Nuclear analysis in support of ITER design

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About me

Joined UNED in 2013

Associate professor of Nuclear Science and Engineering

Member of the *ITER Nuclear Integration Unit* since 2016

Main researcher of over 25 projects for ITER nuclear analysis:

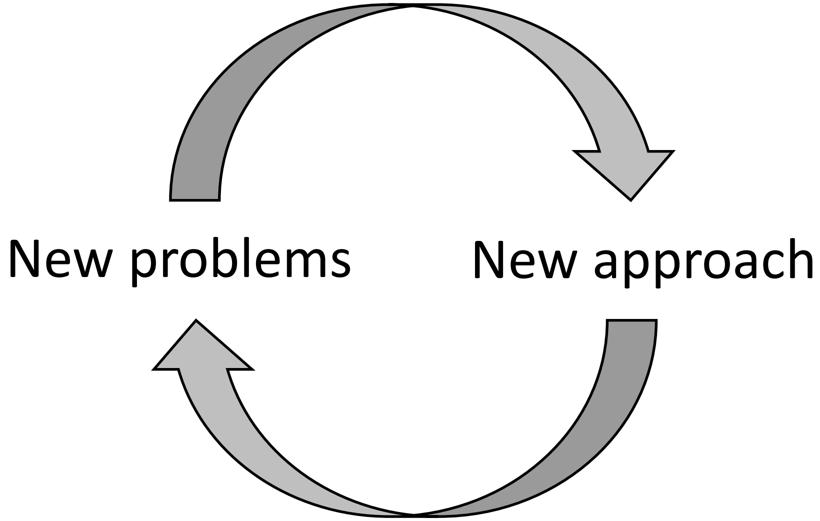
- Final Design Review of all the ITER first plasma port plugs
- European Test Blanket Module for tritium production
- Official ITER radiation atlas of 2016 and 2020
- Implementation of ALARA strategy for ORE

Our goals

UNED has two complementary research lines:

- Analysis and design of nuclear fusion facilities
- Development of computational tools for nuclear analysis

They feed each other in loop:



The loop has been specially vigorous during ITER design

Outline

- Why is ITER nuclear analysis computationally challenging?
- How have the challenges been faced?
- Few remaining challenges

What makes ITER challenging?

We have never built anything nearly comparable

<u>Disclaimer:</u> The views expressed in this presentation are the sole responsibility of the authors and do not necessarily reflect the views of Fusion for Energy (F4E) and the ITER Organization (IO). Neither of these institutions nor any person acting on their behalf is responsible for the use that might have been made of information in this presentation.

The content of this presentation does not commit the IO as nuclear operator.

Comparison JET vs ITER

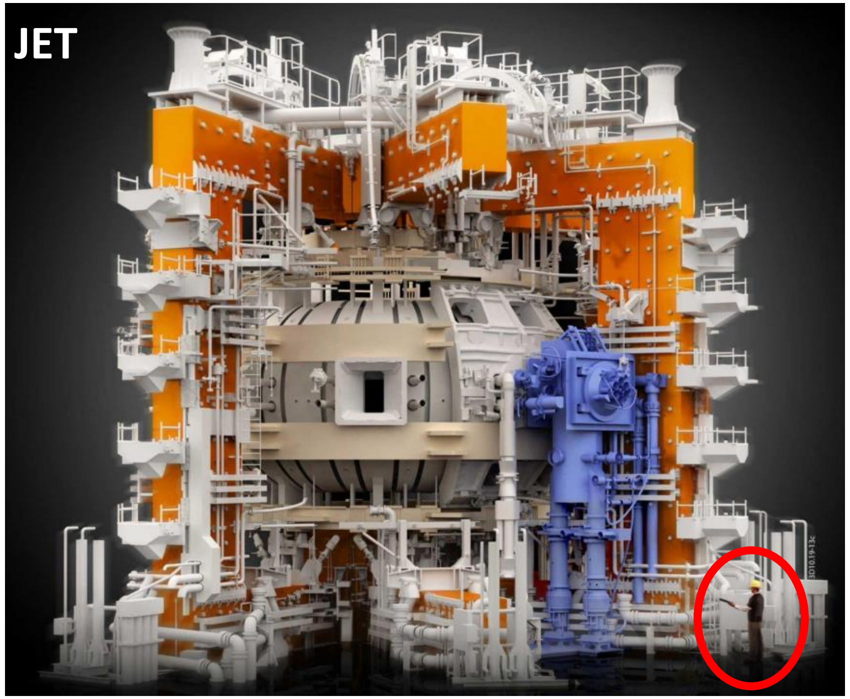
Volume:	**x10**
Power:	**x30**
<u>Neutron budget:</u>	**<u>x1,500,000</u>**

ITER will be the largest nuclear Tokamak:

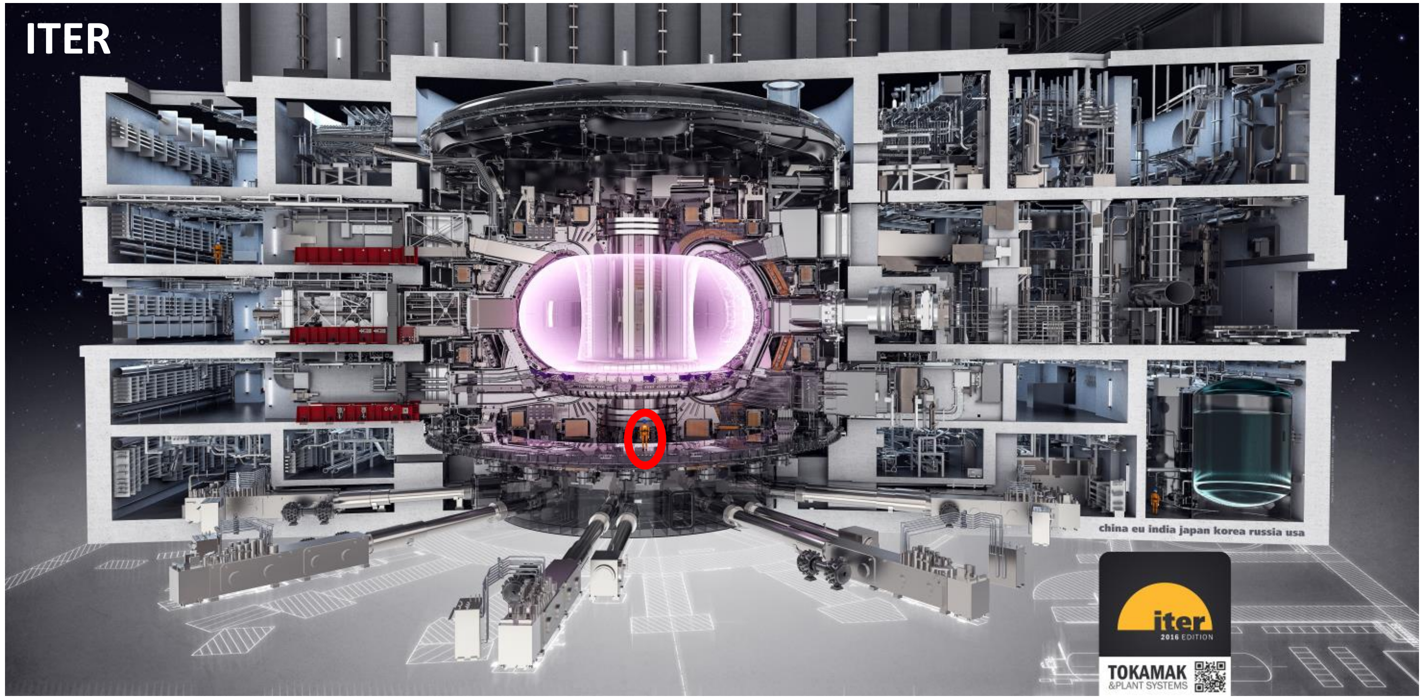
$3 \cdot 10^{27}$ estimated DT neutron budget

⇩

5 kg of neutrons!! Where do these neutrons go?



Courtesy of CCFE



Courtesy of ITER Organization

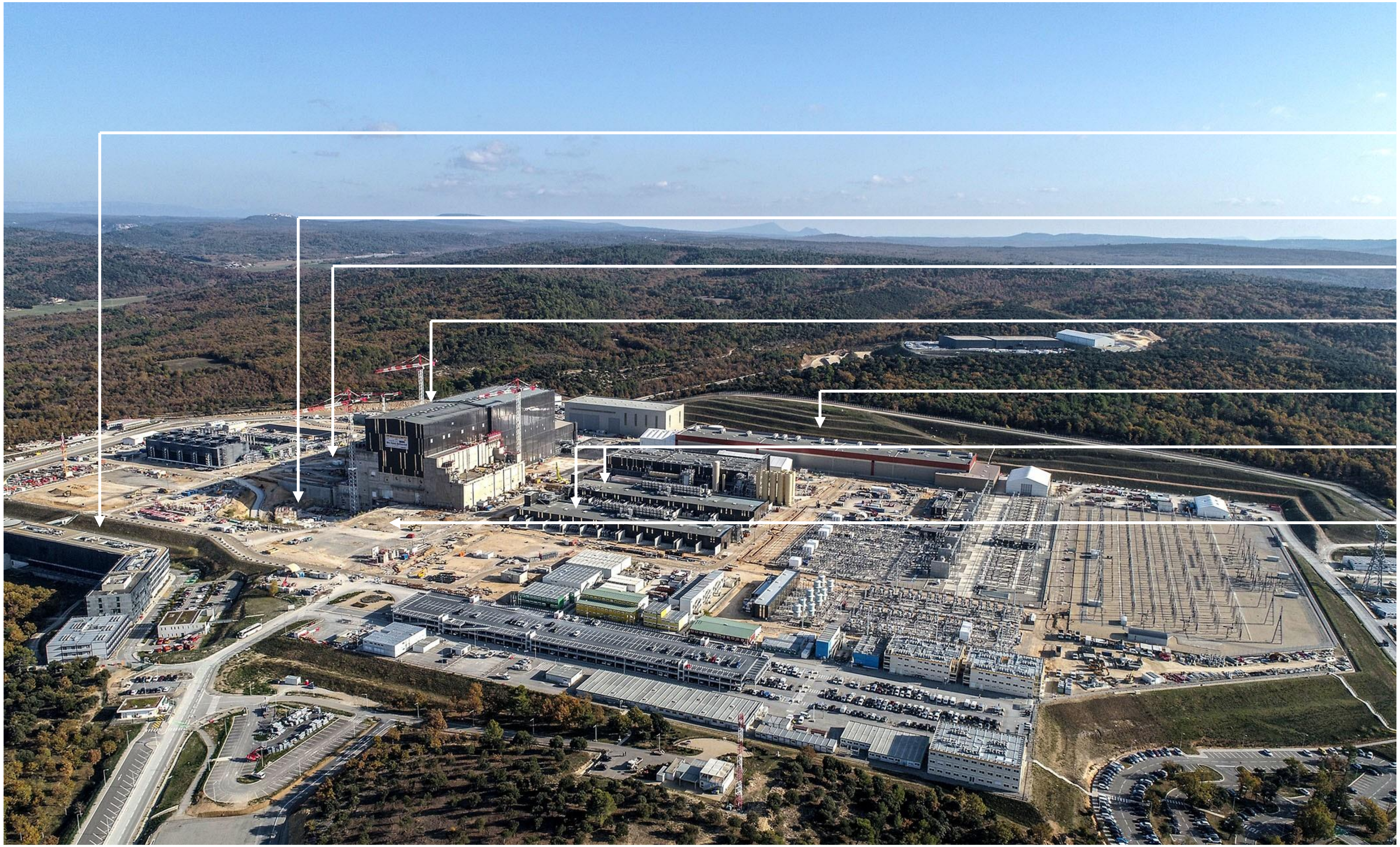
ITER timeline

ITER site by Nov 2020

Courtesy of ITER Organization

ITER timeline

ITER site by Nov 2020



Courtesy of ITER Organization

Physical problem

What makes ITER challenging from radiation standpoint?

- Huge facility
- Complex, new & intense radiation sources

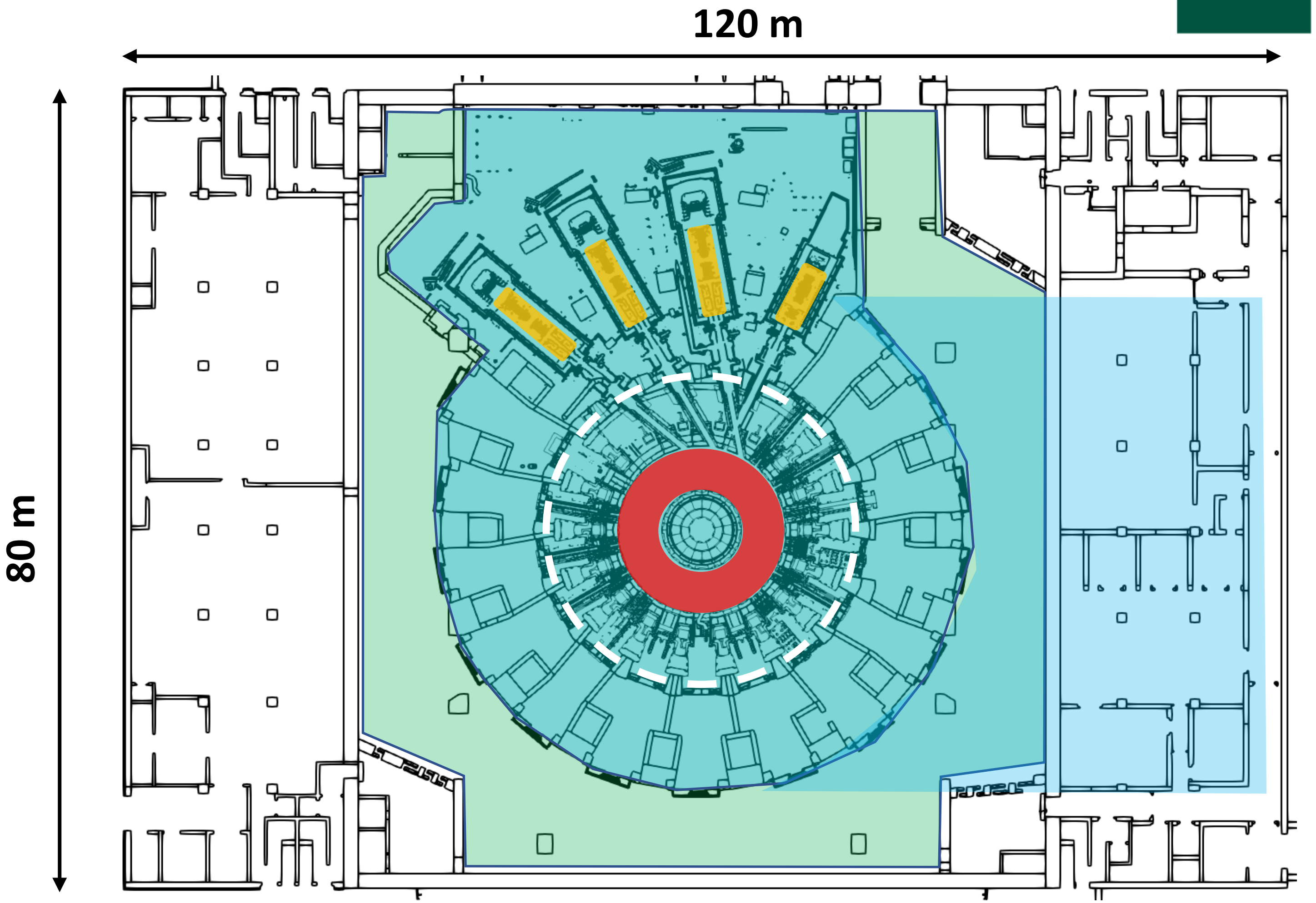
What is ITER?

- **Massive superconducting & nuclear Tokamak**
- **120m x 80m x 80m Tokamak Complex**
- **674 classified rooms**
- **Over 4500 penetrations > 10 cm^2**
- **Walls > 2 m + rebars**
- **Thousand tones of experimental equipment**

ITER radiation challenges

Radiation sources in ITER:

- Plasma DT neutrons and subsequent photons
- Plasma DD neutrons and subsequent photons
- Photo-neutrons from run-away electrons
- Photo-neutrons from Be
- NBI beam impact in Be
- Water activation: ^{16}N, ^{17}N, ^{19}O
- Activated corrosion products
- ERID & calorimeter source
- Radioactive decay of activated components
- Activated W and SS dust



Intense radiation sources of concern are found beyond the bio-shield

ITER radiation challenges

Challenges associated to the radiation ITER field:

- Cooling of components
- Biological doses to workers and public
- Protection of electronic & electric equipment
- Machine calibration
- Forecast and minimization of radwaste stream

The radiation field in ITER will be very complex due to plant geometry and sources nature

Previous techniques are not enough:

→ **new computational technologies to forecast the radiation field**

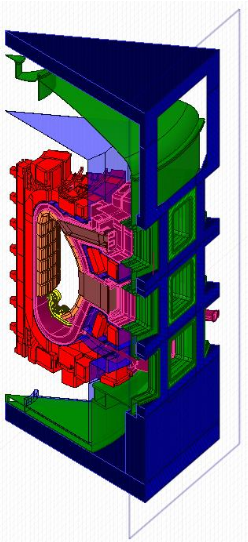
→ **new shielding technologies to mitigate radiation field**

New challenges require new solutions

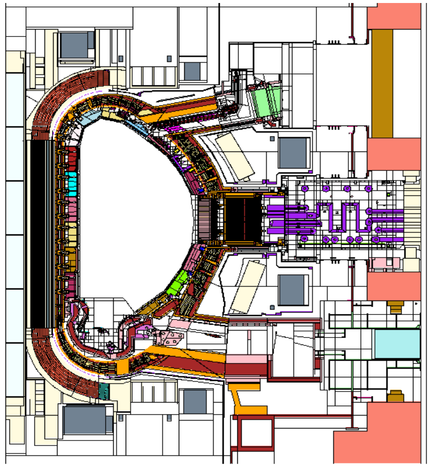
Nuclear analysis has evolved strongly due to ITER

ITER nuclear analysis workflow

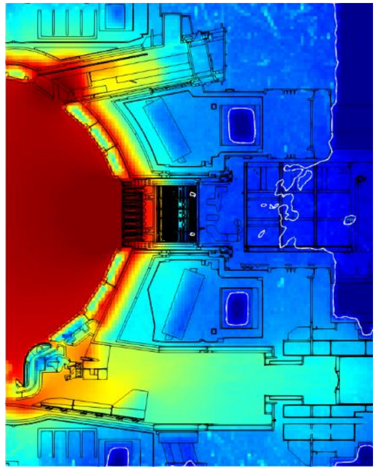
CAD model



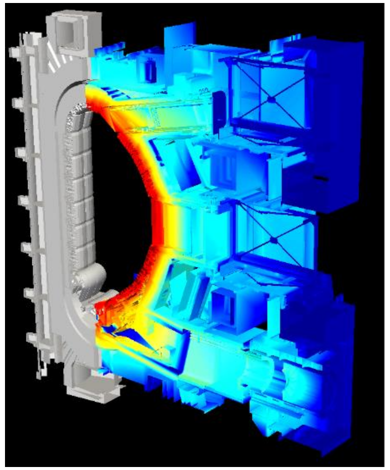
Transport model



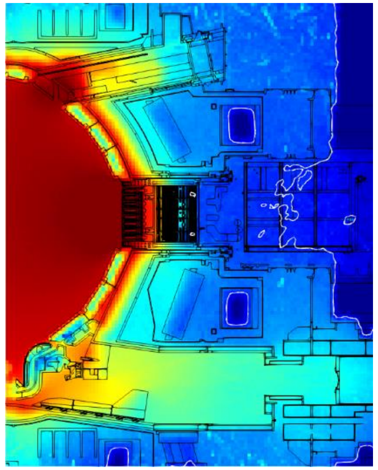
Prompt n-γ transport



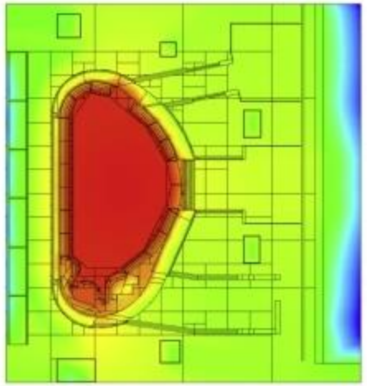
Activation



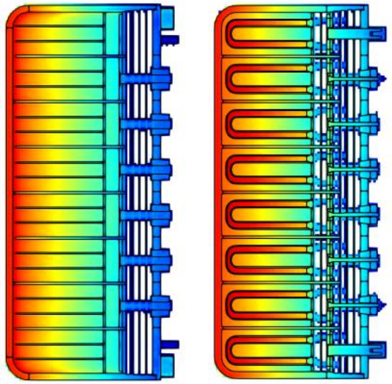
Decay γ transport



Variance reduction



3D high fidelity nuclear responses



Nuclear heating

ITER nuclear analysis workflow

We use a set of tools, of which, many have been developed at UNED (underlined):

CAD modelling: CATIA, Spaceclaim [1], MCAM [2], McCAD [3], DAG-MC [4], Geo-UNED [5]

Radiation transport (n & prompt γ): MCNP5 [6], MCNP6 [7]

Variance reduction: Global variance reduction [8], ADVANTG [9]

Activation: FISPACT [10], ACAB [11]

Decay γ calculations: MC-R2S [12], R2S-mesh [13], R2S-UNED [14], advanced-D1S [15], D1SUNED [16]

Postprocessing & visulization: mesh2vtk, Paraview [17], Unreal Engine [18]

Treatment of special sources: SRC-UNED [19], FLUNED [20], RSTM [21]

Few references are provided for future reading in next slide

ITER nuclear analysis workflow

[1] www.spaceclaim.com

[2] Y. Wu, *Fusion Engineering and Design*, **Volume 84**, (2009)

[3] L. Lu, Y. Qiu, U. Fischer, *Fusion Engineering and Design*, **Volume 124**, (2017)

[4] P.P.H. Wilson, T.J. Tautges, J.A. Kraftcheck, B.M. Smith, D.L. Henderson, *Fusion Engineering and Design*, **Volume 85**, (2010)

[5] J. García, J.P. Catalán, J. Sanz, *Fusion Engineering and Design,* **Volume 168**, (2021)

[6] X-5 Monte Carlo Team, “MCNP – A General N-Particle Transport Code, Version 5”

[7] C.J. Werner (editor), "MCNP Users Manual - Code Version 6.2", LA-UR-17-29981 (2017).

[8] A.J. van Wijk, G. Van den Eynde, J.E. Hoogenboom, Annals of Nuclear Energy, **Volume 38**, (2011)

[9] S.W. Mosher, et al. ADVANTG—An Automated Variance Reduction Parameter Generator, ORNL/TM-2013/416 Rev. 1 ORNL TN (2015)

[10] J.-Ch. Sublet, J.W. Eastwood, J.G. Morgan, M.R. Gilbert, M. Fleming, W. Arter, *Nuclear Data Sheets*, **Volume 139**, (2017)

[11] J. Sanz, O. Cabellos, N. Garcia-Herranz, Inventory Code for Nuclear Applications: User’s Manual V. 2008, December 2008.

[12] A. Davis, R. Pampin, *Fusion Engineering and Design*, **Volume 85** (2010)

[13] P. Perselavtsev, et al. *Fusion Engineering and Design*, **Volume 88** (2013)

[14] P. Sauvan, J. P. Catalán, F. Ogando, R. Juárez and J. Sanz, *IEEE Transactions on Nuclear Science*, **Volume 63** (2016)

[15] G. Mariano, D. Flammini, N. Fonnesu, F. Moro, R. Villari, *Fusion Engineering and Design*, **Volume 157** (2020)

[16] P. Sauvan, R. Juarez, G. Pedroche, J. Alguacil, J.P. Catalan, F. Ogando, J. Sanz, *Fusion Engineering and Design,* **Volume 151** (2020)

[17] Ayachit, Utkarsh, The ParaView Guide: A Parallel Visualization Application, Kitware, 2015, ISBN 978-1930934306

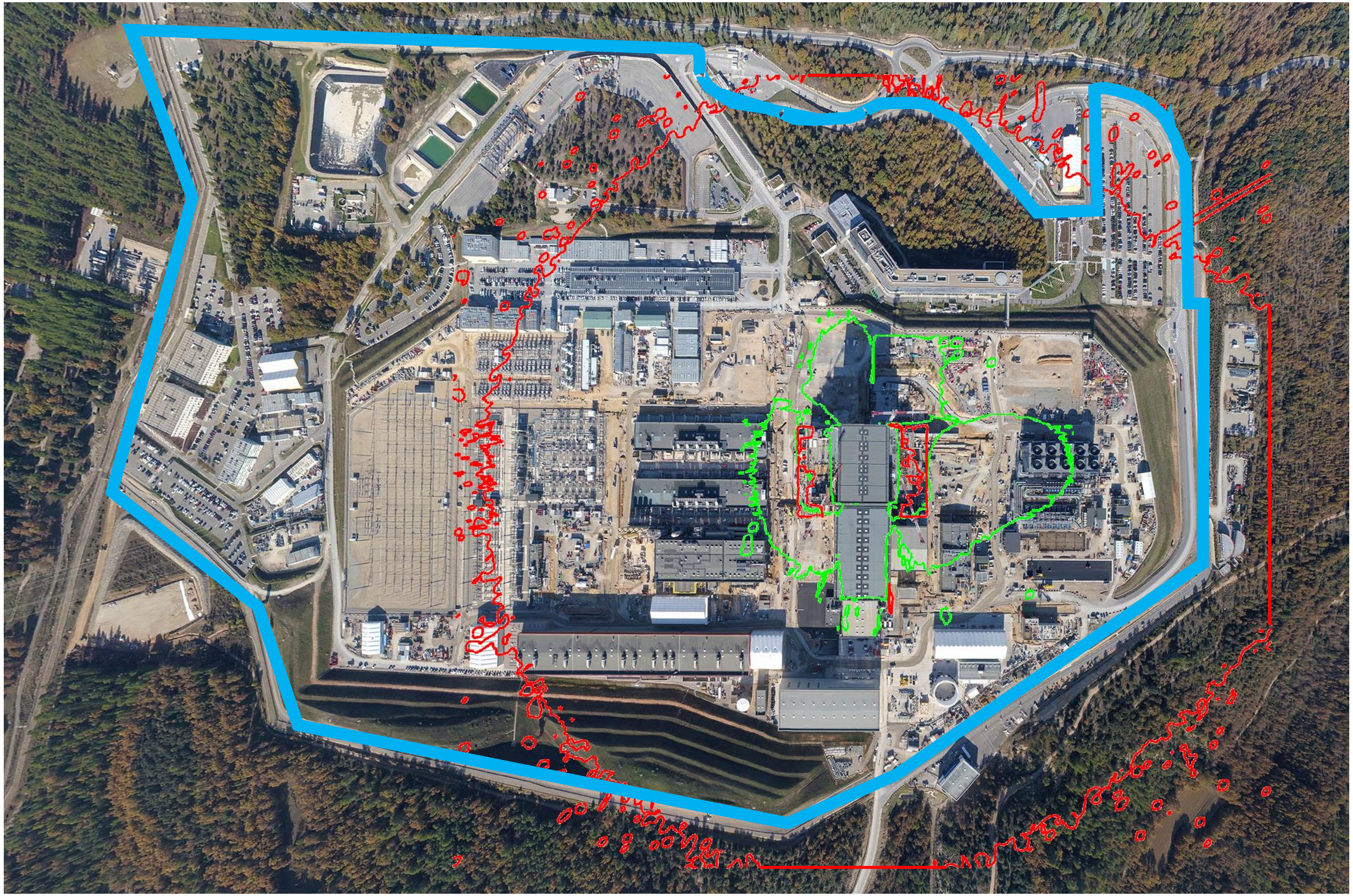
[18] https://www.unrealengine.com/

[19] R. Juárez, J.P. Catalan, F. Ogando, A.J. López- Revelles, P. Sauvan, S. Jakhar, *Nuclear Fusion Journal*, **Volume 58** (2018)

[20] M. De Pietri, J. Alguacil, A. Kolsek, G. Pedroche, N. Ghirelli, E. Polunovskiy, M. Loughlin, *Fusion Engineering and Design*, **Volume 171**, (2021)

[21] R. Pampin, F. Cau, M. Fabbri, J. Izquierdo, A. Portone, *Nuclear Fusion Journal*, **Volume 61**, (2021)

Example: Compliance with regulatory limit for public



Limit for public (beyond fence):

1 mSv/year

(780 hours / year) → **1.28 µSv/h**

0.1 µSv/h

0.01 µSv/h

Example: Compliance with regulatory limit for public

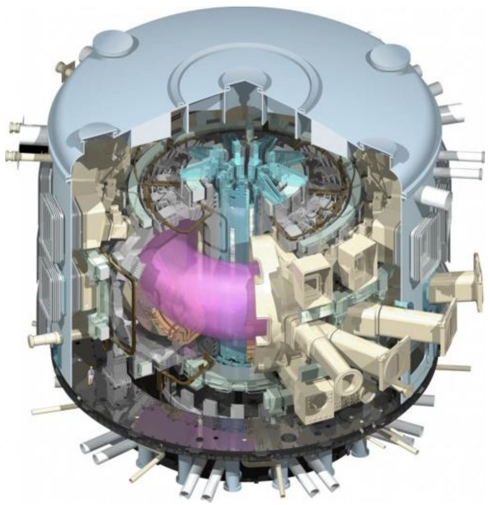
This study took place based on previous works:

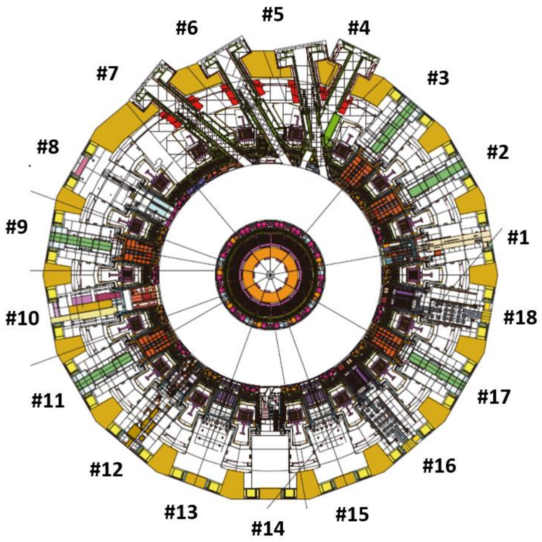
- Ten years of work by multiple institutions: ITER, ORNL, CCFE, AMEC & UNED
- Two previous attempts where many lessons were learnt and methods developed
- Tens of partial studies for decision making during building construction

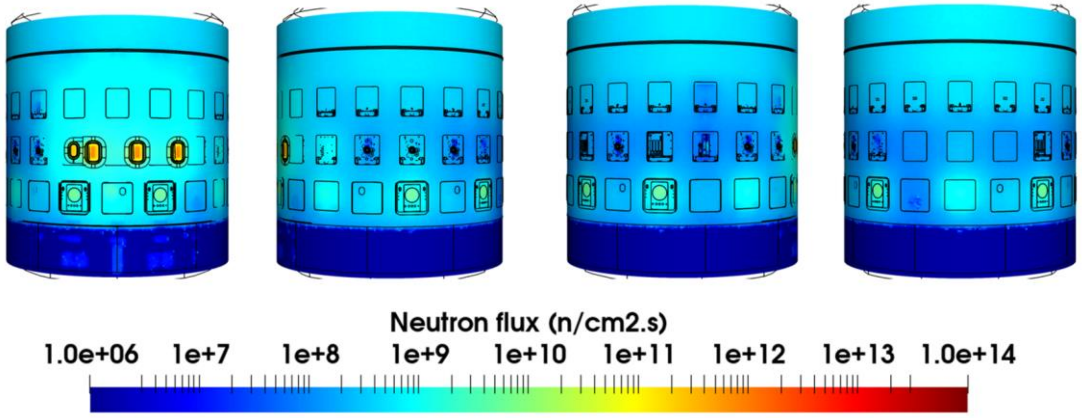
Current demonstration has required:

- **Construction of two of the most complex MCNP models in the world**
- **Dedicated methodology to model the plasma source**
- **Dedicated methodology to model the water radiation source**
- **Over 5,000,000 cpu.hr, among other things, to capture the skyshine**
- **6 people full-time + 2 people part time during 2 years**
- **New tools: D1S-UNED, SRC-UNED and others**

Example: Compliance with regulatory limit for public



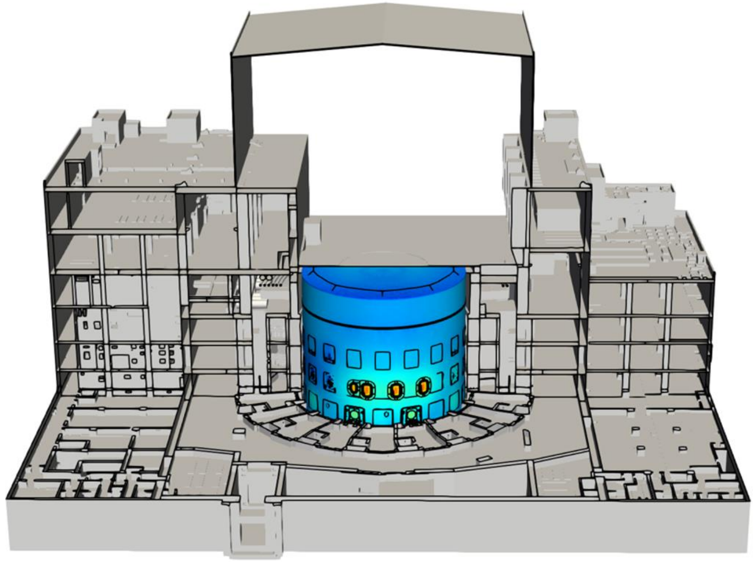




nature energy
ARTICLES
https://doi.org/10.1038/s41560-020-00753-x
Check for updates

A full and heterogeneous model of the ITER tokamak for comprehensive nuclear analyses

R. Juarez[1,4], G. Pedroche[1,4], M. J. Loughlin[2], R. Pampin[3], P. Martinez[1], M. De Pietri[1], J. Alguacil[1], F. Ogando[1], P. Sauvan[1], A. J. Lopez-Revelles[1], A. Kolšek[1], E. Polunovskiy[2], M. Fabbri[3] and J. Sanz[1]

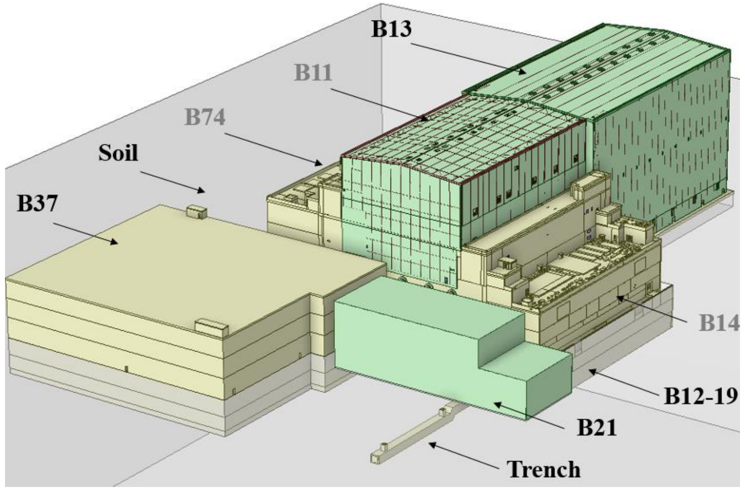


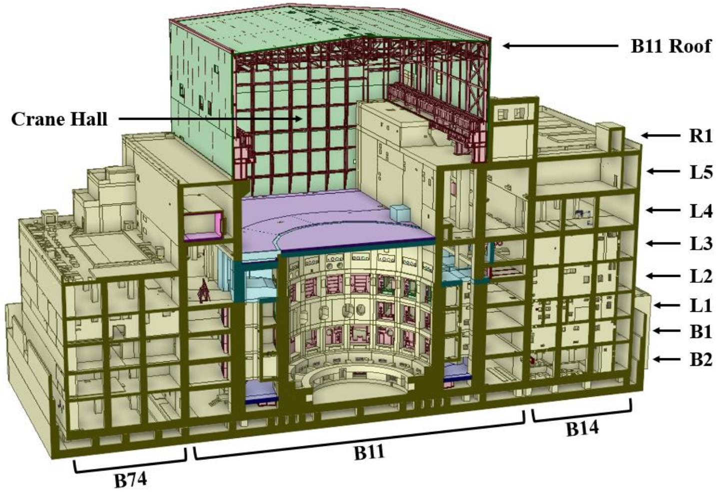
Example: Compliance with regulatory limit for public

Tokamak Complex

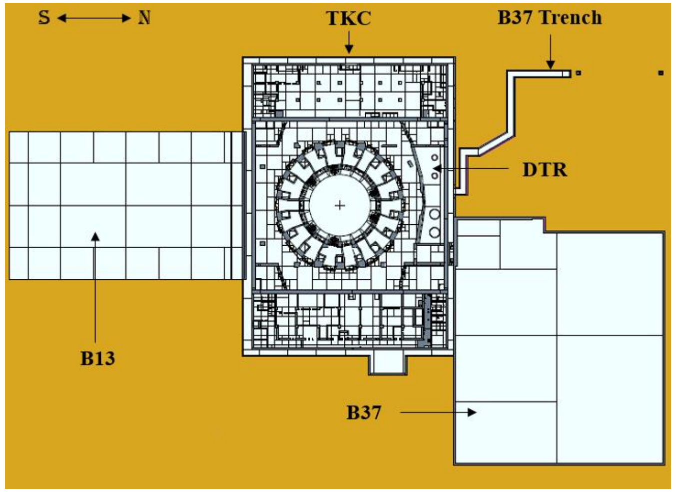
- According to baseline 2020
- It covers 7 edifices and
- Includes soil and 1km of air
- Over 4,500 penetrations traced and reviewed one-by-one
- 674 rooms explicitly modelled
- 14 dedicated shielding measures to meet the limit for public

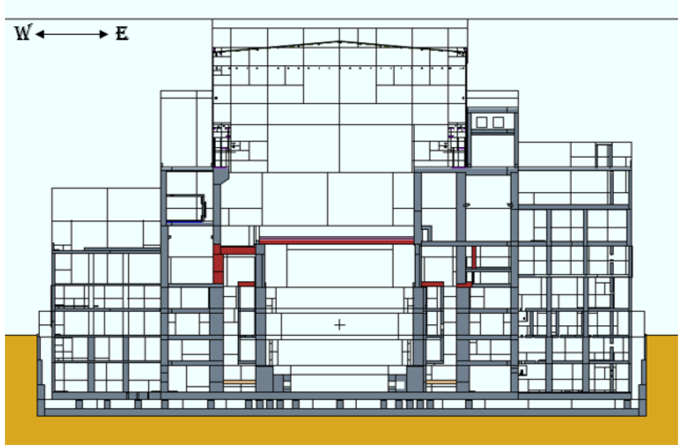
CAD model





MCNP model

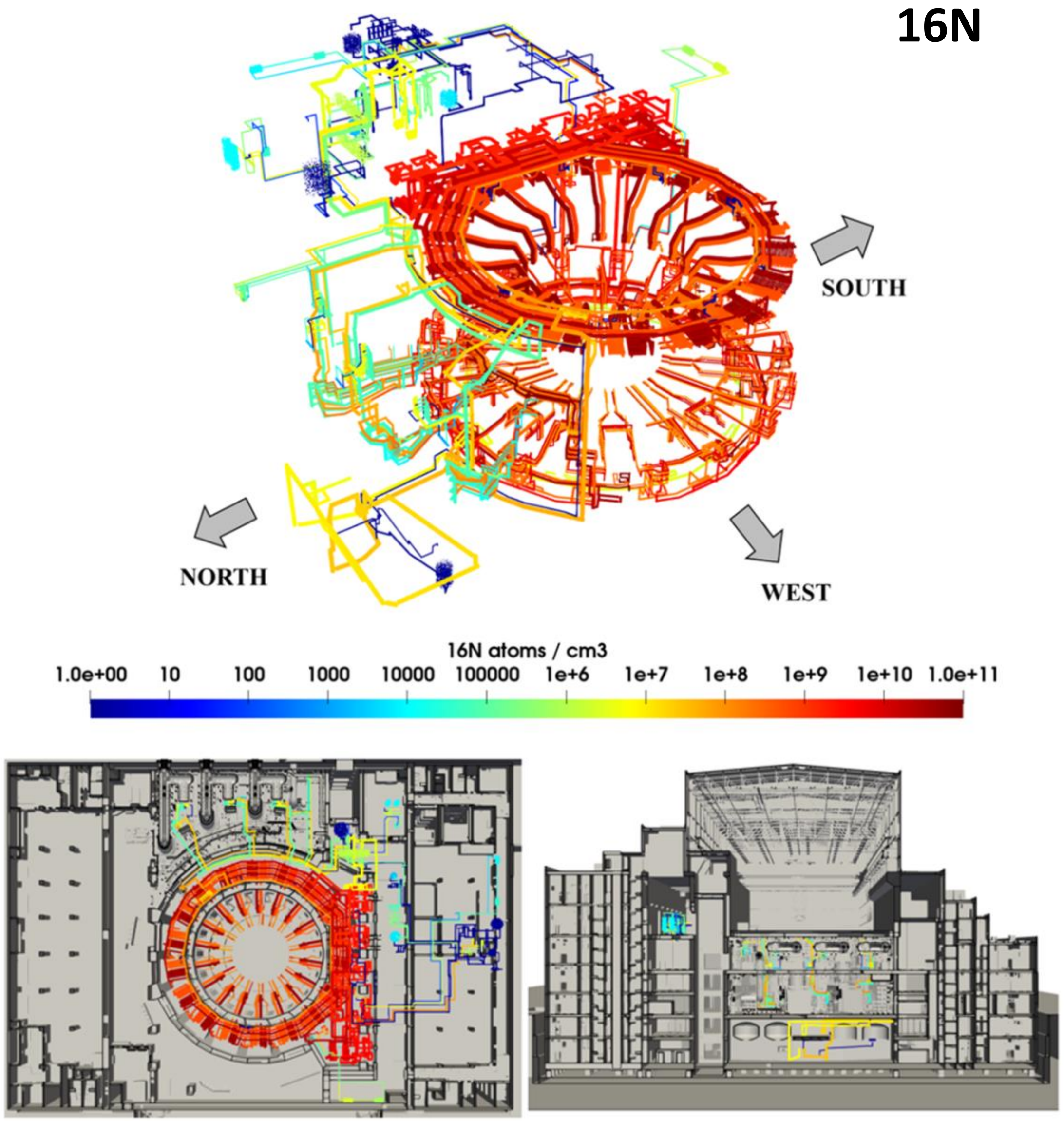




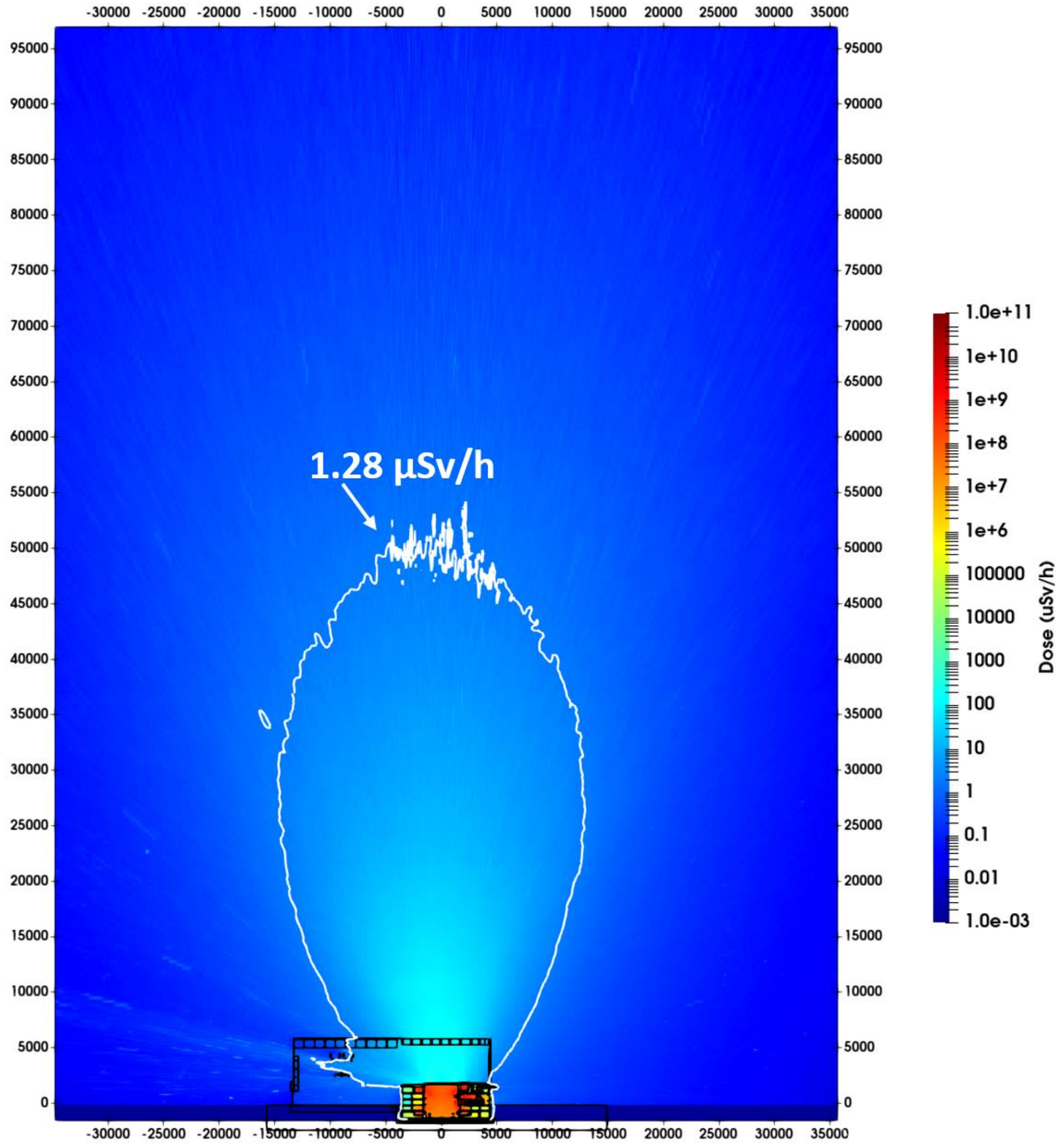
Example: Compliance with regulatory limit for public

ITER Tokamak Cooling Water Circuit

- It contains 500 m^3 of water in 15,000 pipes
- They contain ^{16}N, ^{17}N and ^{19}O decaying as water flows
- Water velocity and pipe shell thickness vary strongly
- The characterization required:
  - P&ID information for every pipe
  - Scripting to implement it in the CAD model
  - Coding of flow diagrams
  - Scripting to compute the isotopes decay along the thousands of paths

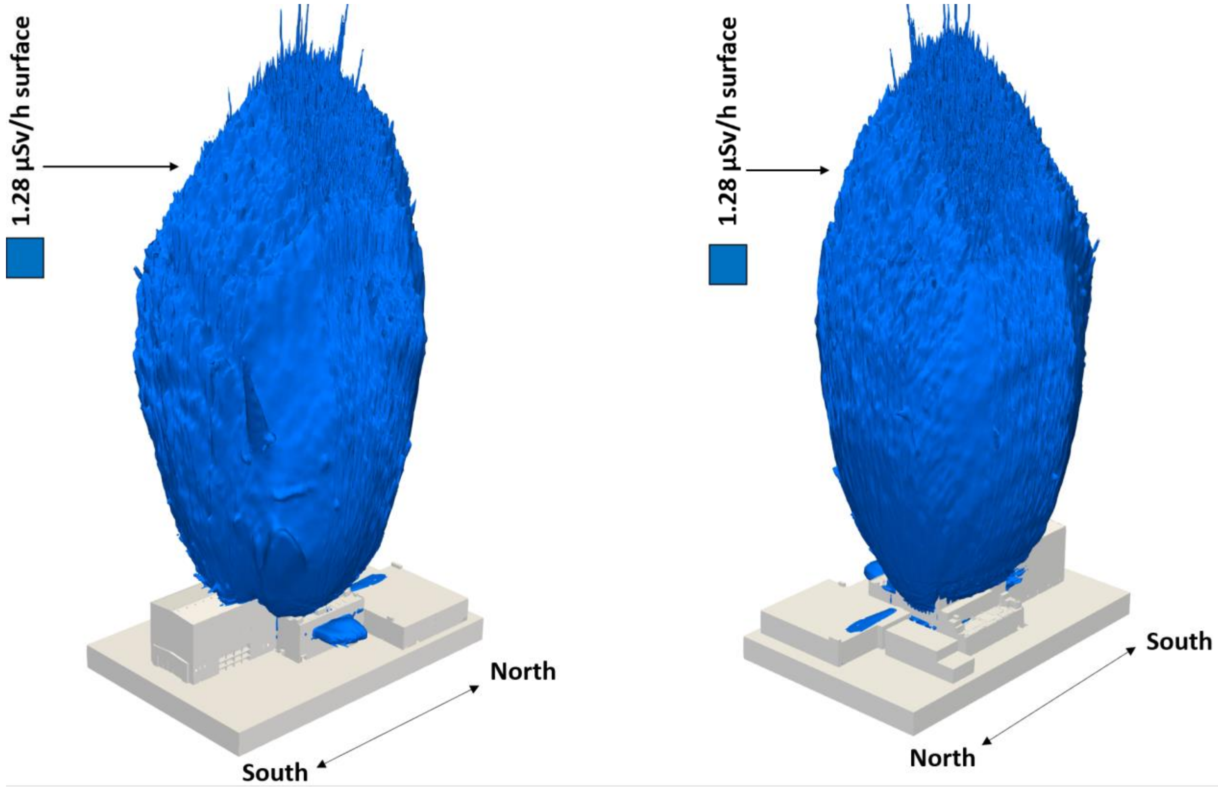


Example: Compliance with regulatory limit for public



ITER skyshine was evaluated for the first time:

- **It is dominated by ^{16}N gammas**
- **It is not a challenge to regulatory limits**
- **It has been computationally expensive to compute**

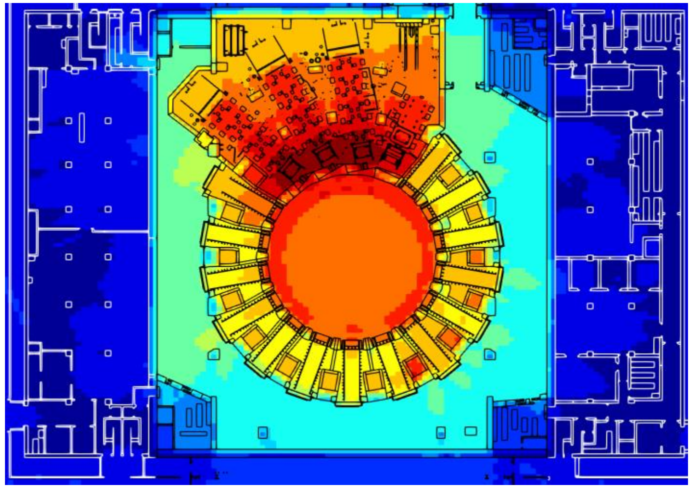


Example: Compliance with regulatory limit for public

Outcome of radiation atlas 2020:

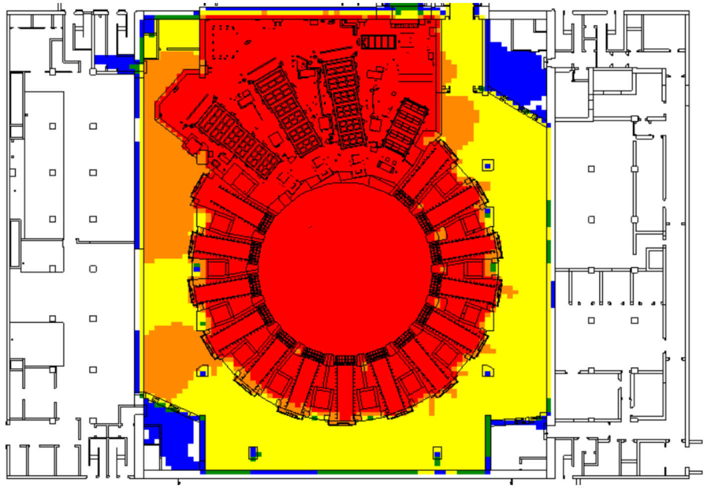
- Compliance of the ITER shielding with regulatory limits for public protection was demonstrated
- Many unknown aspects were faced for the first time
- Autorité de sûreté nucléaire (ASN) must review the work to release the Assembly Hold Point
- Rad levels to define electronic and electric equipment qualification programs were obtained
- Radiological zoning for workers exposure was obtained as well

Rad Map



Radiological zone	Zone	Maximum total effective dose for the entire body - external and internal exposure
White	Unregulated	< 80 µSv/month
Blue	Supervised	1.25 mSv integrated on a month
Green	Controlled	4 mSv integrated on a month
Yellow	Controlled	2 mSv integrated on one hour
Orange	Controlled	100 mSv integrated on one hour AND 100 mSv averaged over a second
Red	Controlled	100 mSv integrated on one hour OR 100 mSv averaged over a second

Zoning



Computational problem

What makes ITER challenging from radiation transport standpoint?

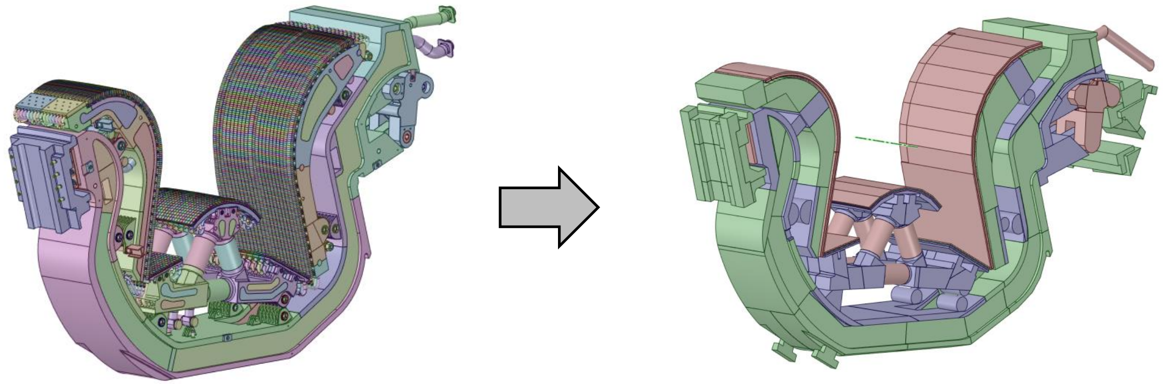
- Extreme geometry modelling
- Modelling of new radiation sources
- High-Performance Computing
- Understanding the complex radiation fields

Extreme geometry modelling

Extreme geometry modelling

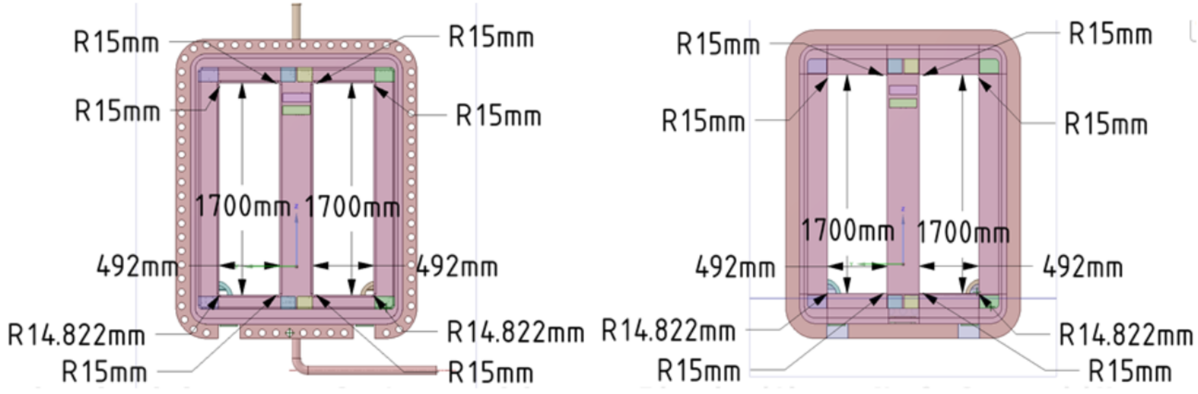
New tools:

- MCAM
- McCAD
- DAG-MC
- SpaceClaim
- GEO-UNED
- UM-MCNP6



New procedures:

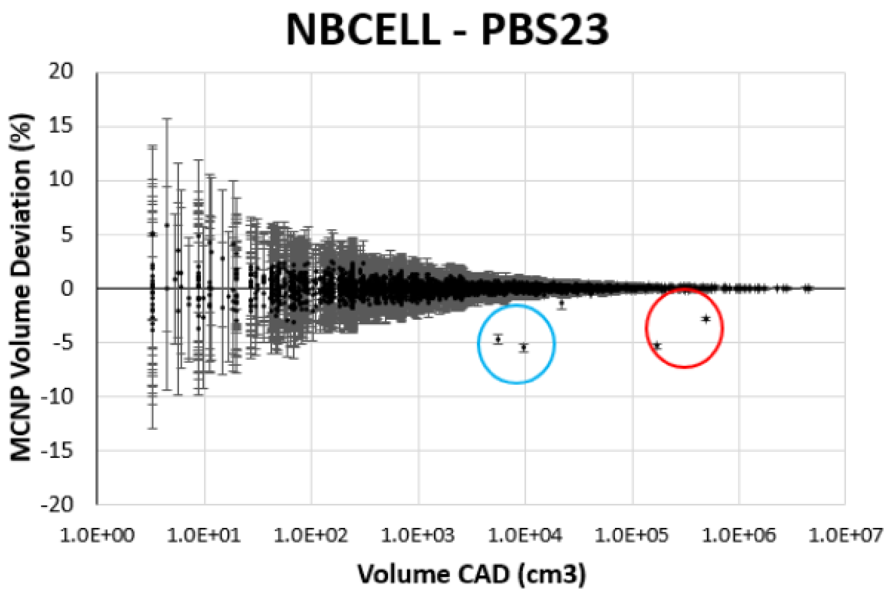
Dimensional control



Original geometry

Simplified geometry

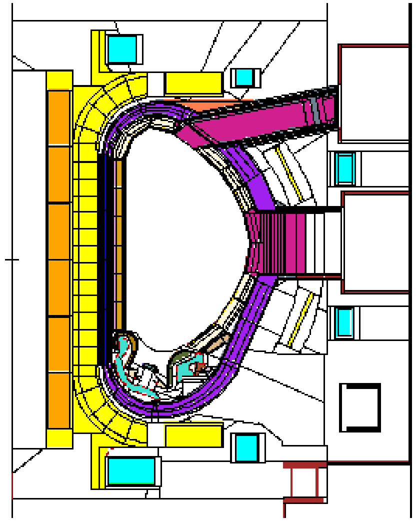
Mass control



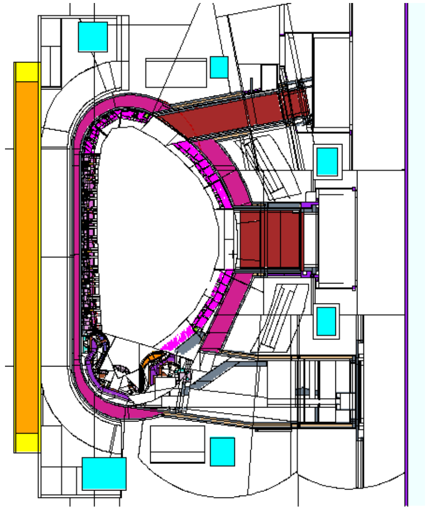
Extreme geometry modelling

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

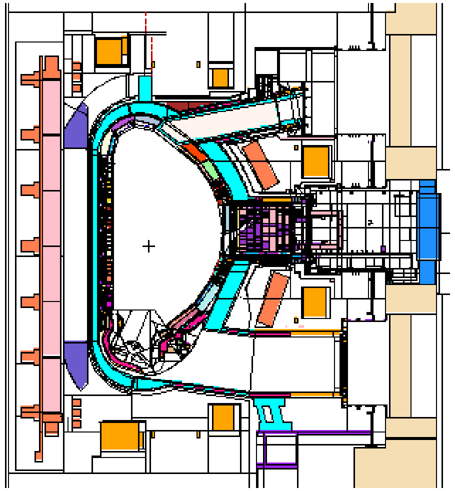
Model	Segment	Period	Surfaces
RC-ITER	18º	1998 – 2000	unknown
Brand	20º	2000 – 2008	1586
A-lite	40º	2008 – 2009	3601
B-lite	40º	2010 – 2013	27918
C-lite	40º	2013 – 2016	34105
C-model	40º	2016 – now	146776
E-lite	360º	2020 - now	461038



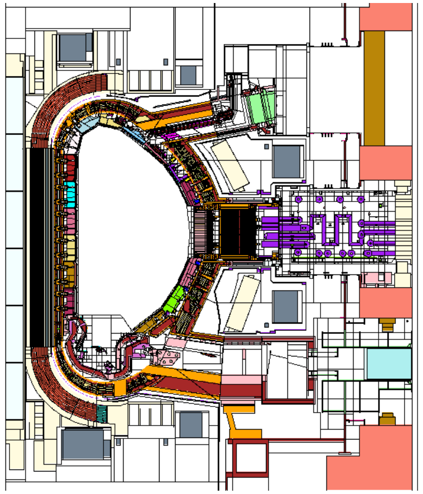
A-lite



B-lite



C-lite



C-model

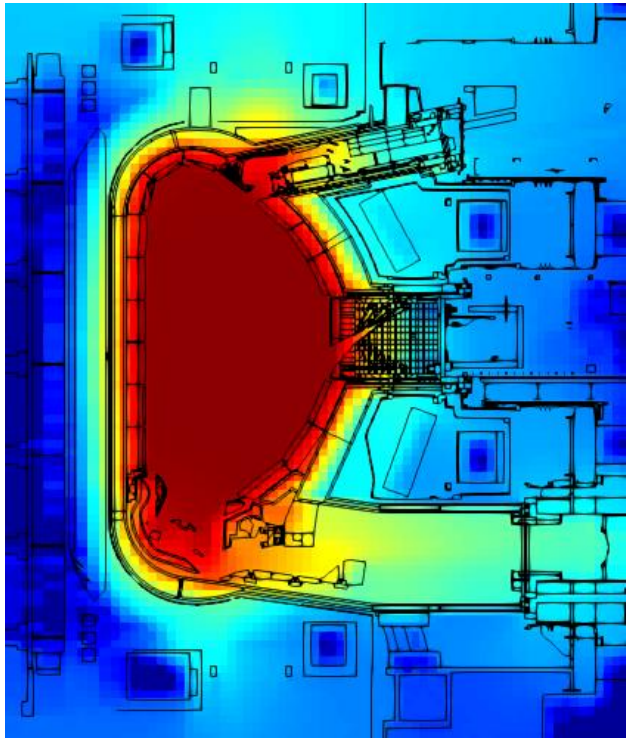
Modelling of new radiation sources

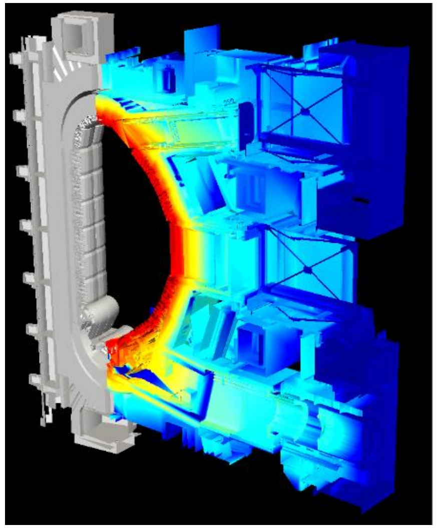
Radioactive captive source

Neutron irradiation induce a radioactive field. It is dominant when the plasma is in shutdown

This affects maintenance operations and drives the Occupational Radiation Exposure (ORE)

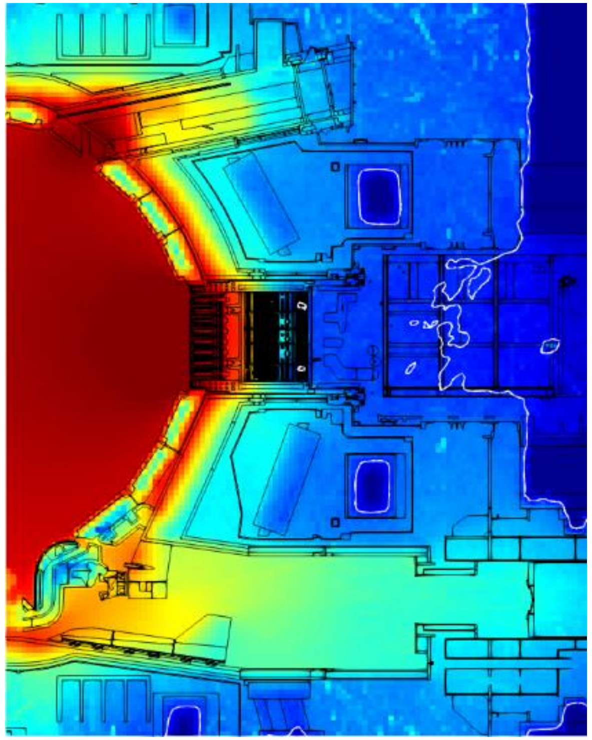
Neutron flux during machine operation





(R2S) Rigorous-two steps method: one activation calculation for each voxel of the mesh. Coupling radiation transport and activation codes

Dose rate at 24 hours cooling time



(D1S) Direct-one step method: tricked radiation transport & nuclear data to include activation & decay in the rad transport

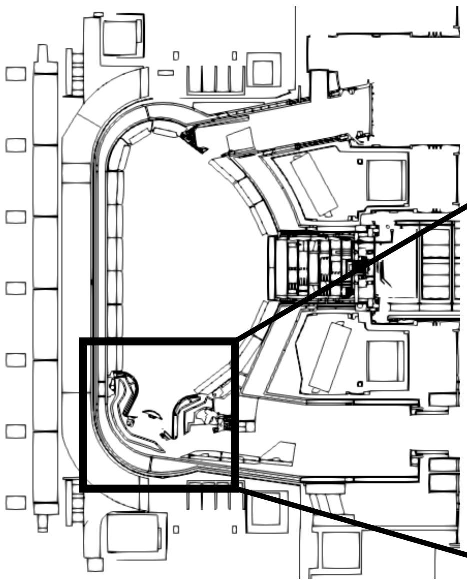
Radioactive sources

R2S and D1S methods have been major advances. Dozens of implementations in MCNP exist already

Spatial resolution has revealed to be critical. Computational loads have rocketed:

- R2S deals with huge meshes of neutron flux in 175 energy bins and hundred thousand activation calculations
- D1S deals with large N-P calculations in which many γ are not interesting

These approaches have triggered improvements in MCNP performance



Decay gamma source distribution
(1x1x1 cm^3 resolution)
Computed with D1SUNED

Radioactive moving source

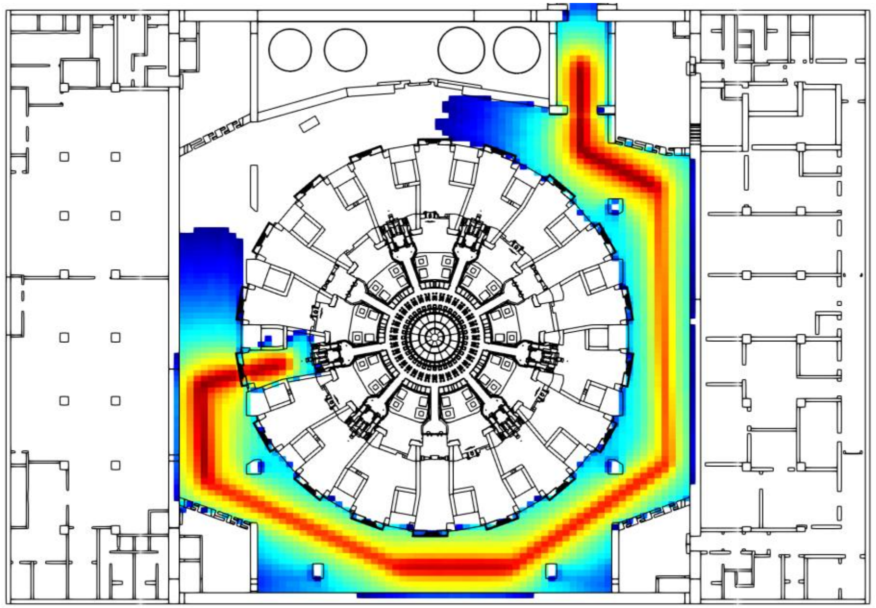
Decay radiation sources show relevance in many situations. Example:

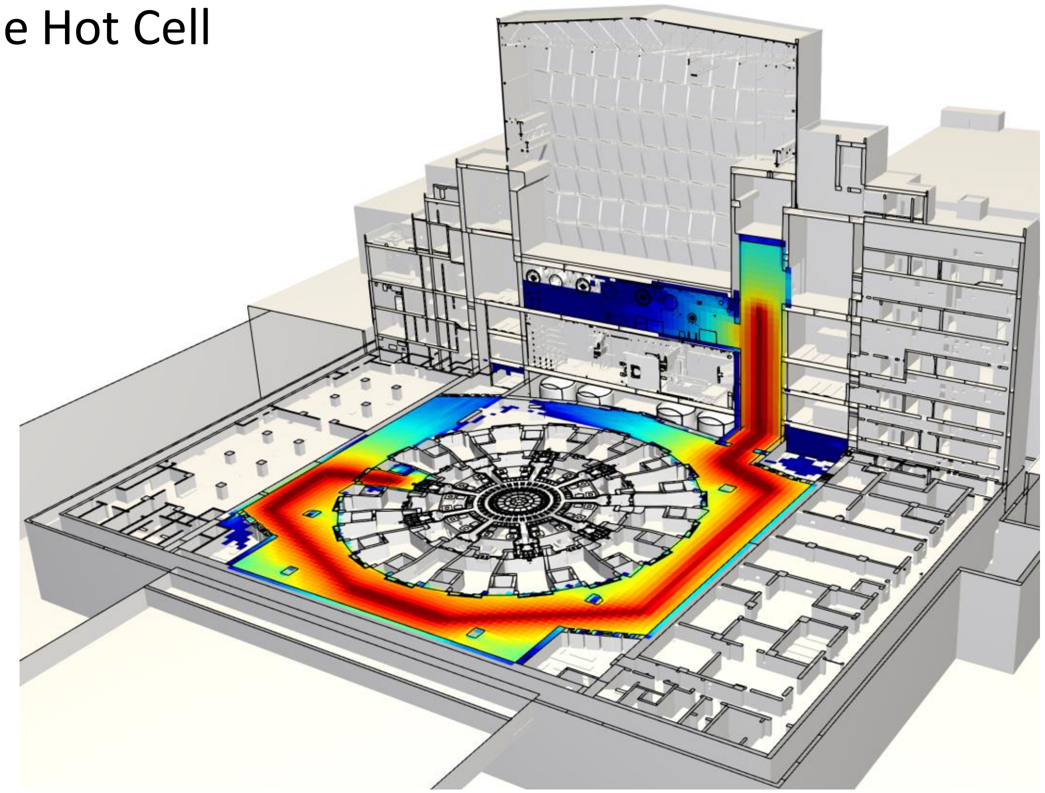
Induced activation produces an intense radiation field during the transportation of a component as well

This affects the functioning of the electronics in the plant.

Example: Dose to silicon of the transit of the divertor to the Hot Cell

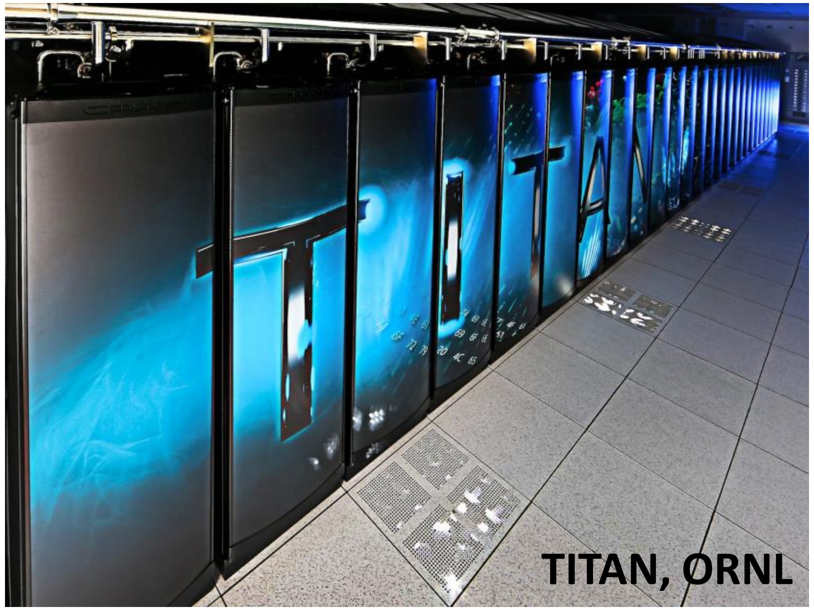
Computed with D1SUNED





Growing High Performance Computing

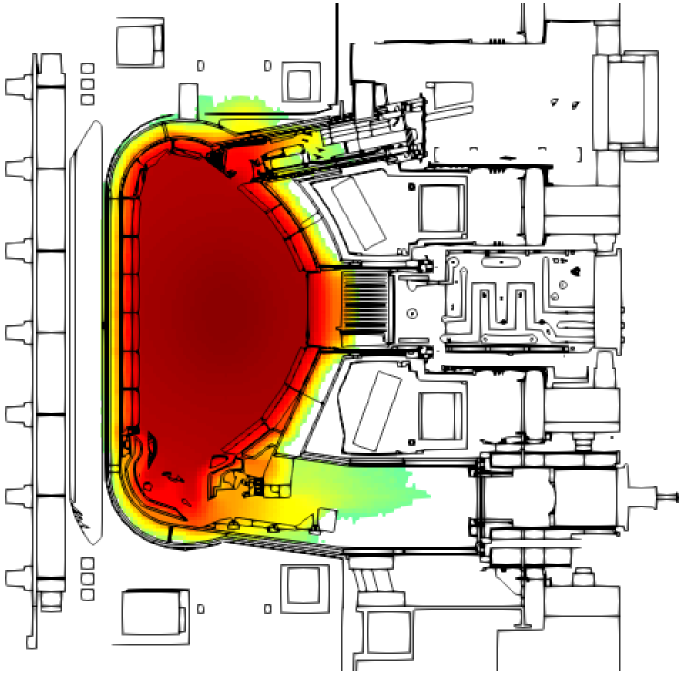
Variance Reduction & HPC



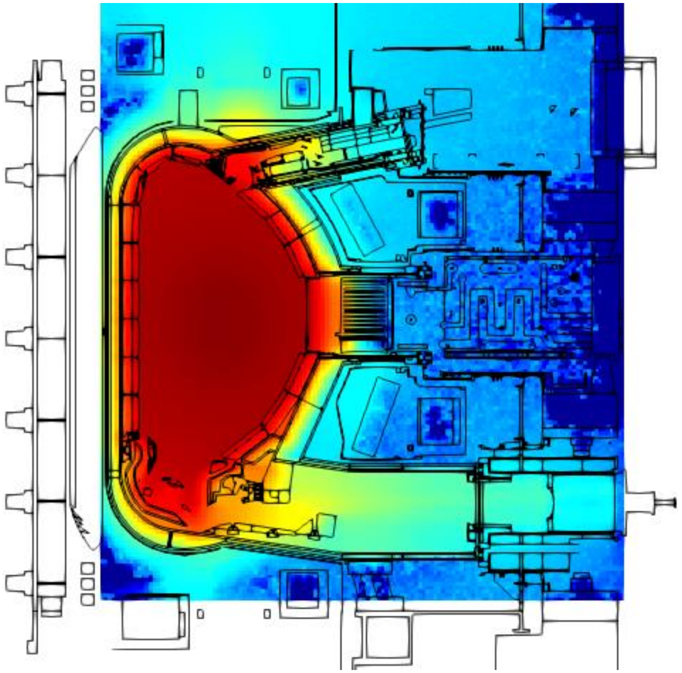
Some of the fastest HPC in the world are involved in the calculations

Research in variance reduction techniques saves millions of cpu.hr

Global Variance Reduction



Analog - NPS 10^9 – 1161 cpu.hr

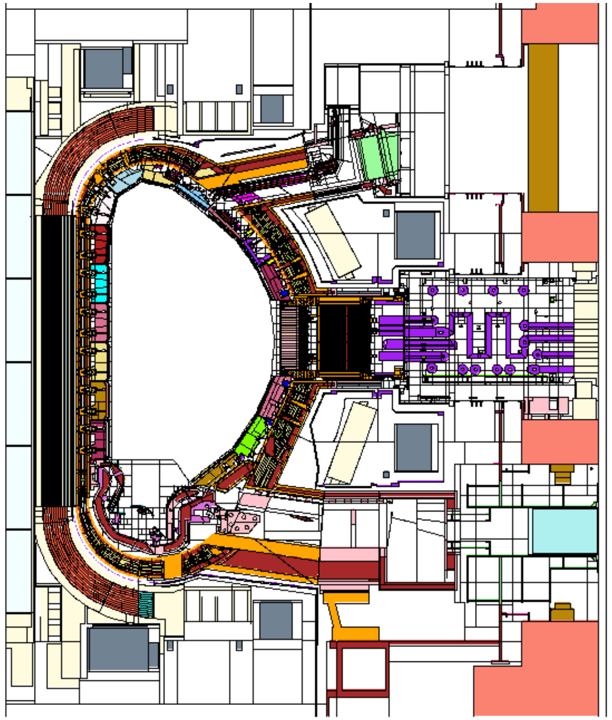


GVR - NPS 10^9 – 2680 cpu.hr

Code performance enhancements

MCNP is a renowned code… unprepared to deal with huge geometries

D1SUNED & ORNL-TL are MCNP modifications to enhance the code performance



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	9E-5	3e-7	x300 lower

These modifications multiply computing power by x5… for free!

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

Understanding complex radiation fields

Understanding complex radiation fields

Complex geometry

+

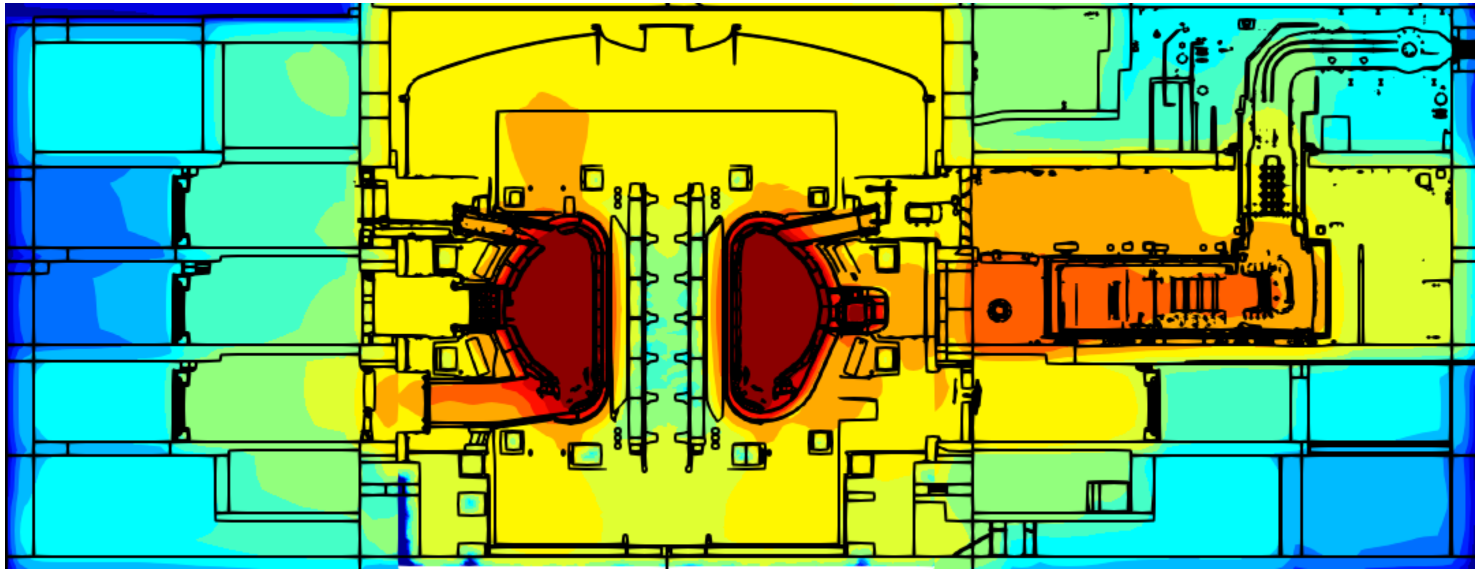
Complex source

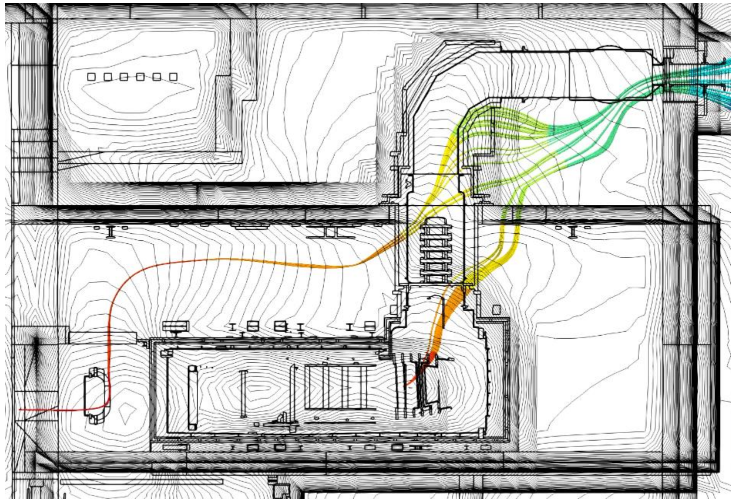
=

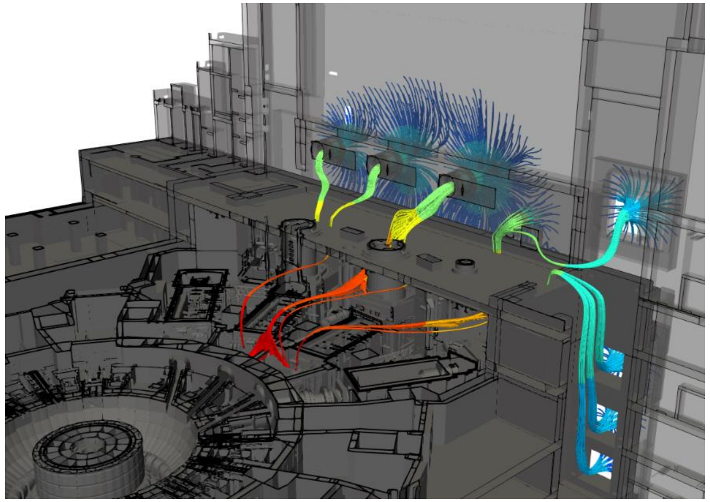
<u>Complex field</u>

Analysis based in 2D plots and contour surfaces can be misleading

Vector analysis has been applied very successfully with Paraview

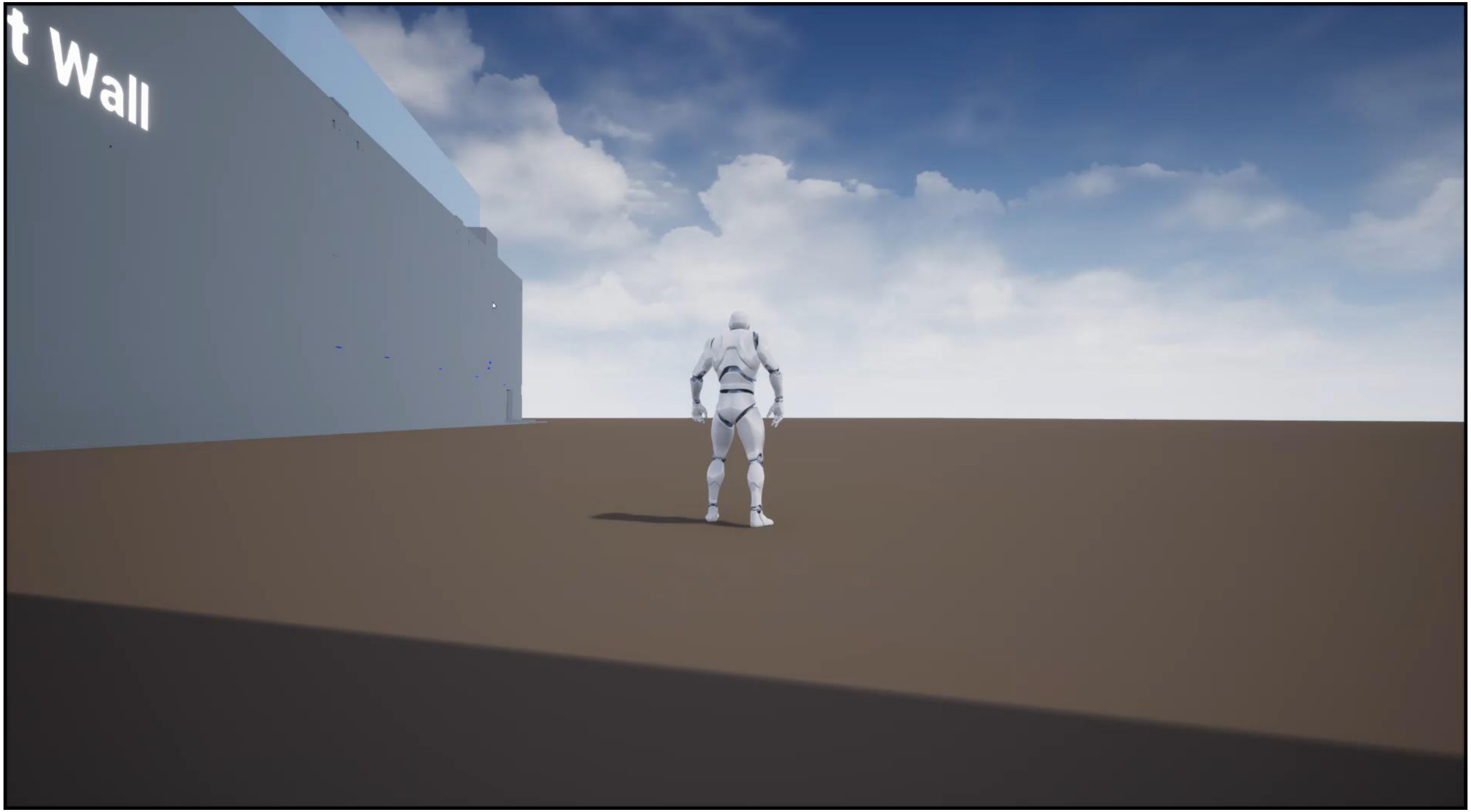






Understanding complex radiation fields

Videogame engines are used since 2020 to create virtual interactive environments



Are there remaining challenges for ITER radiation transport?

Many. To name one:

- Sampling of penetrations

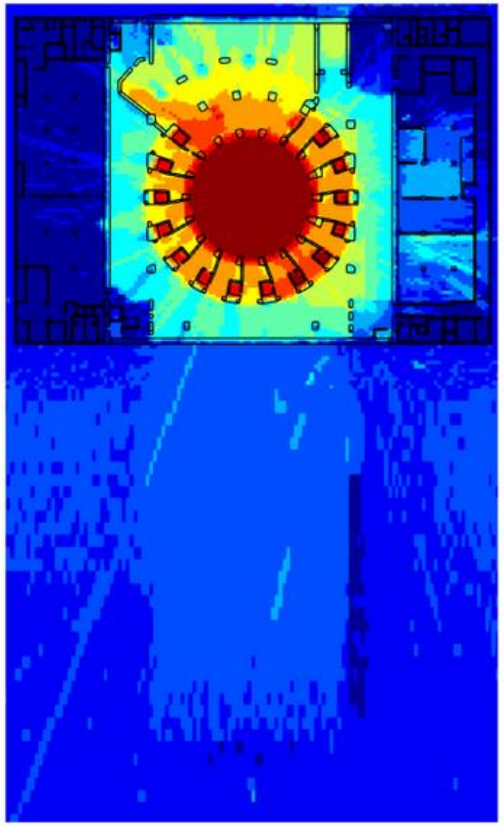
Sampling of penetrations

The number of histories and the variance reduction are parameters driving the sampling of penetrations

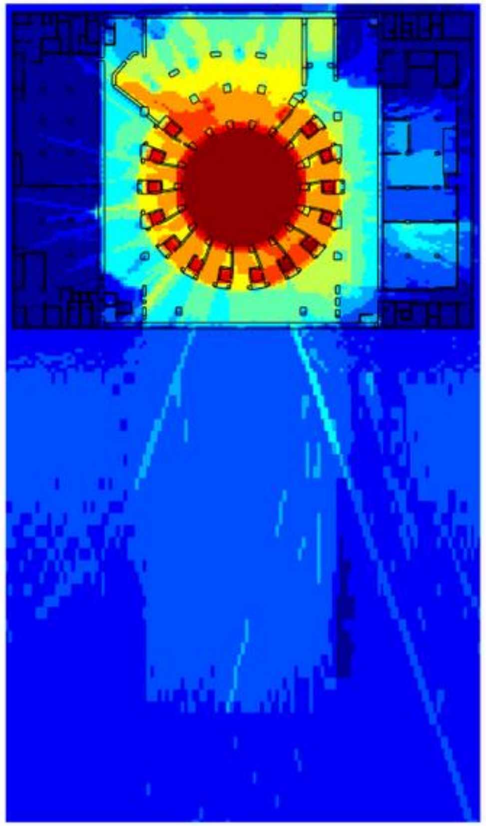
Currently we can run up to 10^{11} histories with efforts; exceptionally even 10^{12} histories once a year

The plasma source emits 10^{19} particles per second

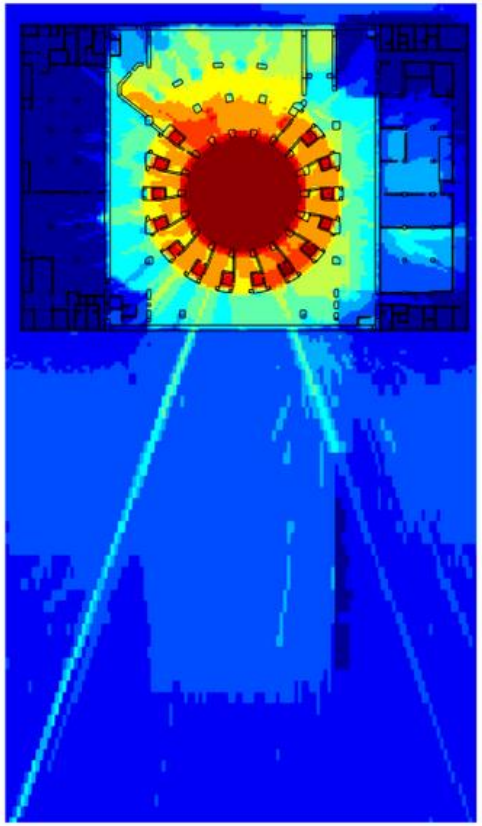
NPS 10^9



NPS $5 \cdot 10^9$



NPS $5 \cdot 10^{10}$



We are still 7 orders of magnitude below

a full sampling of 1 second of the source:

- Moore's law will require 48 years
- **AI-based variance reduction**
- **GPU-based parallelization**
- **Quantum computing**

Conclusions

ITER has driven a strong evolution of the nuclear analysis capabilities during the last 20 years

This in an early benefits of ITER, with direct applications to:

- Other nuclear fusion devices: STEP, DEMO, CFETR, General Fusion, …
- Gen-IV reactors designs: Terrapower, Moltex Energy,…
- Nuclear propulsion reactors: BWXT space propulsion
- Radiation shielding in space: spacecraft design for travel to Mars
- Particle accelerators: IFMIF-DONES, ESS, MYRRHA,…
- Nuclear medicine: proton therapy bunkers

Thank you