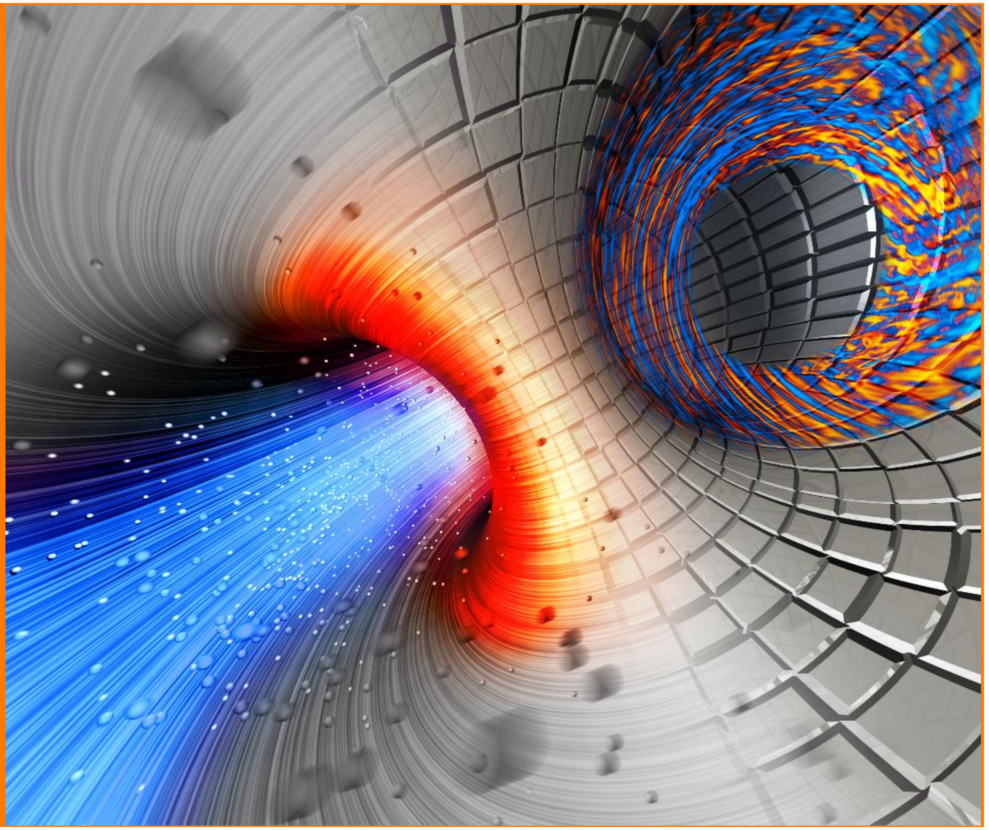
Modeling neutronics for HELIAS stellarator using Serpent2

Tommi Lyytinen, Antti Snicker
Aalto University
et al.



Outline

Introduction to fusion and stellarators

Benchmarking MCNP and Serpent2

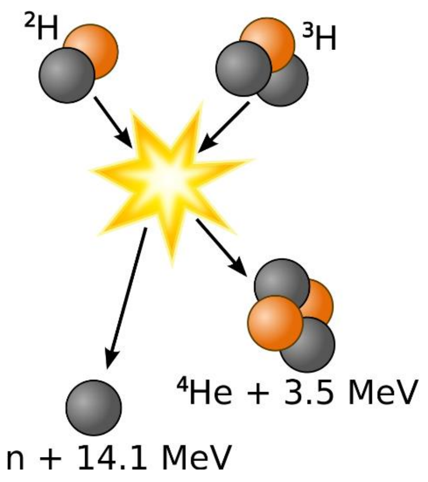
Breeding blanket optimization via parametric model

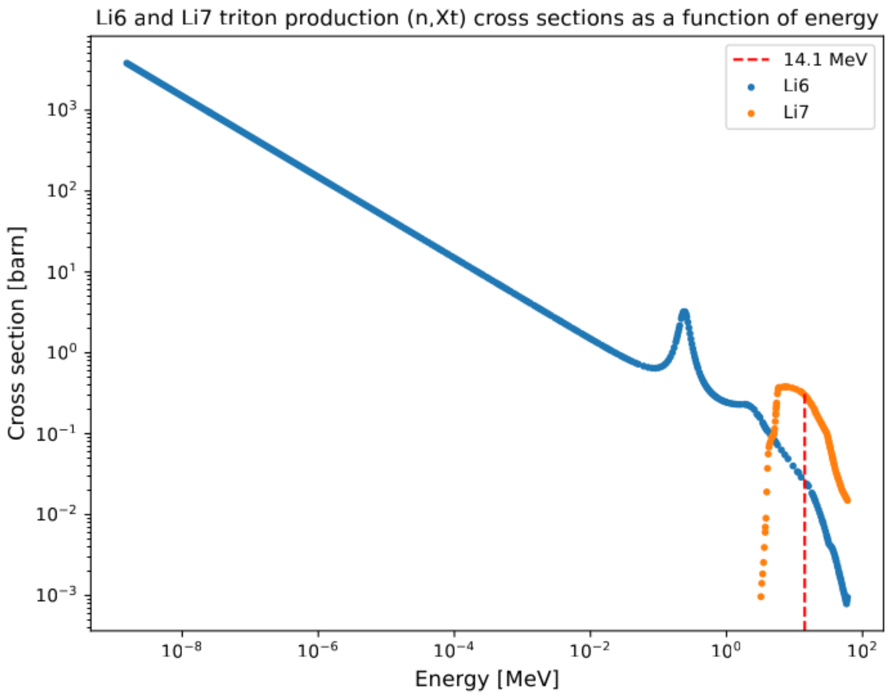
Conclusions/Outlook

Introduction

What is thermonuclear fusion?

- ★ Easiest option DT fusion
  - – Neutron with 14.1MeV energy
- ★ Need a tritium
  - – Lithium breeding reactions
  - – Li7 more abundant
  - – Li6 has better cross-section
  - – Enriched lithium needed
- ★ Magnetic field to confine the plasma
  - – Tokamaks and stellarators





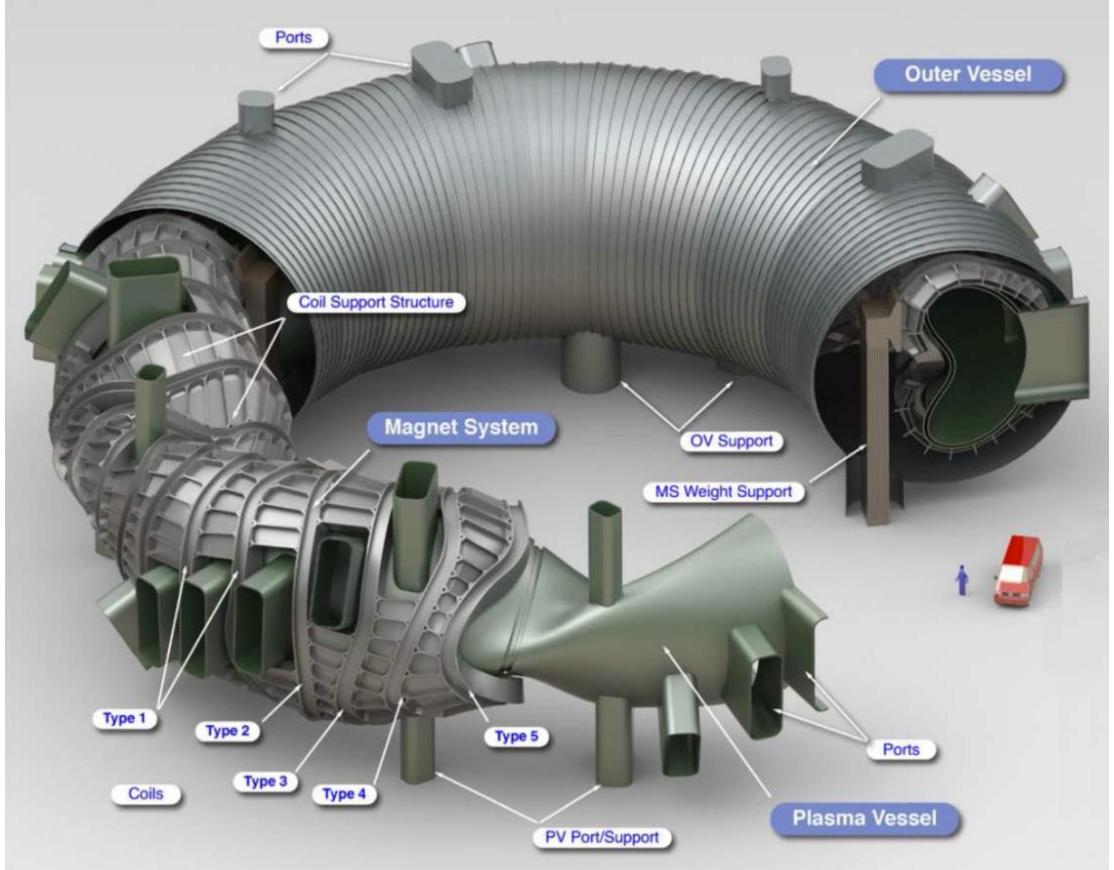
Tokamaks vs. stellarators

- 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

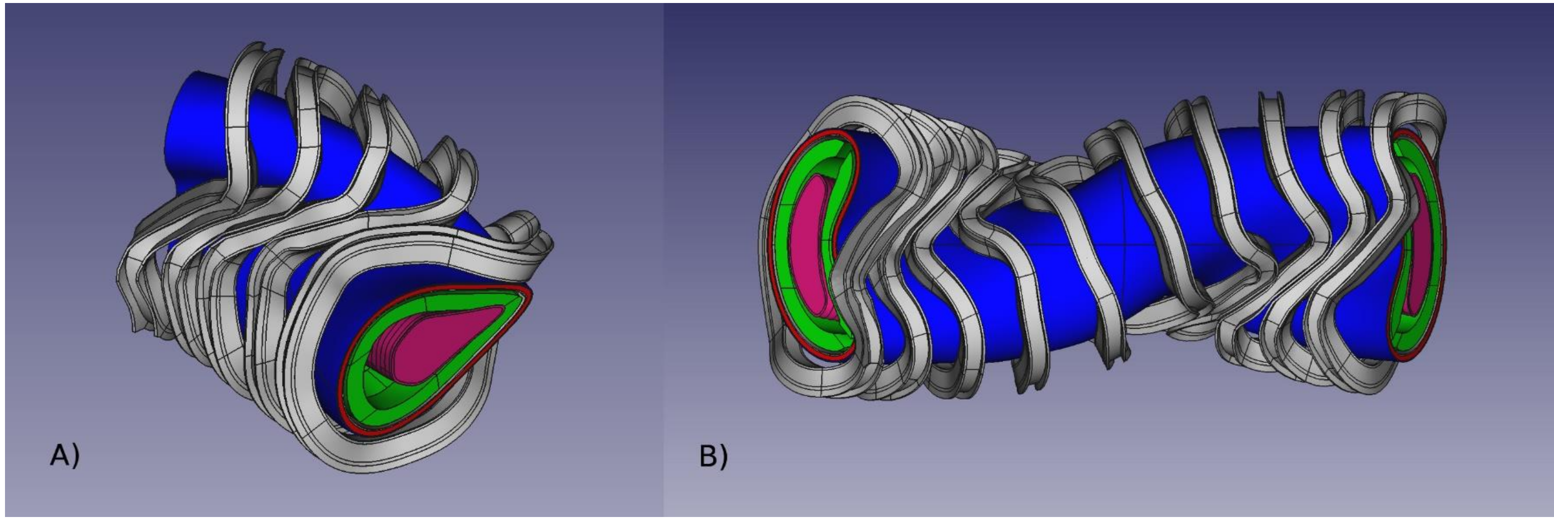
- ★ Basic HELIAS parameters
  - – Major radius 22m
  - – Minor radius 1.8m
  - – Plasma volume 1407m^3
  - – Fusion power 3GW
- ★ Optimized stellarator following W7-X research line
- ★ Geometry induces major design issues



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

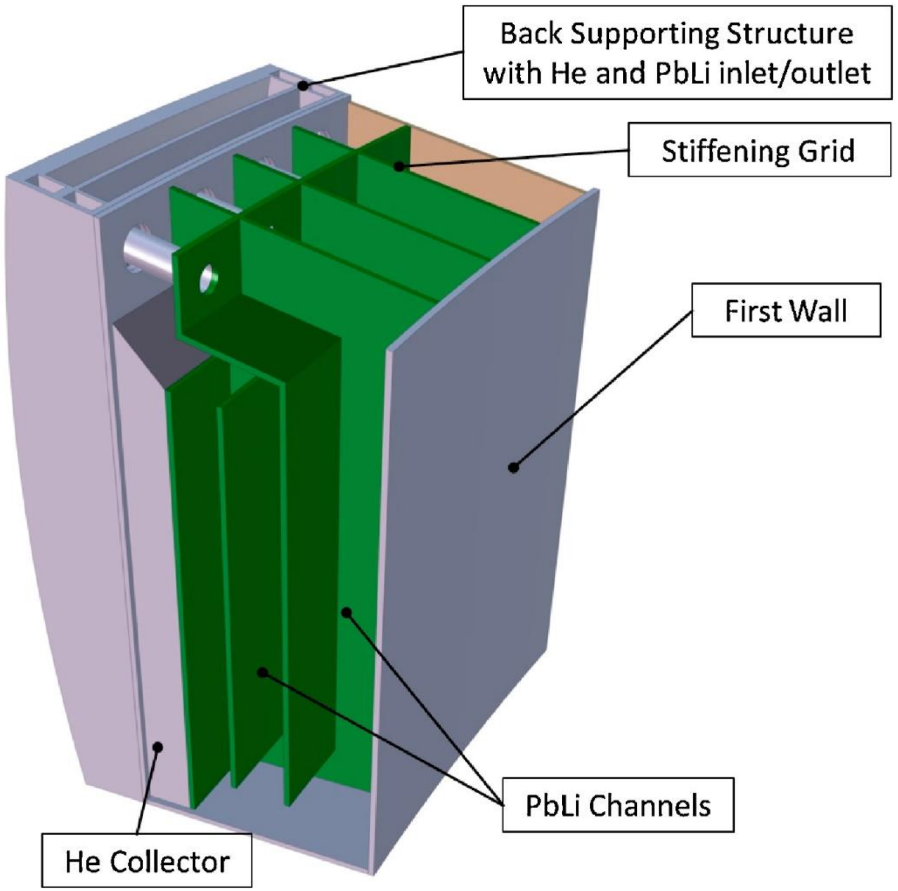
Neutronics (for stellarators)

- ★ 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

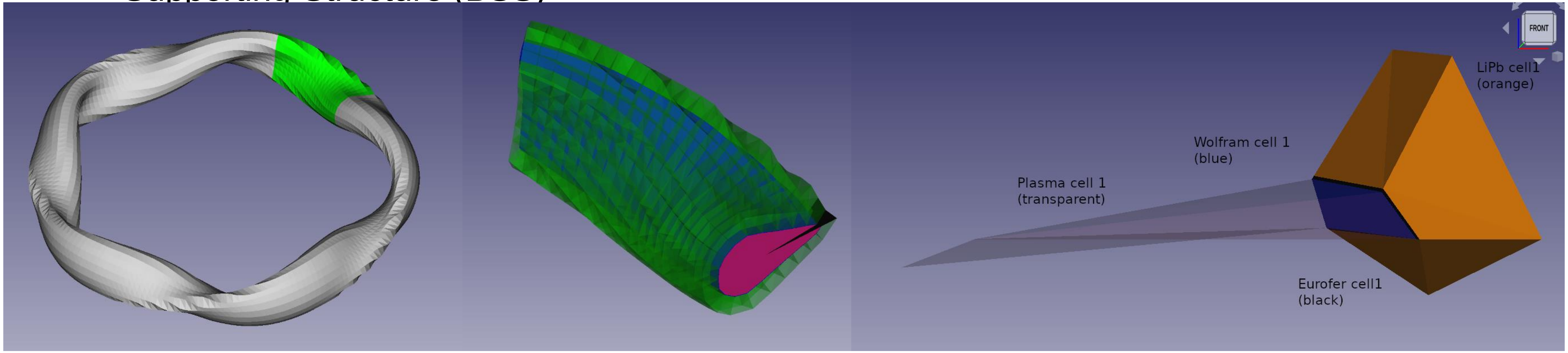


[2] U. Fischer et al. Fus. Eng. and Des. Vol. 109–111,2016, 1458-1463

Benchmarking MCNP vs. Serpent

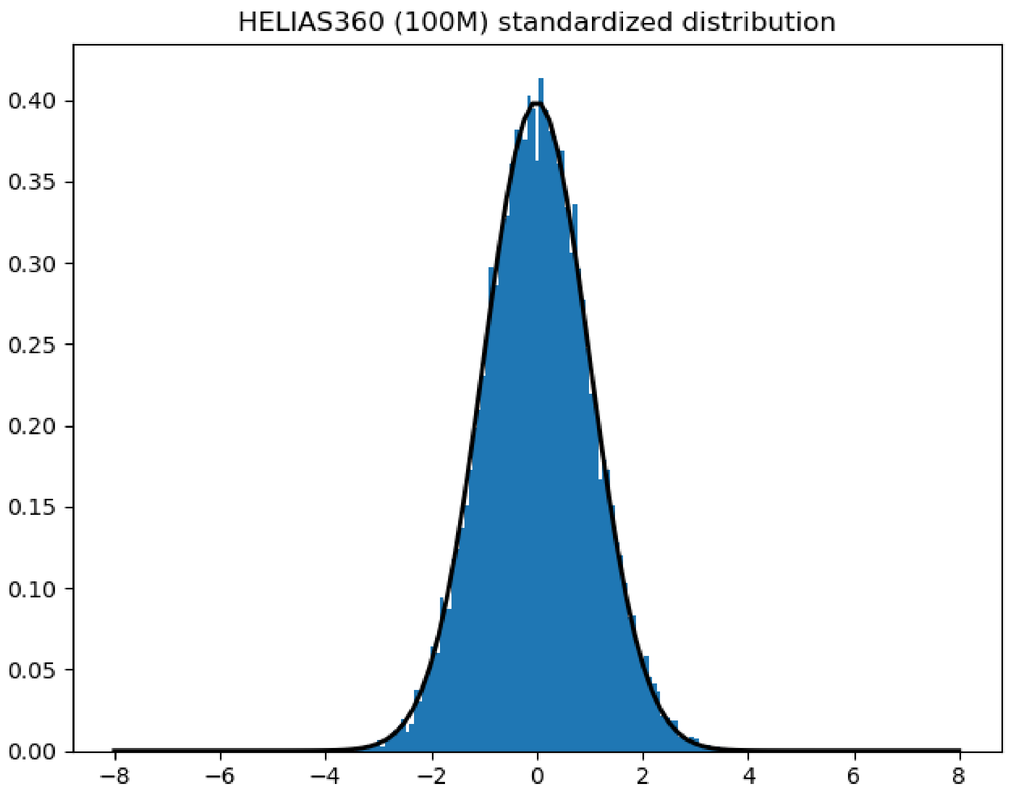
Benchmarking Serpent2 against MCNP6

- 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



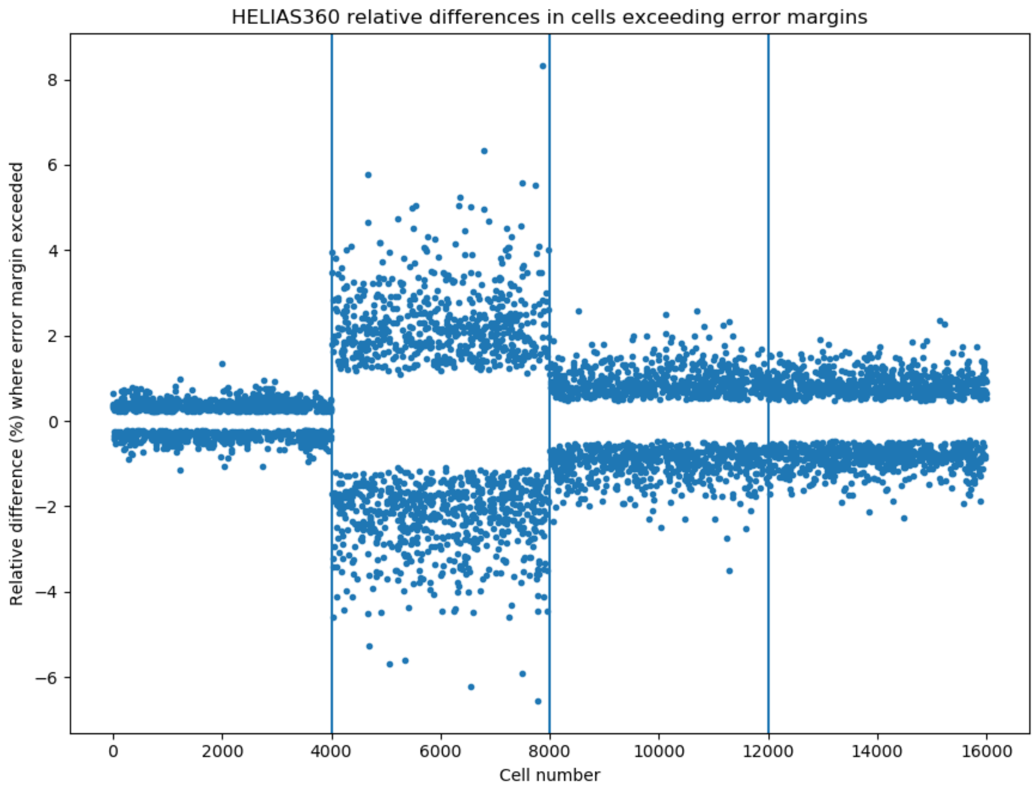
Benchmarking Serpent2 against MCNP6

- 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?



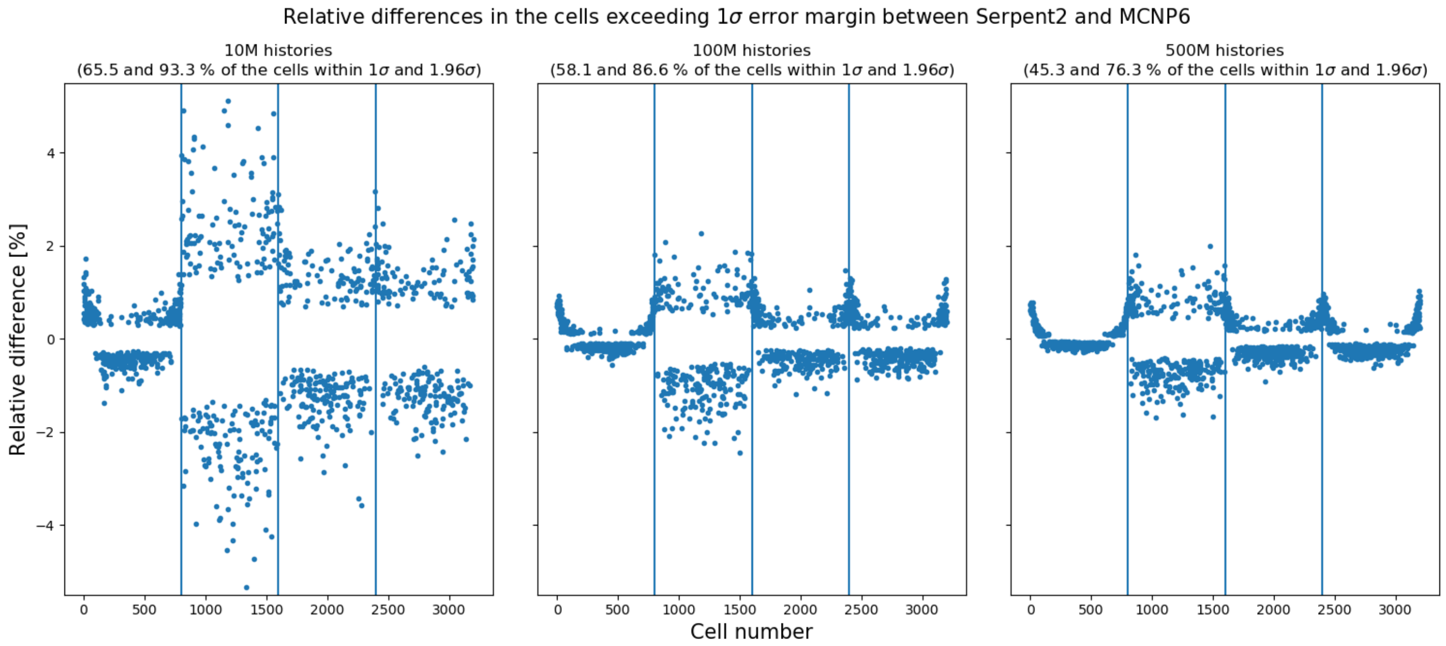
Benchmarking Serpent2 against MCNP6

- ★ 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?



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?



Breeding blanket optimization

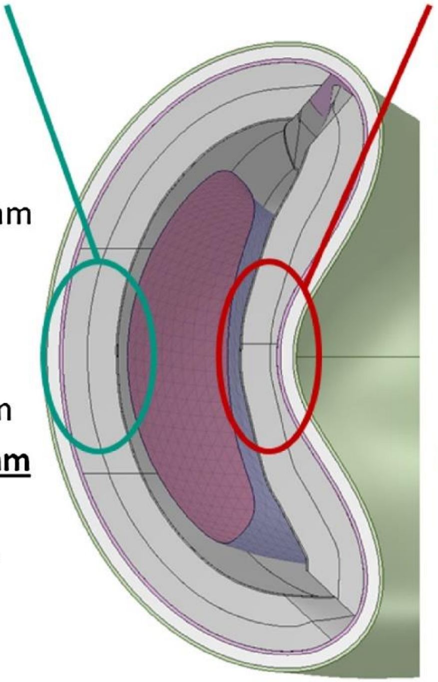
Optimization of the breeding blanket

- ★ 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**

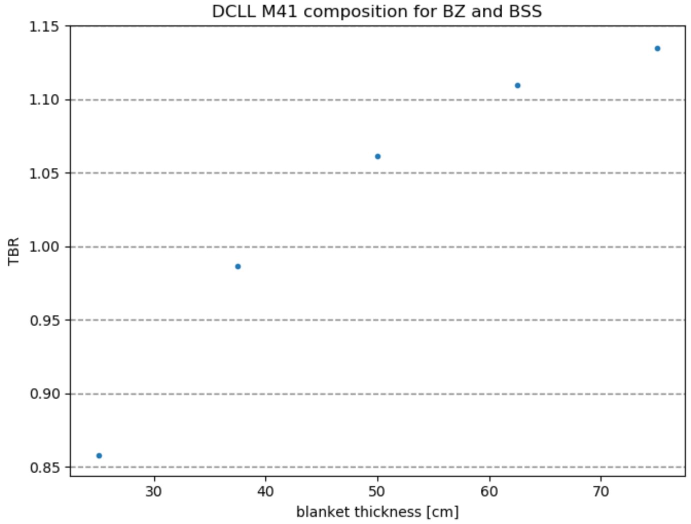
[3] F. Warmer, Fus. Eng. and Des., **123**, 2017, 47-53

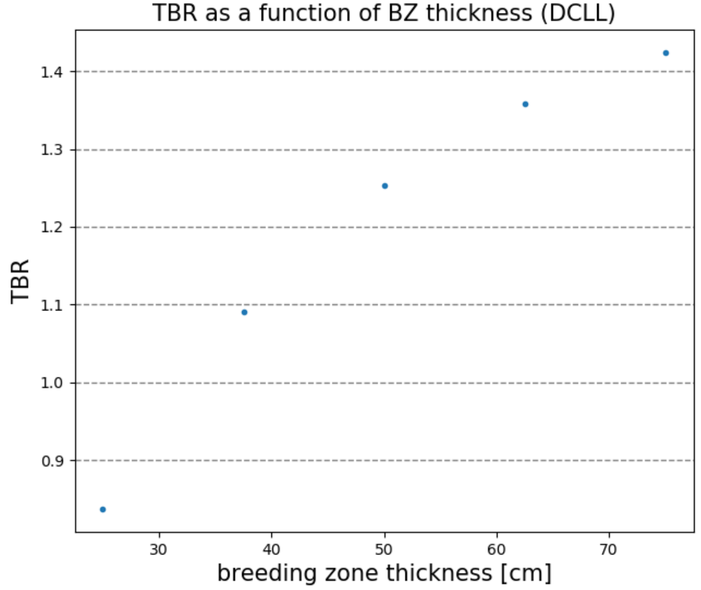
Model generation via parametric model

- 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!

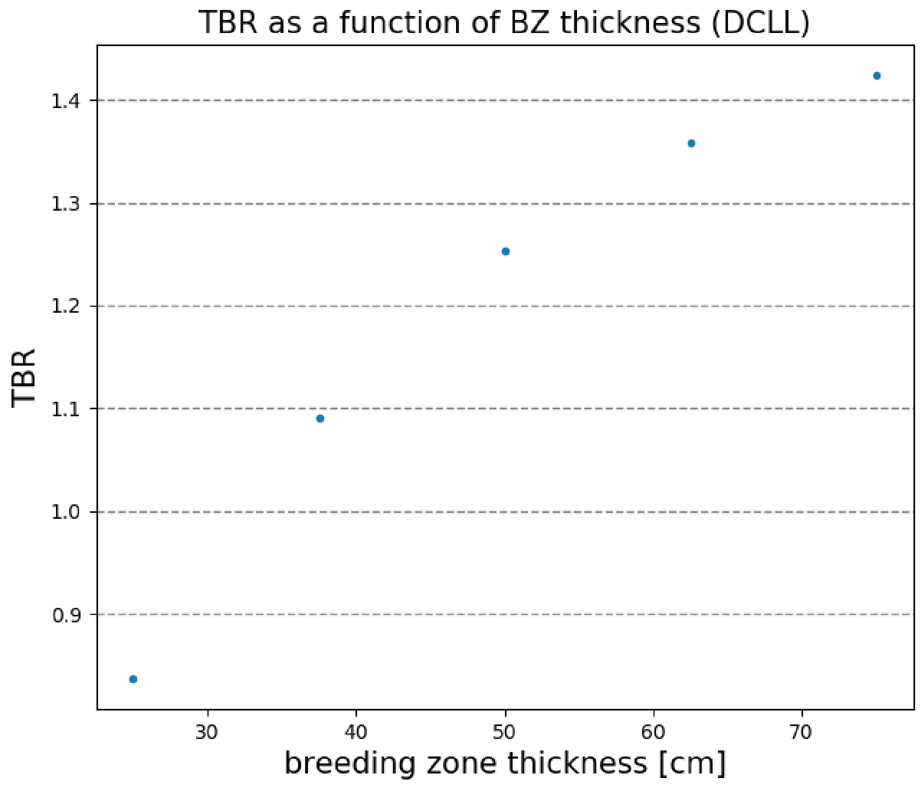




Conclusions/outlook

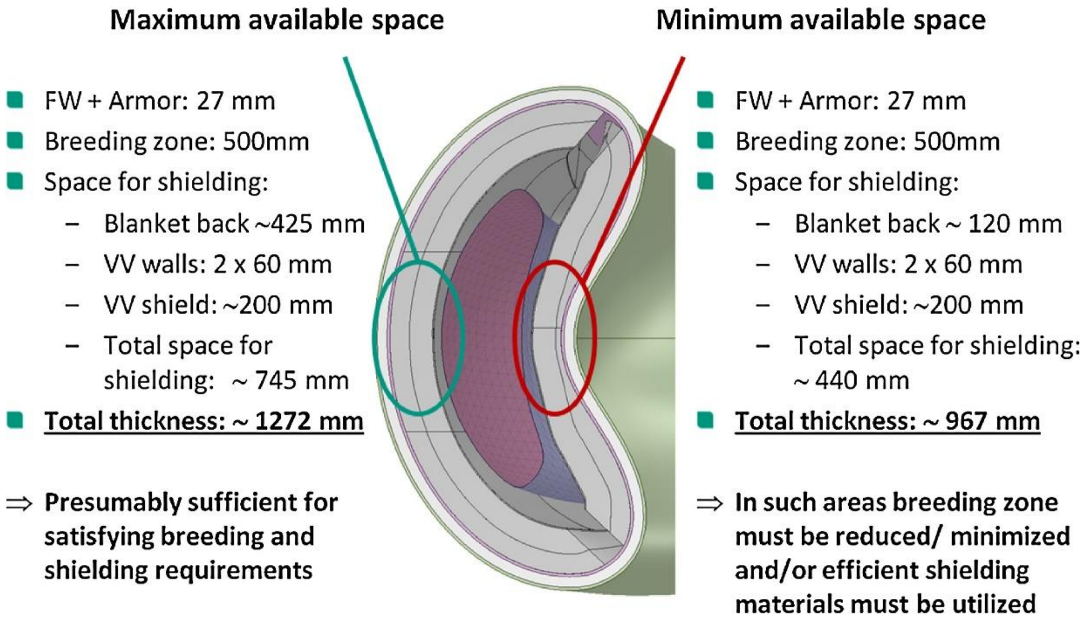
Conclusions

- 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 agains 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 WCLL)
  - 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

Thank you