding blanket optimization via parametric model

Conclusions/Outlook

Introduction

What is thermonuclear fusion?

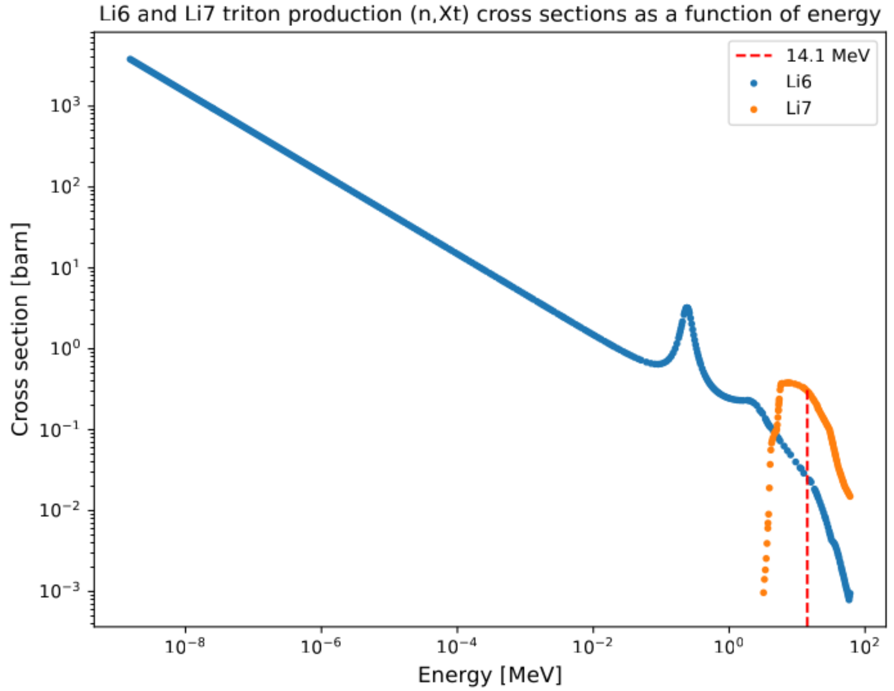
- ★ Easiest option DT fusion
  - Neutron with 14.1MeV energy
- ★ Need a tritium
  - Lithium breeding reactions
  - Li7 more abundant (92%-8%)
  - Li6 suitable cross-section
  - Enriched lithium needed
- ★ Magnetic field to confine the plasma
  - Tokamaks and stellarators



$${}^{2}_{1}H + {}^{3}_{1}H = {}^{4}_{2}He + {}^{1}_{0}n + 17.59\ MeV$$

$${}^{6}_{3}Li + {}^{1}_{0}n = {}^{4}_{2}He\ (2.05\ MeV) + {}^{3}_{1}H\ (2.75\ MeV)$$

$${}^{7}_{3}Li + {}^{1}_{0}n = {}^{4}_{2}He + {}^{3}_{1}H + {}^{1}_{0}n$$



Tokamaks vs. stellarators

- Tokamak
  - Magnetic field from coils and induced current
  - Pulsed operation
  - Forerunner (i.e. 90% of research volume)
  - Close to show-stopping problems
- Design-wise: fusion power plant ~90% the same
- Decision point tokamaks vs. stellarators in future

- Stellarator
  - Magnetic field from coils
  - Steady-state operation
  - Basic performance issues
  - Have we seen all problems?
  - Complicated geometry
  - Currently no show
- Optimized stellarators
  - Wendelstein 7-X as an example
- HELIAS line as a reactor option

HELIAS as a fusion power plant candidate

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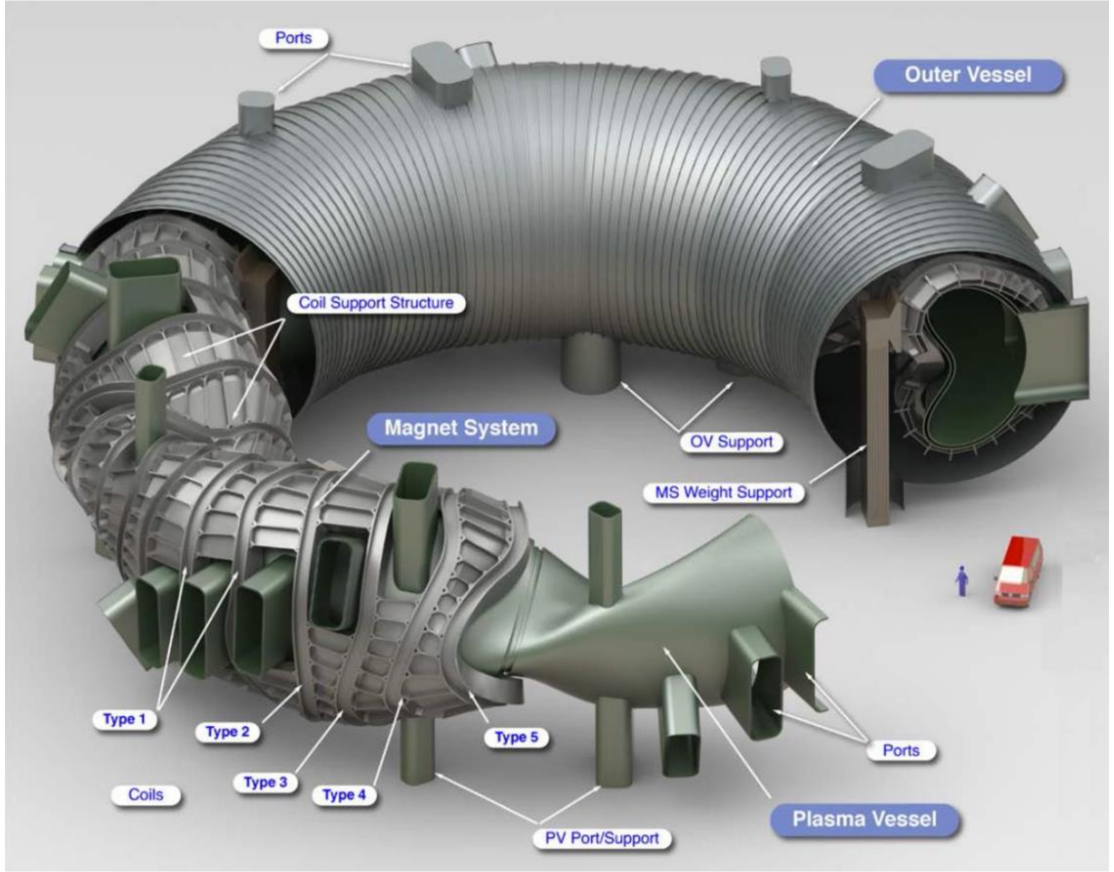
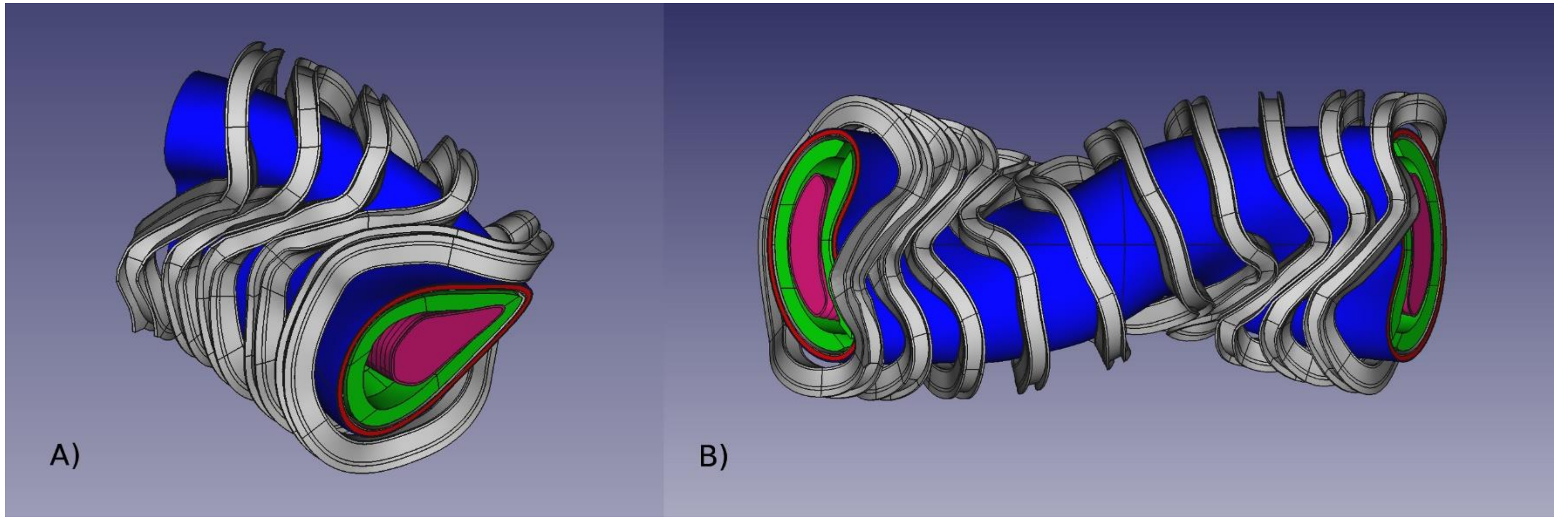
- ★ Basic HELIAS parameters
  - – Major radius 22m
  - – Minor radius 1.8m
  - – Plasma volume 1407m^3
  - – Fusion power 3GW
- ★ Optimized stellarator following W7-X research line
- ★ Geometry induces major design issues



[1] F. Schauer et al. Fus. Eng. and Des., **88**, 2012, 1619–1622

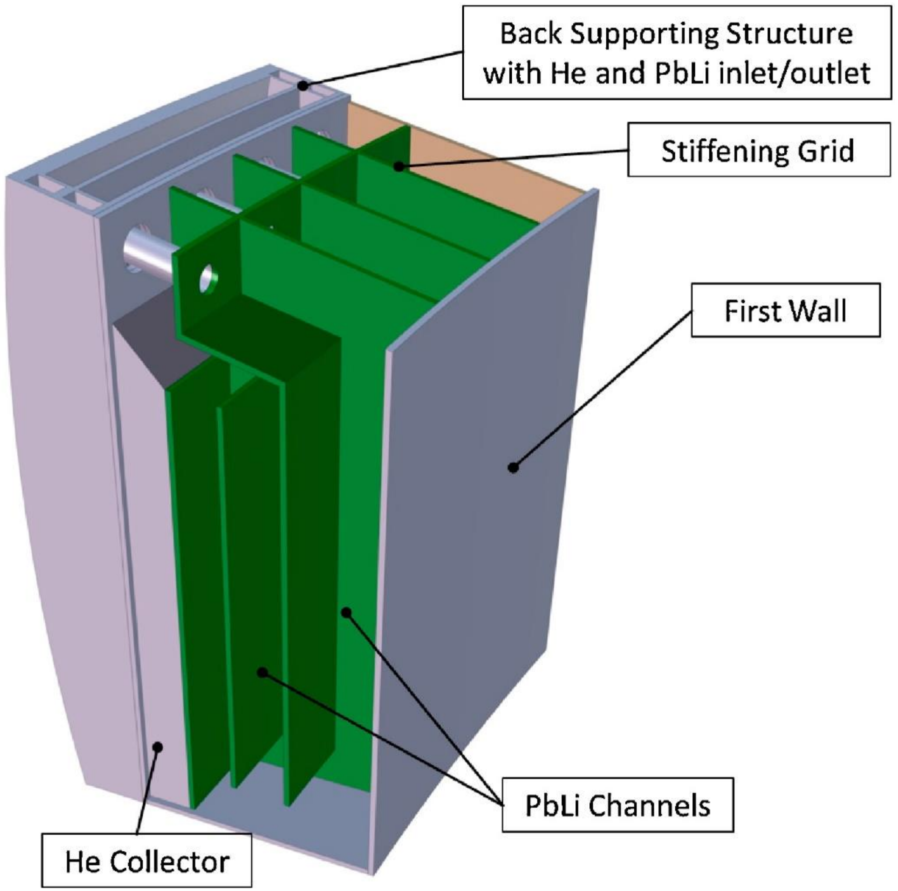
Neutronics (for stellarators)

- ★ Due to complexity, a parametric (CAD) model suggested
  - Faster design iterations
  - Ease neutron analysis
- ★ MCNP vs. Serpent2
  - Codes have been widely benchmarked
  - MCNP6 can work “directly” with CAD just as Serpent2
- ★ Right: example of HELIAS CAD model



Overview of breeding blanket

- ★ Breeding blanket functions
  - – Breed tritium
  - – Slow down neutrons
  - – Heat water
  - – Shield from neutrons
- ★ Various design candidates
  - – W(ater)C(ooled)L(ithium)L(ead)
  - – H(elium)CLL
  - – **D(ual)CLL**
  - – HCP(ebble)B(ed)
- ★ Stellarators
  - – Coils close to plasma
  - – High breeding and shielding

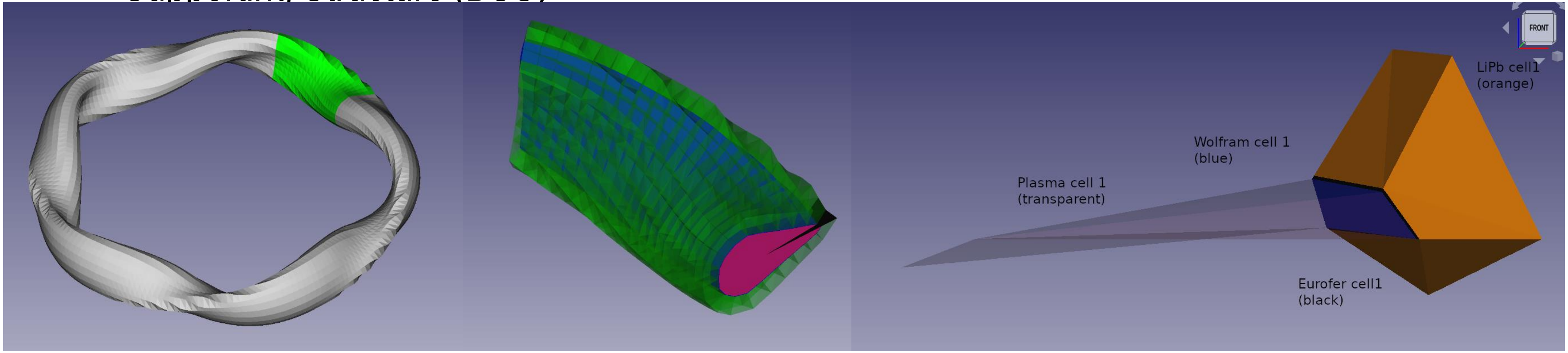


[2] U. Fischer et al. Fus. Eng. and Des. Vol. 109–111,2016, 1458-1463

Benchmarking MCNP vs. Serpent

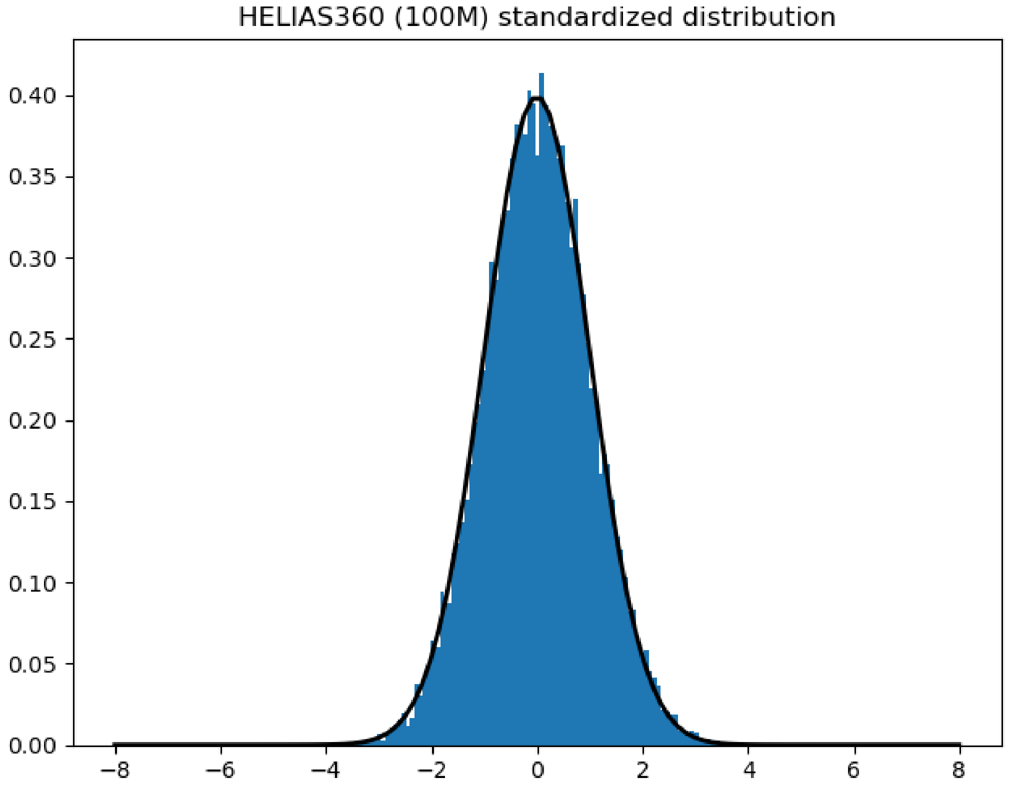
Benchmarking Serpent2 against MCNP6

- ★ CAD geometry with cells
- ★ Four layers, each 4000
  - – Plasma
  - – Wolfram first wall
  - – Eurofer first wall
  - – Breeding Blanket (BB) and Back Supporting Structure (BSS)
- ★ Compare
  - – Relative/average difference in flux (per cell)
  - – 72 degree vs. 360 degree model



Benchmarking Serpent2 against MCNP6

- ★ Average absolute relative difference 0.598% (for all 16000 cells)
- ★ Standardized difference normally distributed
- ★ Relative difference per cell
  - – 360 degree model, acceptable
  - – 72 degree model, issue with boundary conditions?



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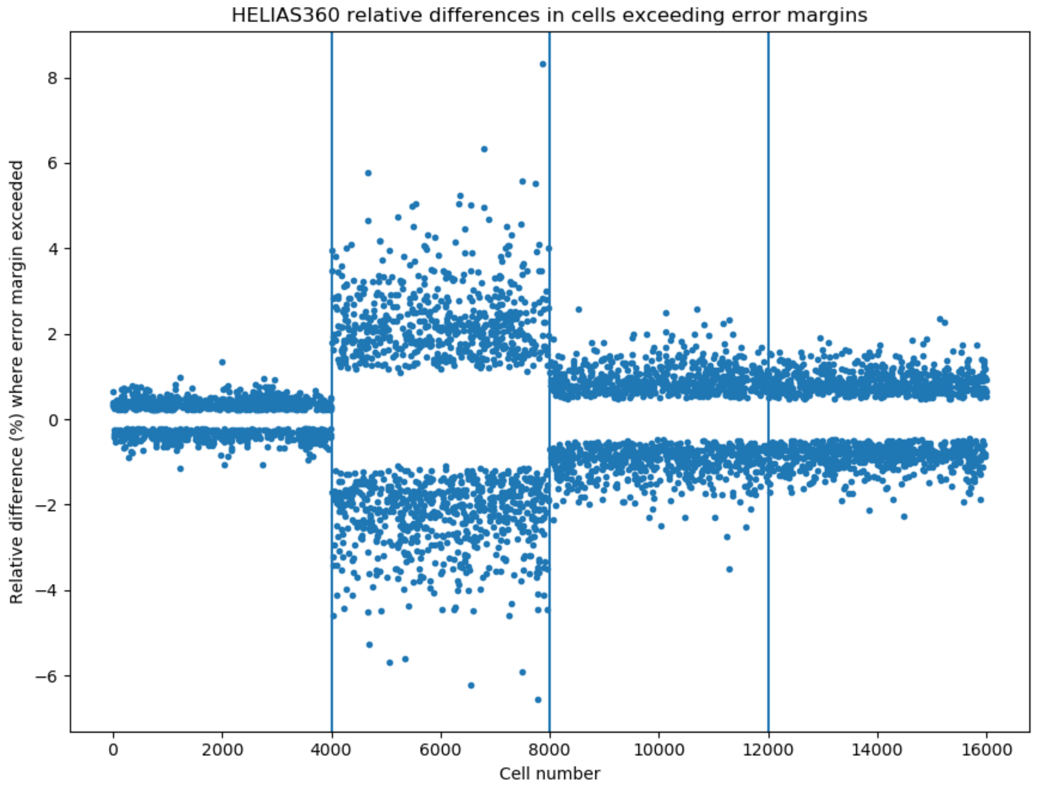

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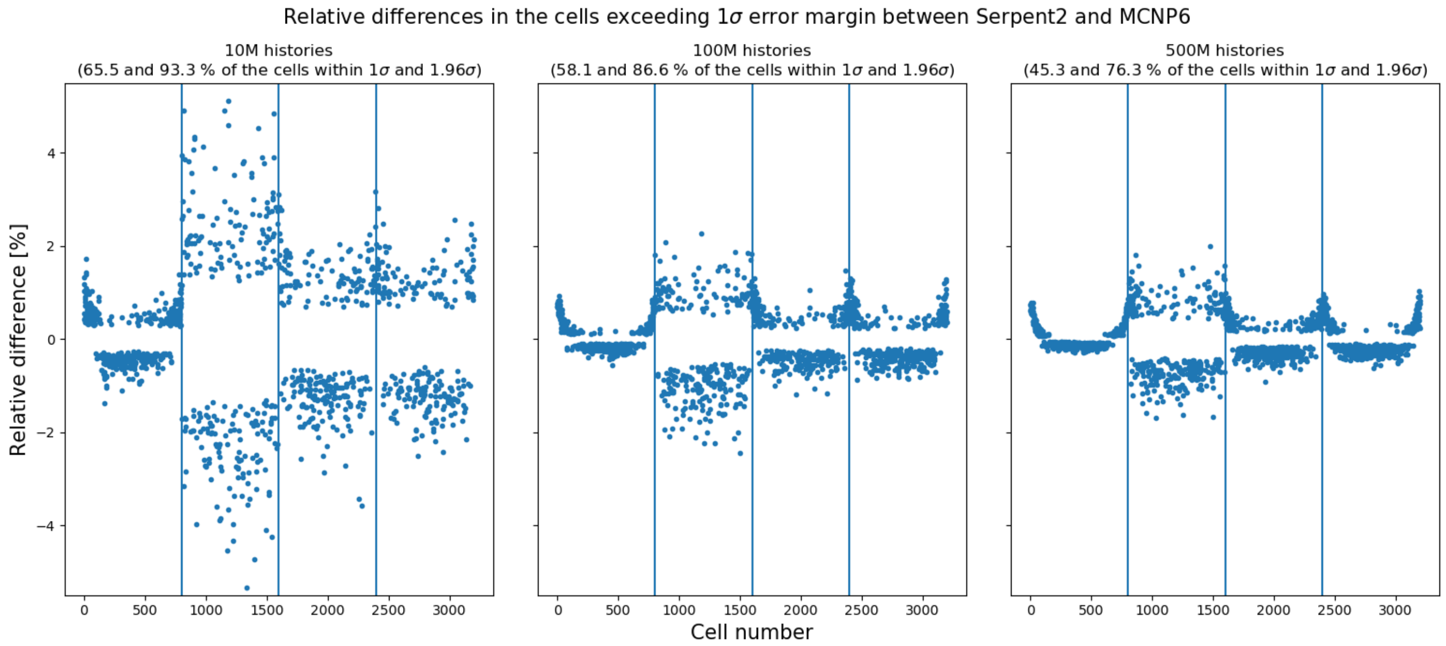

Breeding blanket optimization

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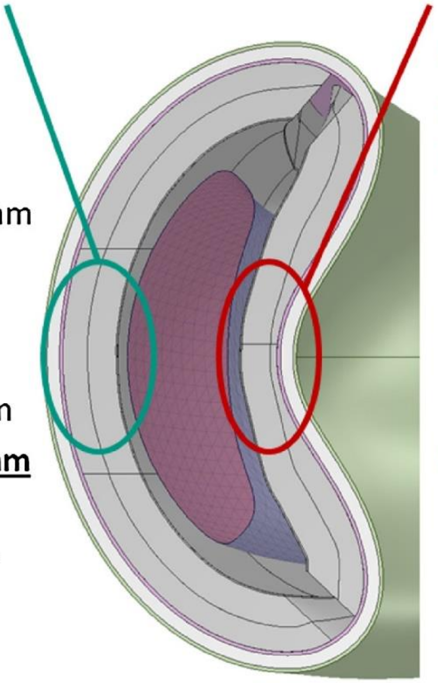
Optimization of the breeding blanket

- ★ To be reactor relevant, tritium breeding ratio (TBR=TPR/(neutron source rate)=# of T per fusion n) needs to exceed 1.15
- ★ Design question: how thick blanket is needed?
- ★ Boundary conditions
  - – Complicated coils (no space)
  - – Detailed design doesn't exist
  - – Detailed choice for blanket type doesn't exist
- ★ Initial study with crude assumptions

Maximum available space

- FW + Armor: 27 mm
- Breeding zone: 500mm
- Space for shielding:
  - Blanket back ~425 mm
  - VV walls: 2 x 60 mm
  - VV shield: ~200 mm
  - Total space for shielding: ~ 745 mm
- **Total thickness: ~ 1272 mm**

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



Minimum available space

- FW + Armor: 27 mm
- Breeding zone: 500mm
- Space for shielding:
  - Blanket back ~ 120 mm
  - VV walls: 2 x 60 mm
  - VV shield: ~200 mm
  - Total space for shielding: ~ 440 mm
- **Total thickness: ~ 967 mm**

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

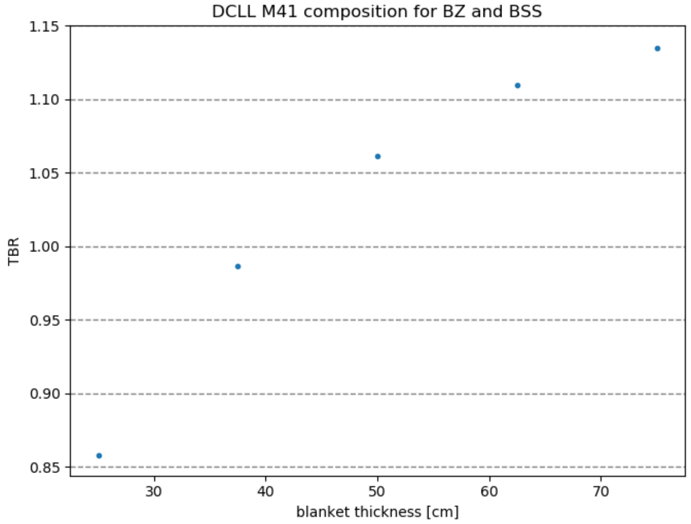
[3] F. Warmer, Fus. Eng. and Des., **123**, 2017, 47-53

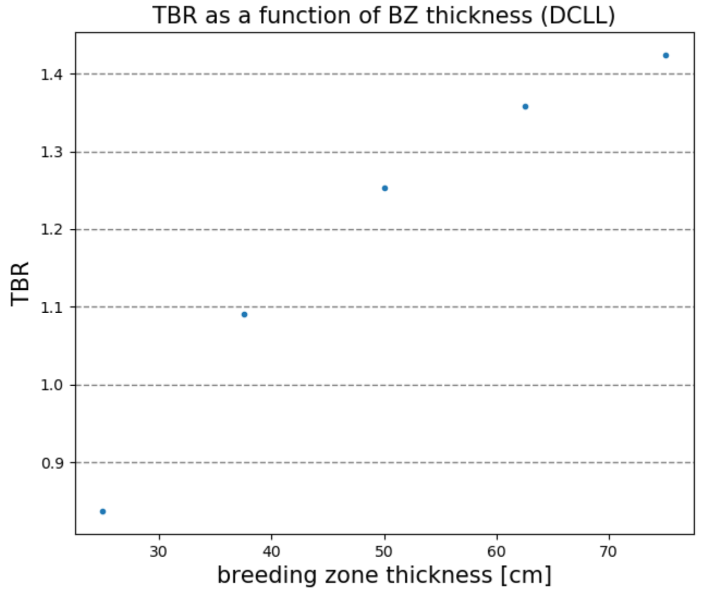
Model generation via parametric model

- Assumptions
  - Arbitrary # layers
  - All shaped like plasma
  - User defined material/thickness per layer
- Idea: scan blanket thickness, calculate TBR
- Two iterations
  - Assume homogenized (breeding zone+ back support structure)
  - Assume homogenized breeding zone and homogenized back support structure

Breeding blanket thickness vs. TBR

- ★ Major difference between the iterations!
- ★ As expected, only with proper breeding zone scan TBR>1.15
- ★ Threshold located at around 45cm -> within the limits
- ★ In future, need to relax several approximations!

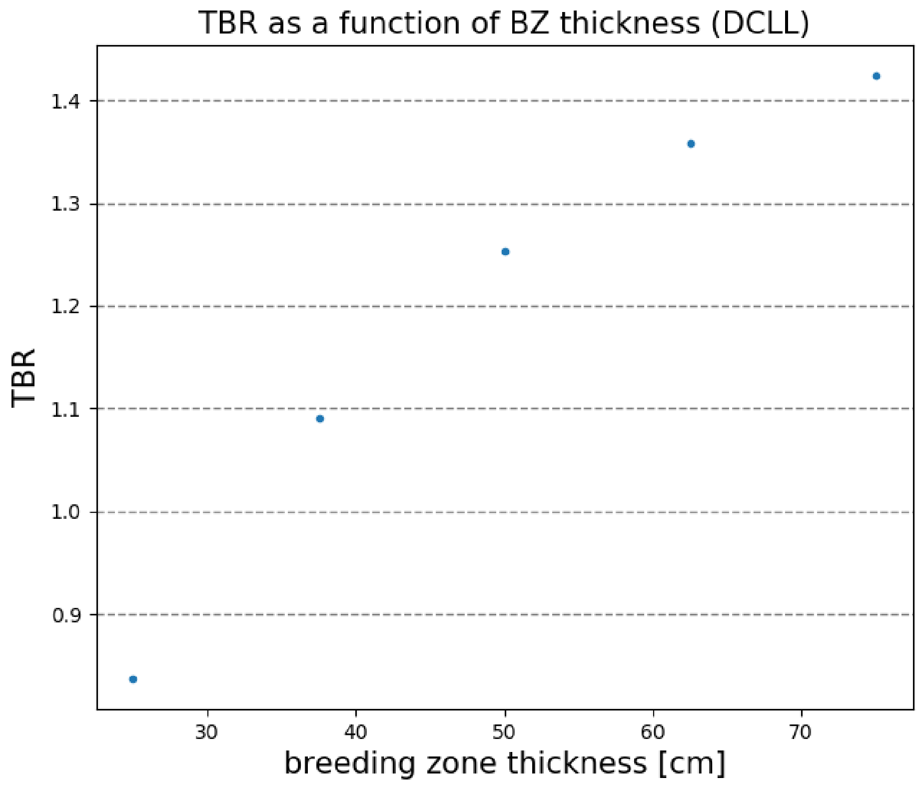




Conclusions/outlook

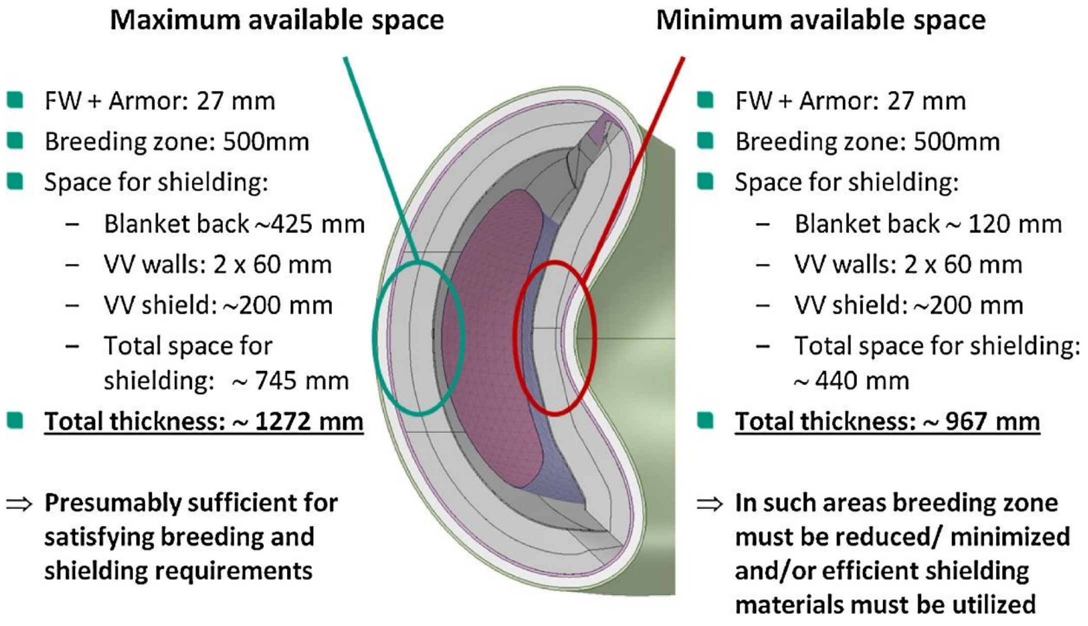
Conclusions

- ★ Stellarators studied as fusion power plant option
- ★ Breeding blanket is a key component of any fusion power plant
- ★ Neutronics essential piece of design
- ★ Serpent2 was benchmarked against MCNP with success
- ★ Serpent2 was used to estimate the necessary breeding blanket thickness



Outlook

- ★ Before design baseline, various options could be looked at
  - – Modifying blanket thickness outboard (more space) vs. inboard (less space)
  - – Need to consider other breeding blanket options (here only DCLL)
  - – Need to consider heterogenous materials
  - – Need to consider proper shape for each layer
- ★ After the design baseline
  - – Could consider combined neutronics+thermohydraulics, see [4] M. Szogradi et al. Fus. Eng. and Des. **184**, 2022, 113308
- ★ Tokamaks with Serpent2…



[3] F. Warmer, Fus. Eng. and Des., **123**, 2017, 47-53

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Thank you