Use of Mesh based Variance Reduction Technique in Shielding Calculations of the Stellarator Power Reactor HELIAS

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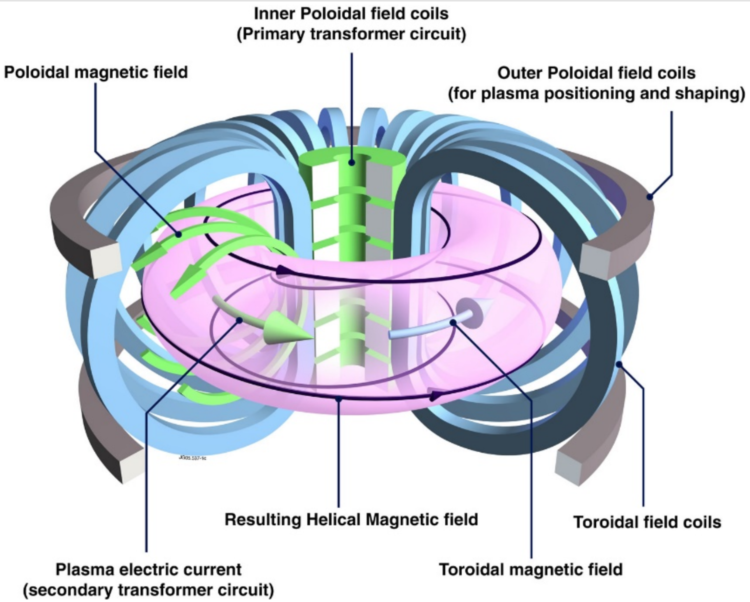
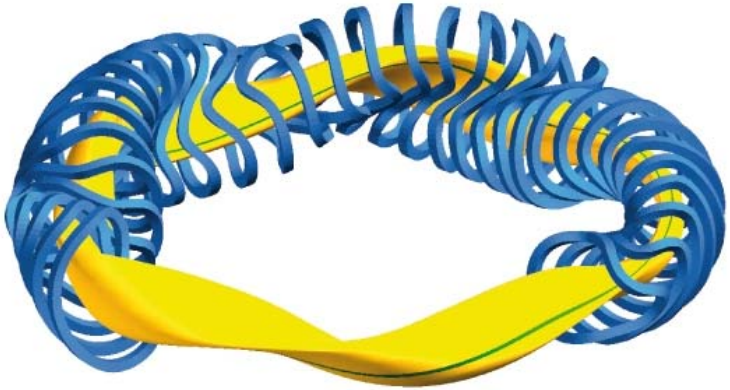
Two concepts of a fusion power reactor



Tokamak

Source: euro-fusion.org



Stellarator

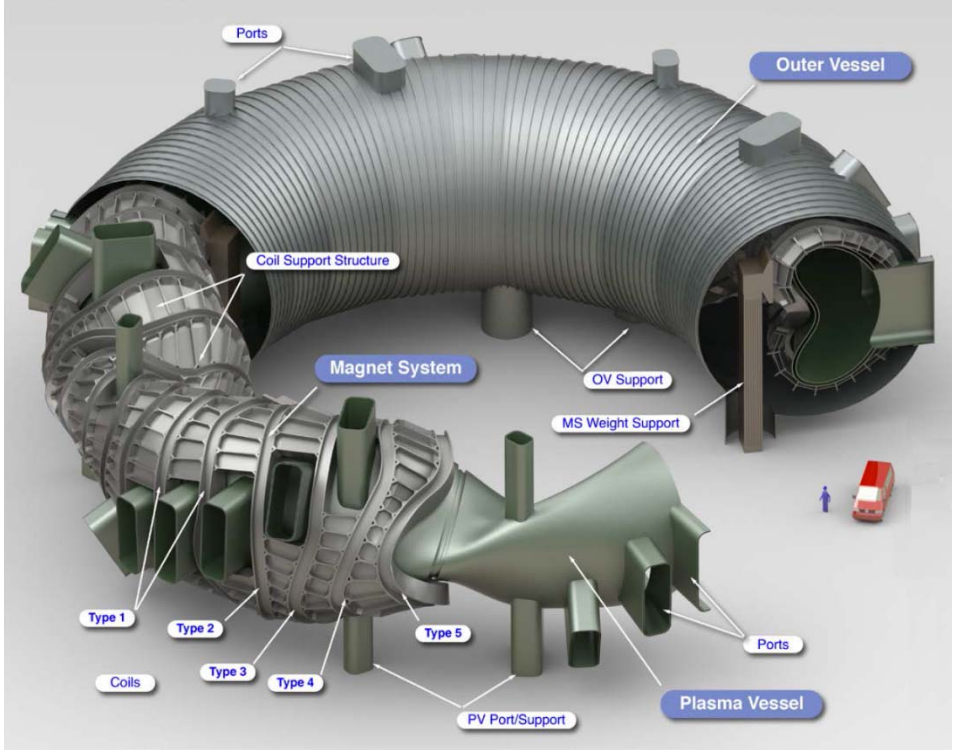
Source: ipp.mpg.de

- Tokamak (Russian “toroidalnaya kamera magnitnaya katishka”)
- Part of the magnetic field is generated through plasma current (transformer principle) → pulsed operation
- ITER should show the generation of energy by controlled fusion reaction

- Stellarator (means: Application of the star energy)
- Magnetic confinement only via external field coils → steady state operation
- Wendelstein 7-X should show that the plasma fulfills the requirements for a power reactor

HELIAS – an overview

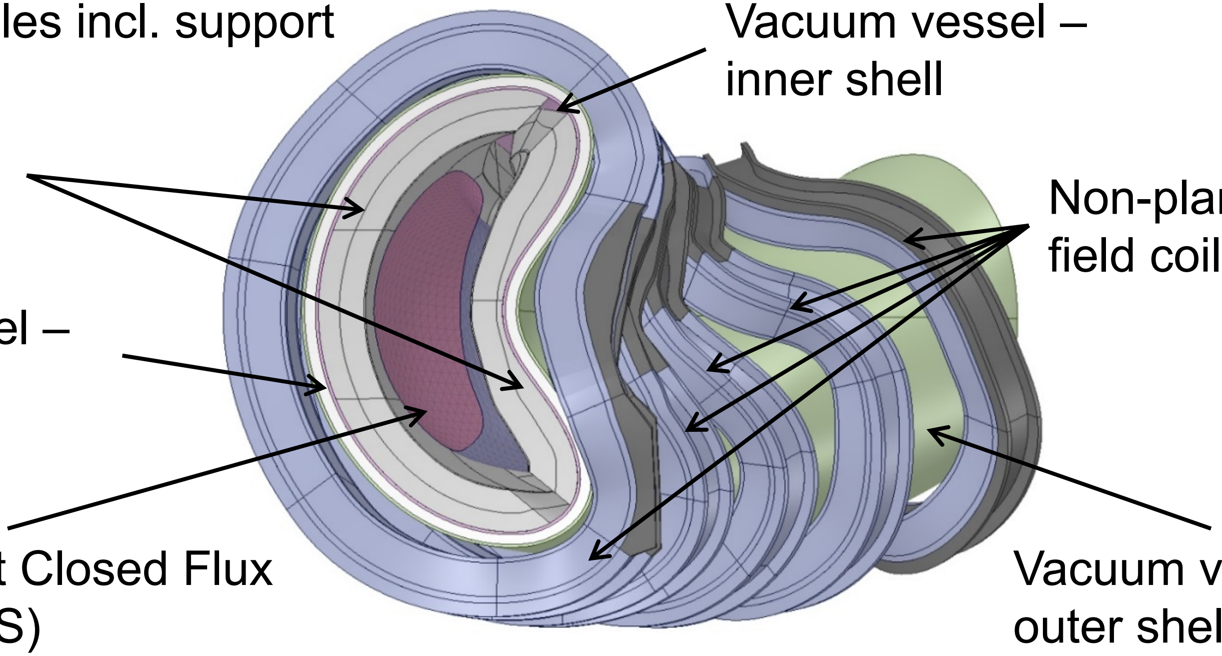
- Stellarator configuration is a possible alternative to Tokamaks
- HELIAS = **HELI**cal-Axis **A**dvanced **S**tellarator
- Extrapolated and upgraded version of Wendelstein 7-X
- Demonstration power reactor study with D-T Fusion
- Plasma volume: ~1400 m^3
- Fusion power: ~3000 MW



HELIAS 5-B

Source: [Sch13] – F. Schauer, et al., *HELIAS 5-B magnet system structure and maintenance concept*, Fus. Eng. Des. 88 (2013)

Geometry and Materials



Blanket modules incl. support structure and shield

Vacuum vessel – inner shell

Non-planar field coils

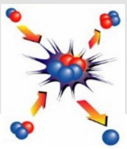
Vacuum vessel – shield

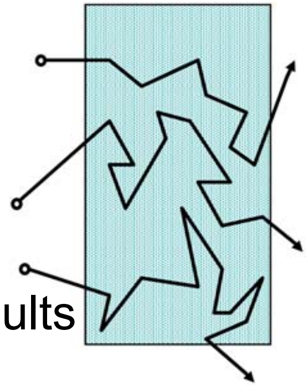
Plasma : Last Closed Flux Surface (LCFS)

Vacuum vessel – outer shell

- Radial build at mid-plane, homogenized material mixtures:
  - 0.2 cm Tungsten Armor → 100% Tungsten
  - 2.5 cm First Wall → 70% Eurofer, 30% Helium
  - 50 cm Breeding Zone → Helium Cooled Pebble Bed (HCPB) with 60% Li-6 enrichment
  - ~10 – 40 cm Back Support Structure → 75% Eurofer, 25% Helium
  - 6.0 cm Inner Vacuum Vessel → 100% Steel (SS-316)
  - 20 cm Vacuum Vessel Shield → 60% Steel (SS-316), 40% Water
  - 6.0 cm Outer Vacuum Vessel → 100% Steel (SS-316)

Fusion Neutronics





- Application based on Monte Carlo Method:
  - Simulation of the true physical process on a microscopic level
  - Probabilistic method → statistical registration of stochastically processes
  - Run many histories to get many events and count them → results are statistically reliable
  - Every history contributes the same weight to the final result
  - Particle transport code MCNP (**M**onte-**C**arlo **N**-**P**article) is standard code in fusion neutronics
- Calculations based on geometry, source (spatial distribution, energy, particle), material data base including nuclear reaction cross sections
- Results are the requested nuclear information, e.g. neutron flux distribution, material load (nuclear heating, degradation), tritium breeding ratio, shielding, shutdown dose rate…

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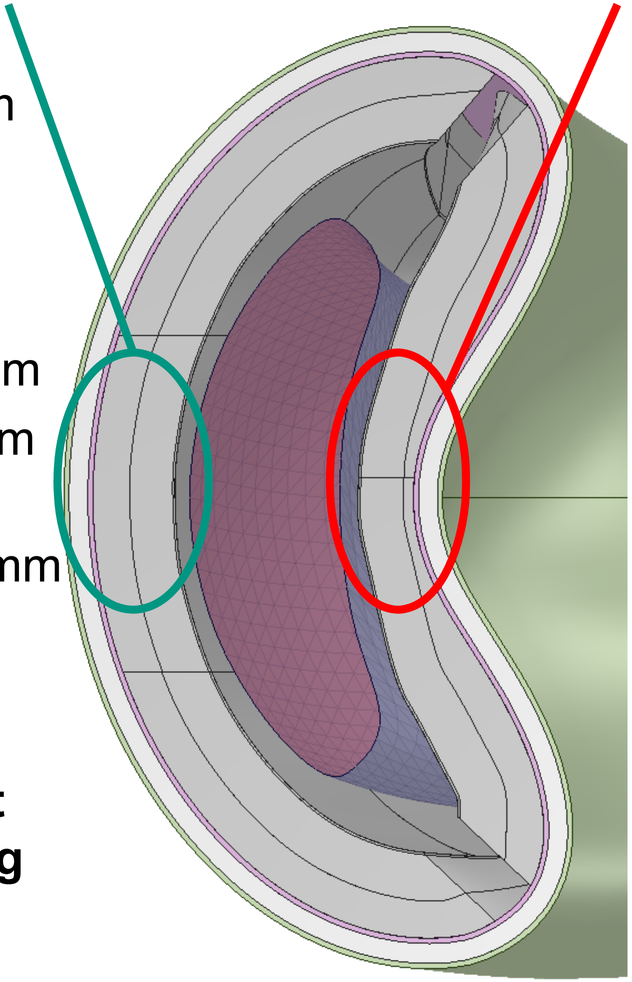
Available radial space for the reactor

Maximum available space

- FW + Armor: 27 mm
- Breeding zone: 500 mm
- 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**



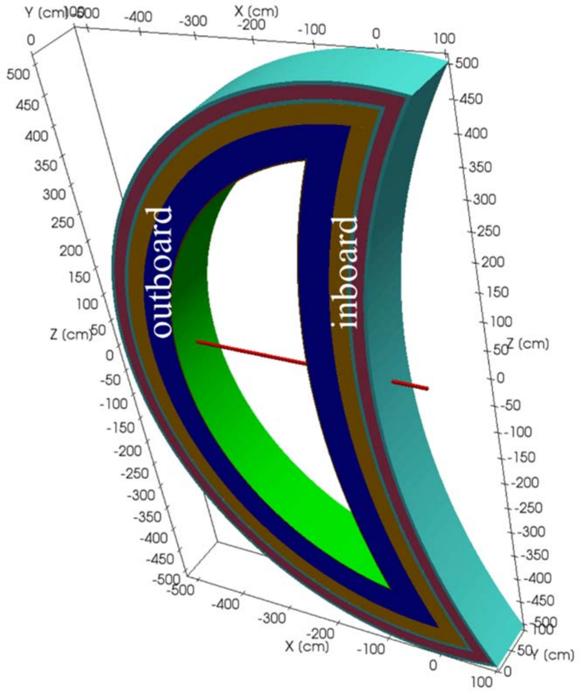
Minimum available space

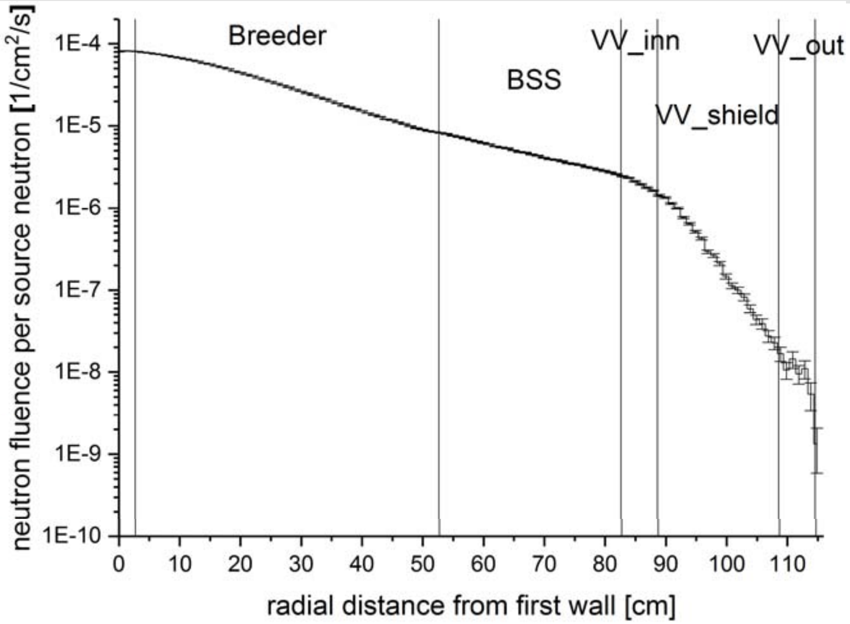
- FW + Armor: 27 mm
- Breeding zone: 500 mm
- Space for shielding:
  - Blanket back ~ 120 mm
  - VV walls: 2 x 60 mm
  - VV shield: ~200 mm
  - Total space for shielding: ~ 440 mm
- **Total thickness:**
  ~ 967 mm

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

Simplified Approach

- Radial build at mid-plane:
    - 0.2 cm Tungsten Armor
    - 2.5 cm First Wall
    - 50 cm Breeding Zone
    - 30 cm Back Support Structure
    - 6.0 cm Inner Vacuum Vessel
    - 20 cm Vacuum Vessel Shield
    - 6.0 cm Outer Vacuum Vessel

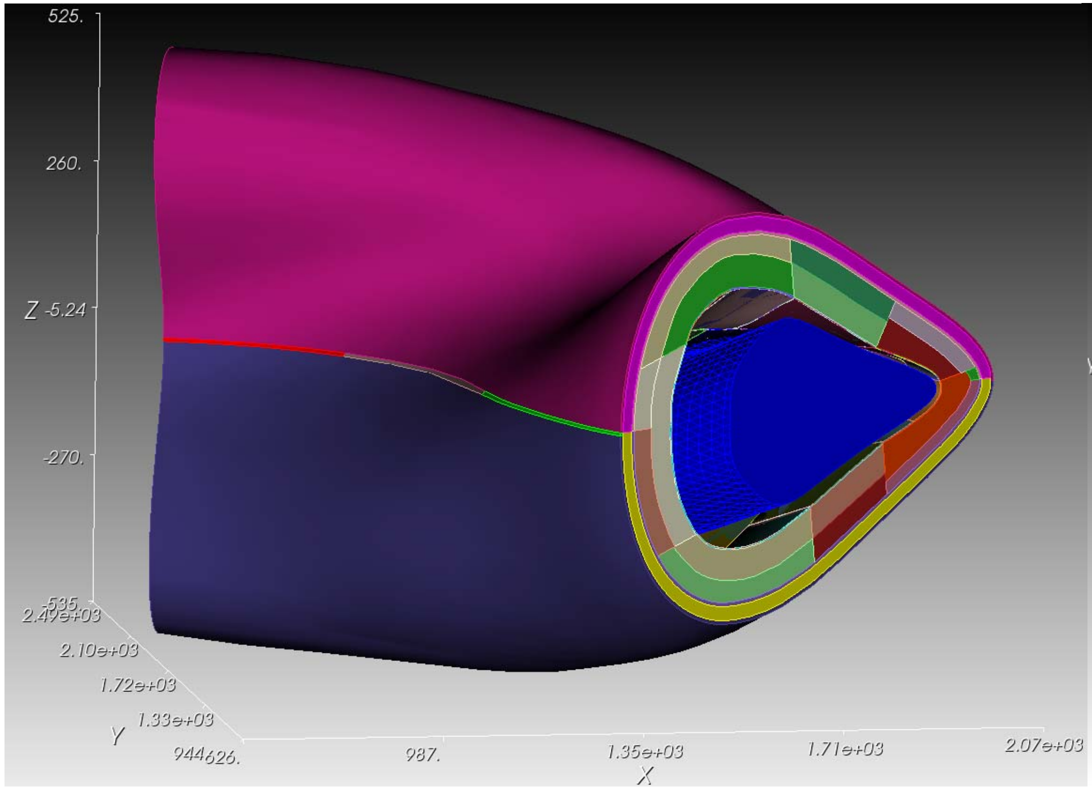


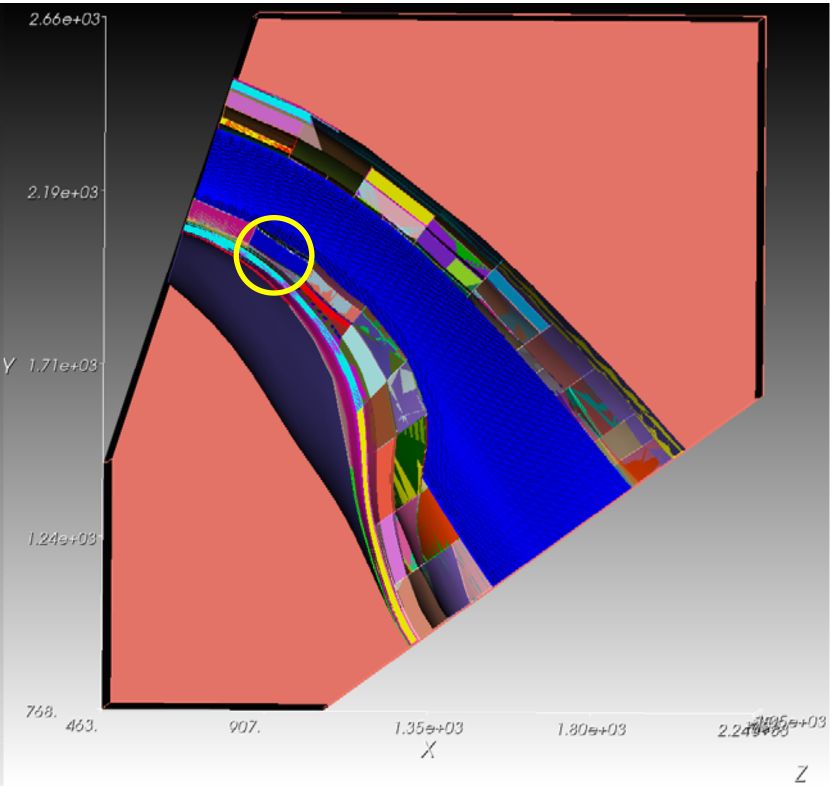


Neutron fluence per source neutron in dependency of the radial distance from the first wall including its corresponding relative statistical error.

- Superconducting field coils are very sensitive for neutron radiation
- Application of Variance Reduction (VR) methods needed to decrease relative statistical error in areas far away from the plasma chamber
- Several options in MCNP available, i.a. the application of mesh based weight windows

HELIAS DAGMC Representation





- HELIAS geometry in DAGMC representation, with LCFS (blue) and bounding box (right picture, orange)
- Area of interest (yellow circle) is inboard side with a high neutron wall load (~1.4MW/m^2) and reduced material thickness ~1m

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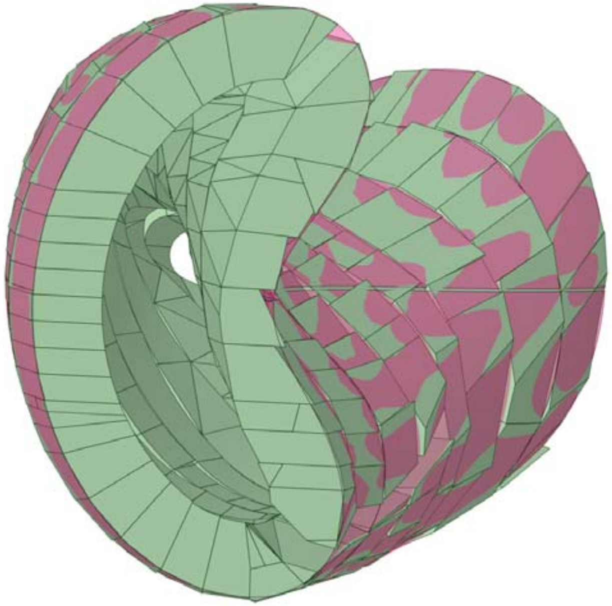
Weight Window Generation

- Weight Window (WW) is a superimposed mesh covering the whole calculation geometry
- Each mesh element contains a particle weight lower-bound value, whereas the upper-bound value is calculated in the MCNP simulation with typically a factor of 5.0
- If the particle weight is above/within/below the weight window cell → particle will be split/kept/killed by Russian Roulette with the particle weight adjusted accordingly

- WW must be generated → MCNP weight window generator or ADVANTG
- MCNP WW generator needs several iteration steps to generate a suitable WW → long lasting process

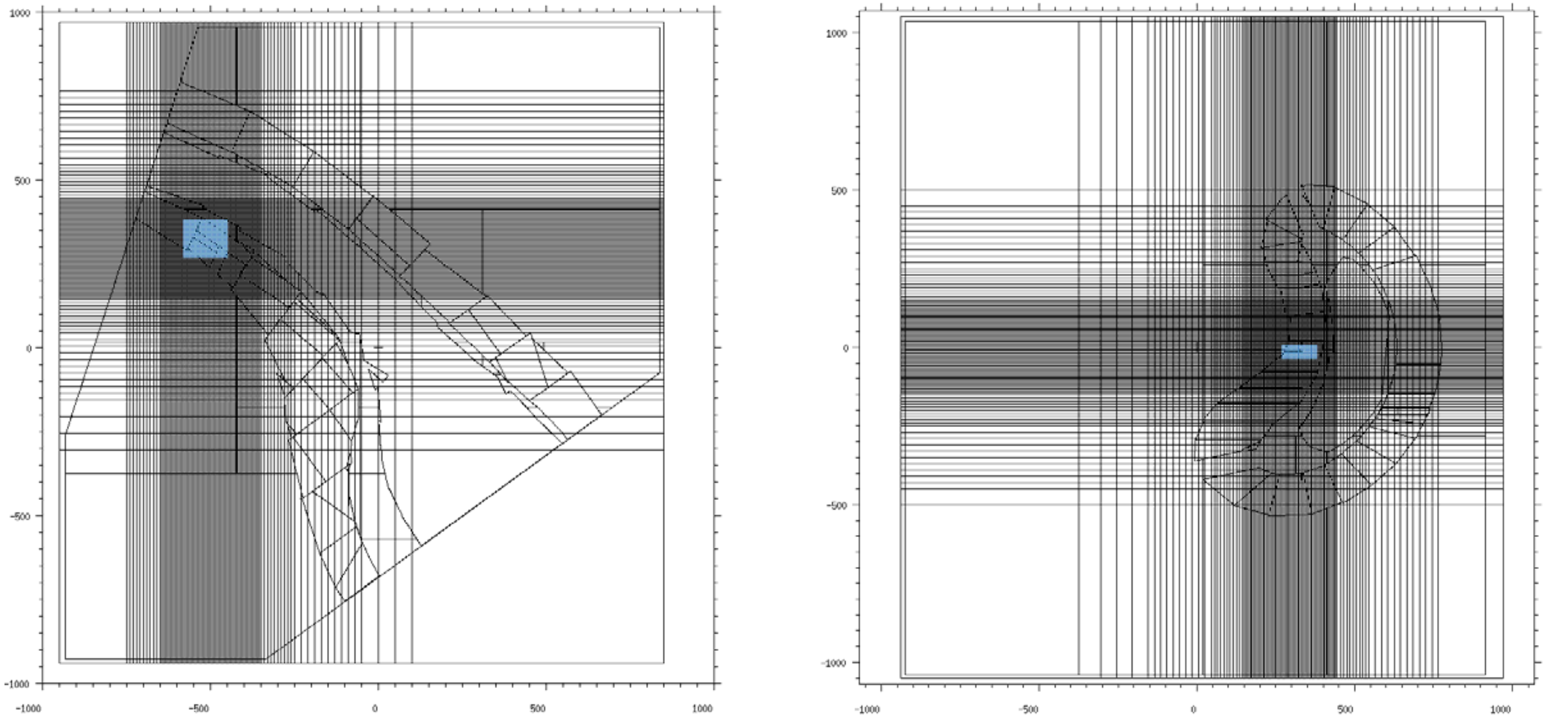
Weight Window Generation

- ADVANTG (AutomateD VAriaNce reducTion Generator) – software that automates the process of generating MCNP compatible weight windows
- Only one run for the WW generation calculation
- Drawbacks of ADVANTG: does neither handle the complex HELIAS geometry nor the user specific source subroutine
- Source definition for ADVANTG: Volumetric source representing the LCFS volume with uniform distribution of neutrons



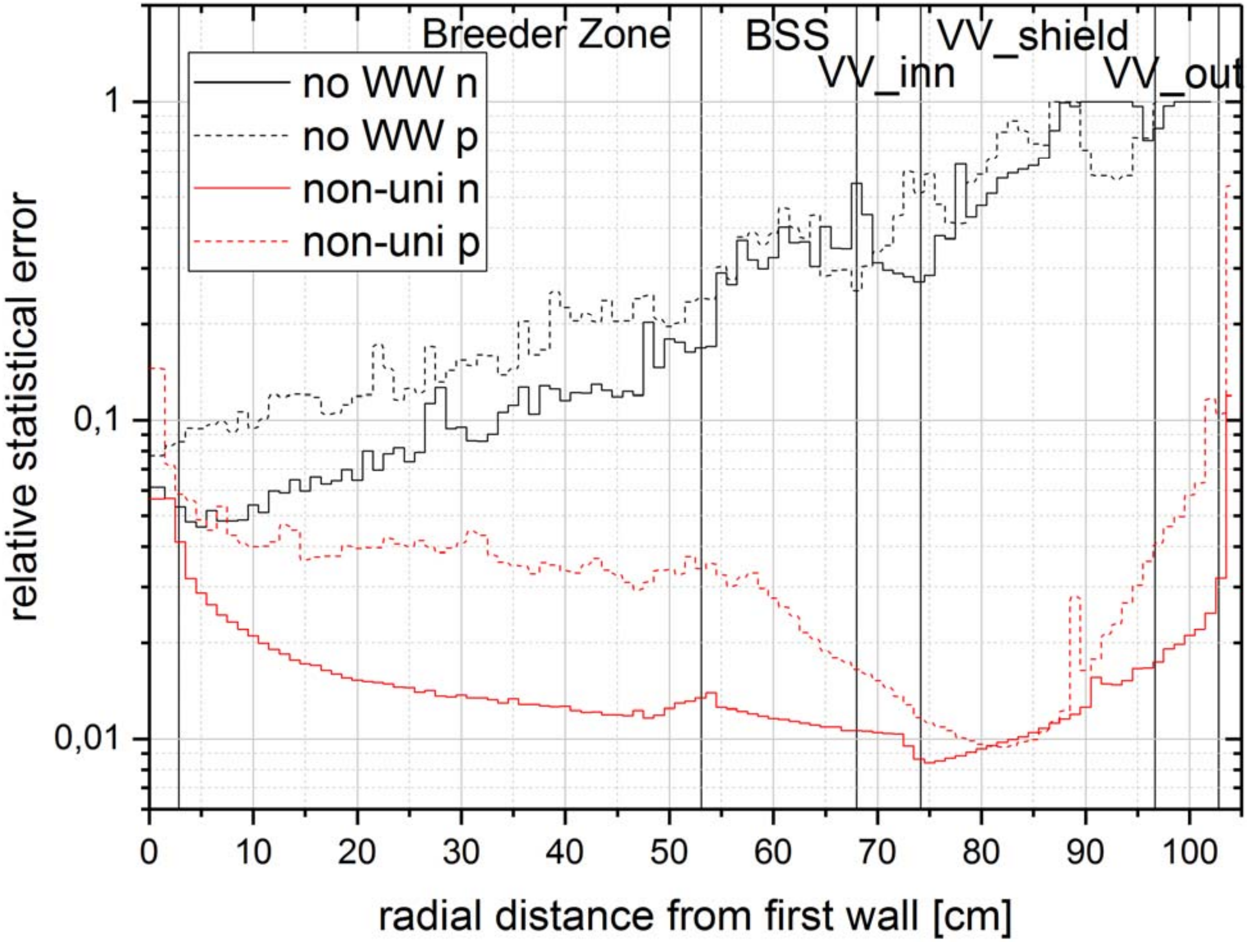
- ADVANTG Geometry: only one material layer (green) with homogenized and weighted mixture of all materials and densities of the real stellarator model
- Pink Vacuum Vessel layer only for visualization

Weight Window Generation



- Different WW mesh settings investigated → uniform and non-uniform setting
- Area of interest (blue) for ADVANTG calculation
- Limitation in ADVANTG of max. number of WW mesh cells at ~10^6 for this geometry
- Pictures show non-uniform (5x5x5 cm^3) mesh in area of interest and coarser in other parts, in xy and xz plane, optimized for neutrons and photons

Relative statistical error



- Relative statistical error determined inside the area of interest with a mesh tally for neutrons and photons
- Statistically error significantly decreased with applied WW

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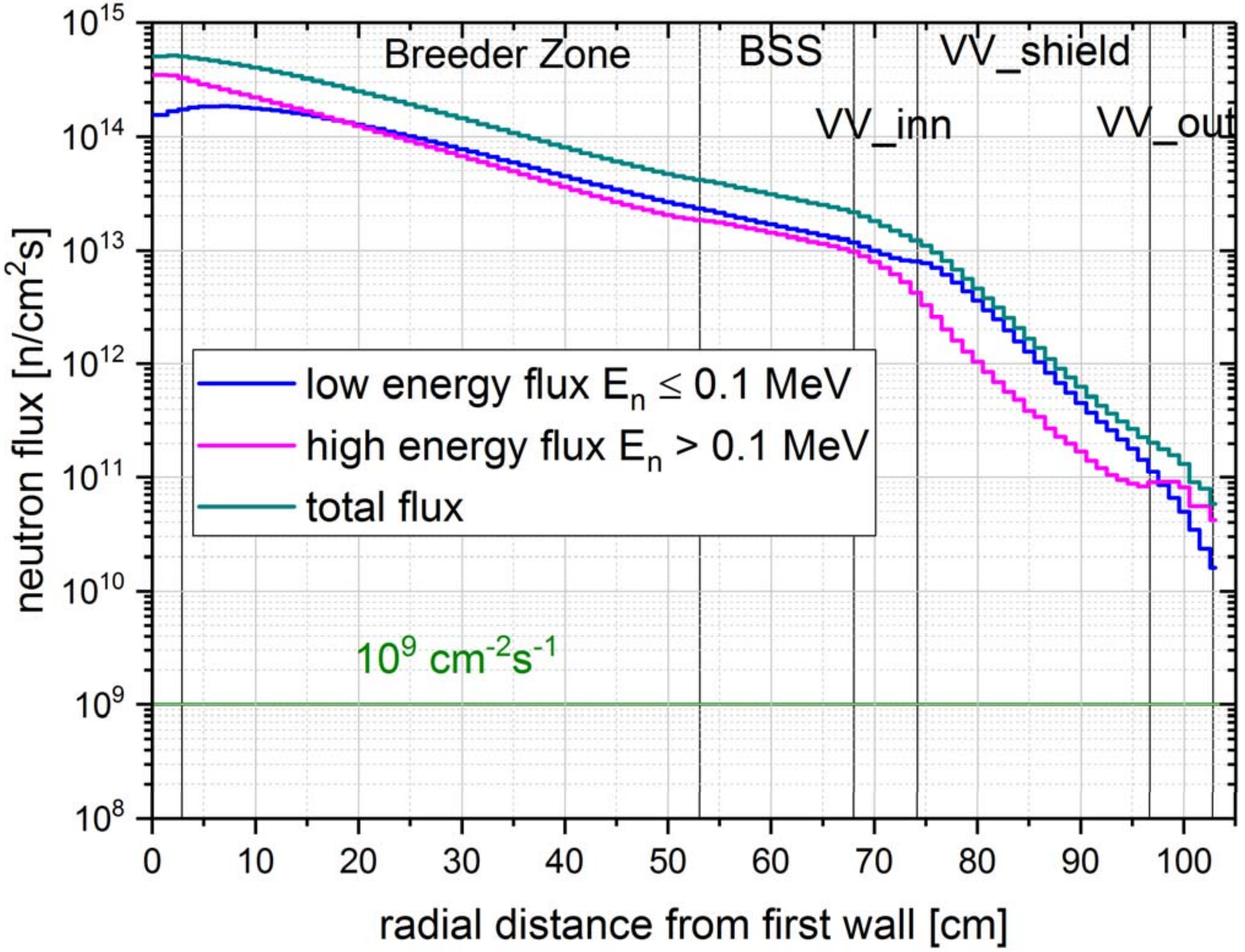
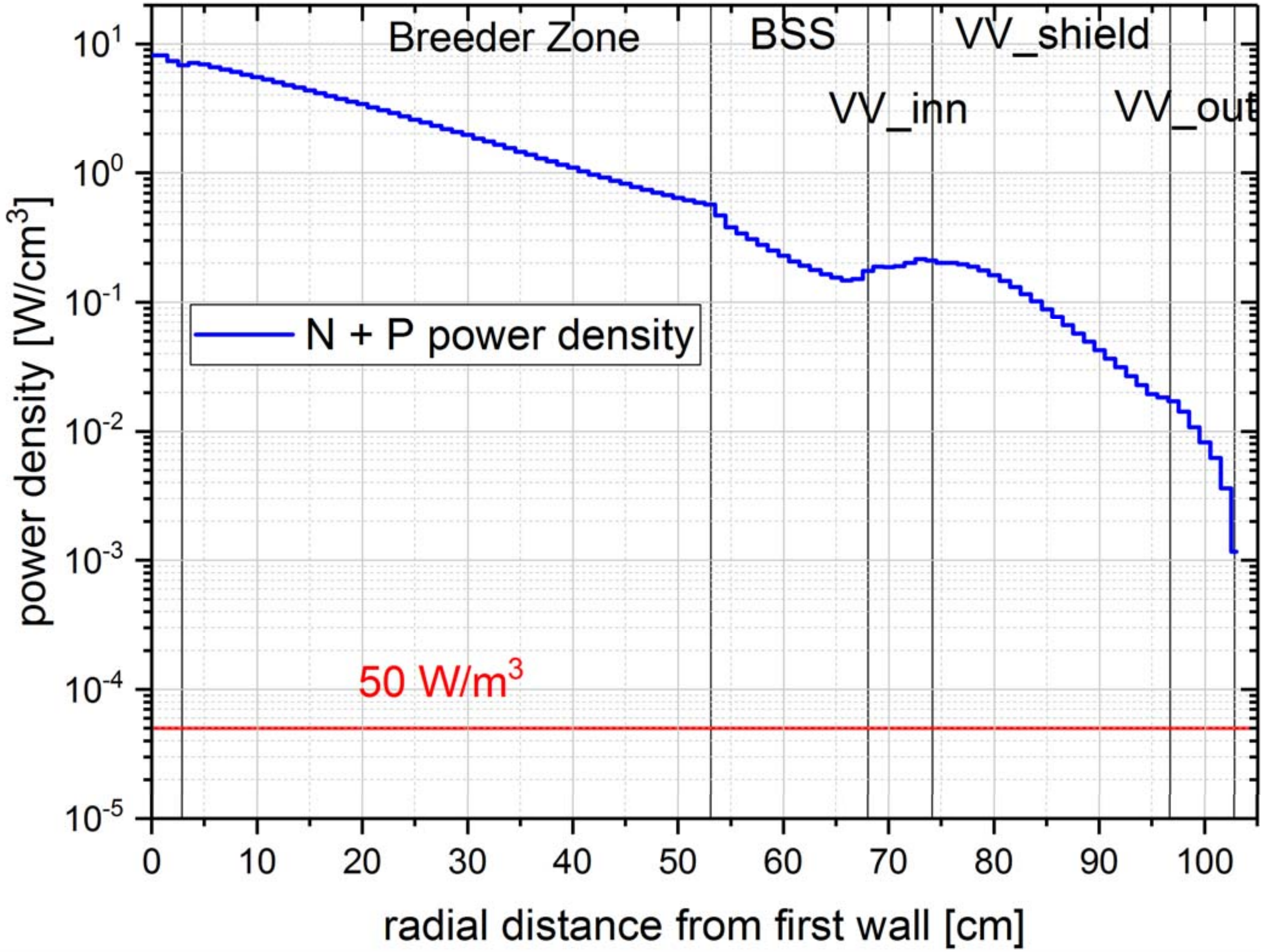
- Mesh based Weight Windows
- Nuclear Responses in Area of Interest
- Conclusion and Outlook

Neutron Flux



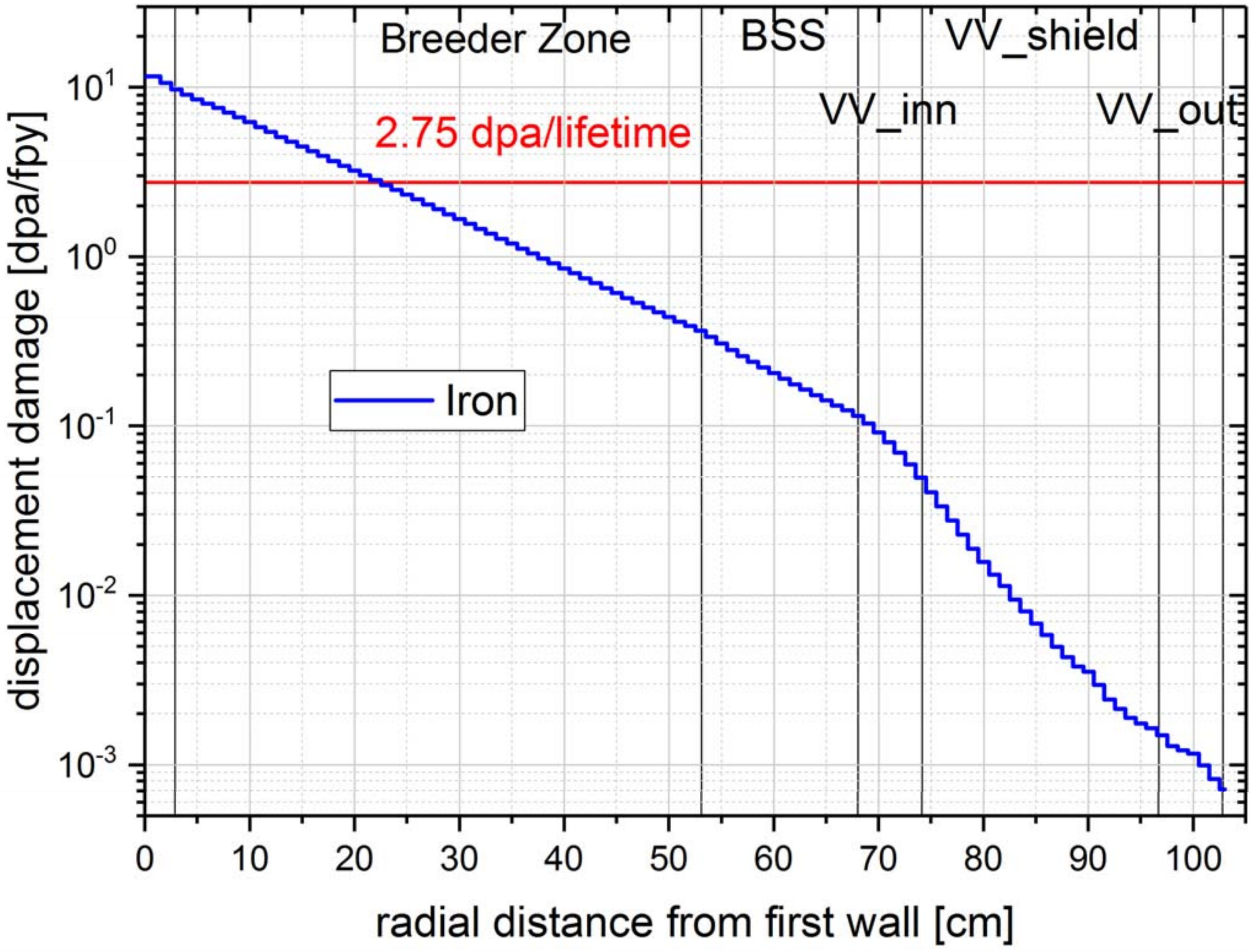
- DEMO requirement: “Maximum neutron fluence to epoxy insulator” → target: **10^{22} m^{-2} → 10^9 cm^{-2}s^{-1}** to coils (irradiation scenario: 20 CY, 6 FPY).

Nuclear Heating



- DEMO requirement: “Peak nuclear heating in winding pack” → limit: **50 W/m^3** to coils.

Displacement Damage



- DEMO requirement: “Lifetime criteria in order to ensure that the fracture toughness is reduced by no more than 30%” → limit: **2.75 dpa/lifetime** to Vacuum Vessel
- VV_inn: **~0.11 dpa/fpy** → lifetime of 25 years guaranteed to reach EU DEMO design limit

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Conclusion and Outlook

- Mesh based weight window method suitable for HELIAS
- Significant difference between non-VR and VR cases
- Statistical reliable radial profiles of relevant nuclear responses from first wall to magnetic field coil
- DEMO requirements for superconducting magnets not fulfilled in critical area

- Recommended design improvements → larger shielding layer and/or more efficient shielding materials