Neutrons and secondary particle analysis in PHITS of HTS components for compact fusion reactors

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Overview

General introduction to the topic

Monte Carlo codes and model description

PHITS–OpenMC cross comparison

VIPER cable analysis

Further developments
Nuclear fusion: challenges

- Extremely high thermal fluxes
- Plasma behaviour and confinement
- Power extraction
- Plasma-surfaces interaction
- Radiation environment and damage of materials
- Tritium breeding and extraction

https://www.iter.org/sci/iterandbeyond
Radiation environment and damage

- **Main topic**: Modelling the neutron radiation effects on HTS magnets in thermonuclear fusion reactors

How is the radiation environment?

Monte Carlo simulations

How do materials react?

Molecular dynamics tools

Is the prediction reliable?

- Literature data
- Ad hoc experiments

Davide Gambino
Talk today, 17:00 – 17:30
Radiation environment and damage

- To predict the neutron distribution inside the reactor MonteCarlo codes are required.

- The PHITS code, developed by JAEA, was chosen for its good geometry handling, the possibility of customizing the code, of transporting any particle and of evaluating the dpa directly and compared with the code OpenMC.

source https://phits.jaea.go.jp/index.html
How do neutrons distribute?

Geometry management

Model geometry (CAD conversion)

Source geometry declaration (PHITS customization)
Model geometry

- To perform the transport simulation, the geometry must be declared in PHITS

- The actual geometry of a fusion device is not trivial, declaring it in PHITS by hand using a combination of elementary surfaces is not feasible/prone to errors and implementation of design changes becomes extremely slow

A smarter way is required

Model geometry

From version 3.30 PHITS supports tetrahedral meshed geometry that can be used to import any CAD.

The DAGMC tool can be used to import CAD in OpenMC.

https://wias-berlin.de/software/tetgen/
Model geometry

- A good 3D model of reactor Vacuum Vessel (VV) represents the first step of the simulations.

- The PHITS/OpenMC cross comparison was carried out on a 10° degree sector of the reactor with reflective boundary conditions and on a complete 360° model.

| Inconel 718 |  |
|-------------|---|---|---|---|---|---|
| Element     | Ni | Cr | Mo | Nb/Cb | Ti | Al |
| Mass %      | 50 | 17 | 2.80 | 4.75 | 0.65 | 0.2 |

To perform a particle transport simulation, a particle source is required.

A toroidal plasma source was available in OpenMC.

We introduced a customized plasma source in PHITS, including all the main physical parameters (e.g., Shafranov factor, helicity...).

Both the sources are based on Fausser et al., Fusion Eng. Des., 2012 and give the same neutron distribution.
Analysis on the VV: spectra

«3D neutronic analysis on compact fusion reactors: PHITS-OpenMC cross-comparison», F. Ledda et al., (submitted to Fusion Engineering and Design)

- 3 different nuclear libraries were tested in PHITS and OpenMC, simulating 1 billion neutrons for run
- The use of different codes has the largest impact on the results
- The discrepancy on the low energy region is due to geometry handling issues in DAGMC

Relative difference = \[ \frac{\phi_{PHITS} - \phi_{OpenMC}}{\phi_{reference}} \]
Analysis on the VV: power deposition

«3D neutronic analysis on compact fusion reactors: PHITS-OpenMC cross-comparison», F. Ledda et al., (submitted to Fusion Engineering and Design)

- The total power deposition evaluated with OpenMC and PHITS are in good agreement
- Power deposition on the first wall is affected by the largest discrepancy
- For this case, the best agreement with the average data in literature was obtained with PHITS running with the native JENDL-4.0 library
Analysis on the VV: TBR

«3D neutronic analysis on compact fusion reactors: PHITS-OpenMC cross-comparison», F. Ledda et al., (submitted to Fusion Engineering and Design)

<table>
<thead>
<tr>
<th>Code</th>
<th>Geometry</th>
<th>Library</th>
<th>TBR value ± uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHITS</td>
<td>Full domain</td>
<td>ENDF/B-VIII.0</td>
<td>1.0766 ± 0.0001</td>
</tr>
<tr>
<td>PHITS</td>
<td>Full domain</td>
<td>JENDL-4.0</td>
<td>1.0736 ± 0.0001</td>
</tr>
<tr>
<td>PHITS</td>
<td>Full domain</td>
<td>FENDL-3.2</td>
<td>1.0703 ± 0.0001</td>
</tr>
<tr>
<td>PHITS</td>
<td>10°domain + reflective BC</td>
<td>ENDF/B-VIII.'</td>
<td>1.0761 ± 0.0001</td>
</tr>
<tr>
<td>OpenMC</td>
<td>Full domain</td>
<td>ENDF/B-VIII.0</td>
<td>1.0626 ± 0.0001</td>
</tr>
<tr>
<td>OpenMC</td>
<td>Full domain</td>
<td>JENDL-4.0</td>
<td>1.0737 ± 0.0001</td>
</tr>
<tr>
<td>OpenMC</td>
<td>Full domain</td>
<td>FENDL-3.2</td>
<td>1.0495 ± 0.0001</td>
</tr>
<tr>
<td>OpenMC</td>
<td>10°domain + reflective BC</td>
<td>ENDF/B-VIII.0</td>
<td>1.0625 ± 0.0001</td>
</tr>
</tbody>
</table>

- The Tritium Breeding Ratio shows a difference between the two codes of the order of the percent
- Neither the effect of the usage of a different code nor of a different library seems to be prevalent
- The best agreement between the two codes is obtained with the nuclear library JENDL-4.0
Analysis on the VV

- Neutron spectra were evaluated in 5 poloidal locations at the interface with the TFC position.

- Point A is the most critical: this spectrum will be used as input for further analyses of the effects on superconductors.
A realistic 3D model of 1 pitch of a superconducting VIPER cable was generated in COMSOL multiphysics® and imported in PHITS
From the VV to the cable

The neutron spectrum evaluated at point A of the reactor geometry was implemented in a planar source emitting collimated neutrons toward the VIPER model.
Results on the cable: neutron spectra

“3D neutronic and secondary particles analysis on YBCO tapes for compact fusion reactors”
F. Ledda, D. Torsello et al. (submitted to IEEE Transactions on Applied Superconductivity)

- We observe an enhancement of the neutron flux on the HTS stacks and a spectral shift
- Material choice should be optimized for the nuclear environment

Presented at Eucas 2023 (poster)
Results on the cable: power deposition

“3D neutronic and secondary particles analysis on YBCO tapes for compact fusion reactors”
F. Ledda, D. Torsello et al. (submitted to IEEE Transactions on Applied Superconductivity)

- For nuclear load evaluation, HTS composition details were deduced from Superpower® tapes
- The HTS stack is the most loaded element in the VIPER cable from a power deposition point of view.
Results on the cable: dpa

“3D neutronic and secondary particles analysis on YBCO tapes for compact fusion reactors”
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<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>dpa after 10 years</td>
<td>0.21 JENDL 4.0</td>
</tr>
<tr>
<td></td>
<td>0.23 ENDF-VIII/B</td>
</tr>
<tr>
<td></td>
<td>0.23 FENDL 3.2</td>
</tr>
<tr>
<td>Neutron heat deposition (kW/m³)</td>
<td>33.6</td>
</tr>
<tr>
<td>Decay heat after 10 years (kW/m³)</td>
<td>0.82</td>
</tr>
</tbody>
</table>

- The HTS stack was assumed to be composed of pure YBCO for dpa evaluation
- Dpa after 10 years supports the order of magnitude and refines a previous estimate (D. Torsello et al., 2023 Supercond. Sci. Technol., 36 014003)
- Decay heat is negligible when compared with direct neutron load
Results on the cable: secondary particles

“3D neutronic and secondary particles analysis on YBCO tapes for compact fusion reactors”
F. Ledda, D. Torsello et al. (submitted to IEEE Transactions on Applied Superconductivity)

- Secondary particles (among which photons, electrons and protons) are generated in the cable, with not negligible fluxes.

- Their effect on HTS performance during reactor operations should be considered: experiments of superconductivity performance under irradiation are crucial.
What next?

• Exploit the MC capability to consider complex geometries and sources, analyzing different cable designs

• Refine the reactor model, including penetrations, ports and instrumentations

• Introduction of more sophisticated dpa formulations, considering also athermal recombination (e.g. ARC-dpa)

• PKA spectra evaluation directly in the MC code

• Employ the MC simulation for reactor design optimization
Thanks for your attention!