Joint ICTP-IAEA Advanced School/Workshop on Computational Nuclear Science and Engineering

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Nuclear analysis in support of ITER design - I

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Presentation #1:

- Introduction to ITER
- Justification of the needs related to geometry modelling
- Advances made for geometry treatment in ITER

Presentation #2:

- Description of the radiation sources of concern in ITER
- Advances in modelling complex radiation sources for ITER
- Advances in visualization to understand complex radiation fields

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

Official slogan:

Fusion energy is virtually limitless, clean and safe

BUT…

- What does “limitless” mean?

  Tritium is **radioactive,** and it does not naturally exist

- What does “clean” mean?

  Reactors will produce **radioactive** wastes

- What does “safe” mean?

  Nuclear fusion presents intense **radiation** fields

We need nuclear analysis to make nuclear fusion limitless, clean and safe

Introduction to ITER

Introduction to ITER

ITER site by Nov 2020

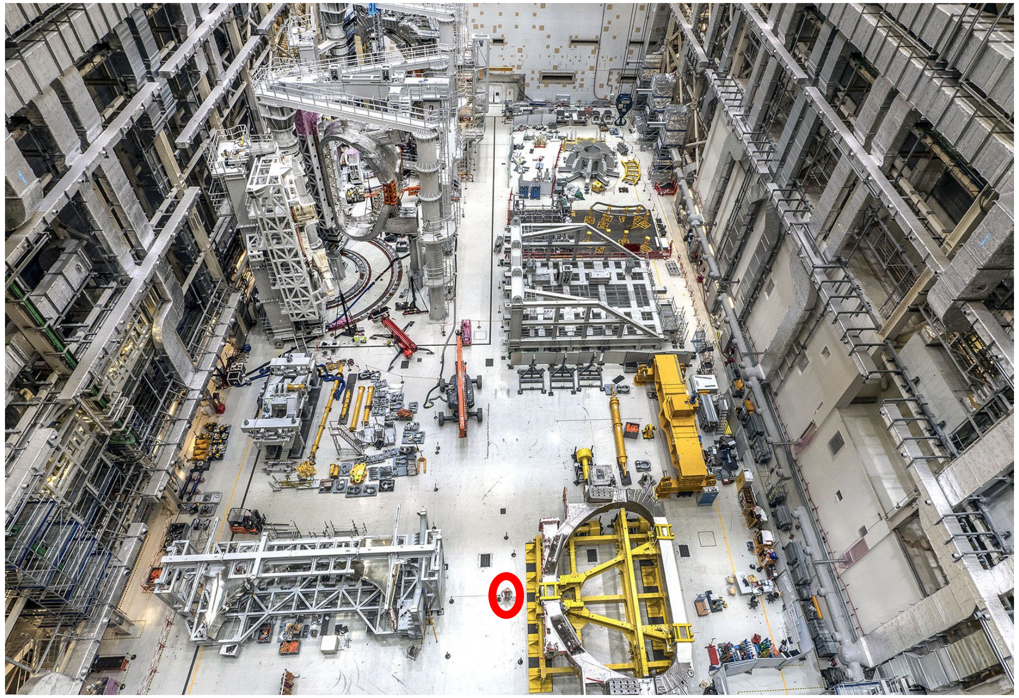
Introduction to ITER

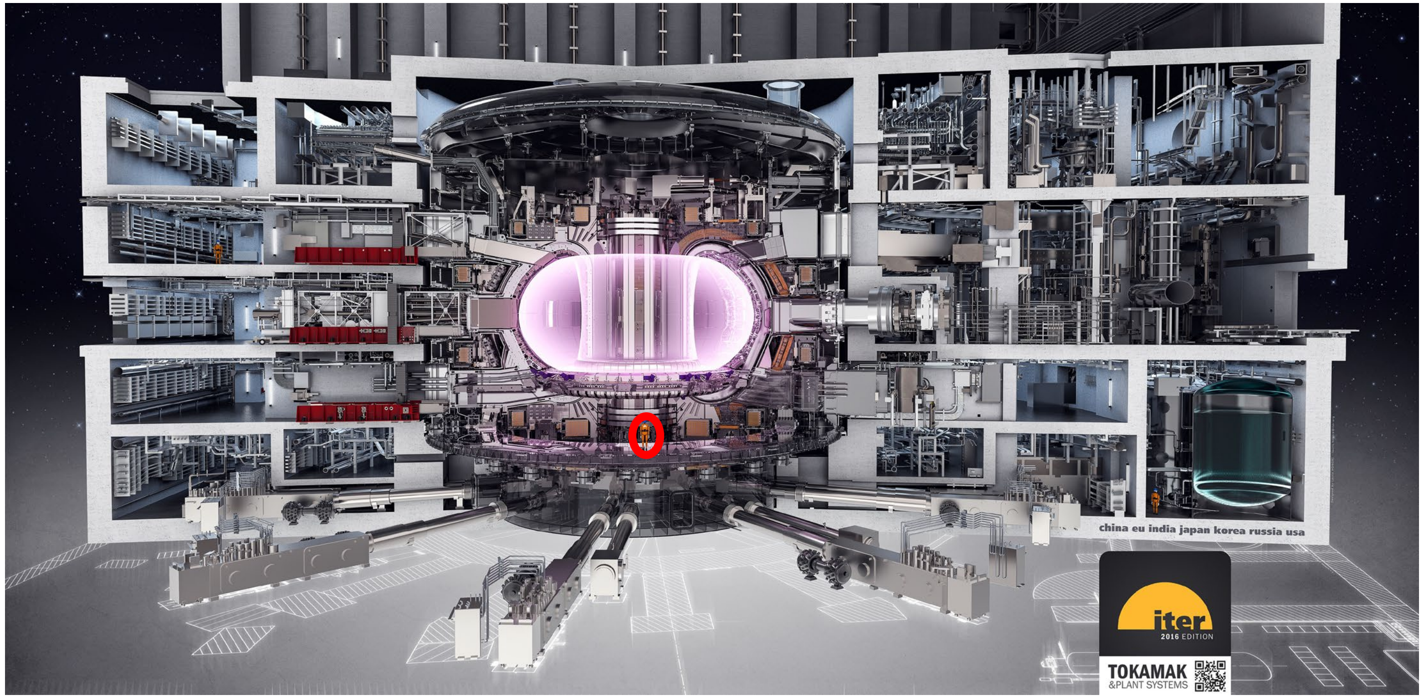
ITER will be a research-oriented nuclear Tokamak. It was agreed in 1985

First plasma is scheduled for 2027:

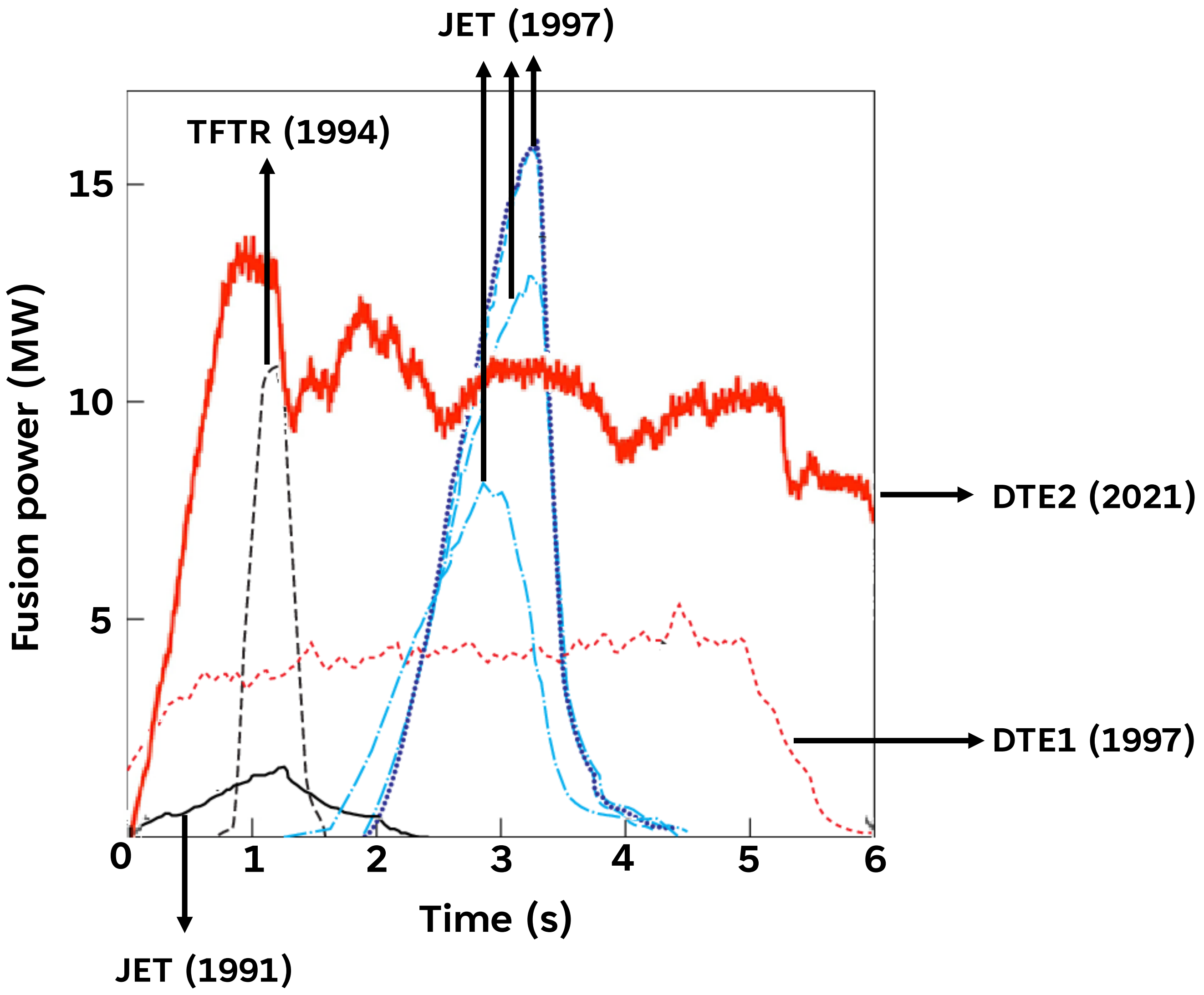
- Tokamak Complex is nearly finished
- The Tokamak is being assembled

First DT pulse is scheduled for 2035



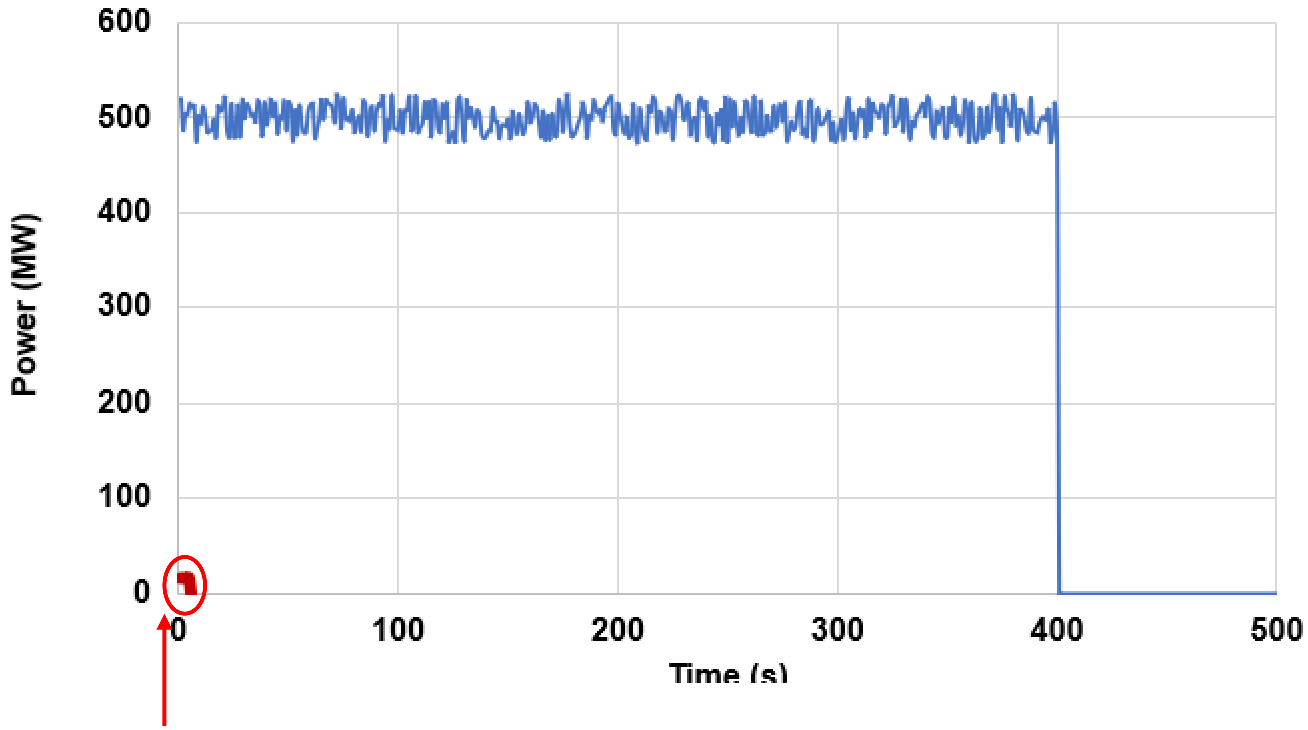


History of nuclear fusion



Machine & date	Milestone
JET 1991	1.7 MW
	First controlled DT fusion experiments on Earth
TFTR 1994	11.5 MW
JET 1997	16 MW
	Energy amplification Q~0.65
	Alpha particle heating clearly observed and consistent with theory
JET 2021	DTE2 campaign: 59 MJ

Introduction to ITER



ITER reference pulse:

500 – 700 MW

Energy amplification Q~10

Pulse duration 400s to 3000s

Previous history of fusion power production on the same scale.

Accumulated history of success in nuclear fusion as per 2022		~ 10^{20} neutrons
First DT pulse of ITER	(2035)	~ 10^{23} neutrons
ITER at end of life	(2050)	~ 10^{27} neutrons

Nothing similar done before!

Radiological protection for workers

Maintenance activities in ITER will be:

- Radioactive environments
- Highly contaminated environments
- Dark rooms & limited visibility
- Assisted breathing with special suits
- Surrounded by sharp objects
- Narrow spaces and limited mobility
- Carrying heavy loads & tools
- Life lines to secure the workers
- Permanent overview of an in-situ supervisor
- Rescue plans
- Time controlled
- Intervention design one-by-one

Really challenging human intervention in about ~100 rooms

Are there similar activities somewhere?

Radiological protection for workers

UNED

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Extravehicular activities in the ISS:
237 interventions for a total of 1491 hours and 54 minutes over 23 years

ITER maintenance:
Hundreds of interventions adding even 2500 hours are expected ITER per year

A lot of work is needed until 2055 and beyond

Protection of electronics

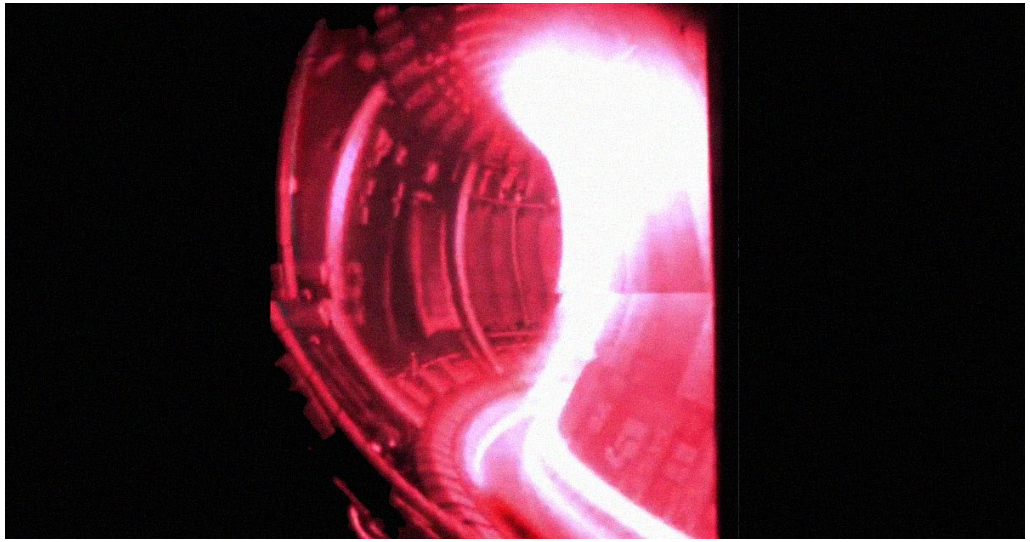
First DT high performance shot at JET in 1991 → 1.7 MW

Radiation induces failures and permanent damage in digital electronics

Courtesy of Michael Loughlin. ORNL

Protection of electronics

JET 1991 — Sophistication of electronics → JET 2021



Tokamaks, like everything else, rely in an increasing use of digital electronics with time.

e.g. AI for prediction and mitigation of disruptions

In ITER electronics is everywhere:

- Radiation kills systems → **frequent (and expensive) replacement of systems**
- Radiation can distort safety-related signals → **unreliable machine**

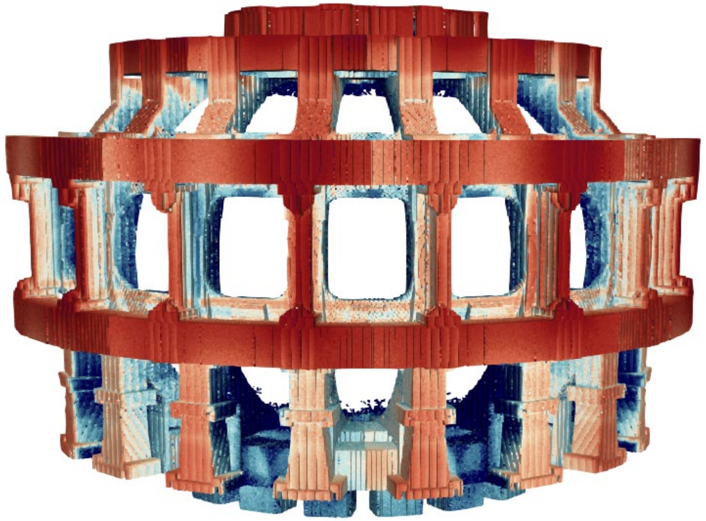
Radiation-induced darkening of optics

ITER will deploy multiple diagnostics systems to monitor the plasma and the machine performance. Most rely on optics to "see"

Optical fibre to transmit signals is found everywhere in the machine

- Radiation induces darkening in the optical elements. reducing the systems performance → **the machine gets blind**
- Radiation can induce luminescence in the optical fibres, leading to ghost signals → **the machine gets unreliable**

Nuclear heating of superconducting coils



ITER magnetic field will:

- be produced by 100.000 km of superconducting strand
- present an intensity of up to 14 T
- operate at 4 K (liquid Helium)
- store a magnetic energy of 51 GJ

Nuclear heat can break the superconducting state, with devastating consequences

→ The second-largest cryogenics plant in the world must be dimensioned accordingly

Summary

ITER current cost estimate is projected to be €25 billion

Radiation-related concern are all across the facility from the first wall to the fence

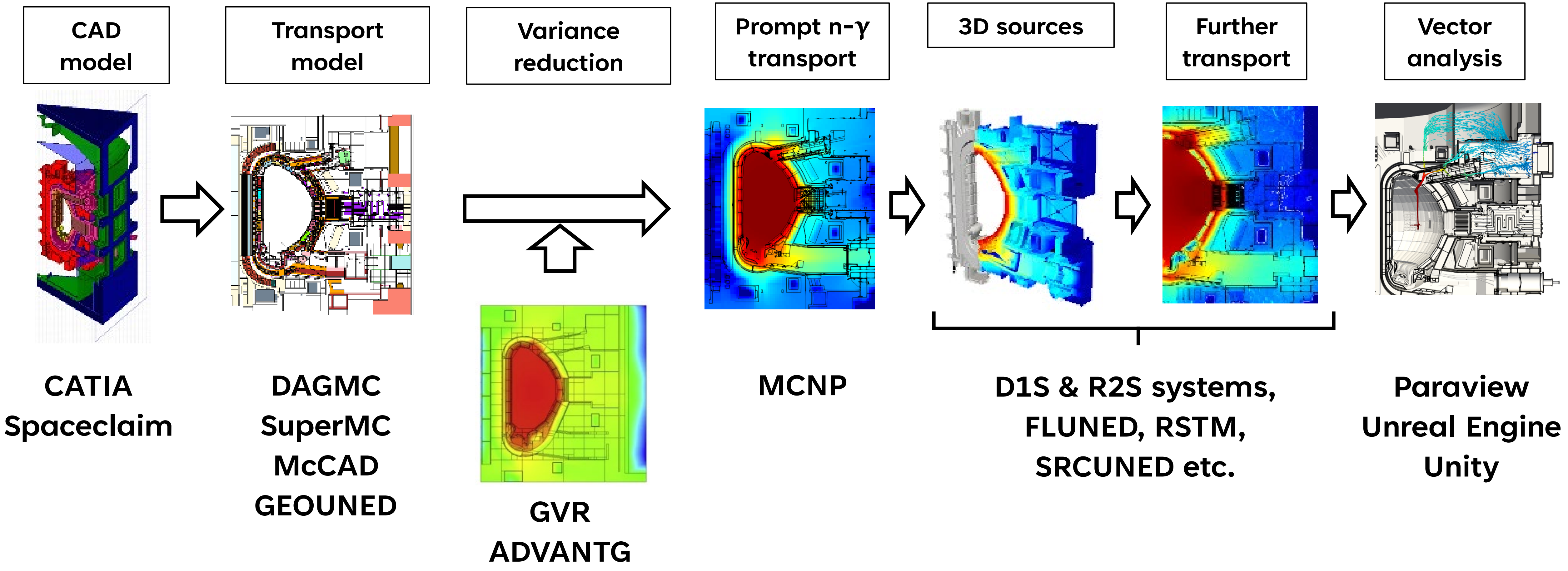
Radiation will make a Tokamak blind, aged, unreliable, unmaintainable and very expensive to build and to operate

→ Actions are worth taking. We assist the design of ITER with nuclear analysis in order to:

1. Comply with the regulatory limits
2. Prolong the life of the machine
3. Reduce CAPEX and OPEX

Overview of the computational cycle followed in ITER

Nuclear analysis for ITER is articulated around MCNP and a set of valuable assets developed during the last 20 years: procedures, code patches, supplementary tools, reference models & sources descriptions



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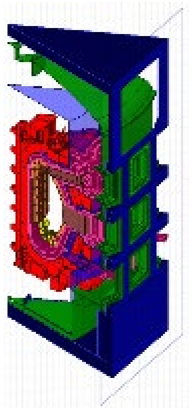
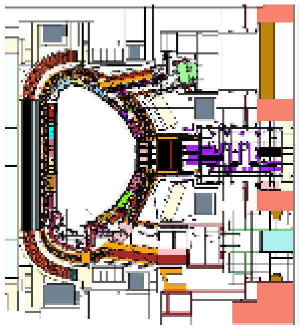
CAD model



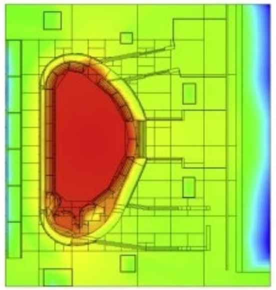
CATIA
Spaceclaim

Transport model



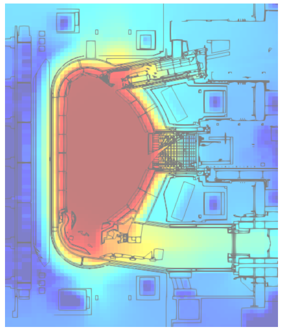
DAGMC
SuperMC
McCAD
GEOUNED

Variance reduction



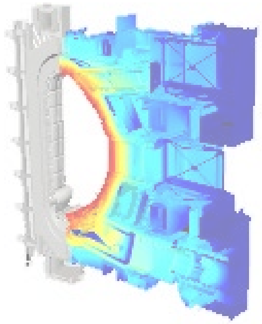
GVR
ADVANTG

Prompt n-γ transport

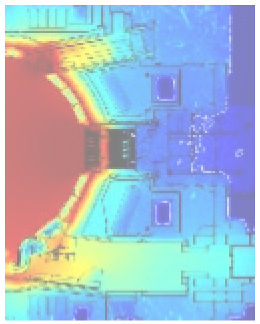


MCNP

3D sources

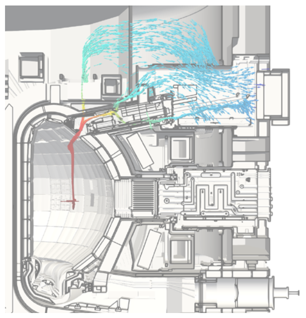


Further transport



D1S & R2S systems, FLUNED, RSTM, SRCUNED etc.

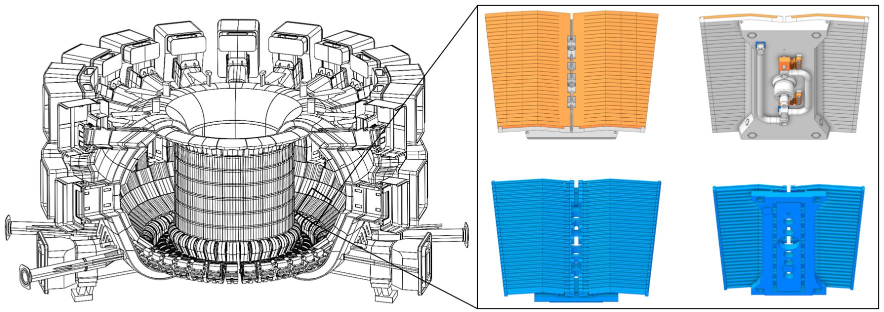
Vector analysis



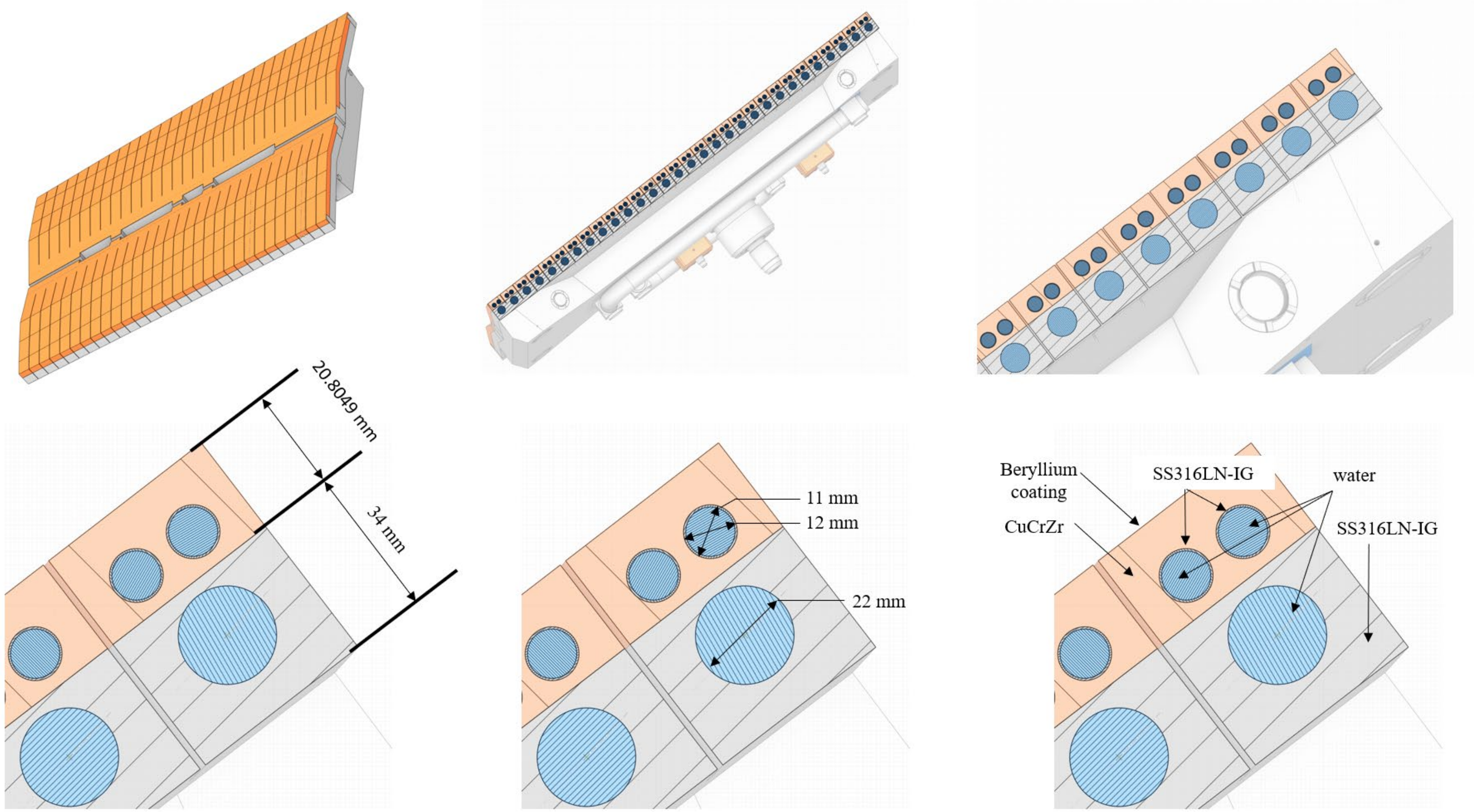
Paraview
Unreal Engine
Unity

Justification of the needs related to geometry modelling

The geometry challenge in ITER neutronics



The degree of heterogeneity of materials with different materials performance in ITER is very high

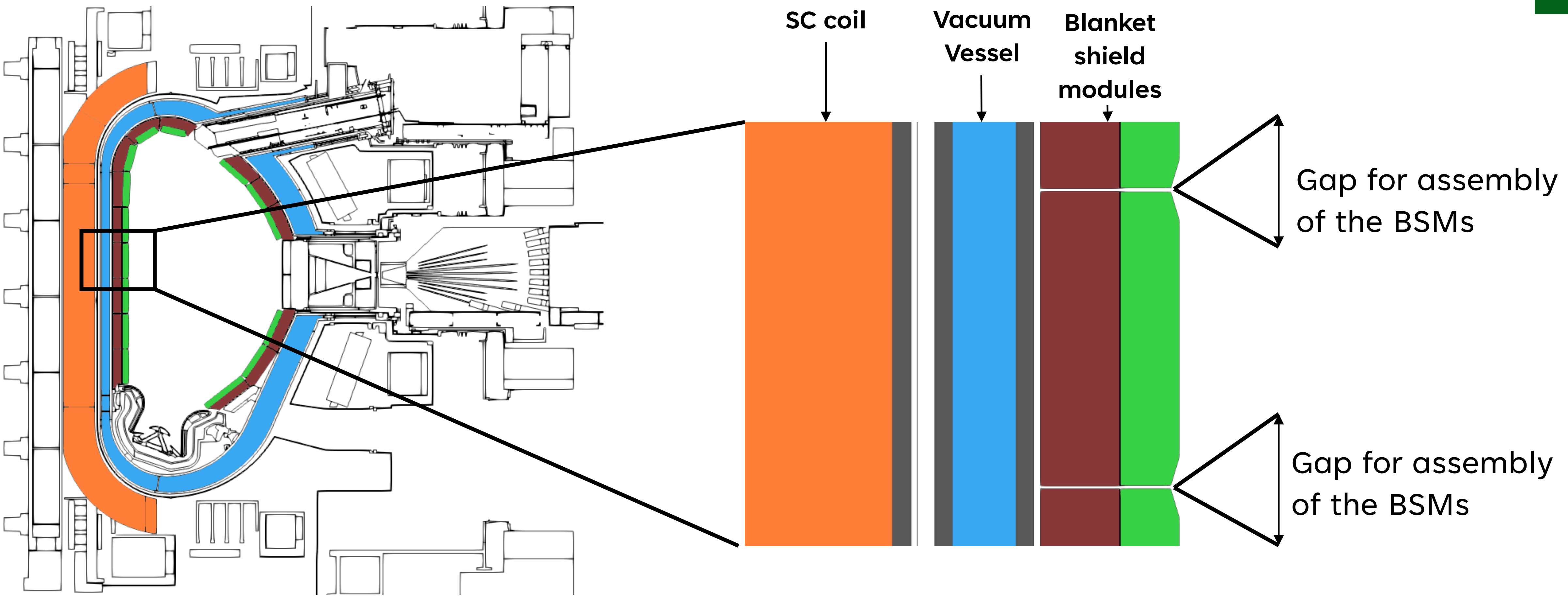


Example: blanket shield modules

- 8 mm beryllium first wall panel
- 21 mm CuCrZr
- 11 mm diameters cooling channels
- 1 mm thick steel pipe
- 34 mm steel bulk

Is this detail really needed?

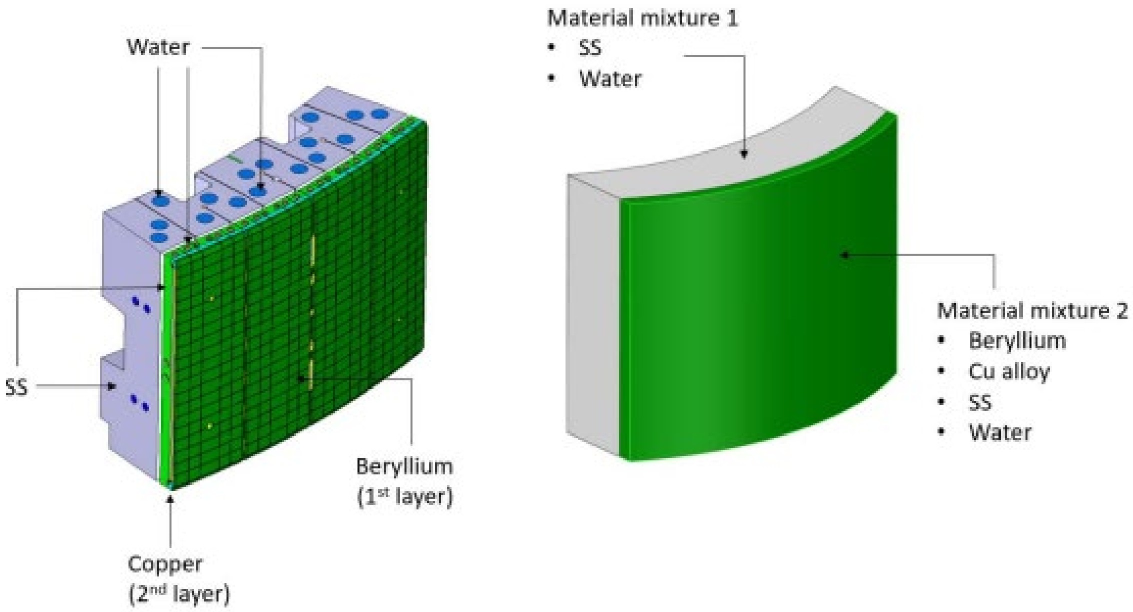
The geometry challenge in ITER neutronics



A reduction from 2 cm to 1 cm in the gaps manifested in a 30% decrease of the integral heating of the coils inboard legs, and a 40% in the peak values*

*H. Iida, “Fast Neutron Flux and Nuclear Heat in the TF Coil Inboard Legs vs. Gap Width among Blanket Modules,” ITER Report ITER_D_226DRK v2.0, 2003.

The geometry challenge in ITER neutronics



When homogenized models of the BSMs are considered*:

- The nuclear heating in the BSMs is up to a 70% higher
- The nuclear heating in the vacuum vessel immediately behind the BSM is a 76% lower
- Some peak values in the vacuum vessel are missed, with an 86% underestimation

Homogenization has proven to introduce strong distortions in the nuclear responses which sense and size are unpredictable

*T. D. Bohm, M. E. Sawan, and P. P. H. Wilson, “The impact of simplifications on 3-D neutronics analysis of blanket modules in iter,” Fusion Sci. Technol., vol. 64, no. 3, pp. 587–591, 2013, doi: 10.13182/FST13-A19156.

The geometry challenge in ITER neutronics

Capturing the complete heterogeneity poses challenges:

1. Hand-made geometry descriptions can hardly overcome 1,000 cells
2. ITER is being analysed all around the world
   - Re-modelling the machine by everyone is inefficient
   - Different modelling approaches lead to different analyses conclusions
3. Computer consumption mounts with geometry complexity:
   - RAM memory, loading time and plotting time
   - Running time and high sampling

The geometry challenge in ITER neutronics

Capturing the complete heterogeneity poses challenges:

1. Hand-made geometry descriptions can hardly overcome 1,000 cells → **CAD to MCNP**
2. ITER is being analysed all around the world
   - Re-modelling the machine by everyone is inefficient → **Reference models**
   - Different modelling approaches lead to different analyses conclusions → **Guidelines**
3. Computer consumption mounts with geometry complexity:
   - RAM memory, loading time and plotting time → **MCNP modifications**
   - Running time and high sampling → **HPC & variance reduction**

Advances made for geometry treatment in ITER

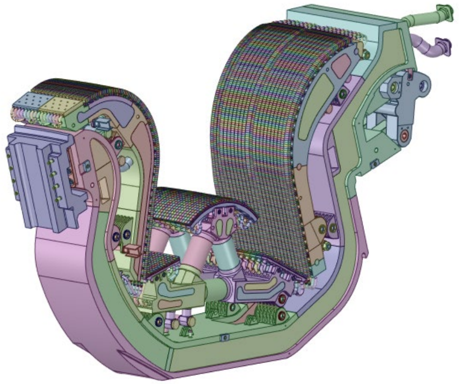
From CAD to MCNP

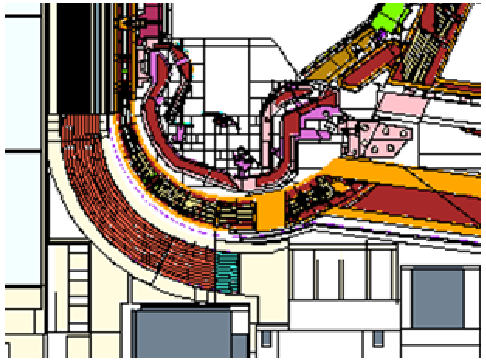
CAD modeling

General order SP-lines

MCNP

First & second order surfaces





From CAD to MCNP

CAD modeling

General order SP-lines

Defeaturing

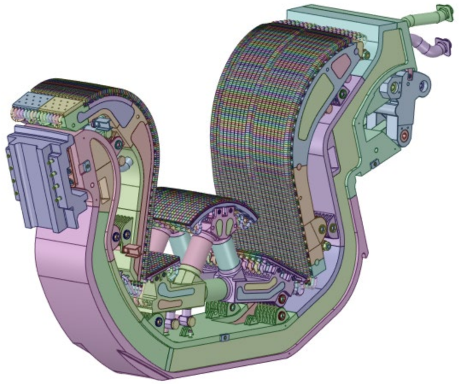
- Reduce surfaces complexity
- Heal the 3D model
- Refurbish by component/material
- Model liquids and gases

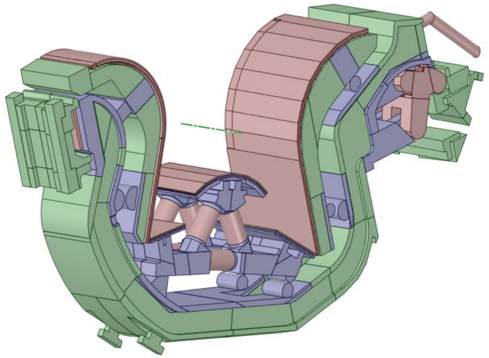
Translating

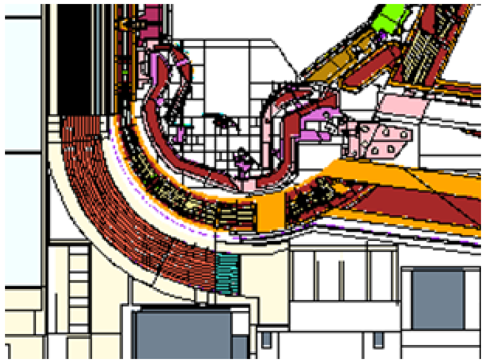
- Comment every cell
- Allocate materials
- Debug lost particles
- Mass preservation
- Integration into reference model

MCNP

First & second order surfaces







From CAD to MCNP

CAD modeling

CATIA

Defeaturing

Spaceclaim

Translating

DAGMC [1]

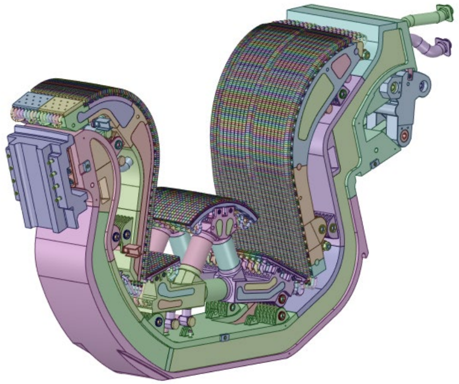
SuperMC [2]

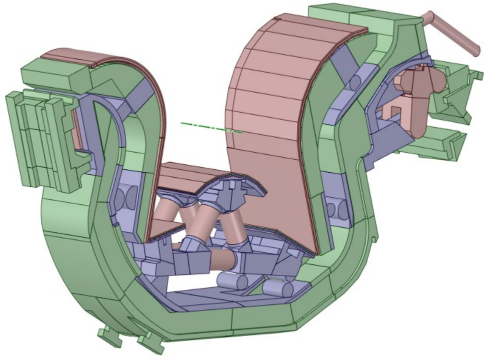
McCAD [3]

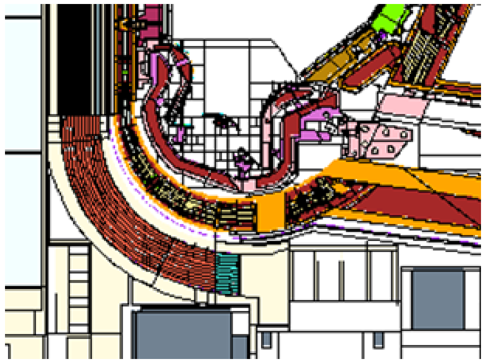
GEO-UNED

MCNP

First & second order surfaces



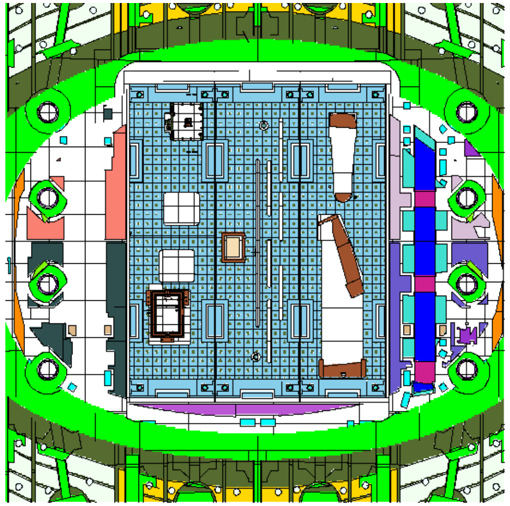


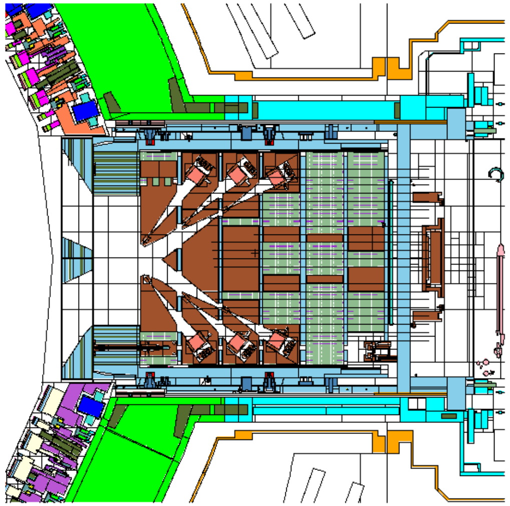


From CAD to MCNP: GEOUNED

GEOUNED is a conversion tool to convert CAD models to MCNP geometry based on CSG approach

- Open source tool based on FreeCAD as interface for OPEN CASCADE CAD engine
- Used as script launched in a system console:
  - ➢ automatization of repetitive/complex tasks (comments, density factors for mass control, ...)
  - ➢ high adaptability to specific problems & easy to extend
- Automatic void generation → essential for complex models. Structured hierarchical voids producing cleaner inputs





Example: EP#12

~20,000 cells

~50,000 surfaces

~20 minutes

Reference models of the ITER Tokamak

UNED

Reference models are built to provide a common environment for all the nuclear analysis and save time to users

Model	Segment	Period	Surfaces
RC-ITER	18º	1998 – 2000	unknown
Brand	20º	2000 – 2008	1586
A-lite	40º	2008 – 2009	3601
B-lite	40º	2010 – 2013	27918
C-lite	40º	2013 – 2016	34105
C-model [4]	40º	2016 – now	146776
E-lite [5]	360º	2020 - now	592516

Increment of a factor > x350 in the complexity of the models achieved in 14 years

Reference models of the ITER Tokamak

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Model	Segment	Period	Surfaces	
RC-ITER	18º	1998 – 2000	unknown	
Brand	20º	2000 – 2008	1586	
				→ **SuperMC (former MCAM)**
A-lite	40º	2008 – 2009	3601	
				→ **Spaceclaim**
B-lite	40º	2010 – 2013	27918	
C-lite	40º	2013 – 2016	34105	
				→ **Guidelines on MCNP model production**
C-model [4]	40º	2016 – now	146776	
				→ **Modifications to MCNP performance**
E-lite [5]	360º	2020 - now	592516	

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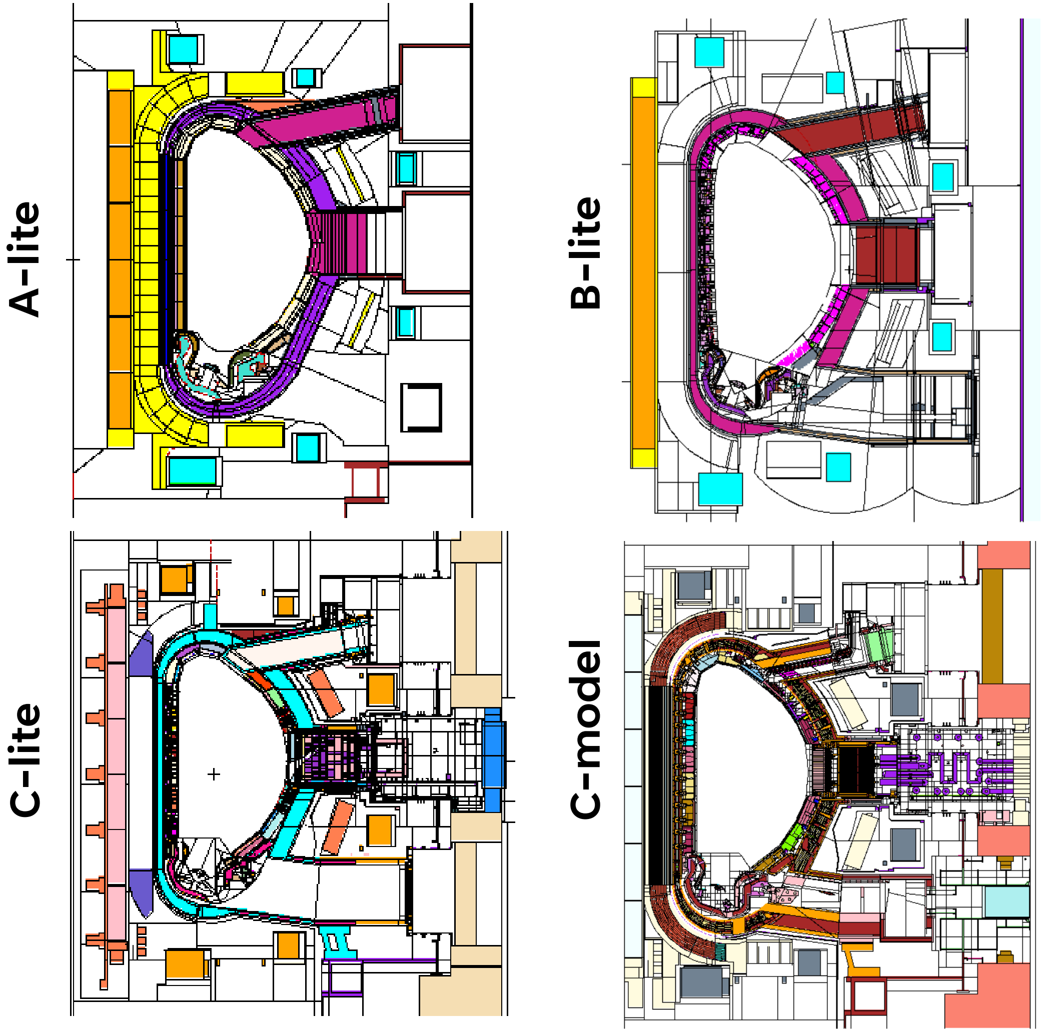
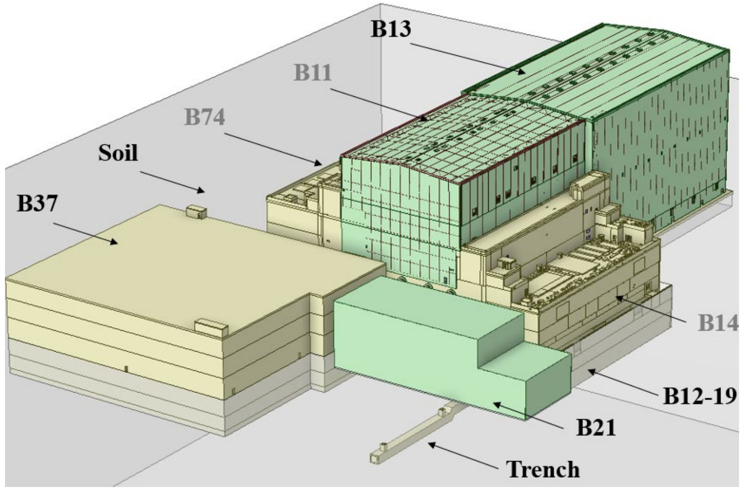
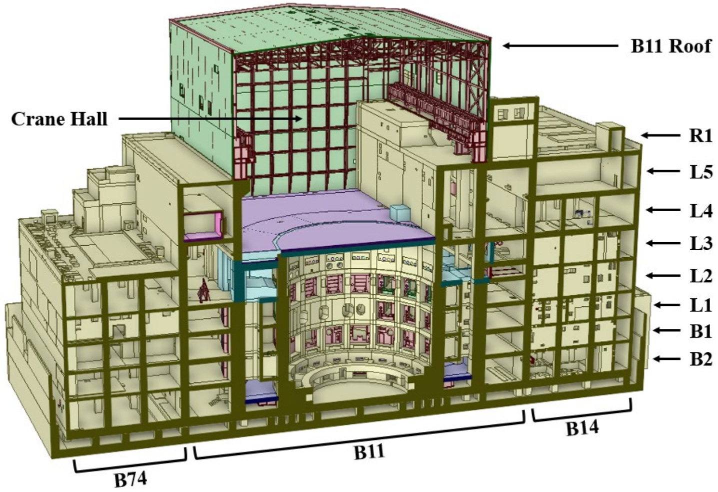


Tokamak Complex model

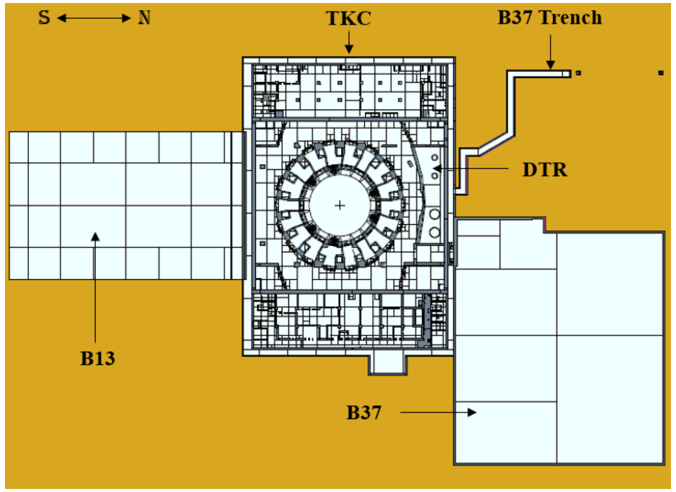
- According to baseline 2020
- It covers 7 edifices and
- Includes soil and 1km of air
- Over 4,500 penetrations traced and reviewed one-by-one
- 674 rooms explicitly modelled
- 14 dedicated shielding measures to improve the design

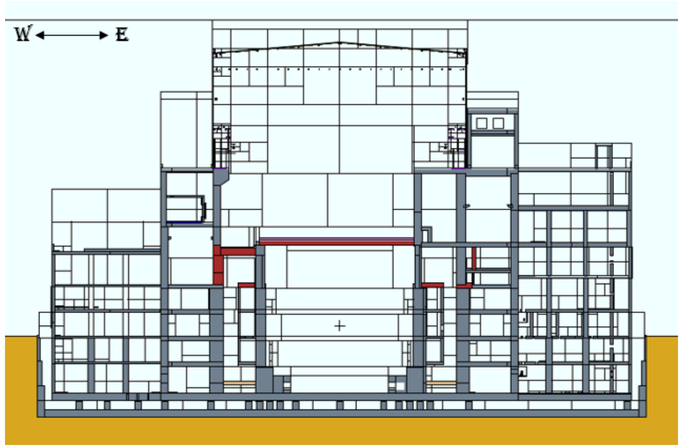
CAD model





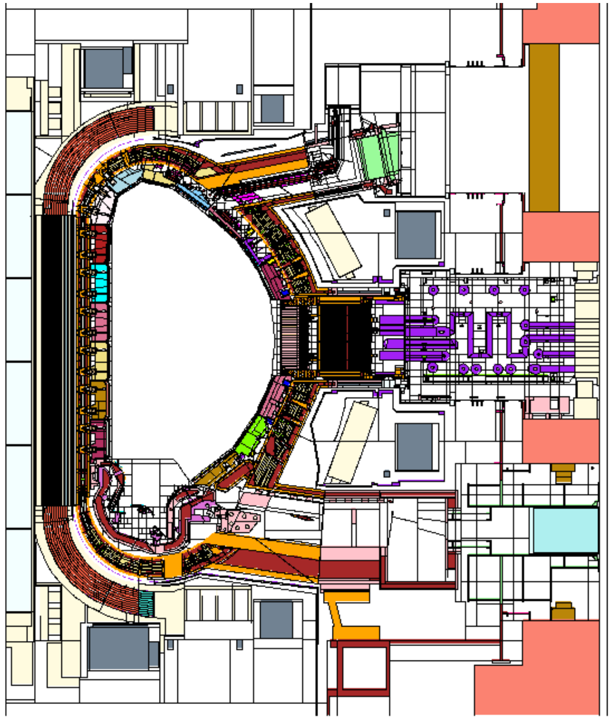
MCNP model





Improvements to MCNP computational performance

C-model R181030 is a 40º representation of the ITER Tokamak



Parameter	MCNP5	D1SUNED	Reduction
RAM memory	10.2 GB/cpu	2.2 GB/cpu	79%
Loading time	304 min	6.5 min	98%
Running time	K	K/5	80%
Plotting time	∞	50 min	∞
Lost Particle Rate	9×10^{-5}	3×10^{-7}	x300 lower

Thanks to D1SUNED, C-model has become a model for regular use

J. Alguacil, et al., "Assessment and optimization of MCNP memory management for detailed geometry of nuclear fusion facilities", *Fus Eng Des* **136** (2018) 386-389

Variance reduction techniques

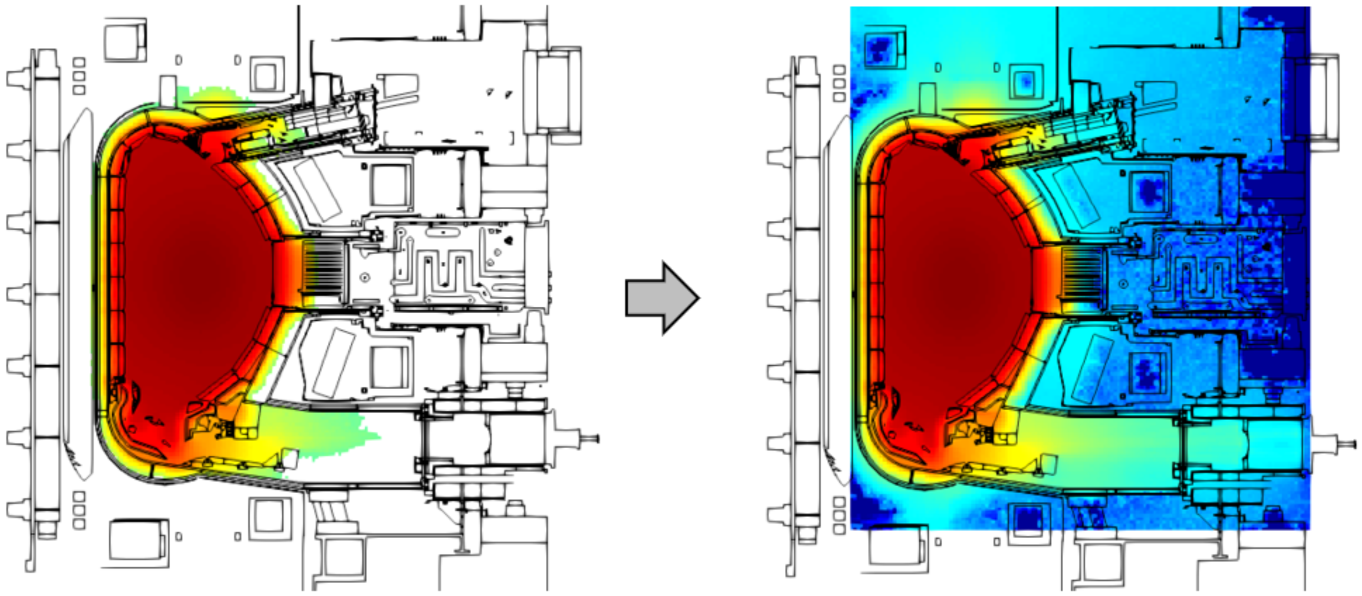
ITER neutronics is very computationally demanding. In example:

Neutron flux in the plasma is ~10^{14} $n.cm^{-2}.s^{-1}$

Limit for safety electronics is 10^{-2} $n.cm^{-2}.s^{-1}$

How do we deal computationally with 16 orders of magnitude attenuation? → variance reduction

Global Variance Reduction



Analog - NPS 10^9 – 1161 cpu.hr

GVR - NPS 10^9 – 2680 cpu.hr

Weight windows technique is assisted by external tools to produce weight maps:

- Global variance reduction [6]
- ADVANTG [7]

<u>Warning:</u> too intense variance reduction may imply source under-sampling and long-histories

References

[1] P.P. Wilson, et al. "Acceleration techniques for the direct use of CAD-based geometry in fusion neutronics analysis", *Fusion Engineering and Design,* **85** (2010), 1759-1765

[2] Y. Wu, FDS team, "CAD-based interface programs for fusion neutron transport simulation", *Fusion Engineering and Design*, **84** (2009), 1987-1992

[3] D. Grobe, et al. "Status of the McCad geometry conversion tool and related visualization capabilities for 3D fusion neutronics calculation", *Fusion Engineering and Design*, **88** (2013), 2210-2214

[4] D. Leichtle, B. Colling, M. Fabbri, R. Juarez, M. Loughlin, R. Pampin, E. Polunovskiy, A. Serikov, A. Turner, L. Bertalot, "The ITER tokamak neutronics reference model C-model", *Fusion Engineering and Design*, **136**, (2018), 742-746

[5] R. Juarez. G. Pedroche, M.J. Loughlin, R. Pampin, P. Martinez, M. De Pietri, J. Alguacil, F. Ogando, P. Sauvan, A.J. Lopez-Revelles, A. Kolsek, E. Polunovskiy, M. Fabbri, J. Sanz, "A full and heterogeneous model of the ITER tokamak for comprehensive nuclear analyses", *Nature Energy* **6** (2021) 150-157

[6] A.J. van Wijk, G. Van den Eynde, J.E. Hoogenboom, "An easy to implement global variance reduction procedure for MCNP", *Annals of Nuclear Energy*, **38** (2011) 2496-2503

[7] S.W. Mosher et al., "ADVANTG-An Automated Variance Reduction Parameter Generator," ORNL/TM-2013/416 Rev. 1, Oak Ridge National Laboratory (2015).