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

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Table of Content

- Introduction
- Problem Statement
- Mesh based Weight Windows
- Nuclear Responses in Area of Interest
- Conclusion and Outlook
Two concepts of a fusion power reactor

- **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

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Tokamak
Source: euro-fusion.org

Stellarator
Source: ipp.mpg.de
Stellarator configuration is a possible alternative to Tokamaks

- HELIAS = HELical-Axis Advanced Stellarator
- Extrapolated and upgraded version of Wendelstein 7-X
- Demonstration power reactor study with D-T Fusion
- Plasma volume: \( \sim 1400 \text{ m}^3 \)
- Fusion power: \( \sim 3000 \text{ MW} \)

**HELIAS 5-B**

Geometry and Materials

Blanket modules incl. support structure and shield

Vacuum vessel – outer shell

Non-planar field coils

Vacuum vessel – inner shell

Plasma: Last Closed Flux Surface (LCFS)

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

• Introduction
• Problem Statement
• Mesh based Weight Windows
• Nuclear Responses in Area of Interest
• Conclusion and Outlook
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 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/m²) and reduced material thickness ~1m
<table>
<thead>
<tr>
<th>Table of Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Introduction</td>
</tr>
<tr>
<td>• Problem Statement</td>
</tr>
<tr>
<td>• Mesh based Weight Windows</td>
</tr>
<tr>
<td>• Nuclear Responses in Area of Interest</td>
</tr>
<tr>
<td>• Conclusion and Outlook</td>
</tr>
</tbody>
</table>
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, the 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
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 determined inside the area of interest with a mesh tally for neutrons and photons
• Statistically error significantly decreased with applied WW
Table of Content

- Introduction
- Problem Statement
- Mesh based Weight Windows
- Nuclear Responses in Area of Interest
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**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).

Andre Häußler | AAA Workshop | GRS – Garching, Germany | 03.12.2018 | Page 17
• DEMO requirement: “Peak nuclear heating in winding pack” → limit: \(50 \text{ W/m}^3\) to coils.
- 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
<table>
<thead>
<tr>
<th>Table of Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction</td>
</tr>
<tr>
<td>2. Problem Statement</td>
</tr>
<tr>
<td>3. Mesh based Weight Windows</td>
</tr>
<tr>
<td>4. Nuclear Responses in Area of Interest</td>
</tr>
<tr>
<td>5. Conclusion and Outlook</td>
</tr>
</tbody>
</table>
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