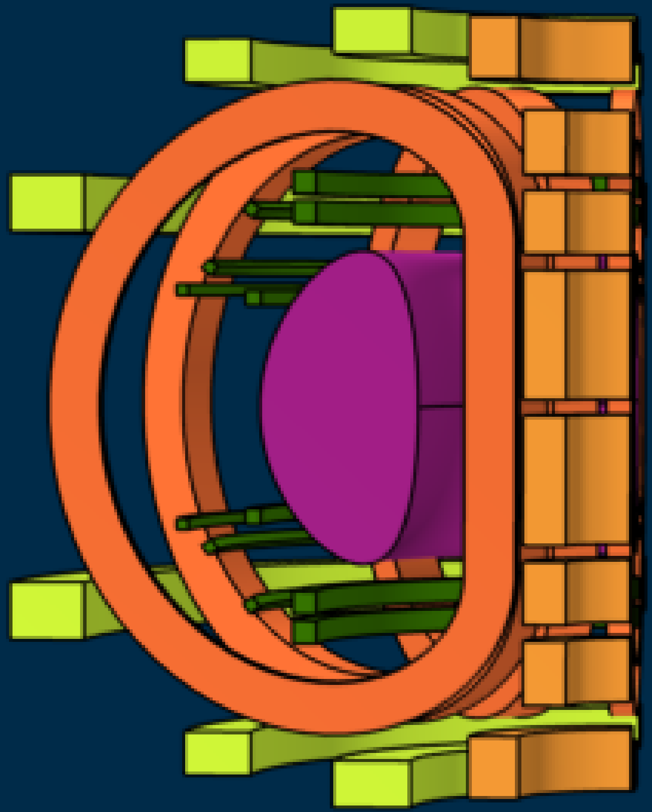


Neutrons and secondary particle analysis in PHITS of HTS components for compact fusion reactors

Federico Ledda, Matteo Di Giacomo, Simone Sparacio, Daniele Torsello, Francesco Laviano

Politecnico di Torino 1859
DISAT chimica fisica materiali scienza e ingegneria
INFN

Ministero dell'Università e della Ricerca
Italiadomani Piano Nazionale di Ripresa e Resilienza
Finanziato dall'Unione europea NextGenerationEU
eni

The collaboration network

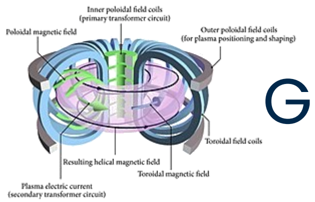
Politecnico di Torino
1859
ESSENTIAL

eni

Massachusetts Institute of Technology
PSFC Plasma Science and Fusion Center Massachusetts Institute of Technology

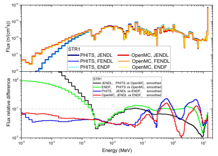
Politecnico di Torino	eni	MIT PSFC
Massimo Zucchetti	Eliana de Marchi	Zachary Hartwig
Raffaella Testoni	Antonio Trotta	Alexsis Devitre
Davide Pettinari	Miriam Parisi	Zoe Fisher
Gabriele Ferrero	Erik Gallo	Samuele Meschini

Overview

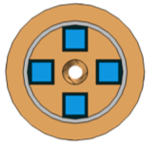


General introduction to the topic

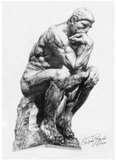
Monte Carlo codes and model description



PHITS-OpenMC cross comparison



VIPER cable analysis



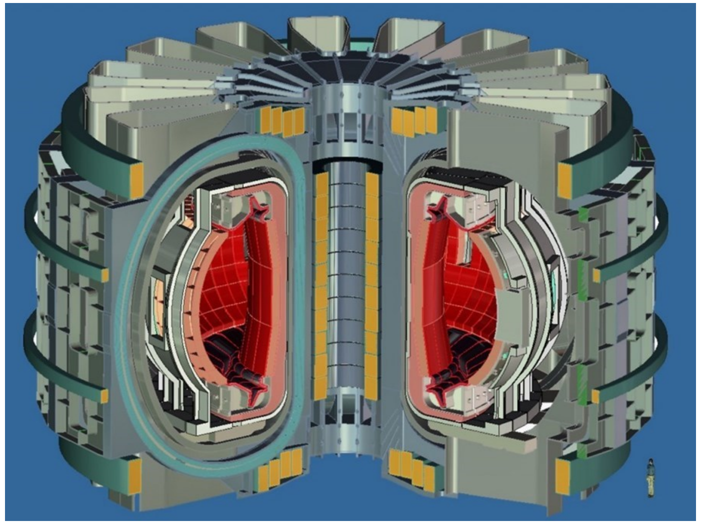
Further developments

Nuclear fusion: challenges

Extremely high thermal fluxes

Plasma-surfaces interaction

Plasma behaviour and confinement



https://www.iter.org/sci/iterandbeyond

Radiation environment and damage of materials

Power extraction

Tritium breeding and extraction

Radiation environment and damage

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

How is the radiation environment? → **MonteCarlo simulations** (PHITS, OpenMC)

How do materials react? → **Molecular dynamics tools** (LAMMPS, LINKÖPING UNIVERSITY)

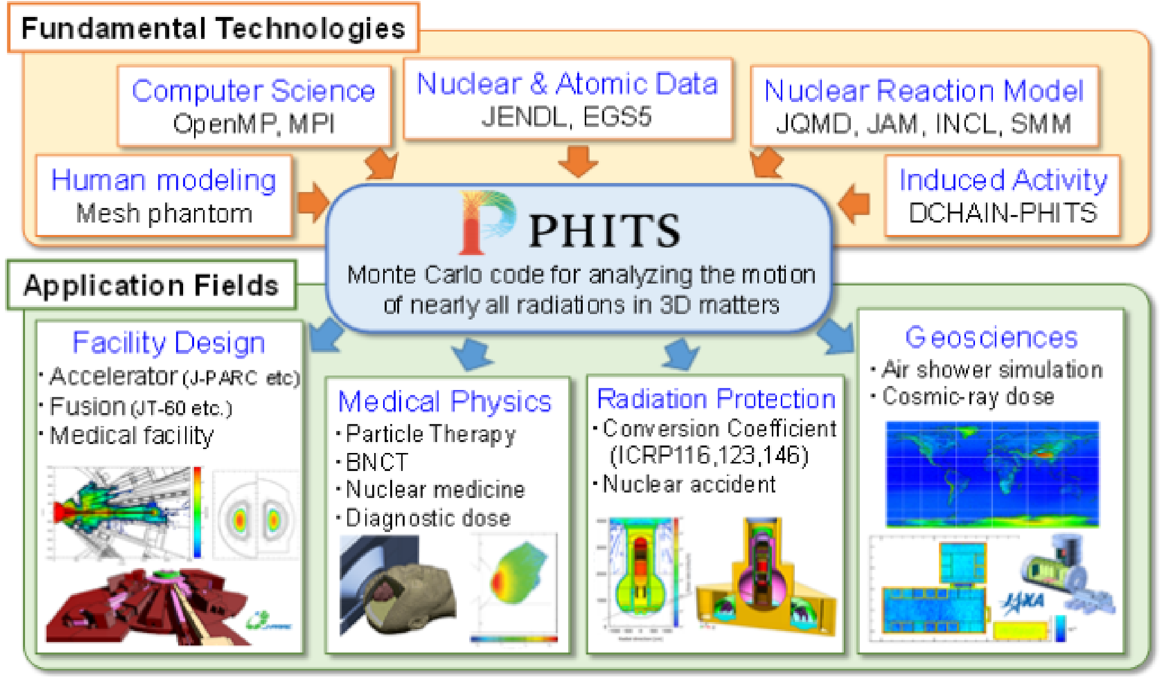
Is the prediction reliable? →
- **Literature data**
- **Ad hoc experiments**

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**

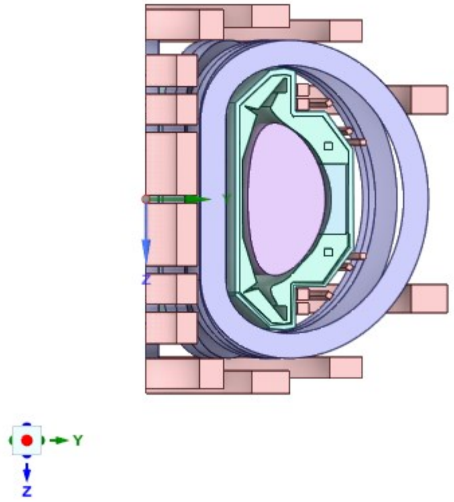


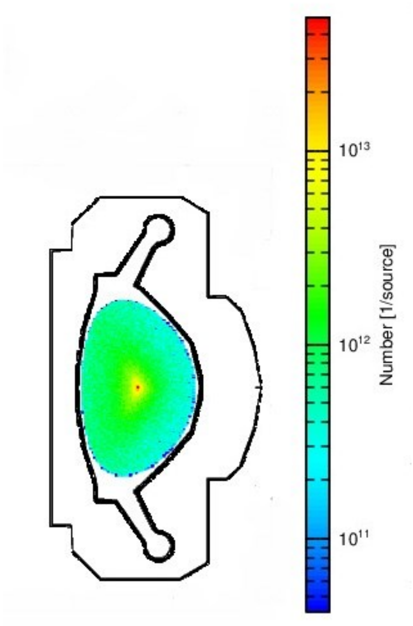
source https://phits.jaea.go.jp/index.html

How do neutrons distribute?

Geometry management

- Model geometry (CAD conversion)
- Source geometry declaration (PHITS customization)

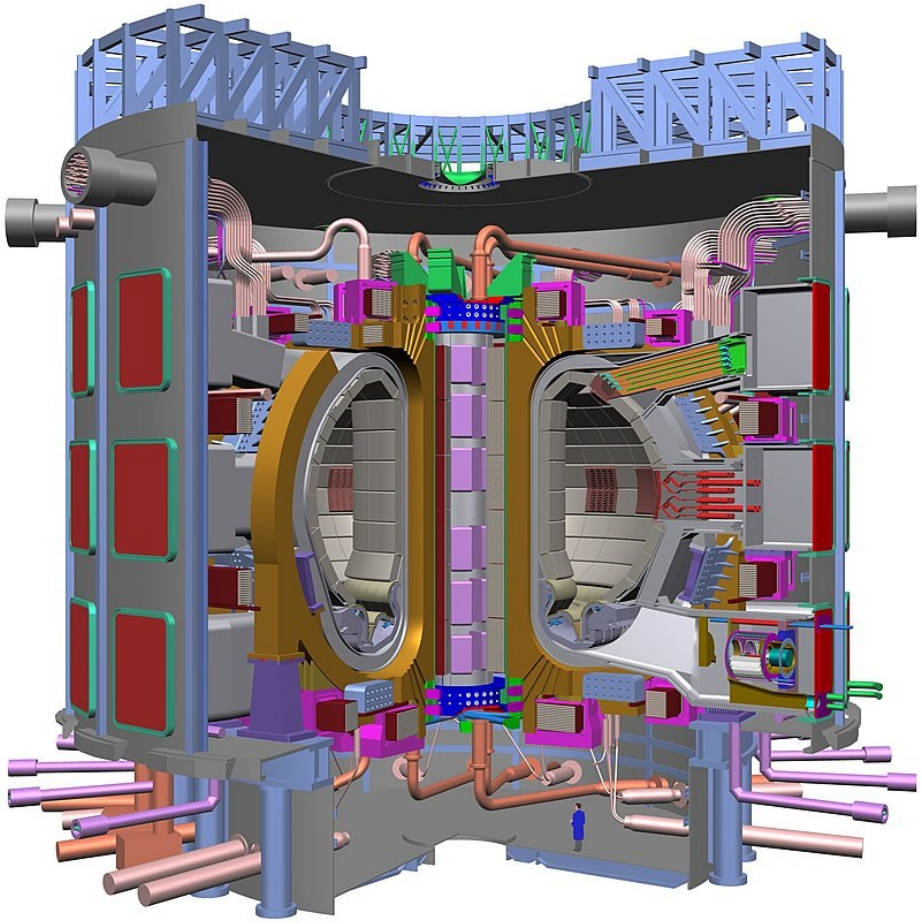




Model geometry

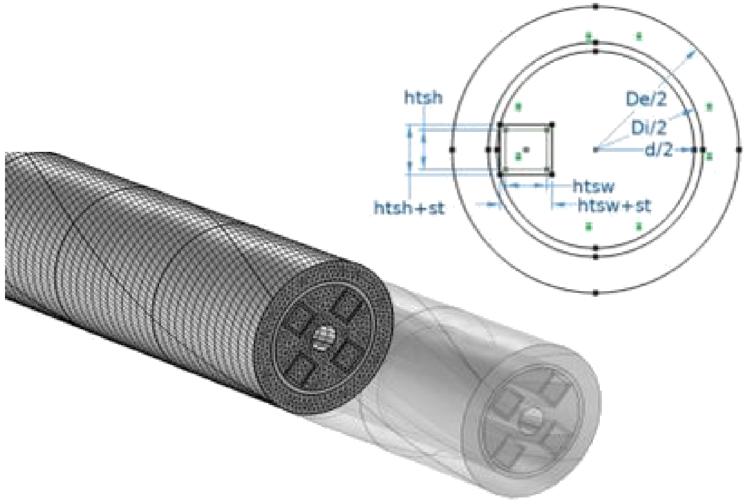
- To perform the transport simulation, the geometry must be declared in PHITS
- The actual geometry of a fusion device is not trivial, declaring it in PHITS by hand using a combination of elementary surfaces is not feasible/ prone to errors and implementation of design changes becomes extremely slow

↳ **A smarter way is required**



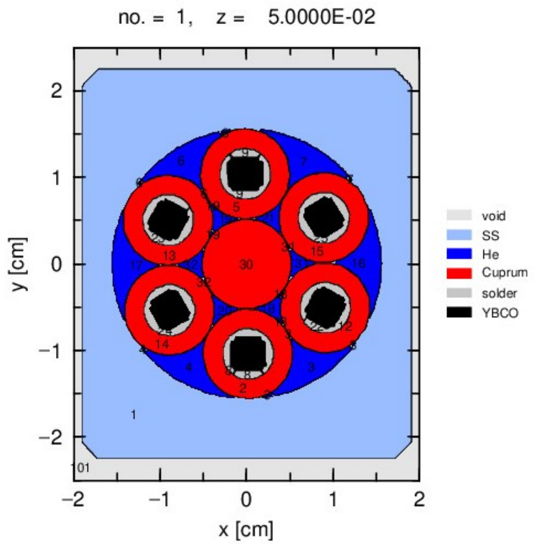
https://commons.wikimedia.org/wiki/Category:Tokamaks#/media/File:U.S._Department_of_Energy_Science_425_003_001_(9786811206).jpg

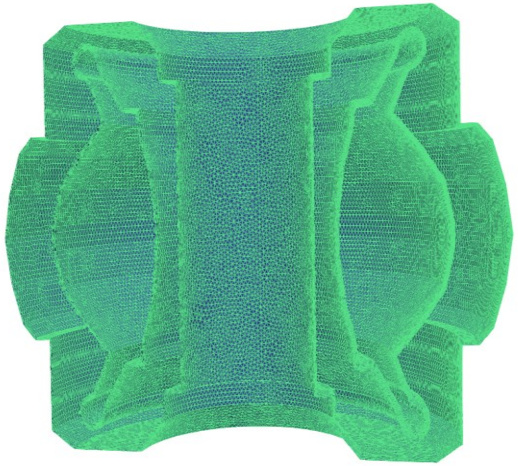
Model geometry

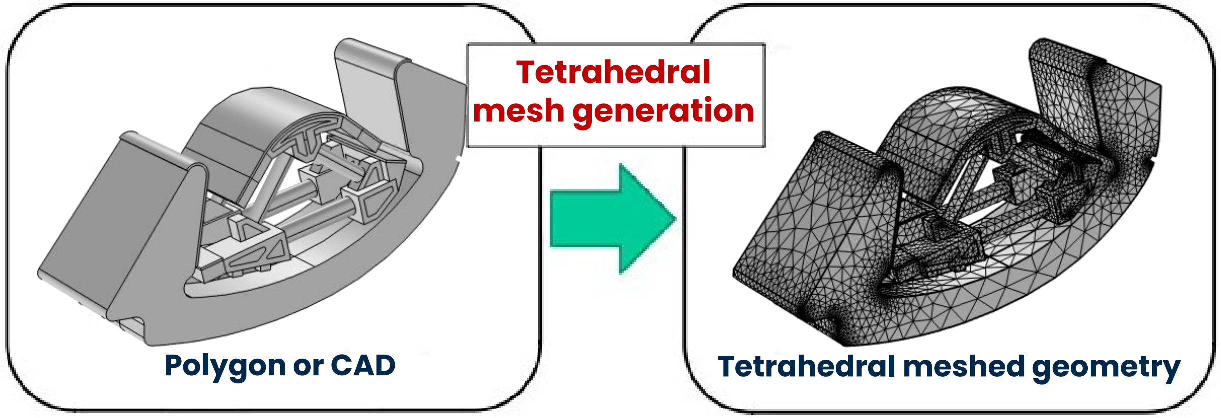


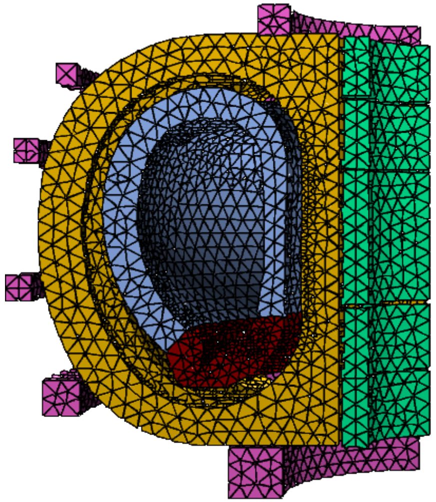
From version 3.30 PHITS supports tetrahedral meshed geometry that **can be used to import any CAD.**

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









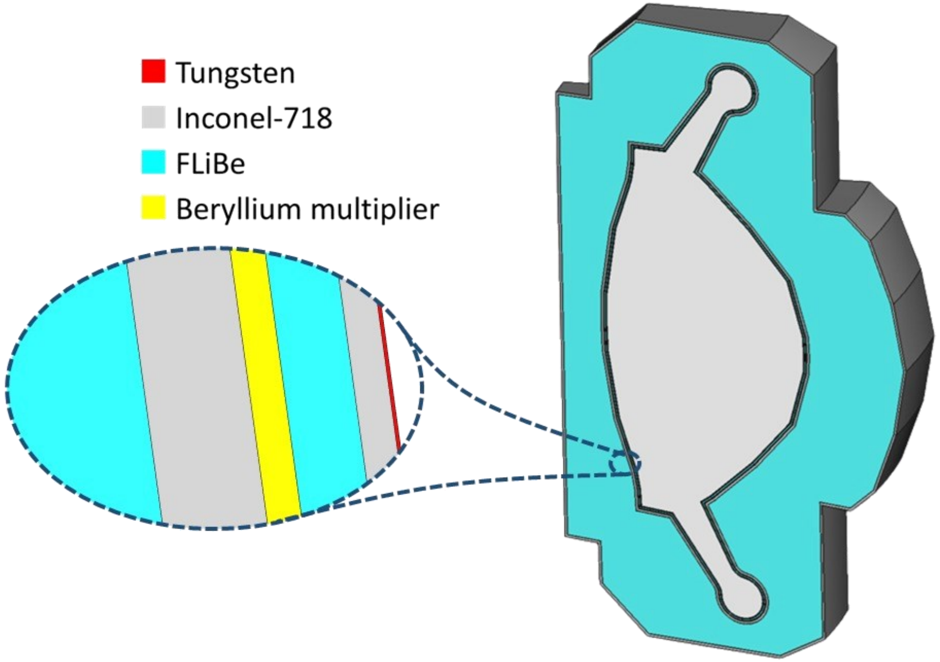
https://wias-berlin.de/software/tetgen/

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**

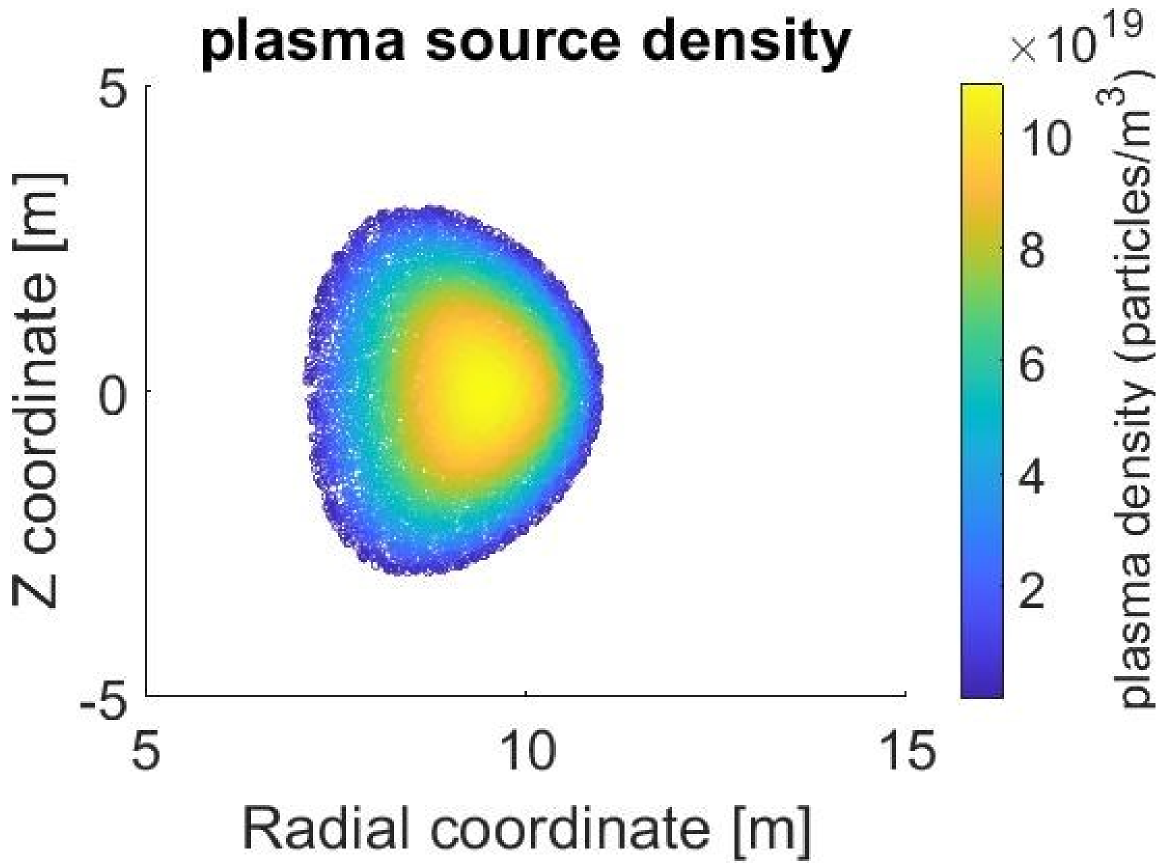
Sorbom et al, Fusion Eng. Des., 2015

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



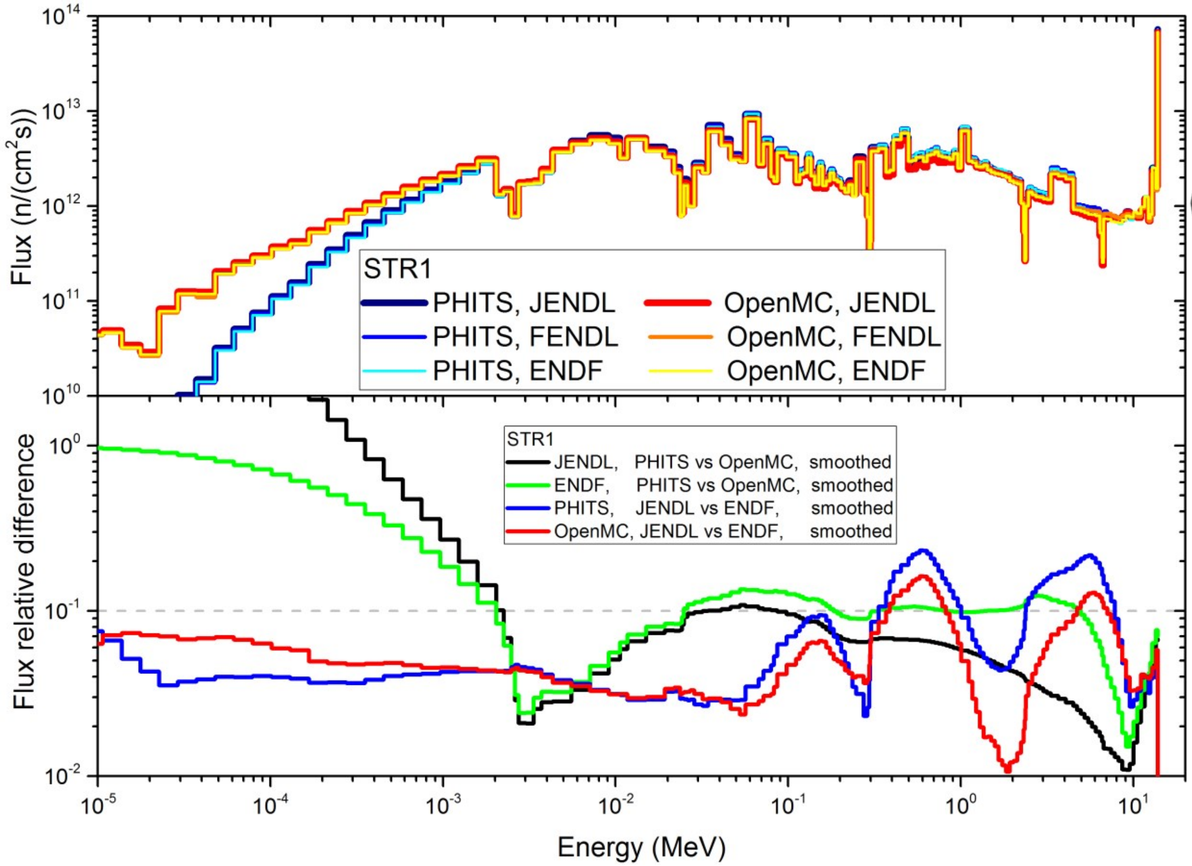
Source geometry

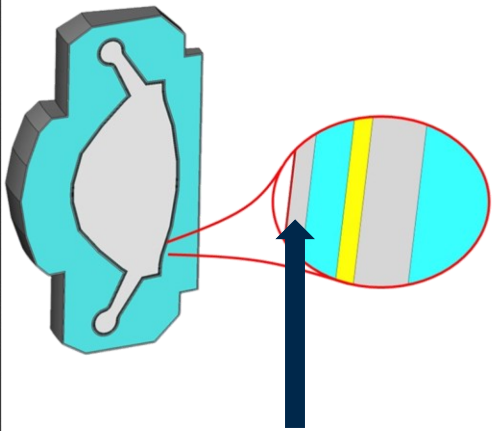
- To perform a particle transport simulation, a particle source is required
- A **toroidal plasma source was available in OpenMC**
- **We introduced a customized plasma source in PHITS**, including all the main physical parameters (e.g Shafranov factor, helicity…)
- Both the sources are based on **Fausser 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*)



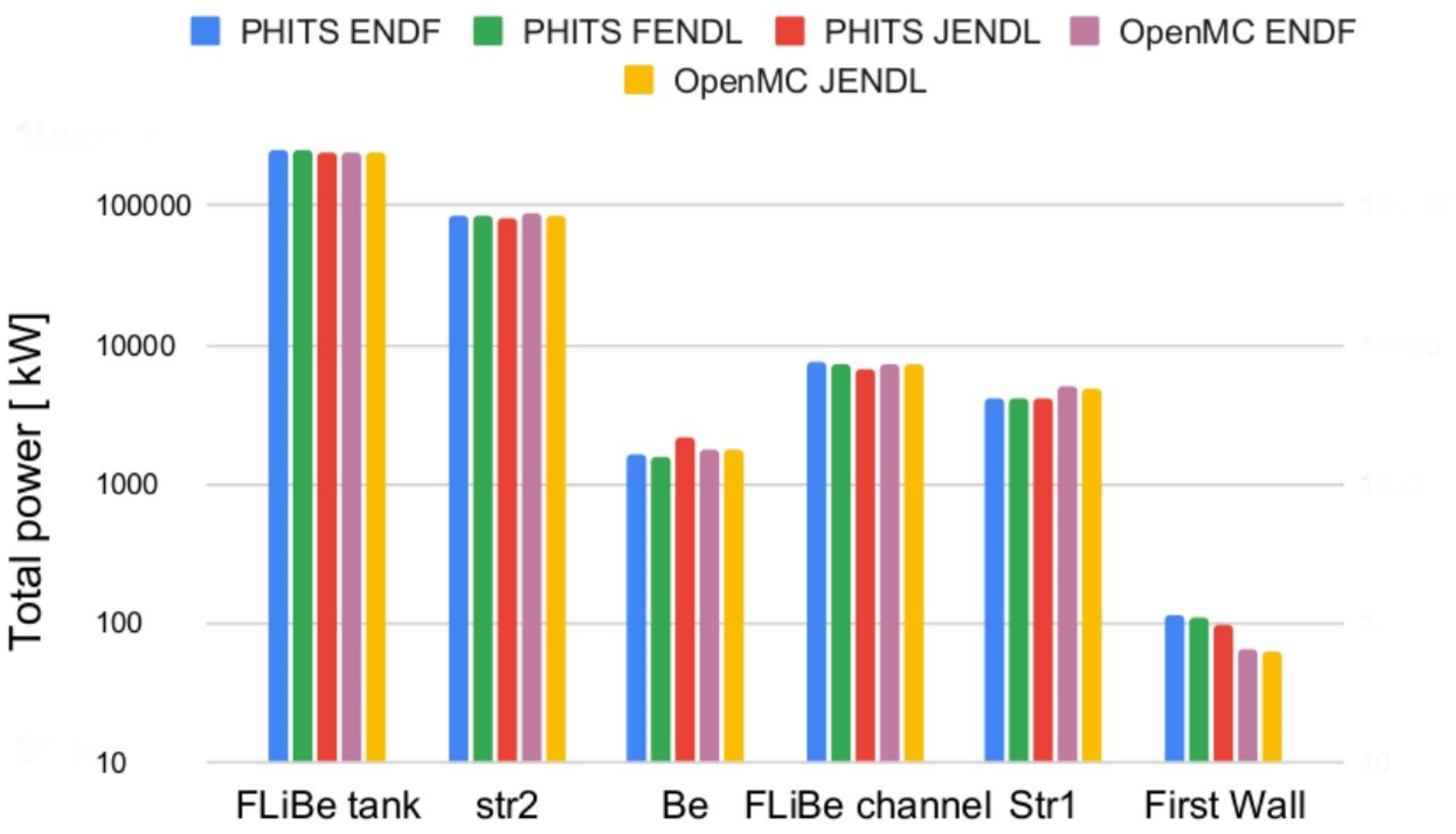


Relative difference $= \left|\frac{\phi_{PHITS} - \phi_{OpenMC}}{\phi_{referemce}}\right|$

- 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

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

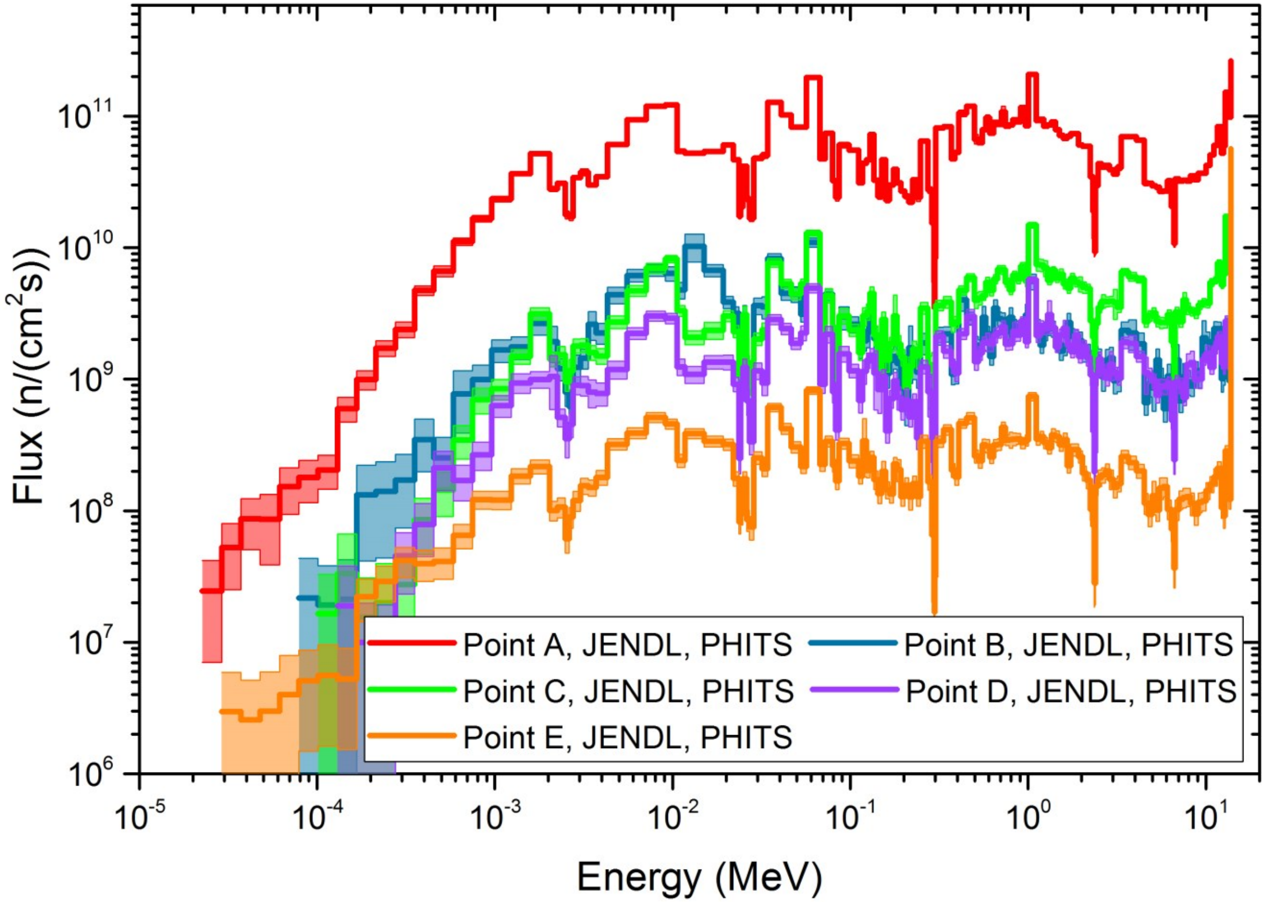
Analysis on the VV: TBR

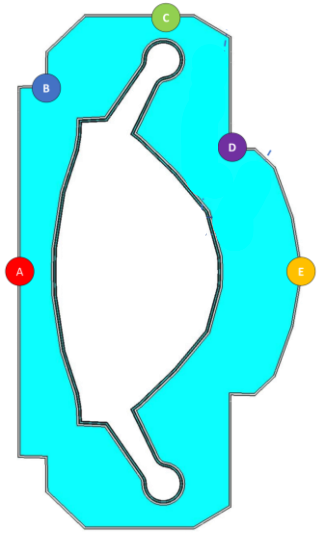
«3D neutronic analysis on compact fusion reactors: PHITS-OpenMC cross-comparison»,
F. Ledda et al., (submitted to *Fusion Engineering and Design*)

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

- 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

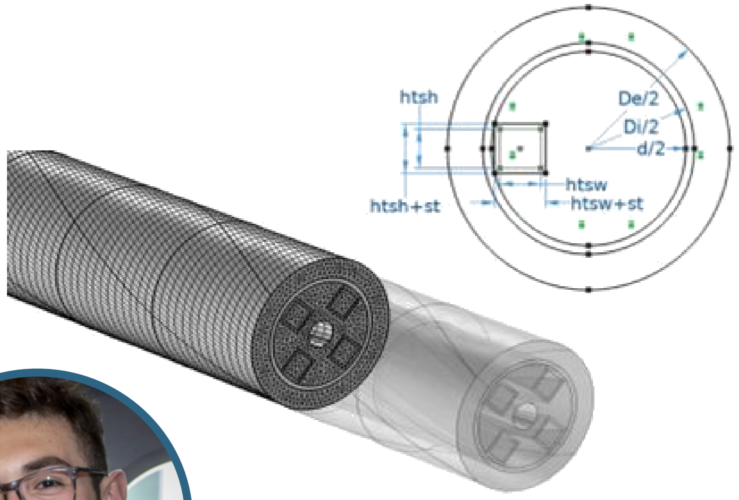




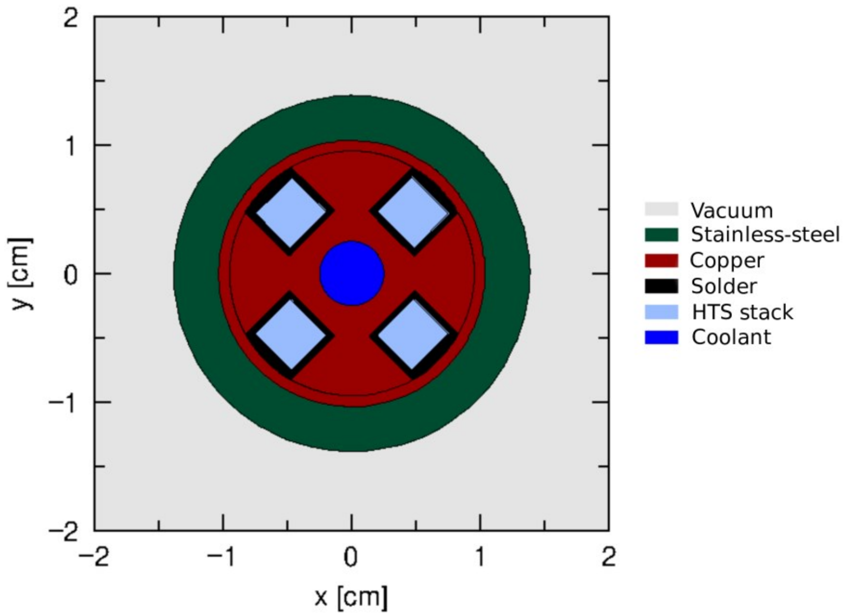
- Neutron spectra were evaluated in 5 poloidal locations at the interface with the TFC position
- Point A is the most critical: this spectrum will be used as input for further analyses of the effects on superconductors

From the VV to the cable

A realistic 3D model of 1 pitch of a superconducting VIPER cable was generated in COMSOL multiphysics® and imported in PHITS

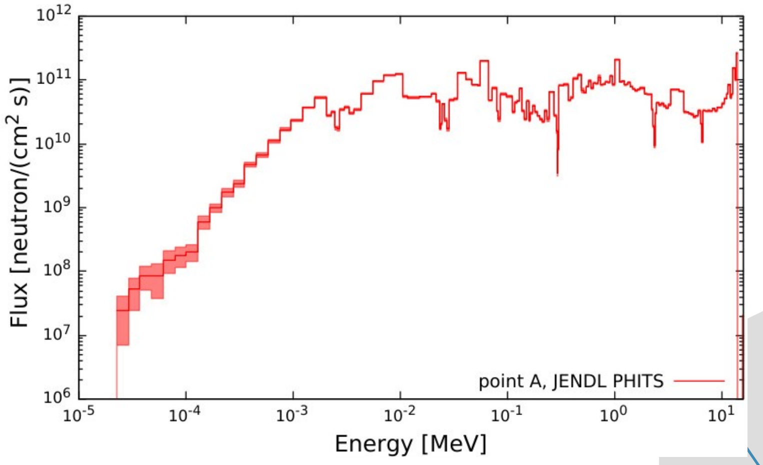


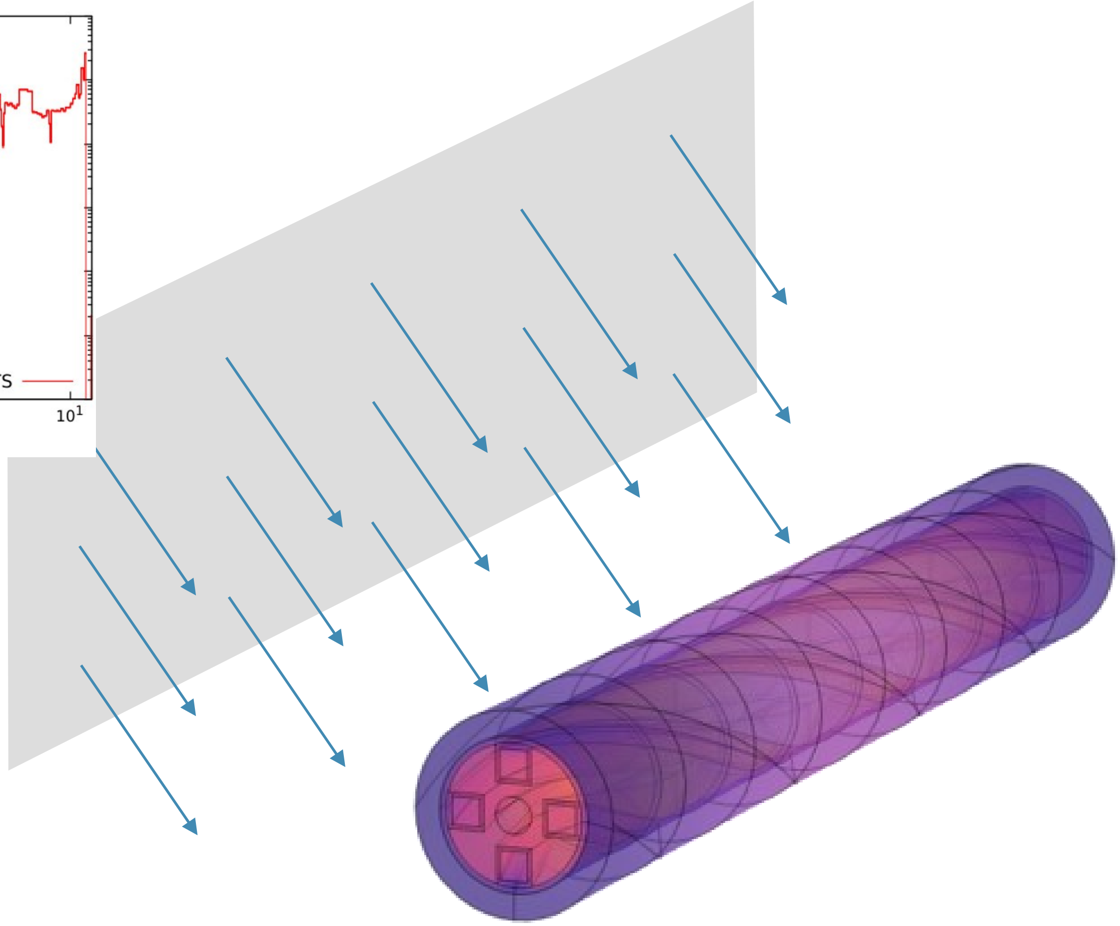
Simone Sparacio



From the VV to the cable

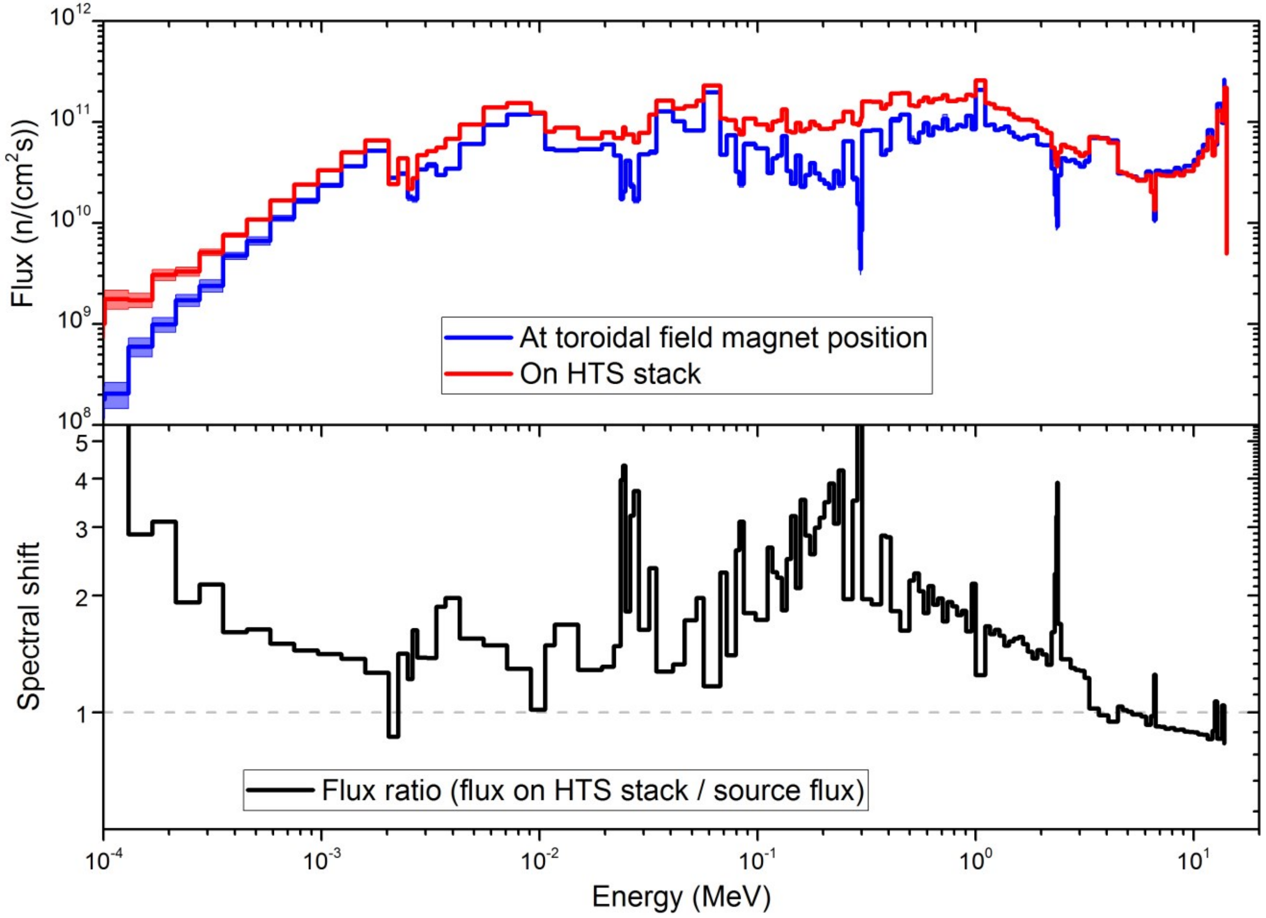
The neutron spectrum evaluated at point A of the reactor geometry was implemented in a planar source emitting collimated neutrons toward the VIPER model





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)

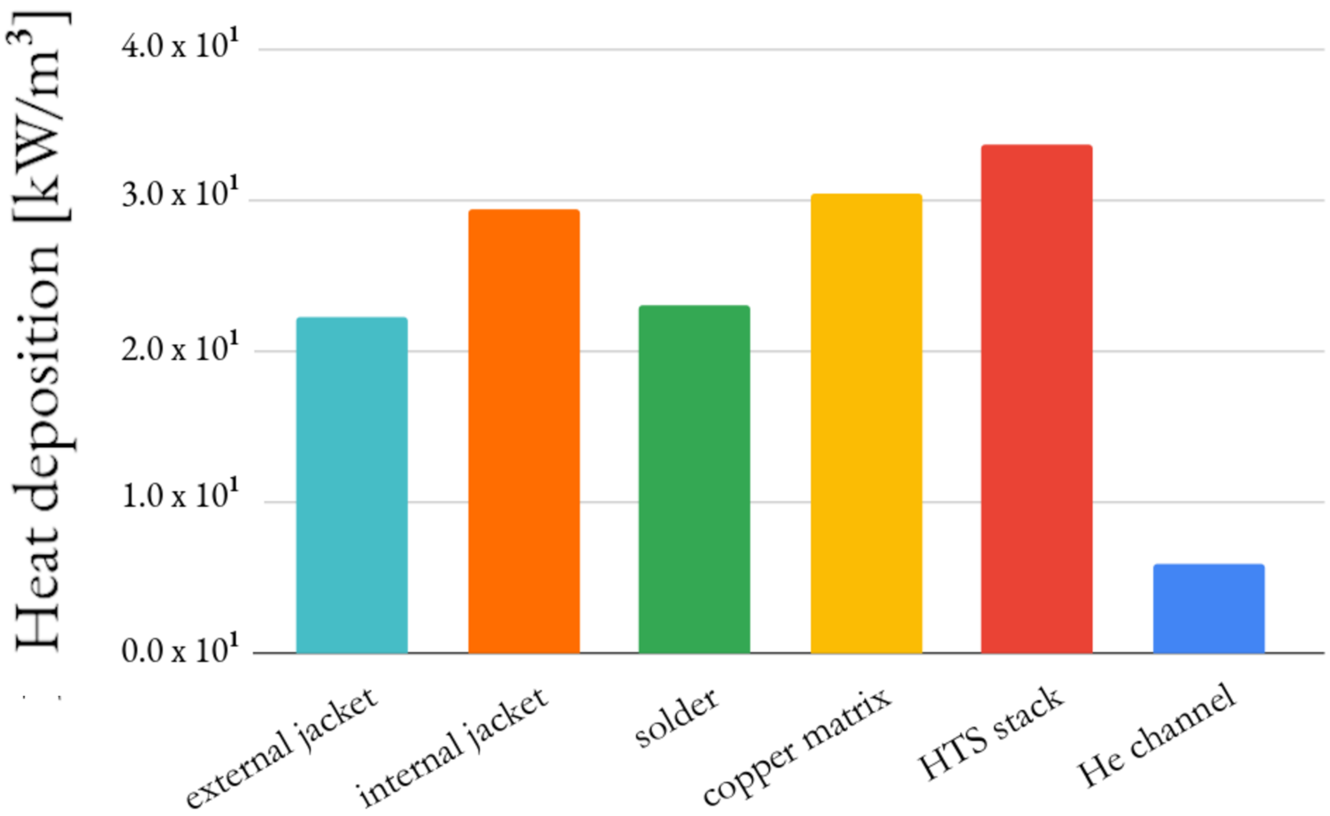


- We observe an enhancement of the neutron flux on the HTS stacks and a spectral shift
- Material choice should be optimized for the nuclear environment

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.
- Further thermal analysis in **S.Sparacio et al., submitted to IEEE Trans. Appl. Supercond., talk tomorrow, 12:30 – 13:00**

Results on the cable: dpa

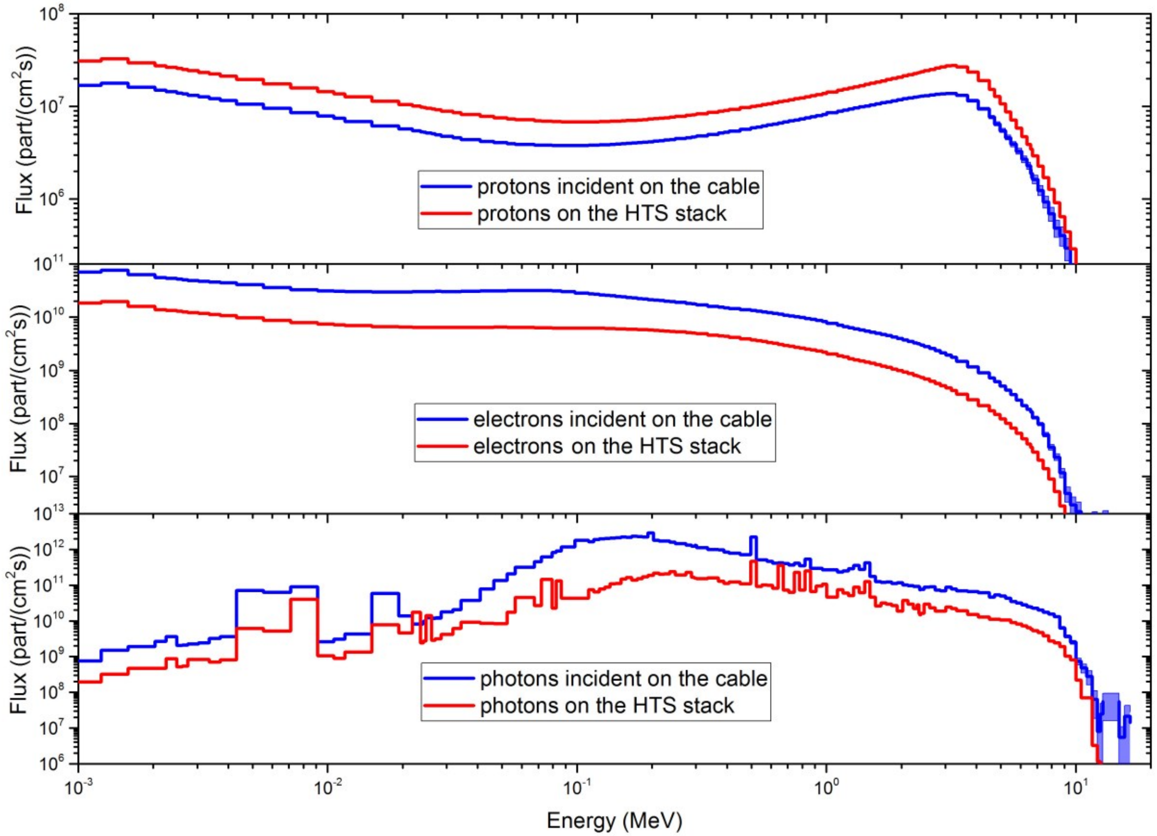
"3D neutronic and secondary particles analysis on YBCO tapes for compact fusion reactors"
F. Ledda, D. Torsello et al. (submitted to IEEE Transactions on Applied Superconductivity)

Quantity	Value
dpa after 10 years	0.21 JENDL 4.0
	0.23 ENDF-VIII/B
	0.23 FENDL 3.2
Neutron heat deposition (kW/m^3)	33.6
Decay heat after 10 years (kW/m^3)	0.82

- 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)

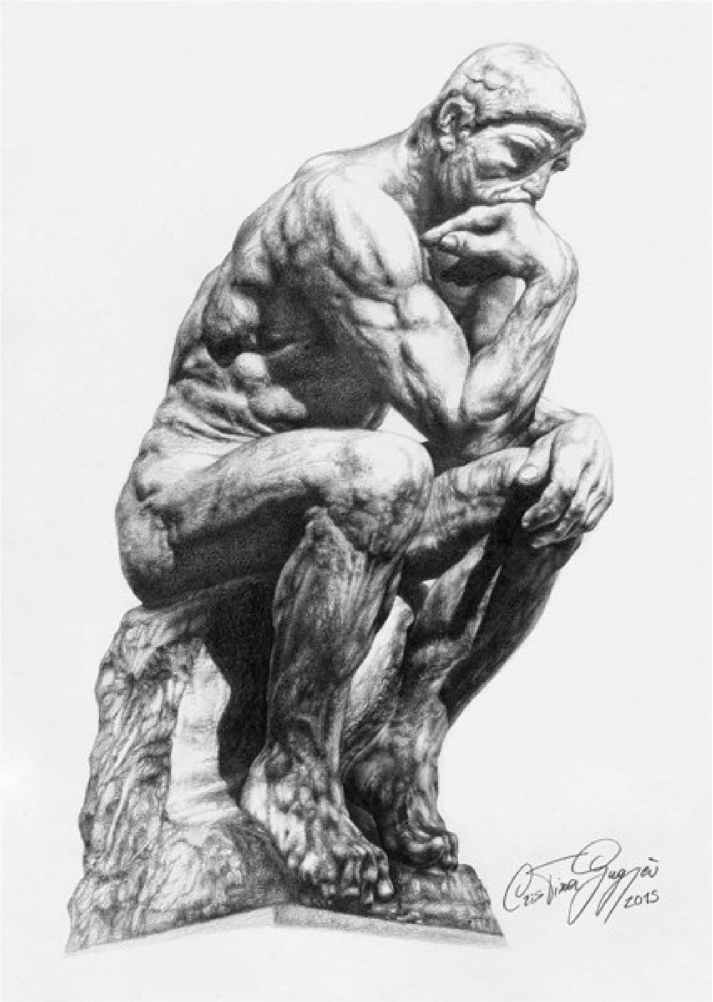


- Secondary particles (among which photons, electrons and protons) are generated in the cable, with not negligible fluxes
- Their effect on HTS performance during reactor operations should be considered: **experiments of superconductivity performance under irration are crucial**

Politecnico di Torino DiSAT INFN eni

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!

IREF23

Politecnico di Torino 1859

chimica fisica materiali DiSAT scienza e ingegneria

INFN

Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

Finanziato dall'Unione europea NextGenerationEU

eni