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

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Nuclear analysis in support of ITER design - II

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Presentation #1:

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

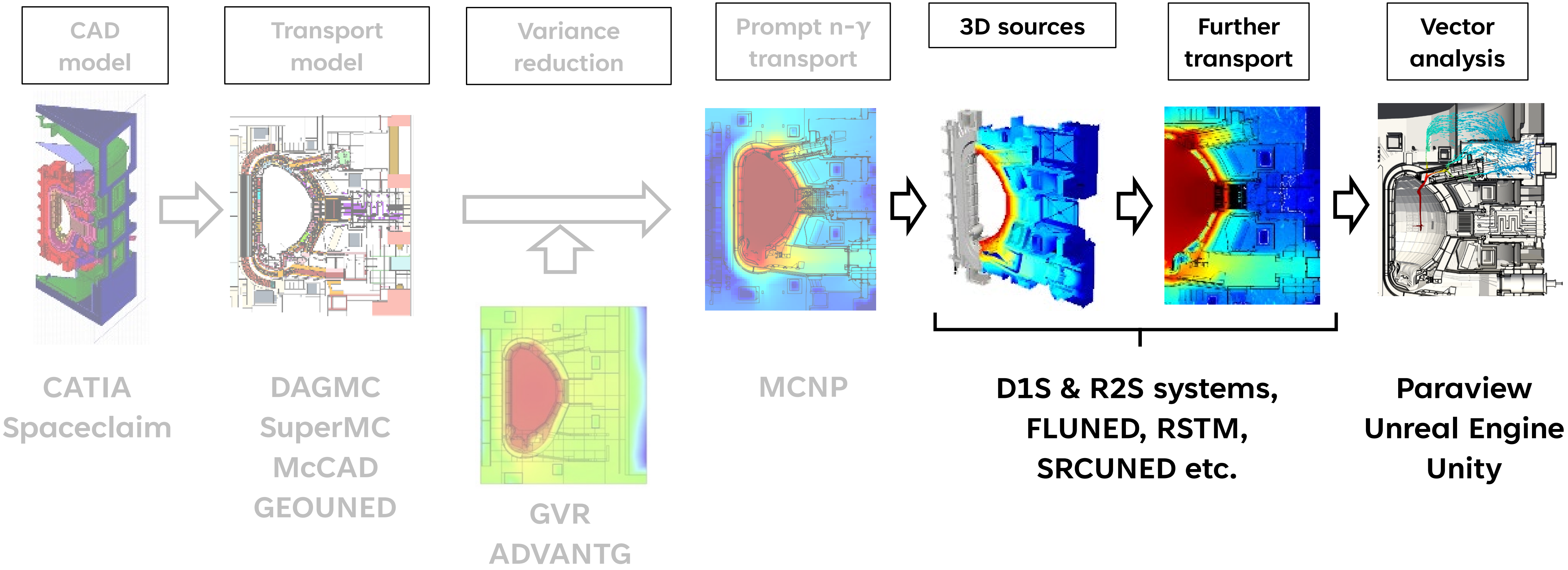
Presentation #2:

- 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.

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



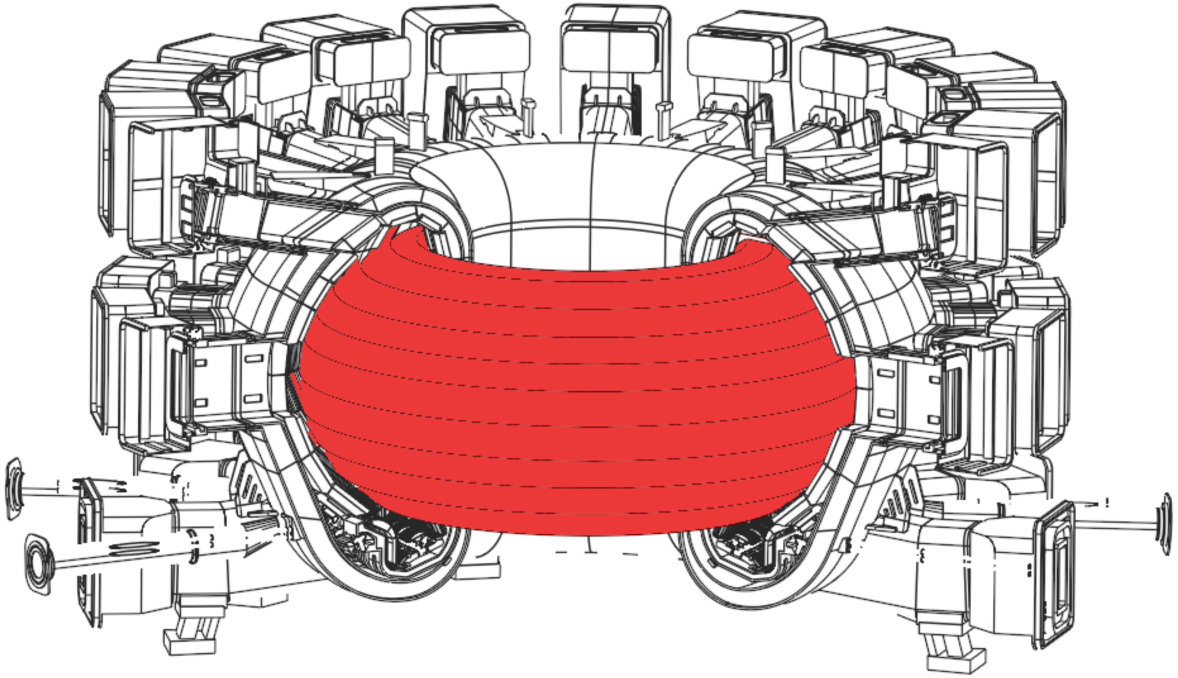
Description of the radiation sources of concern in ITER

Prompt sources: They emit simultaneously to the physical mechanism that triggers them. Both vanish together

Delayed sources: They emit simultaneously to the physical mechanism that triggers them, but they continue emitting after its cease

Prompt sources

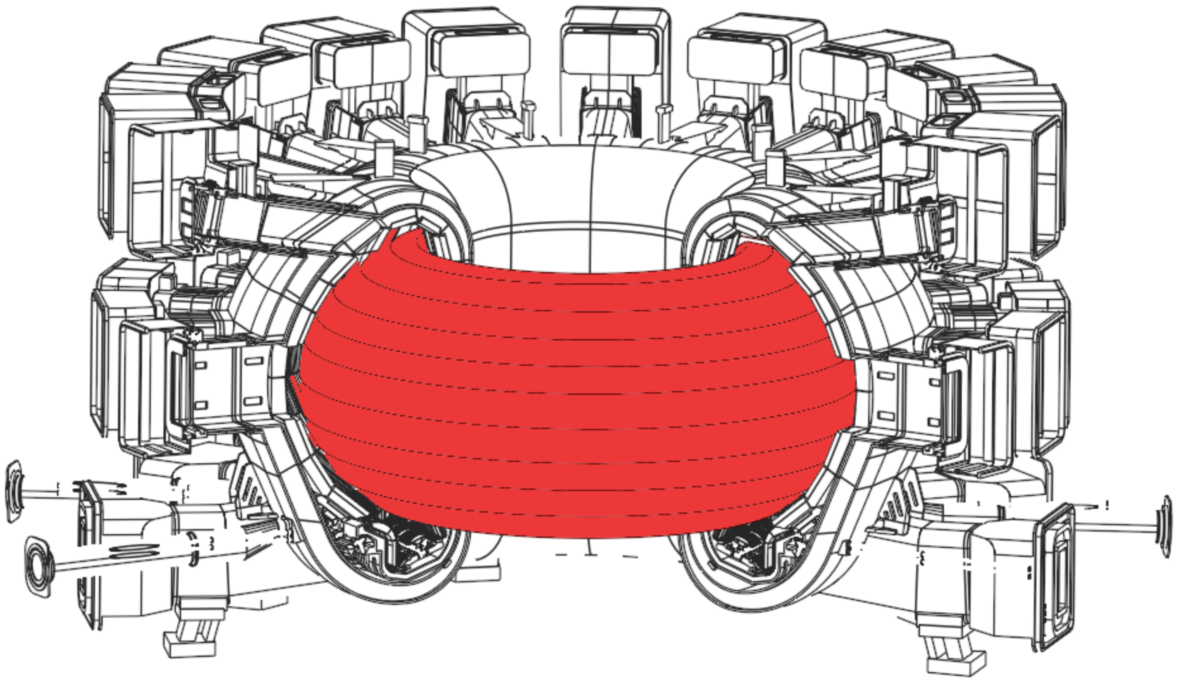
Plasma sources



Species	Neutrons in PFPO
DD	2.3×10^{16}
DT	3.6×10^{12}
H(D)-Be	2.2×10^{19}
H-Be	5.5×10^{19}
^{4}He(α)-Be	7.9×10^{18}
^{3}He-Be	4.9×10^{18}

Pre-Fusion Power Operation (PFPO) phase will operate only ^{1}H and He plasmas, and it will emit as many neutrons as those emitted in the history of success in nuclear fusion as per 2022

Plasma sources



Species	Neutrons in PFPO	Neutrons in FPO
DD	2.3×10^{16}	Negligible
DT	3.6×10^{12}	3.0×10^{27}
H(D)-Be	2.2×10^{19}	Negligible
H-Be	5.5×10^{19}	Negligible
^{4}He(α)-Be	7.9×10^{18}	Negligible
^{3}He-Be	4.9×10^{18}	Negligible

Pre-Fusion Power Operation (PFPO) phase will operate only ^{1}H and He plasmas, and it will emit as many neutrons as those emitted in the history of success in nuclear fusion as per 2022

Fusion Power Operation (FPO) phase will emit 7 orders of magnitude more by operating ^{2}H and ^{3}H plasmas

DT plasma source

Fission of U-235

One fission reaction:

- Releases 215 MeV in average
- Releases 2.4 neutrons in average
- <E> carried by neutrons is 4.8 MeV

→ 0.01 neutrons/MeV emitted at E~2 MeV

Fusion of DT

One DT fusion reaction:

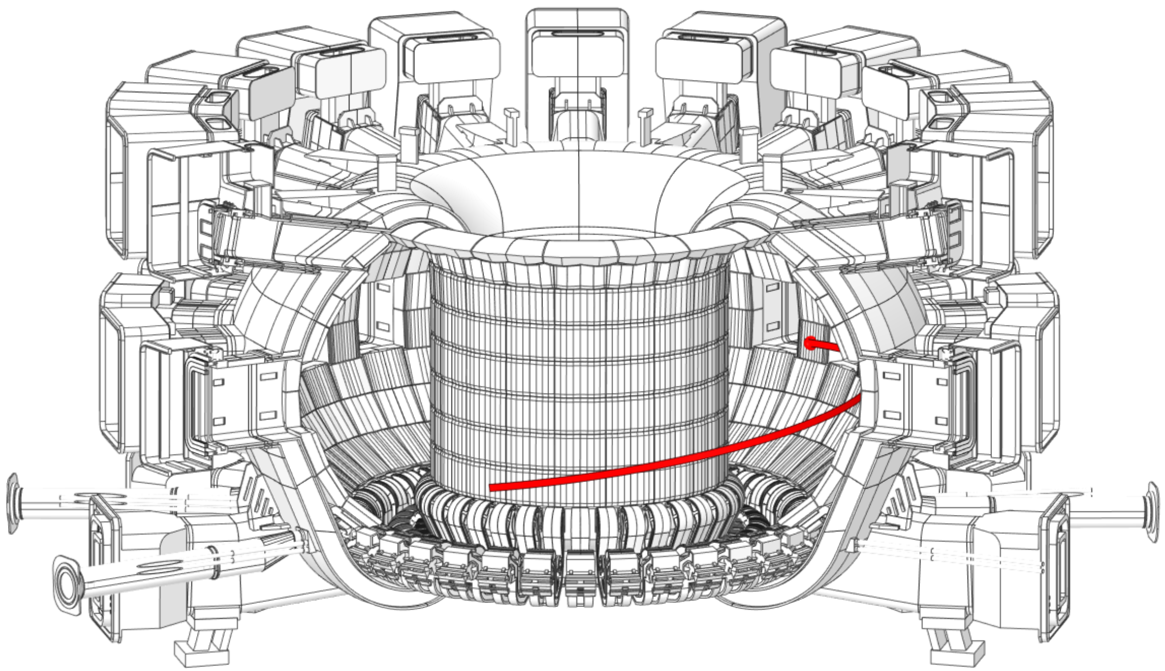
- Releases 17.6 MeV in average
- Releases 1 neutron
- <E> carried by neutrons is 14.1 MeV

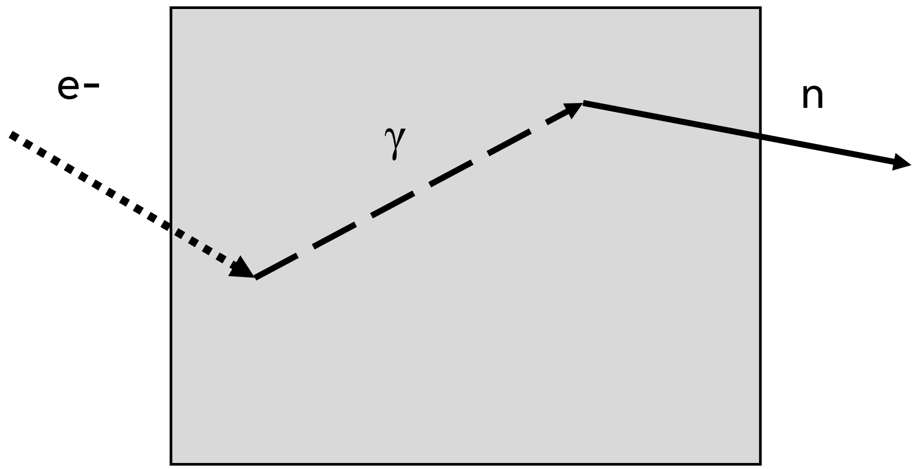
→ 0.057 neutrons/MeV emitted at E~14.1 MeV

Nuclear fusion presents:

- **6 times more neutrons per MeV of released energy**
- **More penetrating & damaging neutrons (7 times more energetic neutrons)**
- **Presence of threshold reactions inaccessible to fission → ^{16}N & ^{17}N**

Runaway electrons as radiation source



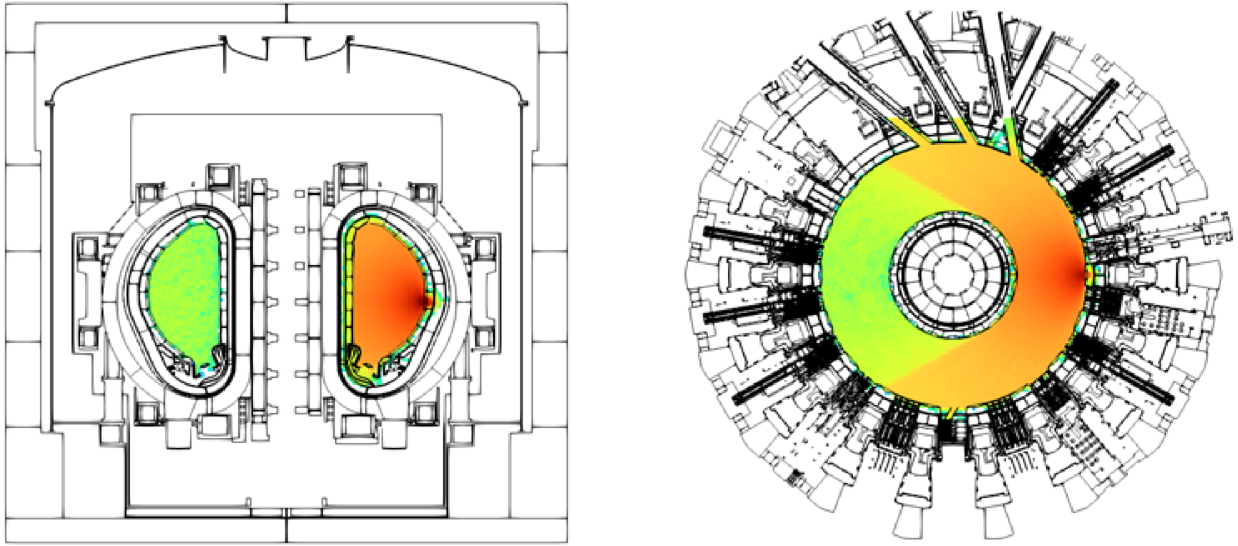


Following a “disruption”, an electron beam can carry up to 80% of the initial pre-disruption plasma current

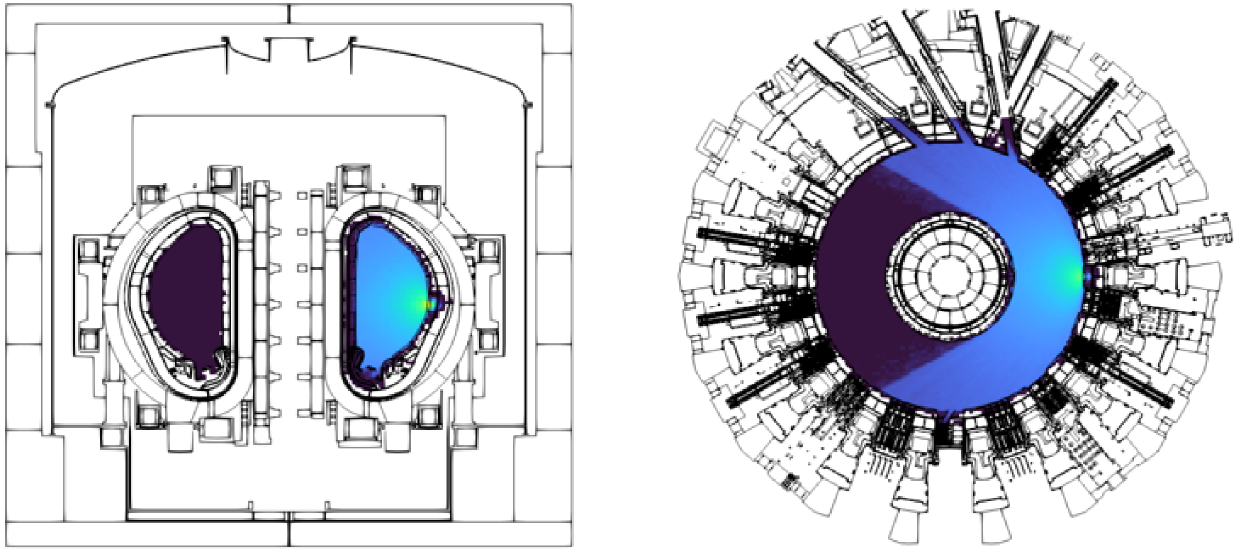
High energy electrons (> 10 MeV) are slowed down in the material with an accompanying emission of bremsstrahlung photons, which impact the materials and produce photoneutrons.

Runaway electrons as radiation source

Photon field



Neutron field



Over 200 Runaways Electron events can take place before DT plasmas

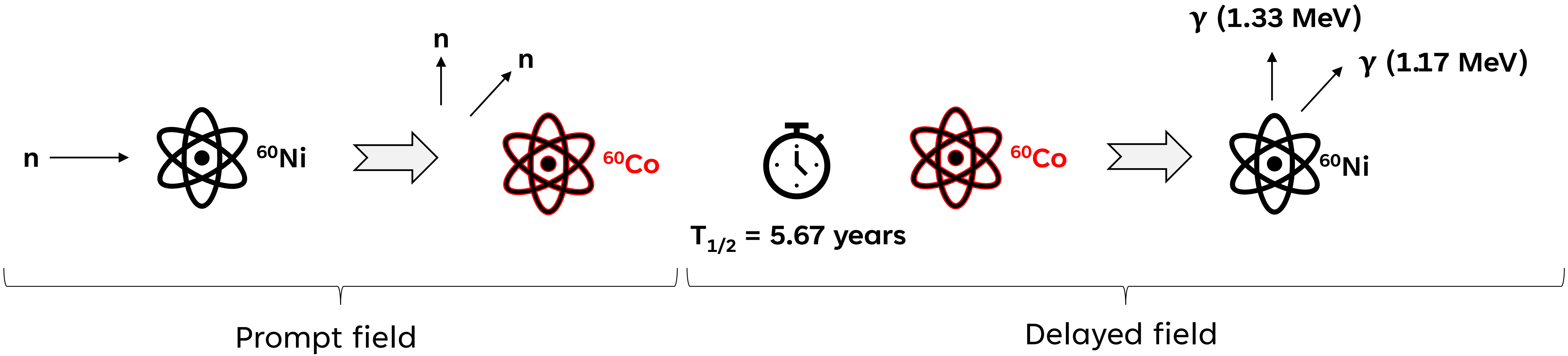
This will be likely the dominant source of radiation for the first plasma & PFPO, inducing activation hot spots.

After FP and during PFPO in-vessel human intervention will occur

Delayed sources

Activation

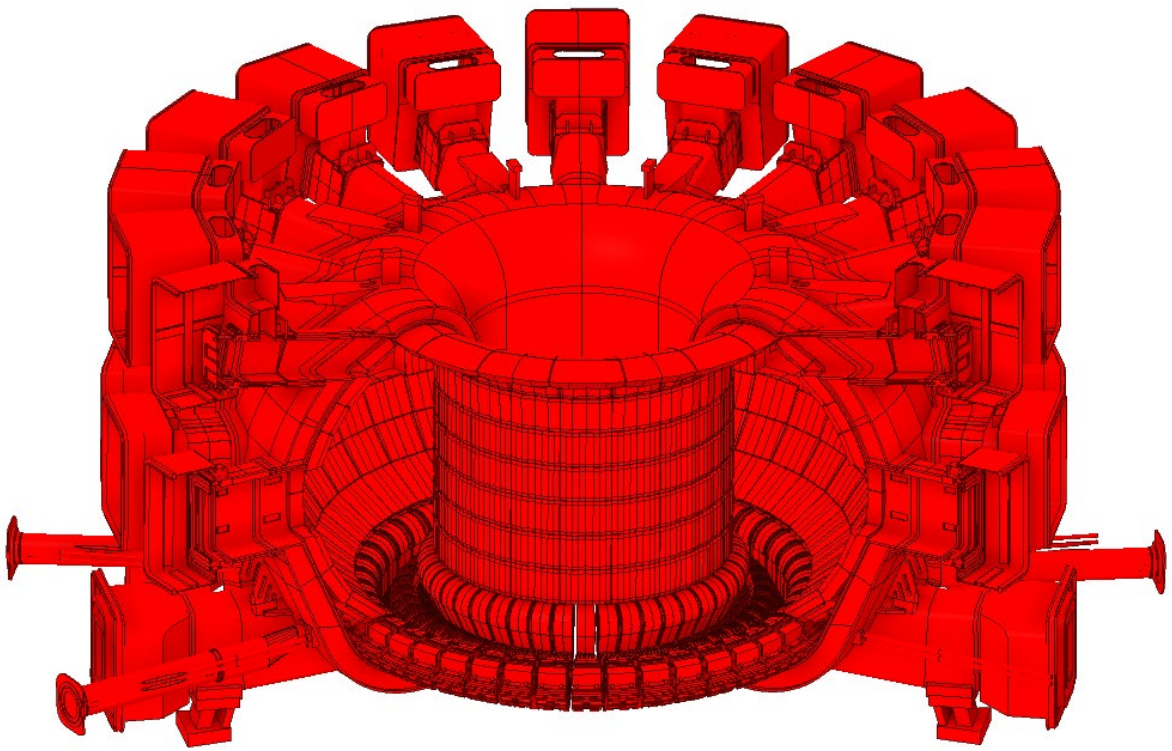
Nuclear reactions of photons, neutrons, protons… induce radioactive isotopes, AKA material activation

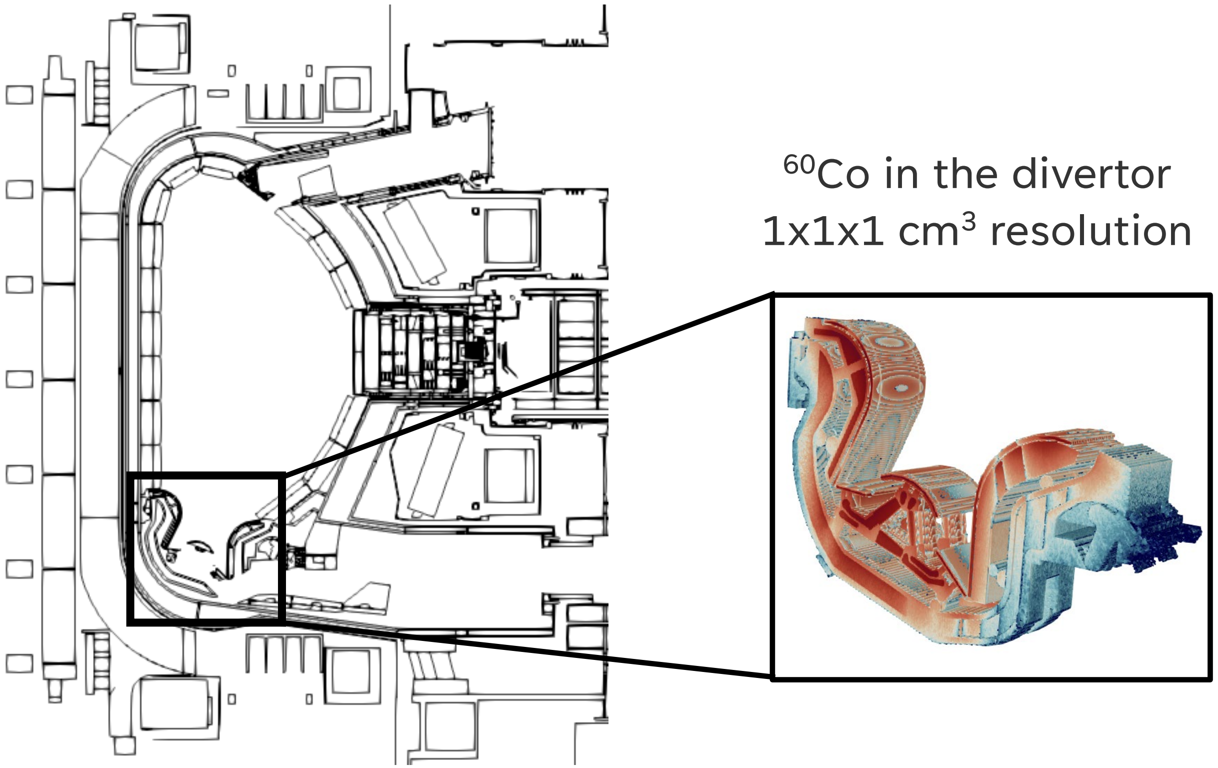


Radioactive material can:

- Remain where created
- Flow in water / PbLi current
- Be deposited elsewhere
- Be transported to other parts of the facility (e.g. to the hot cell)

Activation of structures



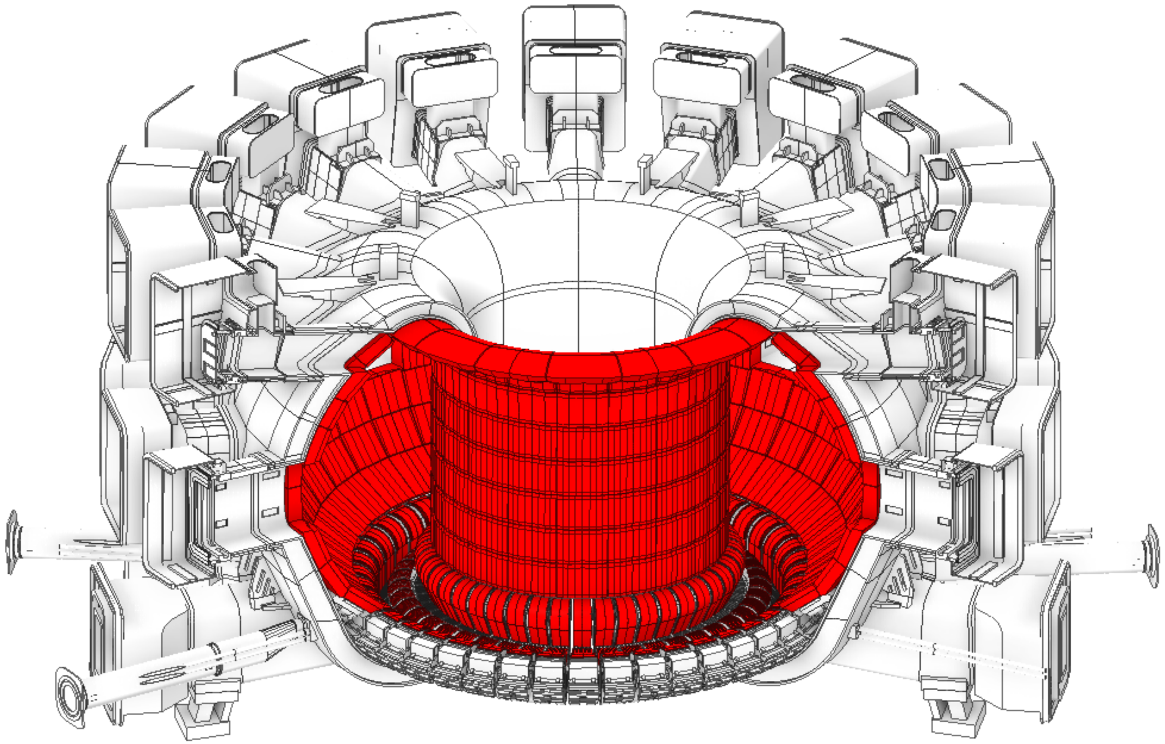


^{60}Co in the divertor
1x1x1 cm^3 resolution

The maintained neutron irradiation makes the Tokamak and the facility to become radioactive. This source of radiation is found all across the entire facility: 80m x 80m x 120 m

Given its large impact, we need to characterize it with a resolution within 1 cm

Tokamak Dust



Tokamak operation produces erosion dust from plasma-wall interactions. Highly radioactive dust spreads inside the chamber.

In-vessel remote handling will mobilize few grams, posing a challenge to remote handling tools once extracted from VV

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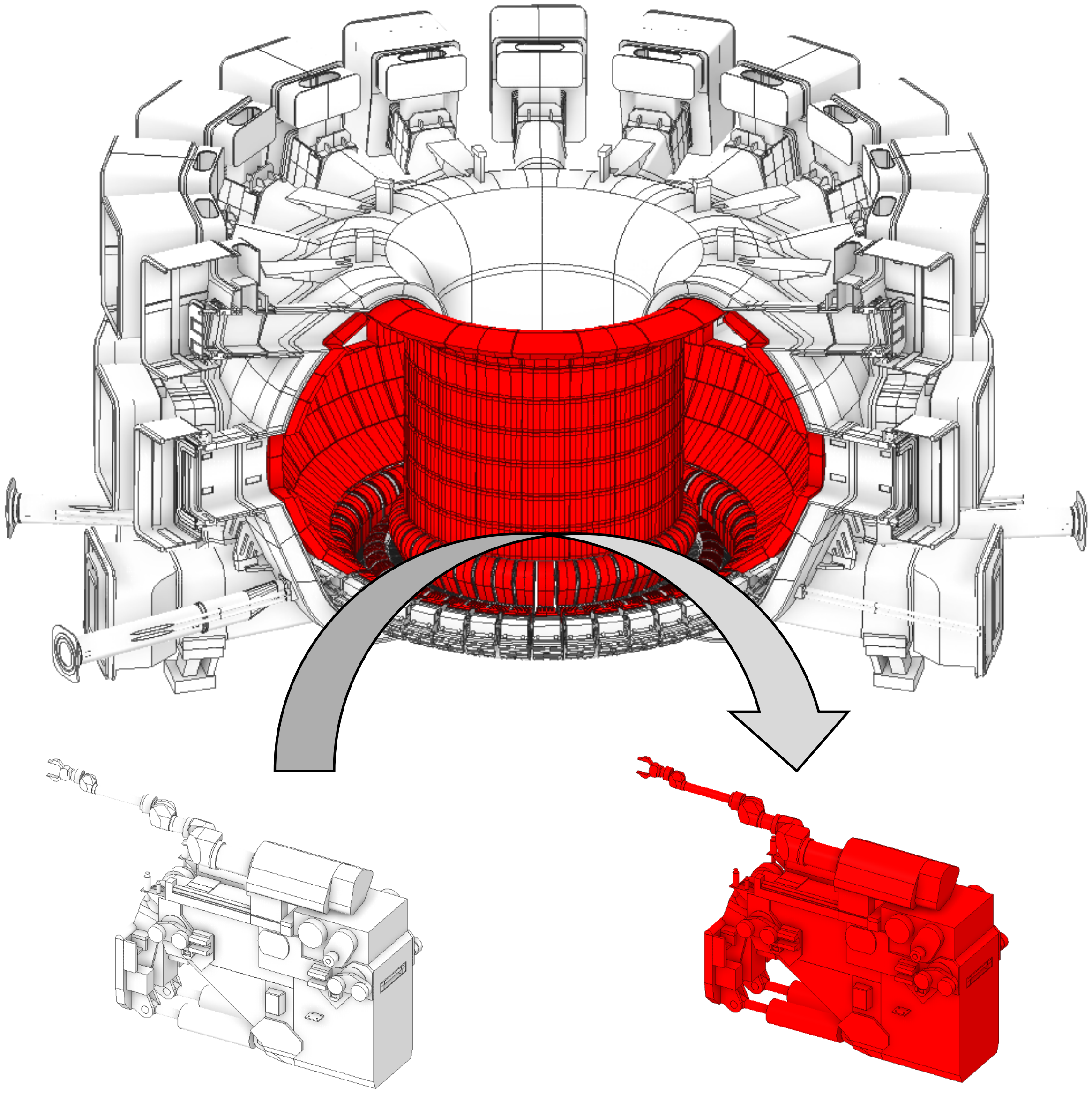
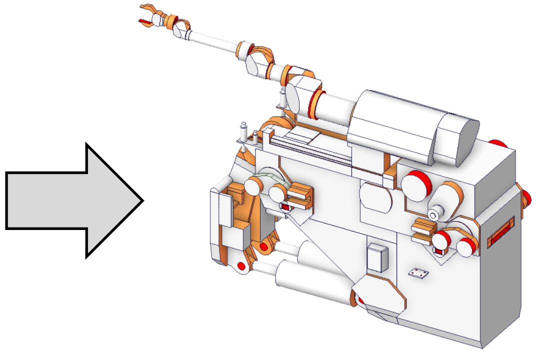
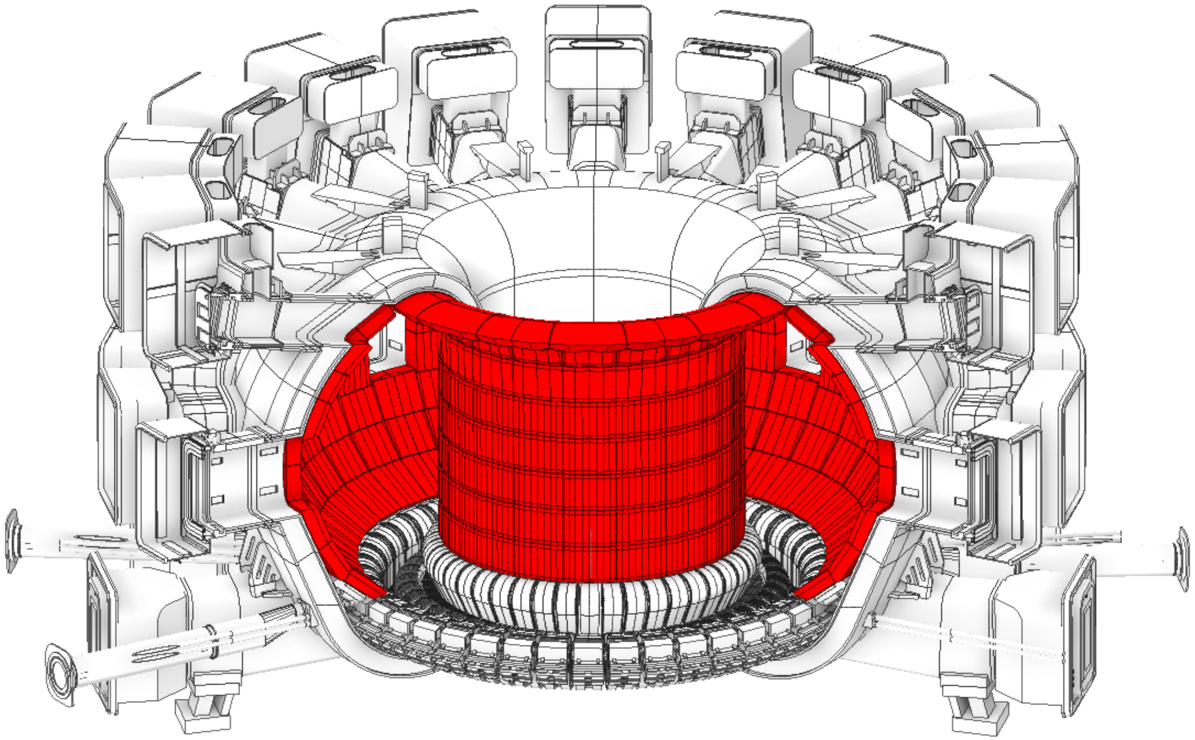
In-vessel remote handling will mobilize few grams, posing a challenge to remote handling tools once extracted from VV





Decontamination in the Hot Cell is needed before carrying out hands-on maintenance of the RH tools

Photoneutrons from Be



The in-vessel region is highly activated.

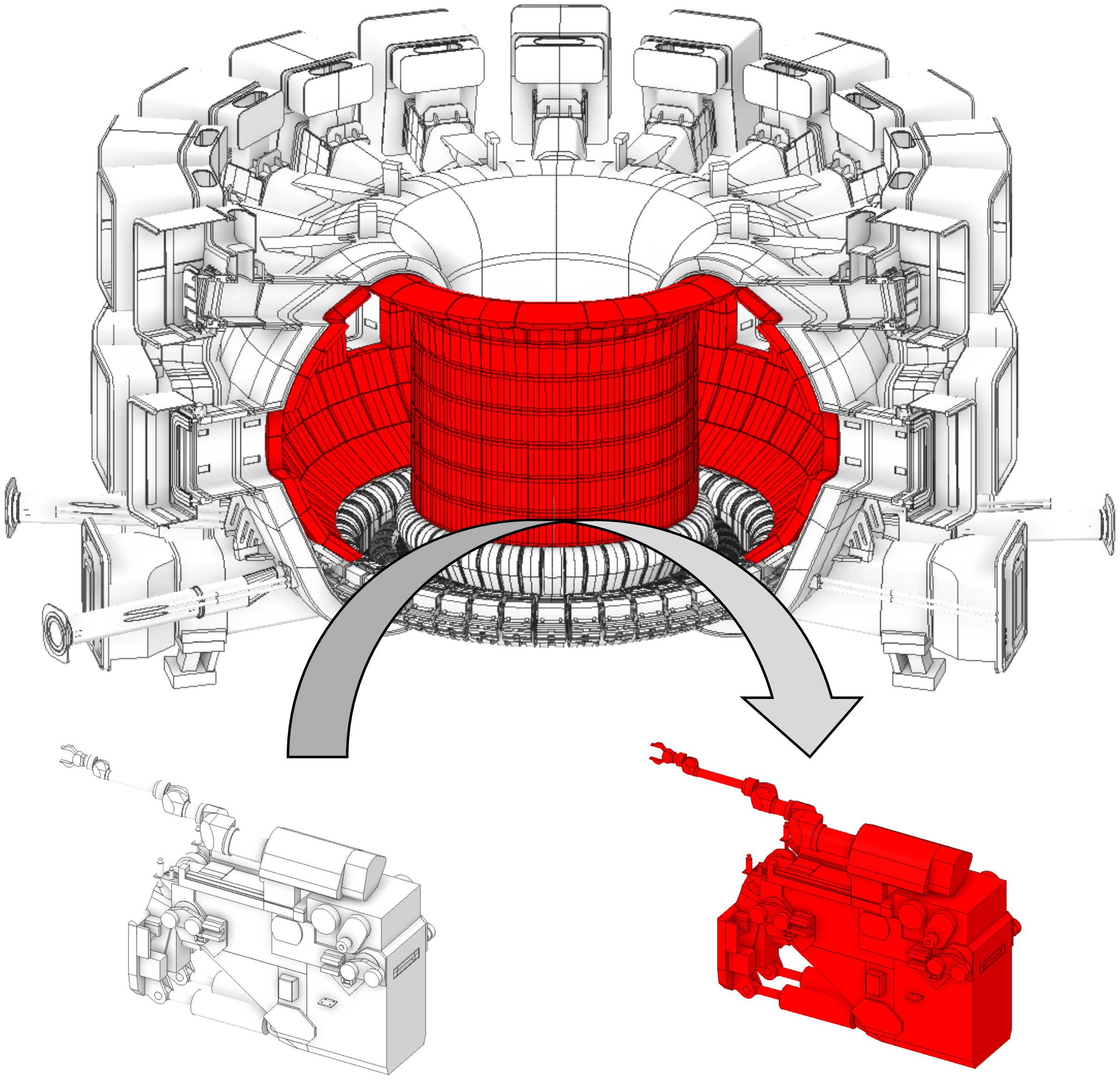
emitting photons, which induce photoneutrons

in the beryllium first wall

Remote handling equipment electronics can fail

Remote handling equipment gets activated

Photoneutrons from Be



The in-vessel region is highly activated.

emitting photons, which induce photoneutrons

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Remote handling equipment electronics can fail

Remote handling equipment gets activated

It cannot be removed and it poses a challenges

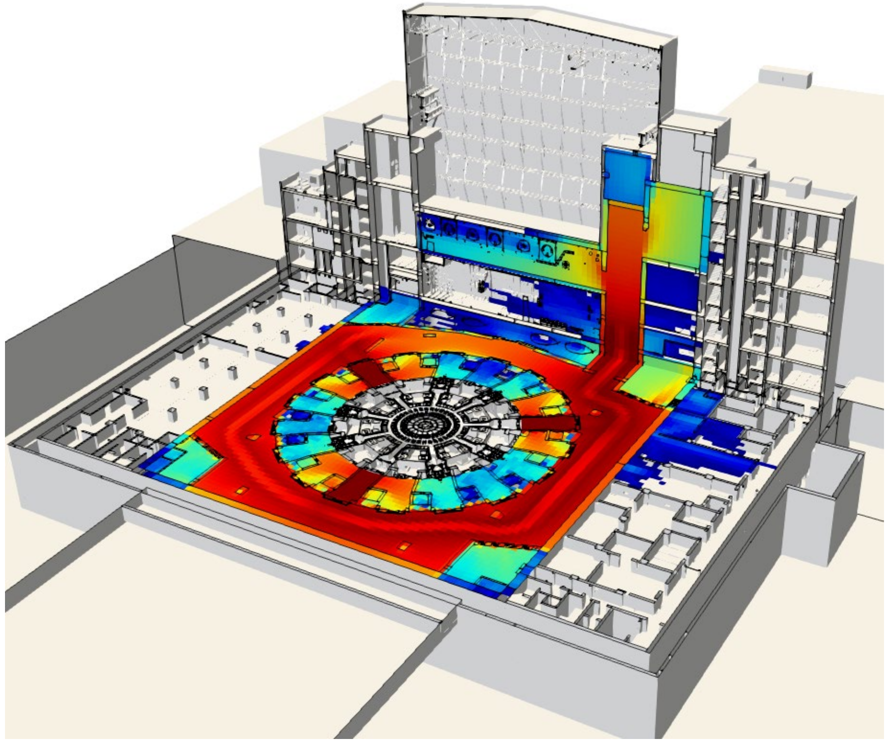
for hands-on maintenance of the RH tools

Transportation of an activated component

Activated components impart dose rates and integrated doses during their transit to the Hot Cell that must be considered to protect electronics and workers

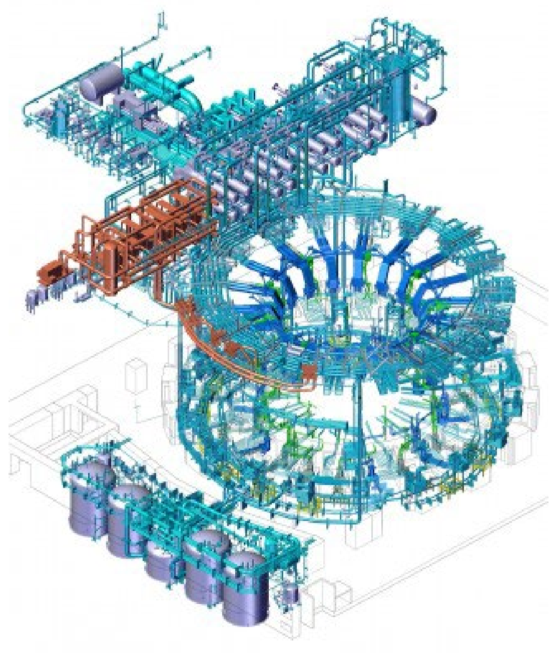
120 minutes transit – dose rate from transporting EP#8

Dose from 54 divertor cassettes extractions

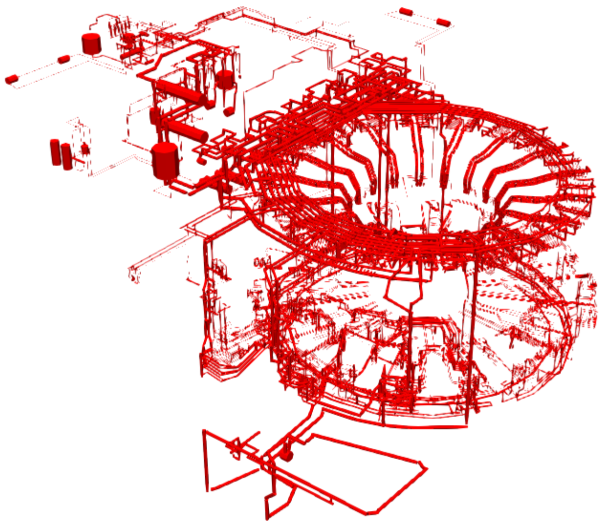


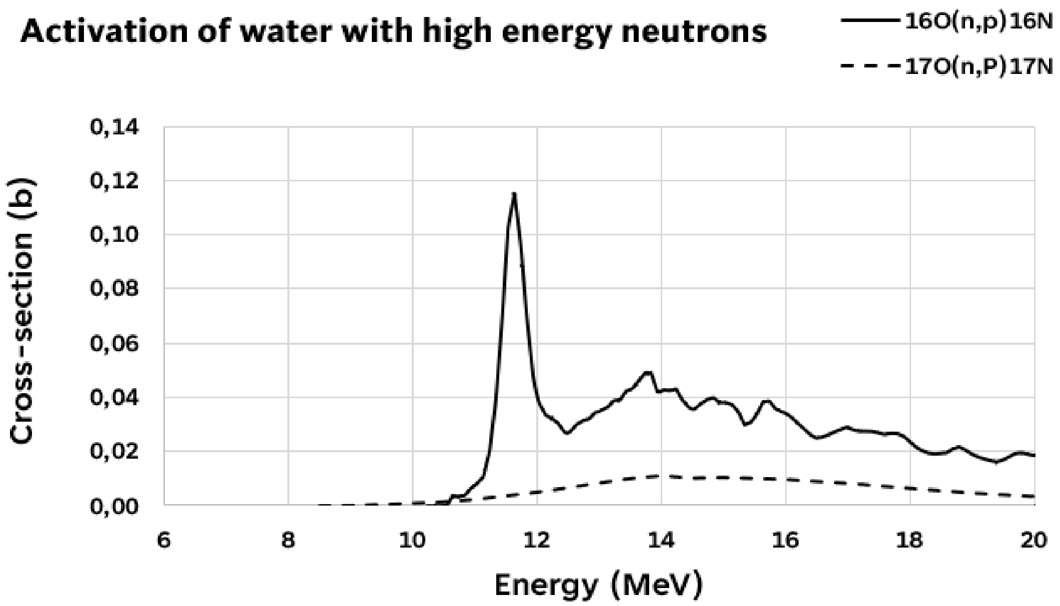
^{16}N & ^{17}N in activated water

TCWS



Pipes carrying activated water

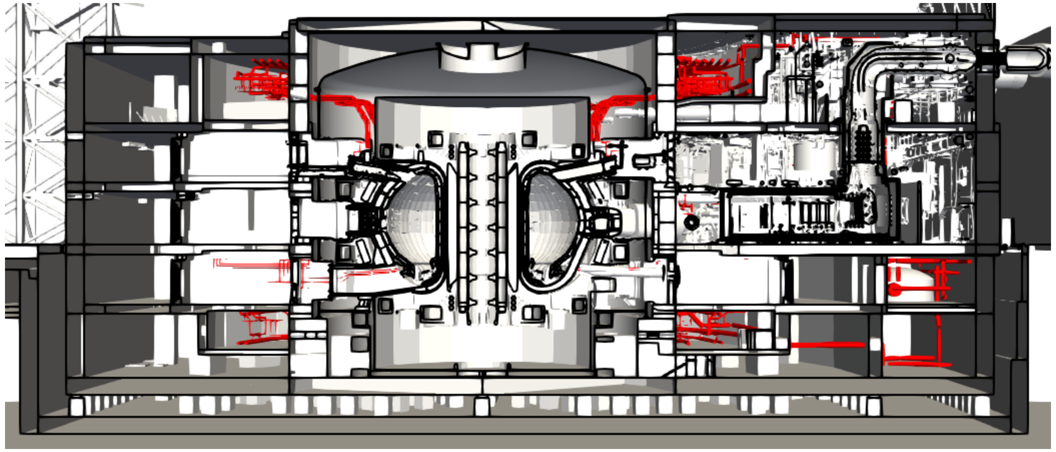


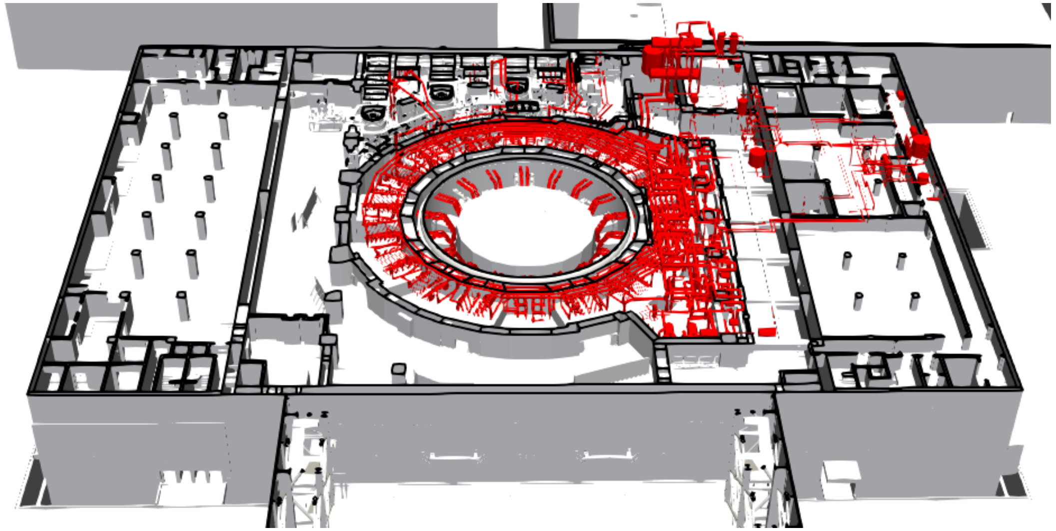


Irradiation of cooling water in-vessel leads to the production of noticeable amounts of ^{16}N & ^{17}N:

- ^{16}N – gamma emitter ~ 6 MeV - $T_{1/2}$ = 7.16 s
- ^{17}N – neutron emitter ~ 4 MeV - $T_{1/2}$ = 4.40 s

^{16}N & ^{17}N in activated water





The water flows very fast (> 5 $m.s^{-1}$) in the TCWS

Notable ^{16}N and ^{17}N concentrations reach remote regions of the facility after only few half-lives

This represents a challenge inside and outside the facility to biological dose rates

TCWS carries activated water in over 15,000 pipes

Activated Corrosion Products

When highly activated Steel is eroded from the in-vessel components. it is transported all around ITER circuit

Activated corrosion products (ACPs)

- Some ACPs are in suspension and evacuated with the water itself
- Some ACPs get deposited and remain in the pipes. turning them into radiation sources

The ITER TCWS will deploy about XX cm2 of wetted Surface exposed to ACPs → the largest concern for maintenance activities

Distribution of radiation sources in ITER

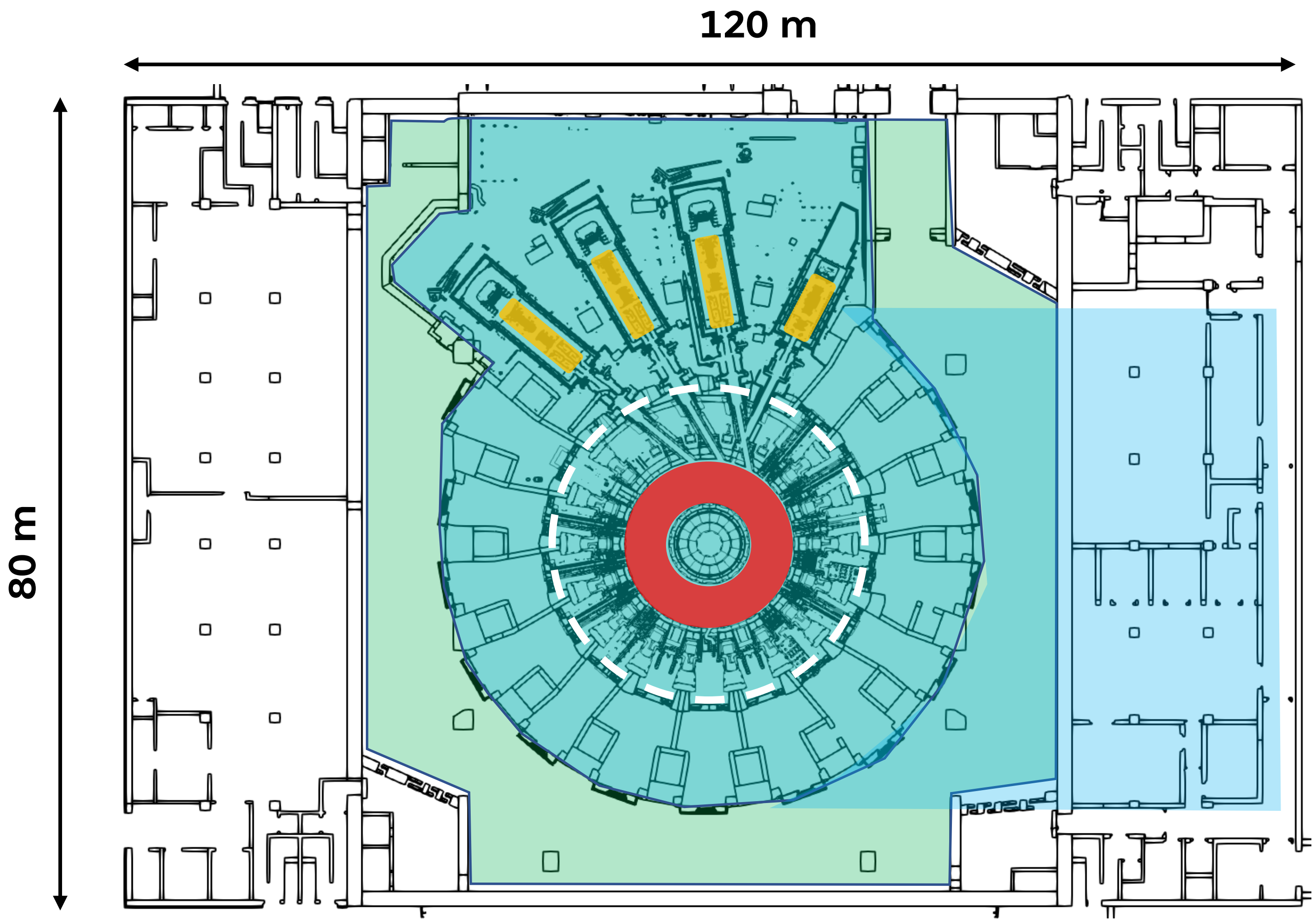
Radiation sources in ITER:

- 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
- Activated corrosion products

- ERID & calorimeter source

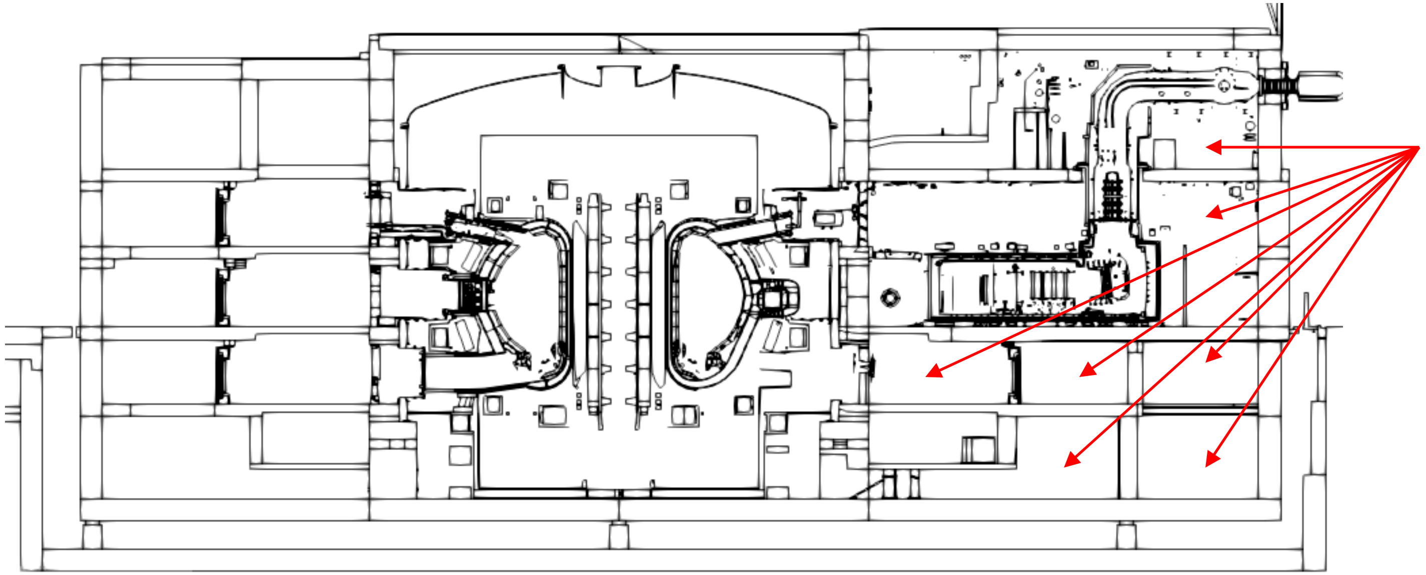
- Radioactive decay of activated components
- Activated W and SS dust



Sources modelling

Advances in modelling complex radiation sources for ITER

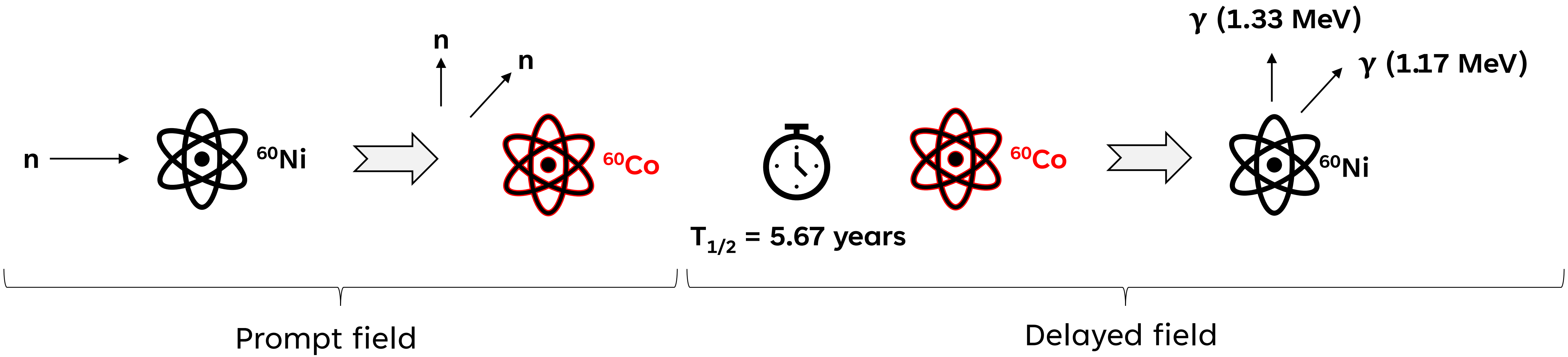
Determination of 3D activation sources



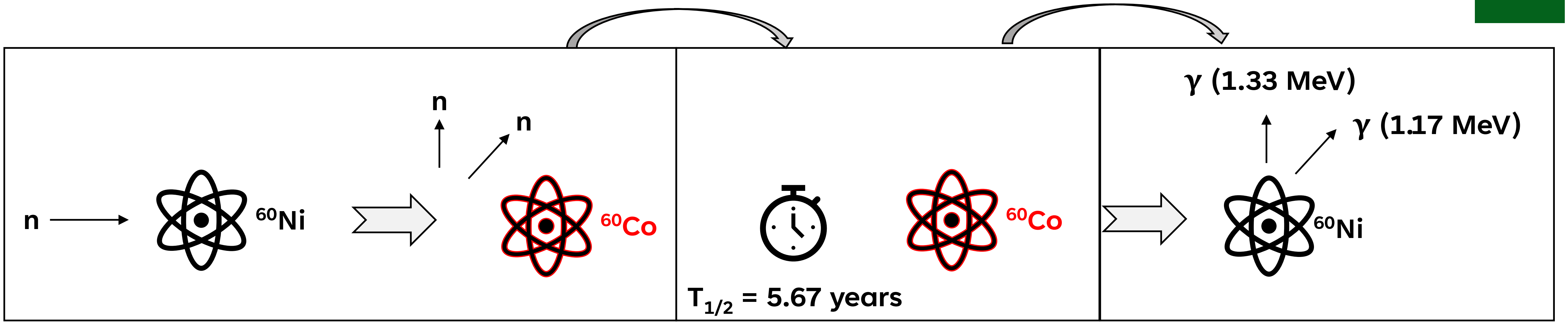
What is the dose rates in these rooms some cooling time after the plasma is shutdown?

We need to determine 3D activation sources:

- Rigorous two-steps method
- Direct one-step method



Rigorous two-Steps method

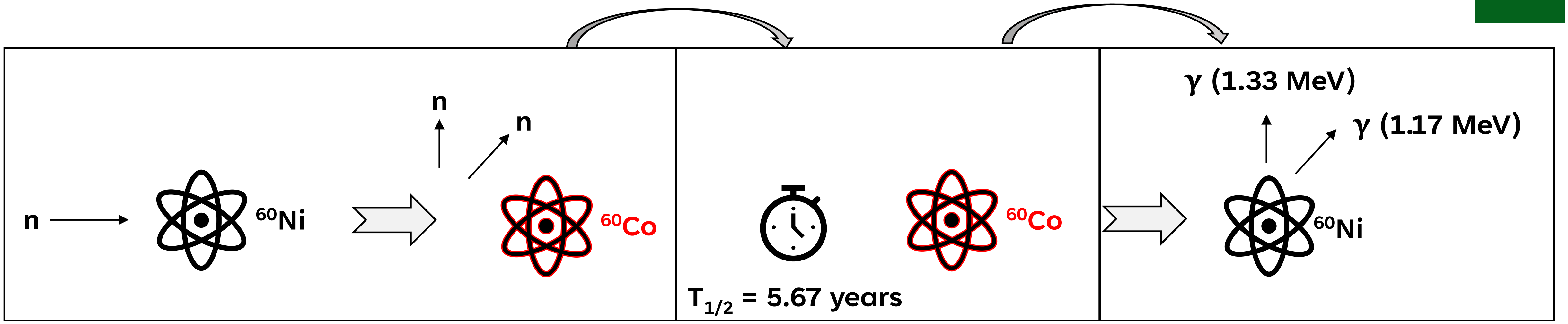


MCNP run to have one neutron flux in on cell

One activation calculation to obtain the decay source in the cell
FISPACT / ACAB codes

MCNP run to have the delayed field from the activation of the cell

Rigorous two-Steps method



MCNP run to have one neutron flux

One activation calculation to obtain the decay source

MCNP run to have the delayed field

Generalization

MCNP run to have N neutron fluxes in a mesh

Massive activation calculation to obtain the decay source in every voxel

MCNP run to have the delayed field from the entire mesh

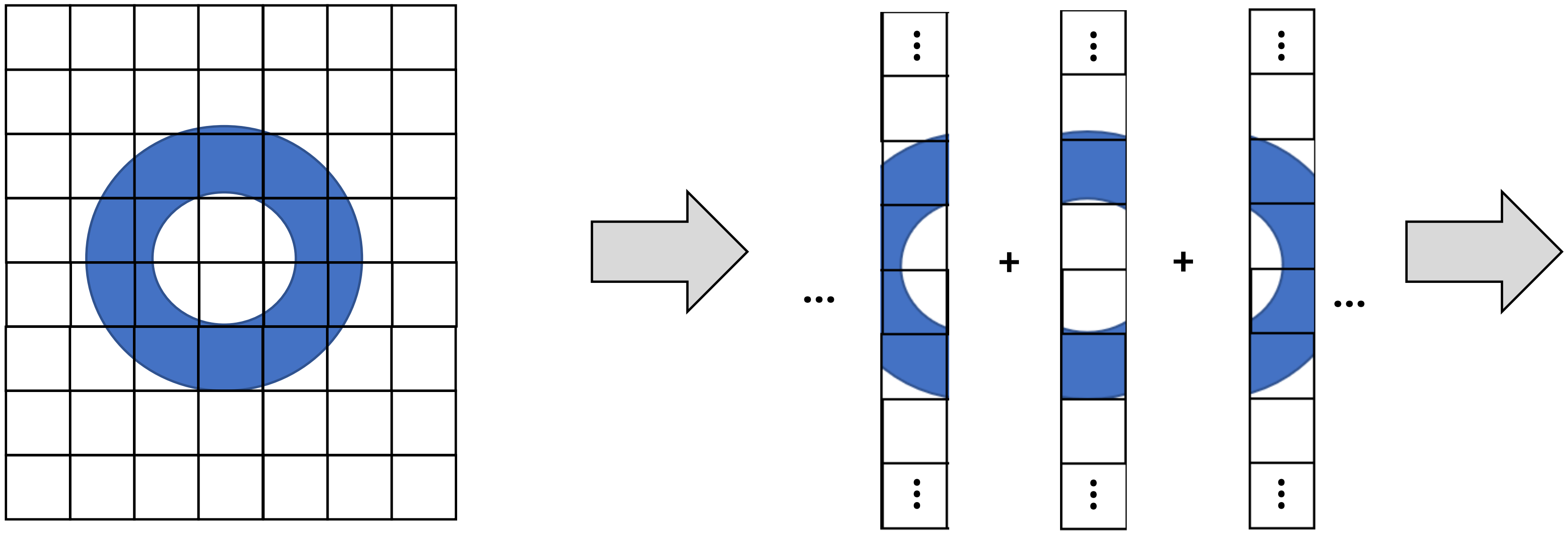
Rigorous two-Steps method

The R2S method was designed to determine 3D radiation sources with a dedicated thorough treatment of the activation regardless of the fluence and material composition

Neutron flux in every voxel

Massive activation calculation

Decay photon intensity in every voxel



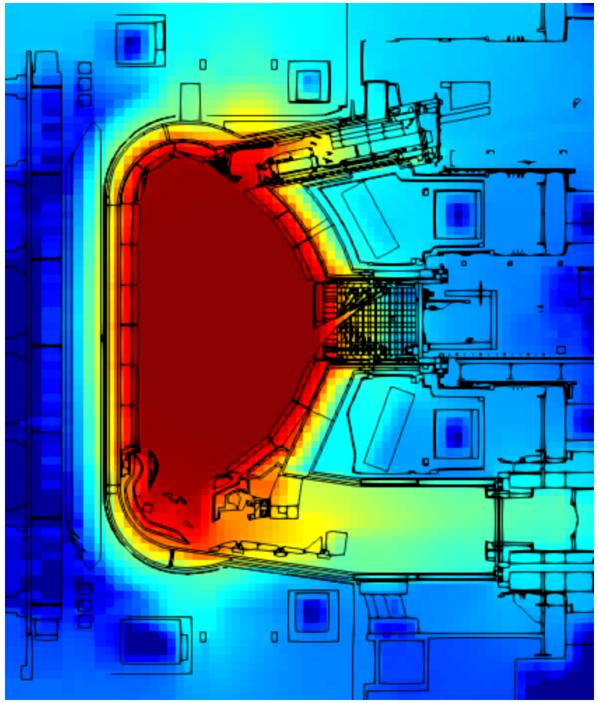
Neutron flux run (MCNP)

One activation calculation for every voxel of the mesh (FISPACT, ACAB)

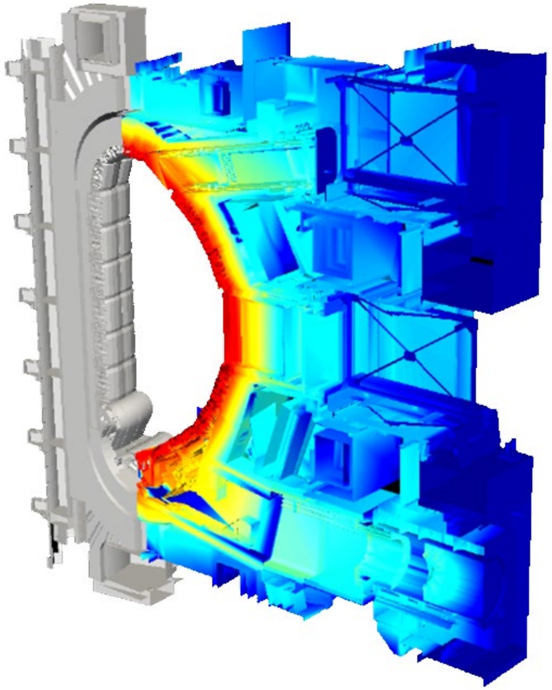
Decay photon run (MCNP)

Rigorous two-Steps method

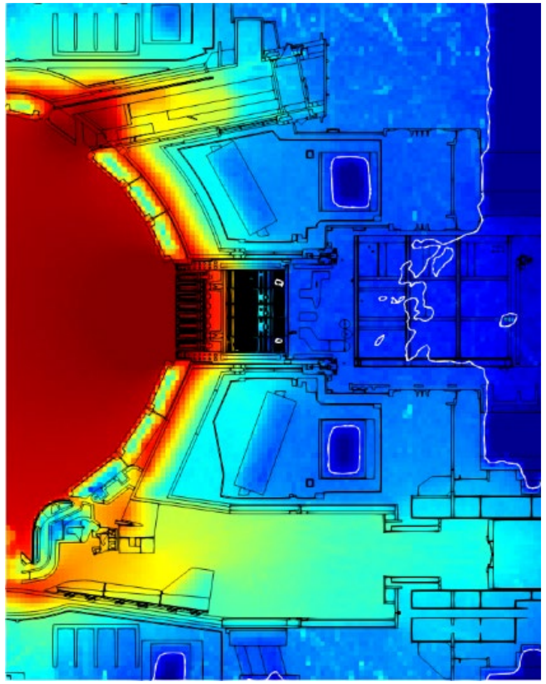
The R2S method was designed to determine 3D radiation sources with a dedicated thorough treatment of the activation regardless of the fluence and material composition



Neutron flux run
(MCNP)



One activation calculation for every voxel of the mesh
(FISPACT, ACAB)



Decay photon run
(MCNP)

Rigorous two-Steps method

The R2S method was designed to determine 3D radiation sources with a dedicated thorough treatment of the activation regardless of the fluence and material composition

Conceptual steps:

1. Determine the neutron flux with energy resolution in a mesh covering the material irradiated
2. Arrange one activation simulation for every voxel of the mesh to determine the decay photon source intensity in every voxel. Gather the information in a 3D array
3. Use the modified radiation transport code to consider the 3D array as radiation source (decay gamma source)

Basics of the method:

- An interface to couple the neutron flux mesh and the activation code, and arrange the results must be created
- The radiation transport code must be modified to read as radiation source such 3D array

Rigorous two-Steps method

Drawback: computer resources are tremendous

- Spatial resolution of the neutron flux ~ 1 cm
  - → 2.7×10^{10} voxels to cover the entire Tokamak
  - → 7.7×10^{11} voxels to cover the entire Tokamak Complex
- Neutron flux energy resolution of 175 bins (Vitamin-J)

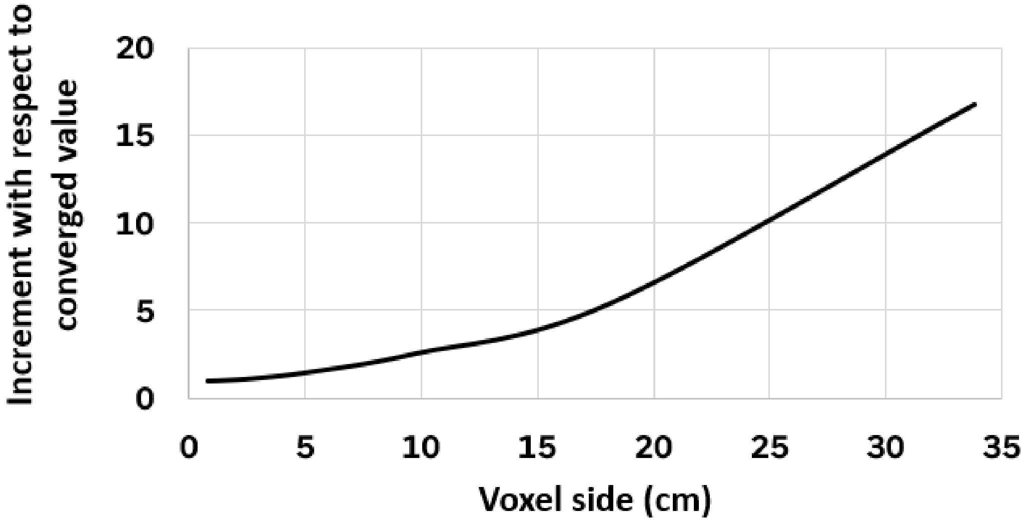
Currently we cannot afford such meshes and such number of activation calculations

Solutions so far: Either limit the region extension or sacrifice accuracy with coarse meshing

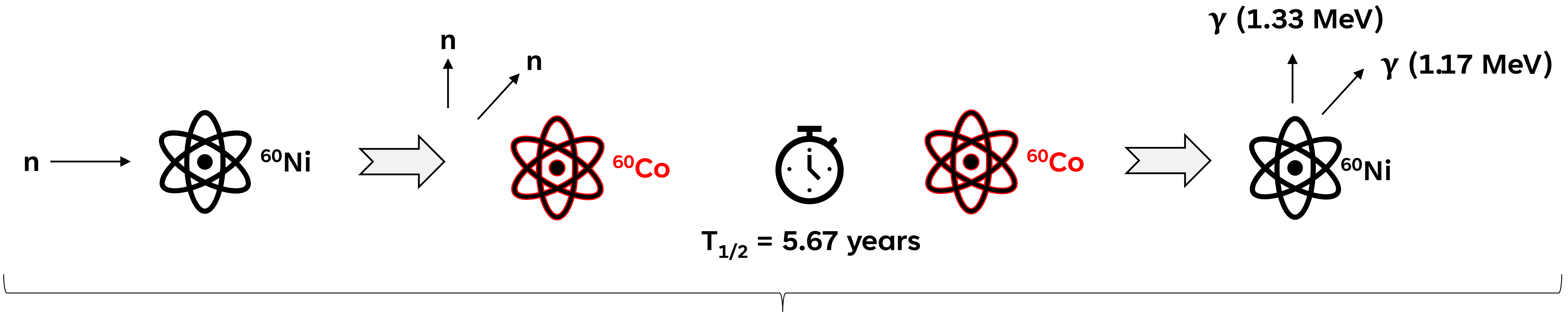
Even in simple geometries the impact of the voxel size is strong.

Example: irradiation of a rectangular slab

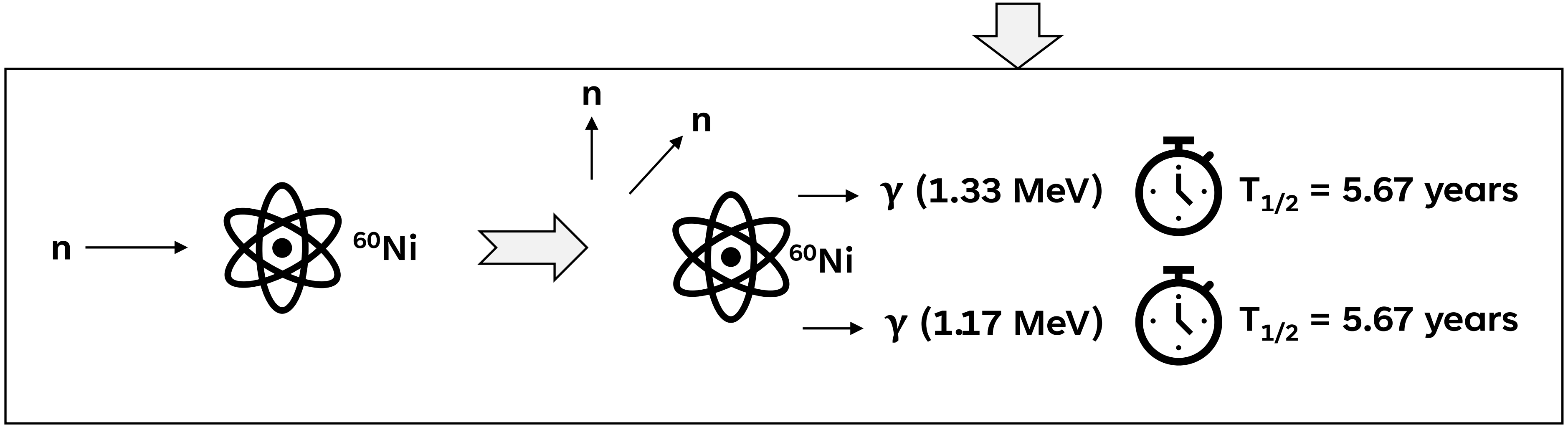
Residual dose rate dependance on the neutron flux resolution



Direct one-Step method

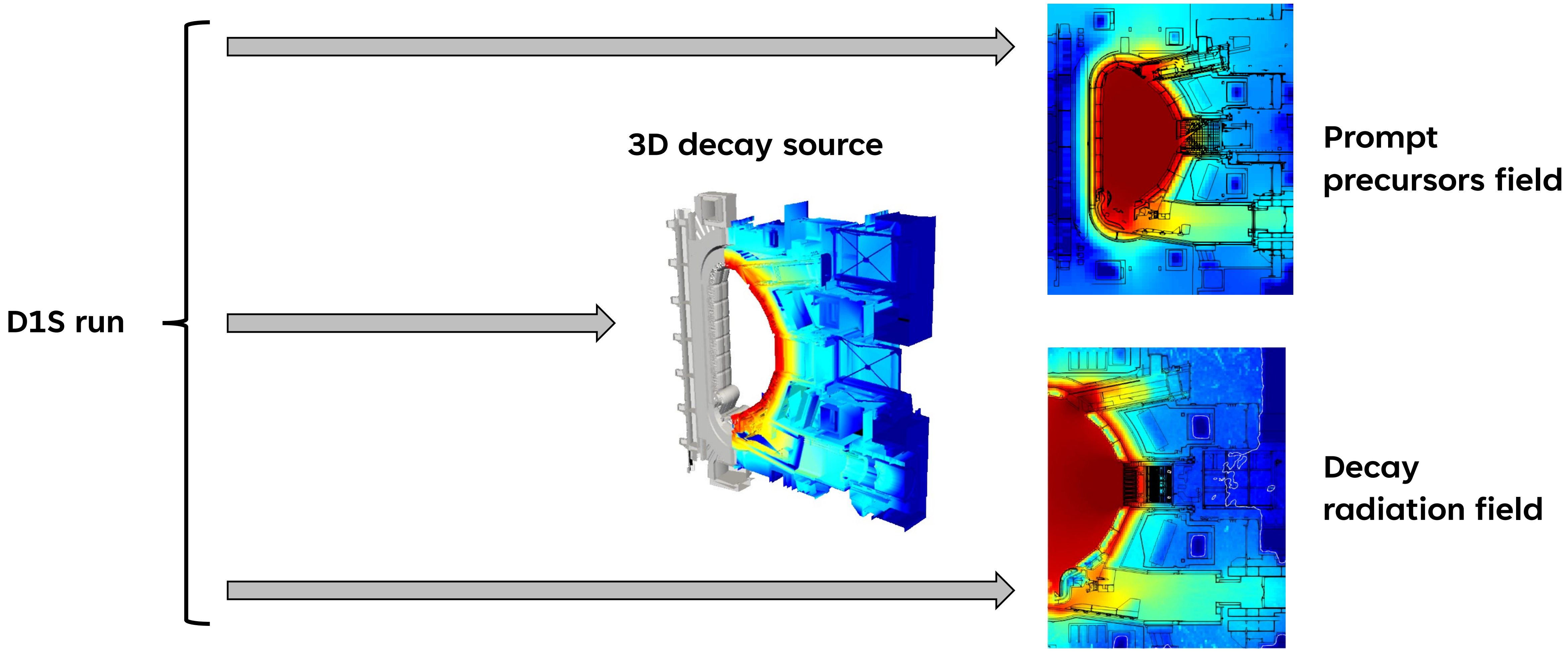


D1S calculation runs together
precursor prompt and decay fields



Direct one-Step method

Everything is computed in the same run: Prompt precursors field, secondary decay field and 3D decay source!



Direct one-Step method

The D1S method was designed to exploit MC high-fidelity capabilities under certain assumptions:

The production of radioisotopes of concern must be lineal with flux intensity everywhere

Conceptual steps:

1. Check the compliance of the D1S assumption for all the radioisotopes of concern, irradiation scenario and cooling times
2. Trick the nuclear data libraries to introduce the decay radiation instead of the secondary prompt
3. Run together precursor prompt & secondary decay radiation

Basics of the method:

- Script to modify nuclear data must be created
- The radiation transport code must be modified to introduce time correction factors to account for the irradiation scenario and cooling time in the secondary decay radiation transport

Comparison R2S vs. D1S

Method	Advantages	Drawbacks	References
Rigorous two-Steps	No restrictions to the inventory Conceptual simplicity	Limited accuracy Tedious interfaces Large disk consumption	[1, 2]
Direct one-Step	MC-like accuracy Very agile	Validity subjected to certain irradiation scenarios, cooling time and materials Long preparatory work	[3, 4]

Both methods are complementary. Over a dozen of implementations of these methods exist already

D1SUNED is the official one for ITER calculations, available upon request to ITER Organization for ITER applications and UNED for other applications

Unexpected positive side-effect: a standard format to define 3D radiation sources has been defined

Advances in visualization to understand complex radiation fields

Visualization

Complex geometry

+

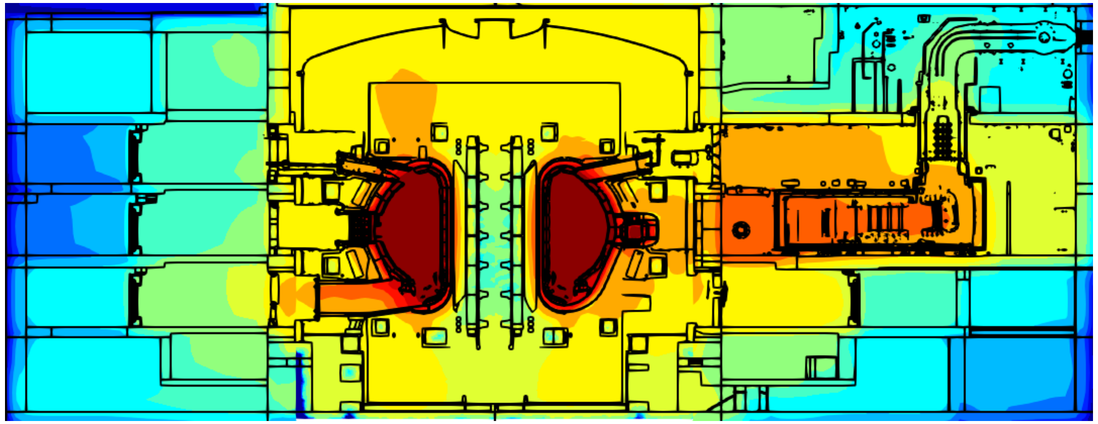
Complex source

=

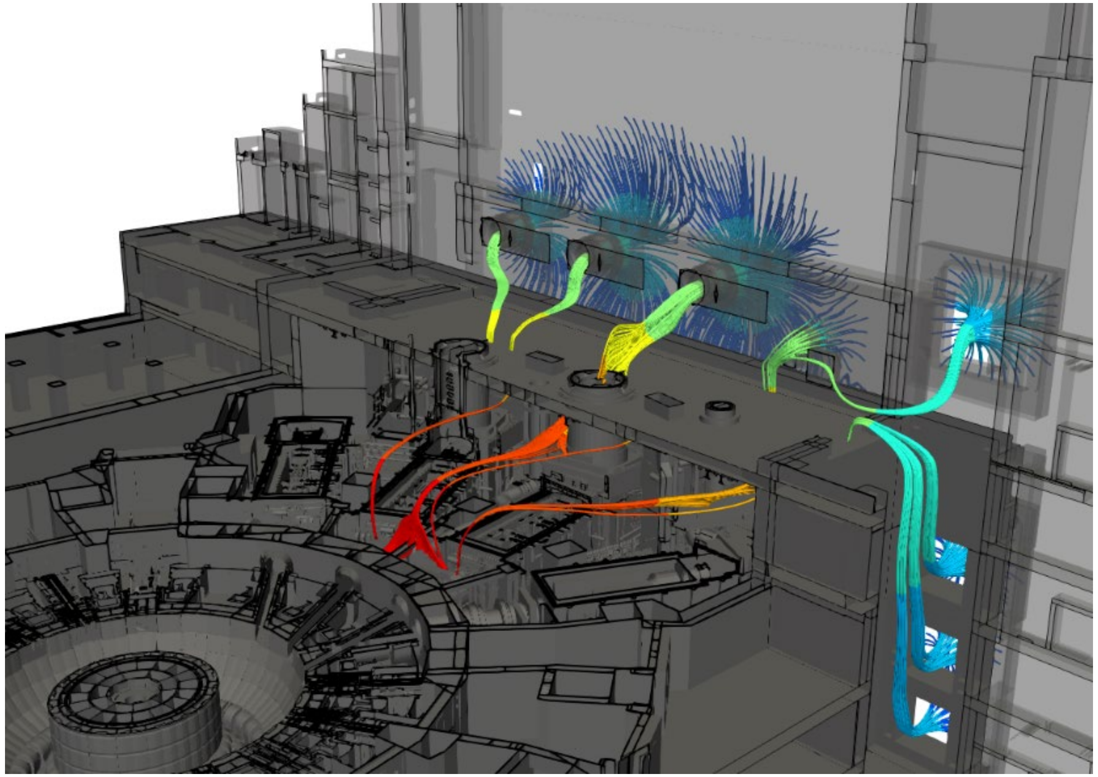
Complex field

We need to sophisticate visualization techniques as much as the rest of the cycle

Understanding complex radiation fields



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



Vector analysis greatly simplified the task [5]:

- Field lines indicates traced from tally regions backward identify the path with minimum variation up to the source = least shielded path
- Great support to identify the most effective means to reduce quantities
- It is agnostics of the radiation transport code

Thank you very much

We are recruiting!

References

[1] Y. Chen and U. Fischer, "Rigorous MCNP based shutdown dose rate calculations: Computational scheme verification calculations and application to ITER", *Fusion Engineering and Design*, **107** (2002)

[2] P. Sauvan, J. P. Catalán, F. Ogando, R. Juárez and J. Sanz. “Development of the R2SUNED Code System for Shutdown Dose Rate Calculations”, *IEEE Transactions on Nuclear Science, Volume* **63** (2016), 375-384

[3] D. Valenza, H. Iida, R. Plenteda and R. Santoro, "Proposal of shutdown dose estimation method by Monte Carlo code", Fusion Engineering and Design, **55** (2001) 411-418

[4] P. Sauvan, R. Juarez, G. Pedroche, J. Alguacil, J.P. Catalan, F. Ogando, J. Sanz, “D1SUNED system for the determination of decay photon related quantities”, *Fusion Engineering and Design* **151** (2020) 111399

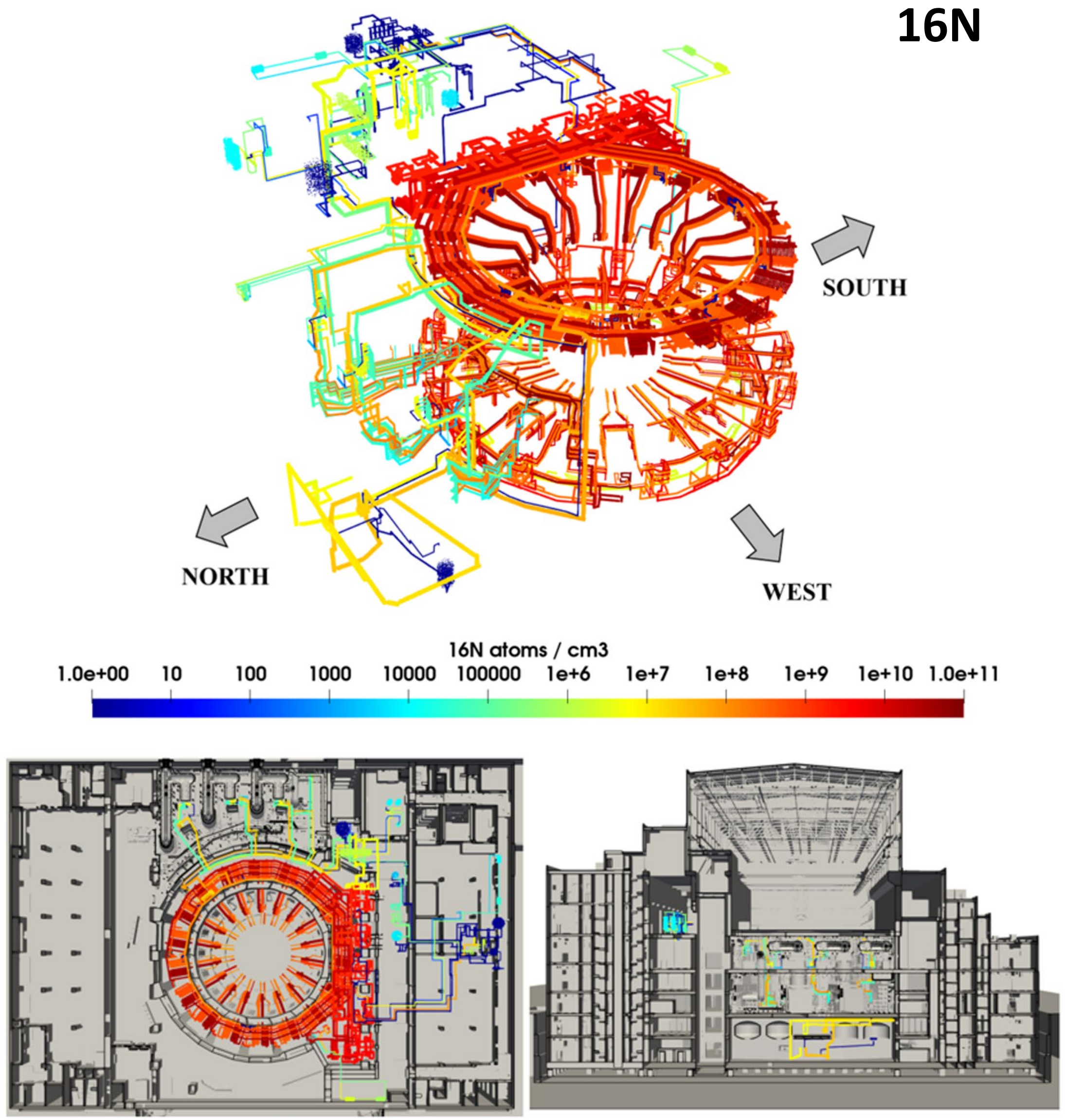
[5] R. Juarez. M.J. Loughlin, A. Lopez-Revelles, G. Pedroche, A. Kolsek, P. Sauvan, J. Sanz, “Improved radiation shielding analysis considering vector calculus“, *International Journal of Energy Research* (2020) 1-12

[6] J.P. Catalan, F. Ogando, R. Juárez, P. Sauvan, G. Pedroche, J. Alguacil, J. Sanz, “Development of radiation sources for nuclear analysis beyond ITER bio-shield: SCR-UNED code”, *Computer Physics Communications* (2022)

Bonus: FLUNED

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



SRC-UNED

The plasma source is in E-lite. Many of the answers of interest are in the Tokamak Complex

We need to couple them: SRC-UNED [6]

Record tracks in a boundary surfaces

Distribute the tracks in a grid to build PDFs in every voxel

Assembly the grids at every surface as a patchwork mosaic

Sample the PDFs as source