ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

SATIF-16
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Shielding aspects of Accelerators, Targets and Irradiation Facilities

Nuclear design of a shielded cabinet for electronics: the ITER Radial Neutron Camera case study

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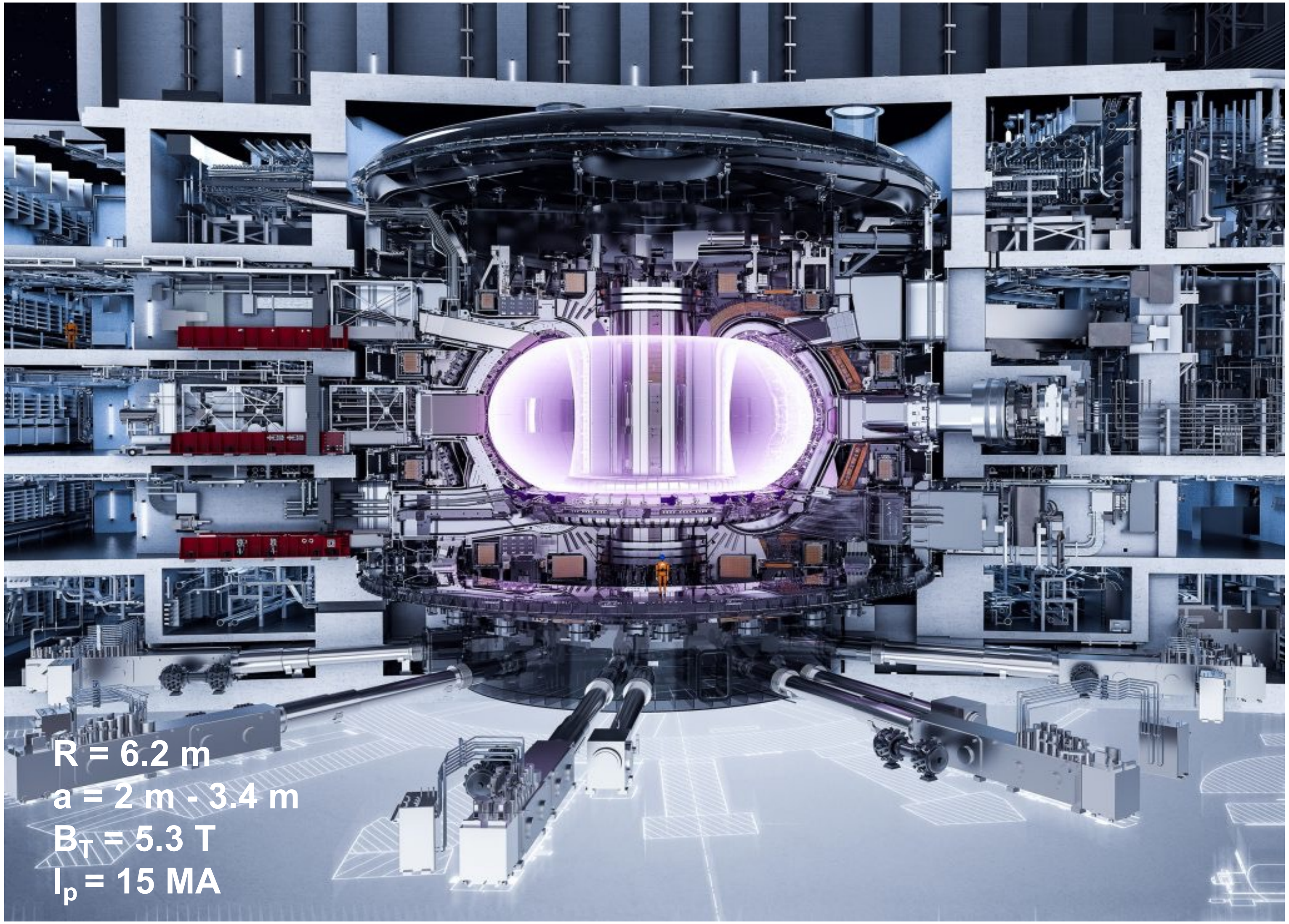
Summary

- The International Thermonuclear Experimental Reactor - ITER
- ITER Radial Neutron Camera
  - Diagnostic system layout
  - Measurement & plasma parameters
- Nuclear radiation environment in ITER: effects on electronics
- Design of a shielded cabinet for the RNC preamplifiers
- Conclusions

The International Thermonuclear Experimental Reactor: ITER

ITER is a **TOKAMAK** (**то**роидальная **ка**мера с **ма**гнитными **к**атушками): a device which uses **magnetic fields** generated by external magnets **to confine plasma** in the shape of an axially-symmetrical torus.

ITER is the world's largest and most advanced fusion experiment: it will be the first magnetic confinement fusion reactor to produce a net surplus of thermal fusion energy. It's currently being built in southern France within an international collaboration between **Europe**, **China**, **India**, **Japan**, **Korea**, **Russia** and the **USA**.



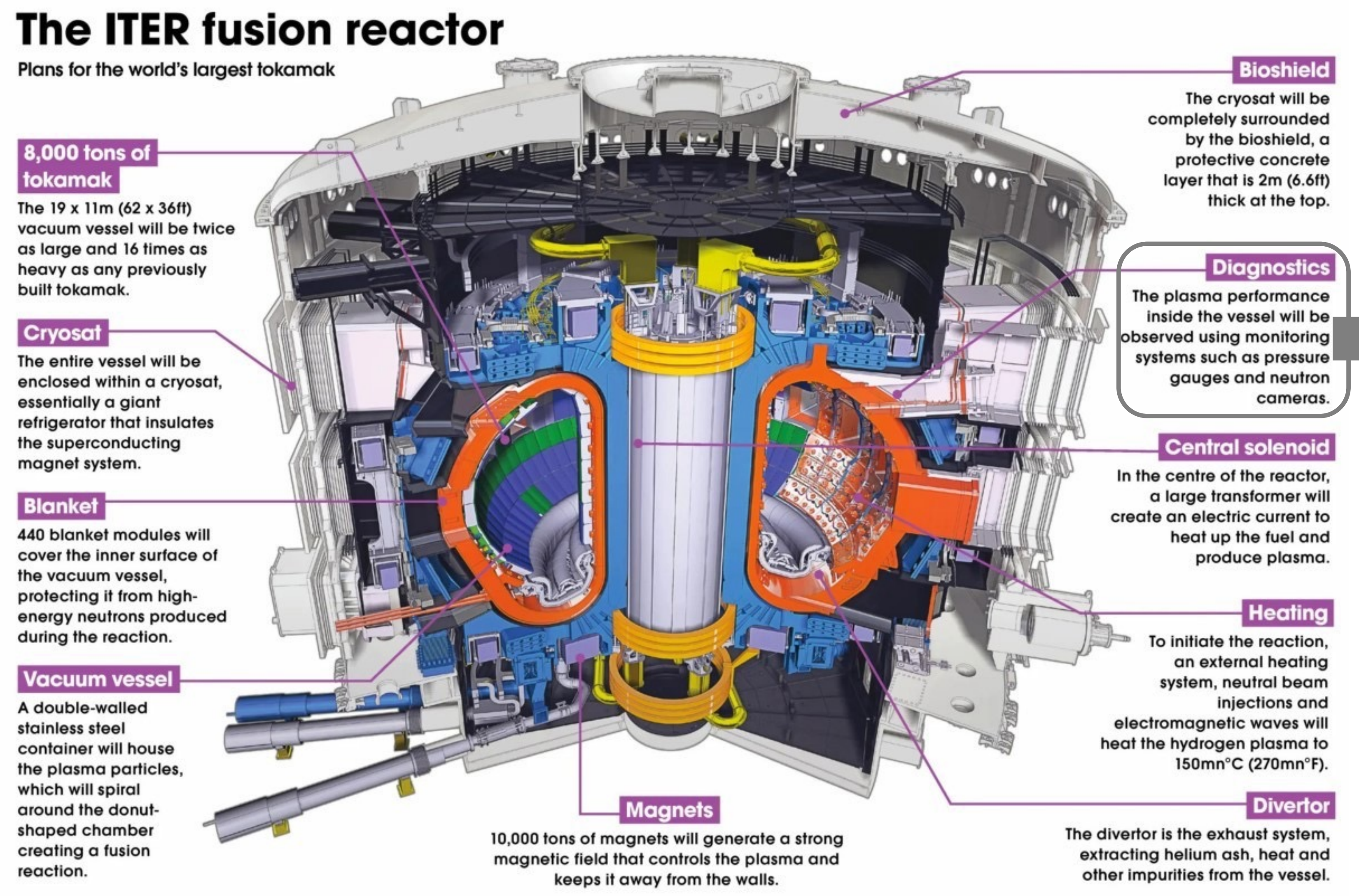
ITER main objectives

- **Achieve a deuterium-tritium plasma in which the fusion conditions are sustained mostly by internal fusion heating.** Fusion research today is at the threshold of exploring a ‘burning plasma’ in which the heat from the fusion reaction is confined within the plasma efficiently enough for the self-heating effect to dominate any other form of heating

$$D + T \rightarrow {}^{4}He\ (3.5MeV) + n\ (14.1MeV)$$

- **Generate 500 MW of fusion power in its plasma.** In 1997, JET produced 16 MW of fusion power from a total input heating power of 24 MW (Q=0.67). ITER is designed to yield in its plasma a ten-fold return on power (Q=10, DT plasma, 400 s), or **500 MW** of fusion power from 50 MW of input heating power
- **Contribute to the demonstration of the integrated operation of technologies for a fusion power plant.** ITER will bridge the gap between the present smaller-scale tokamaks and the future demonstration fusion power plant

ITER: an overview

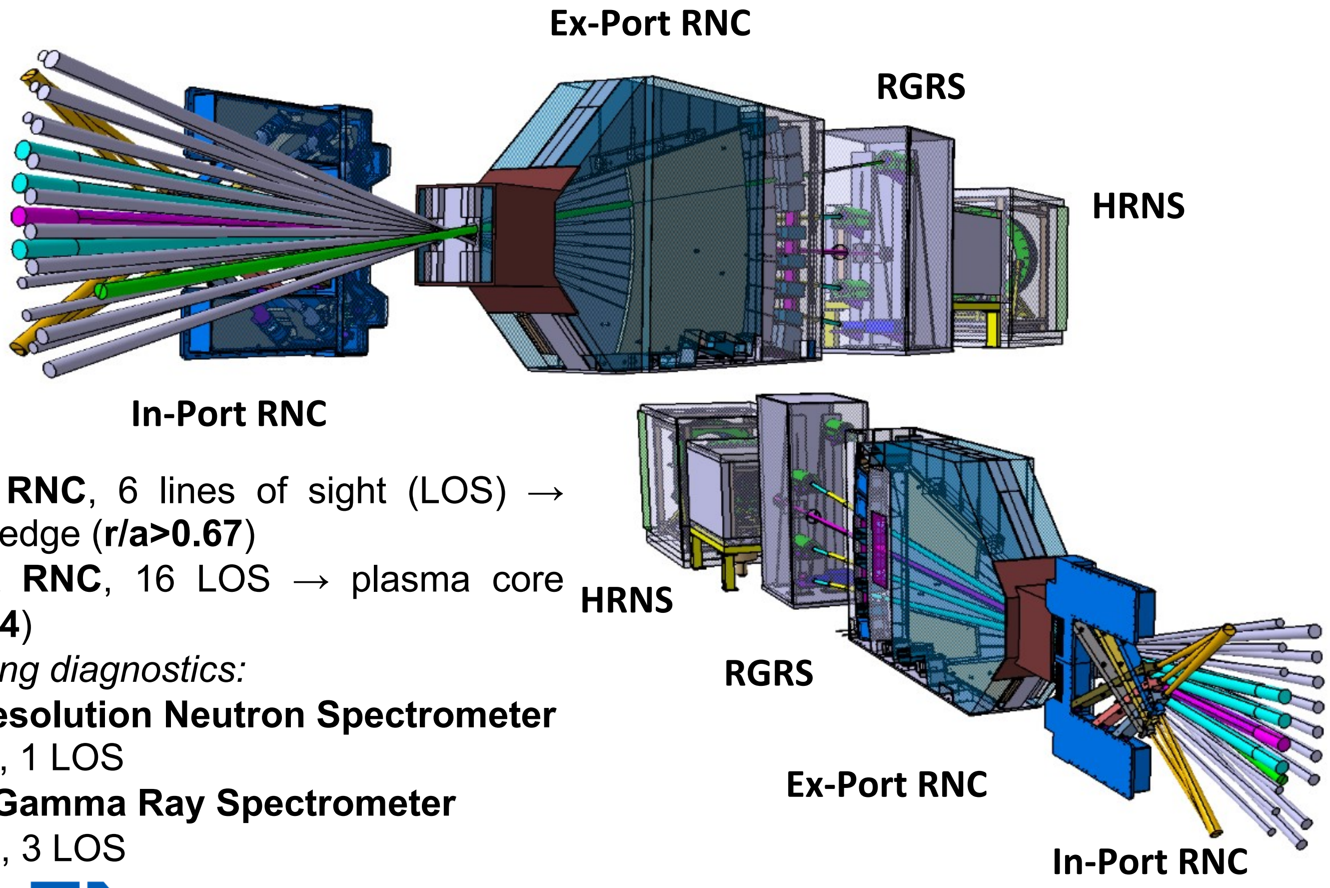


The ITER diagnostics systems will provide accurate measurements of the **plasma behaviour and performance**.

Measurements will be used for different operational roles ranging from **real time machine protection to physics understanding**. Most of these systems will have active sensors (e.g. cameras, detectors) and signal conditioning electronic components (e.g. preamplifiers) located in the Tokamak building.

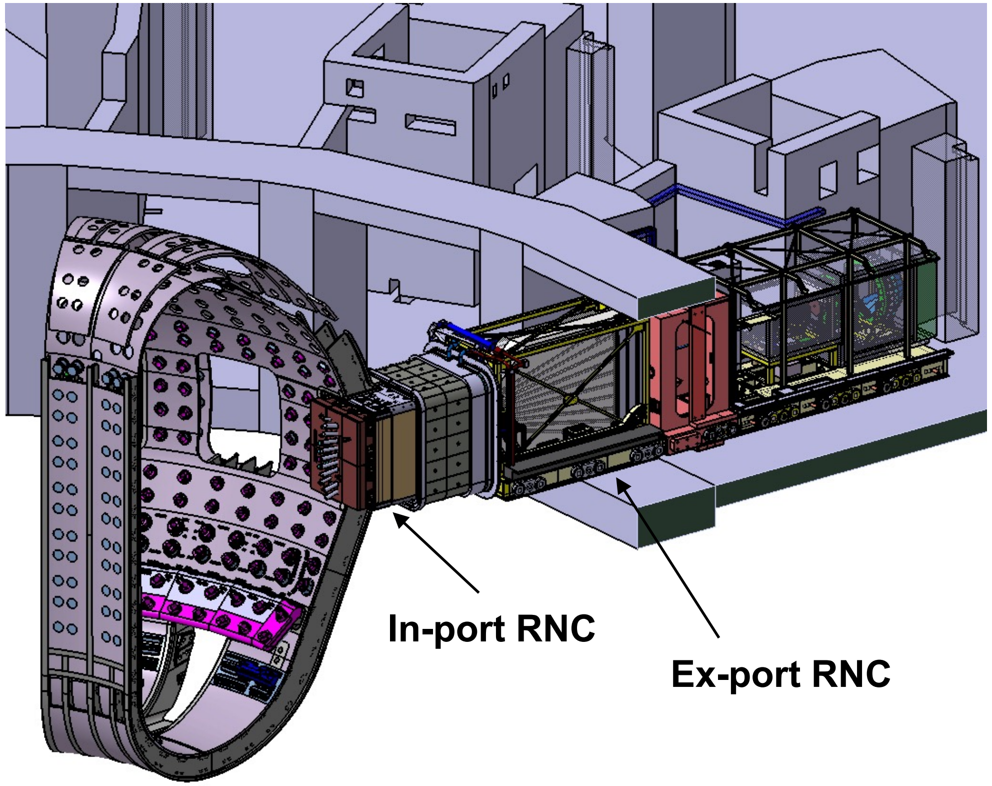
The ITER Radial Neutron Camera

The ITER **Radial Neutron Camera (RNC)** is a multichannel detection system hosted in the Equatorial Port Plug 1 (EP01). It is **designed to measure the uncollided neutron flux from the plasma, providing information on the neutron emissivity profile, and the total neutron source strength**, as well as spatial resolved measurements of several parameters needed for fusion power estimation, plasma control and plasma physics studies.



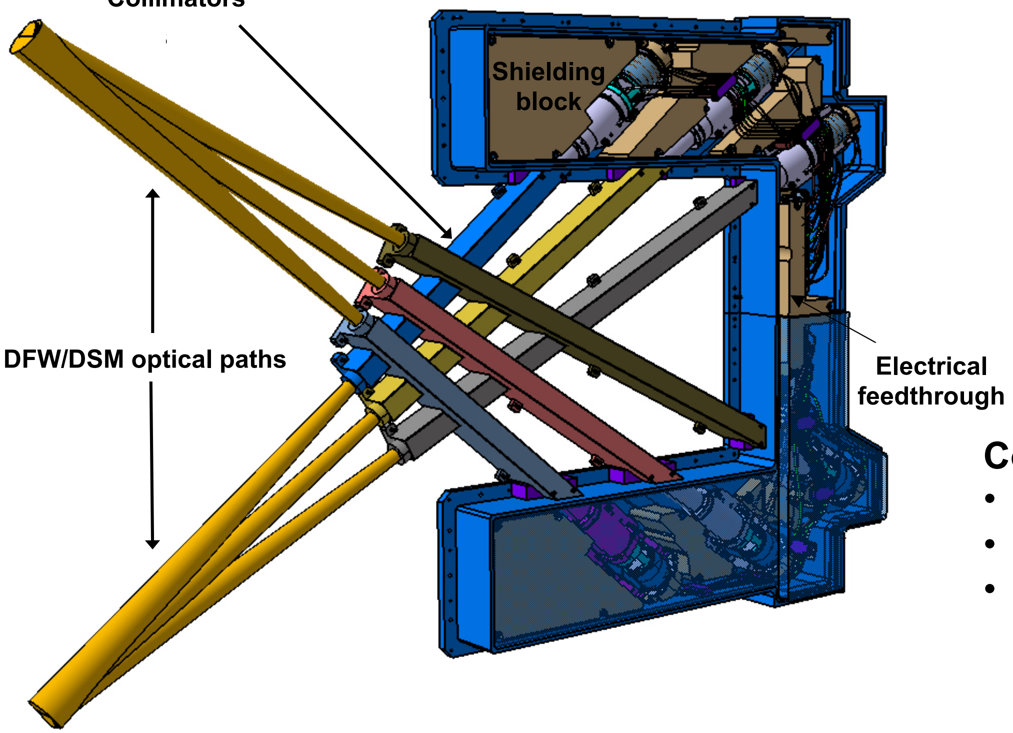
- **In-port RNC**, 6 lines of sight (LOS) → plasma edge (**r/a>0.67**)
- **Ex-Port RNC**, 16 LOS → plasma core (**r/a<0.54**)

  Interfacing diagnostics:
- **High Resolution Neutron Spectrometer** (HRNS), 1 LOS
- **Radial Gamma Ray Spectrometer** (RGRS), 3 LOS

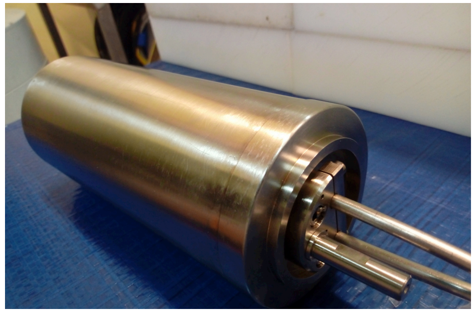


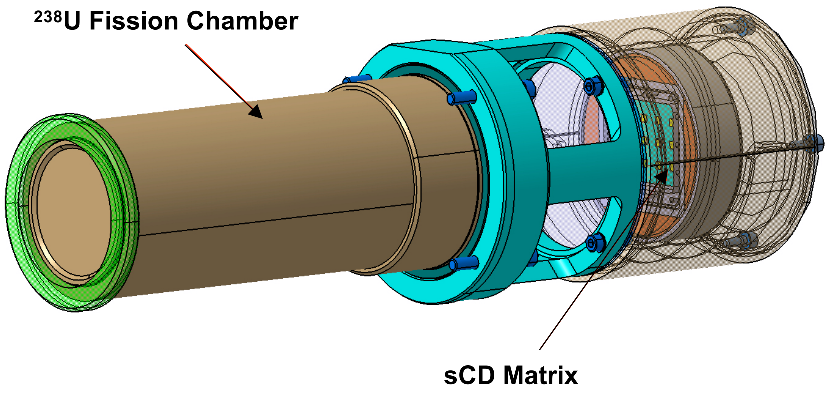
In-port ITER RNC layout

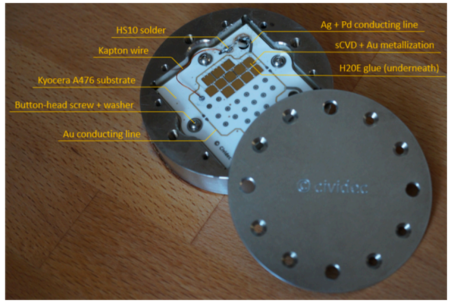
In-port RNC subsystem



Detector assembly





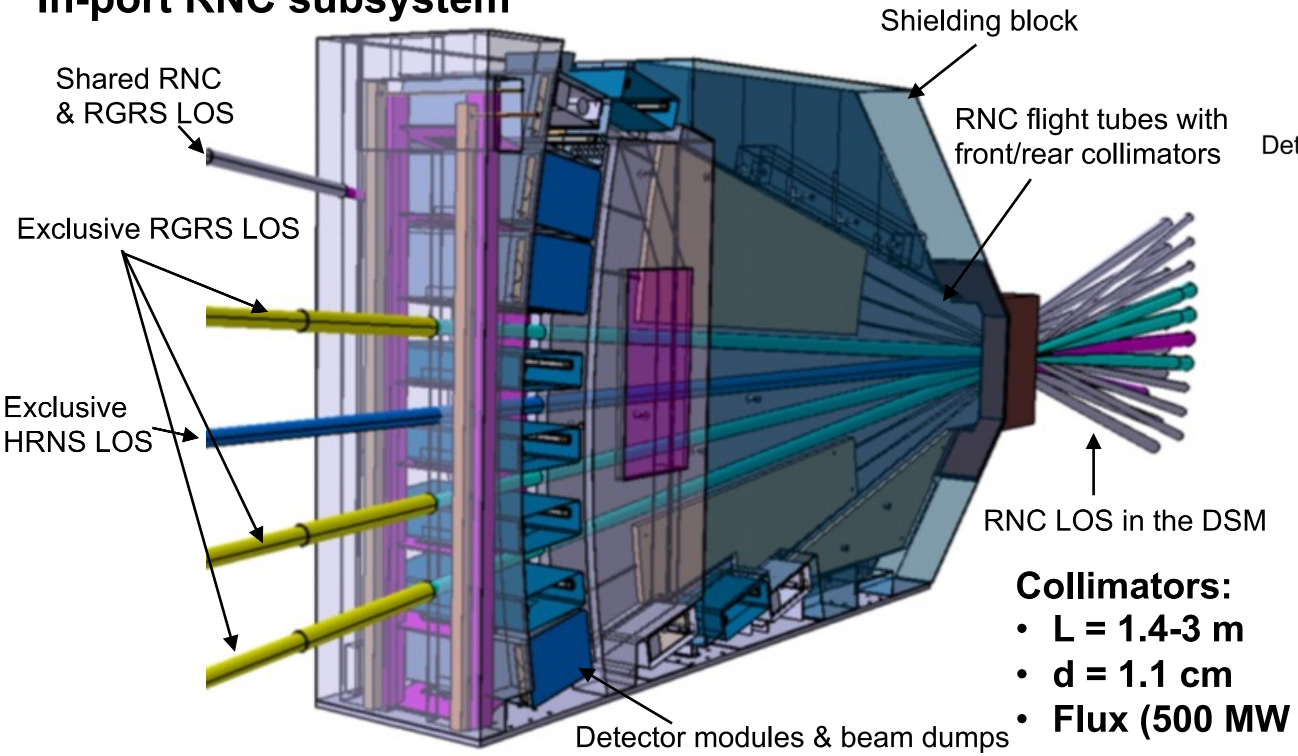


Collimators:
- **L = 0.95-1.5 m**
- **d = 3.2 cm**
- **Flux (500 MW scenario):** **~ 4-7x10^8 n cm^{-2} s^{-1}**

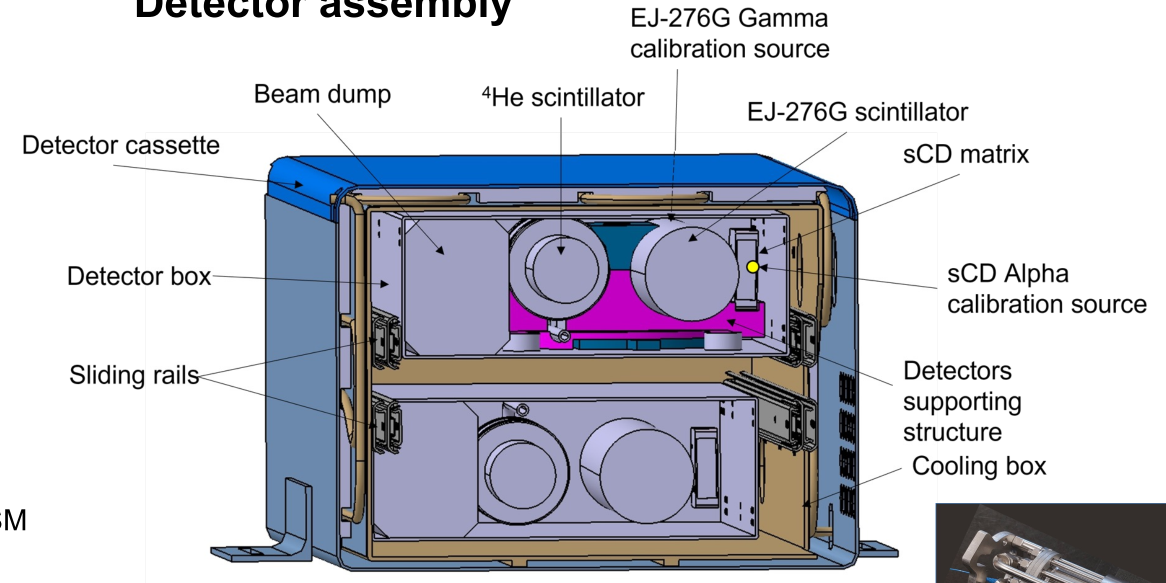
- Embedded in the **EP01 diagnostic shielding module (DSM) drawer #3**
- **Conical optical paths** hollowed out in the diagnostic first wall (DFW) and Diagnostic Shielding Module (DSM)
- **Removable SS316L(N)-IG cassette** (20 mm thickness) equipped with electrical and vacuum feedthroughs
- In-line detection system: a **single Crystal Diamond matrix** as main detector, also enabling spectrometric measurements and a **^{238}U fission chamber** as complementary detector
- **B_4C shielding blocks and beam dumps**

Ex-port ITER RNC layout

In-port RNC subsystem

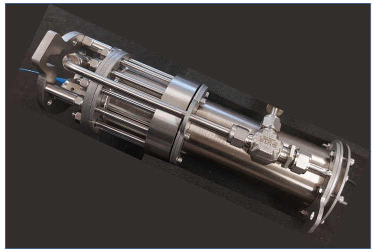


Detector assembly



Collimators:

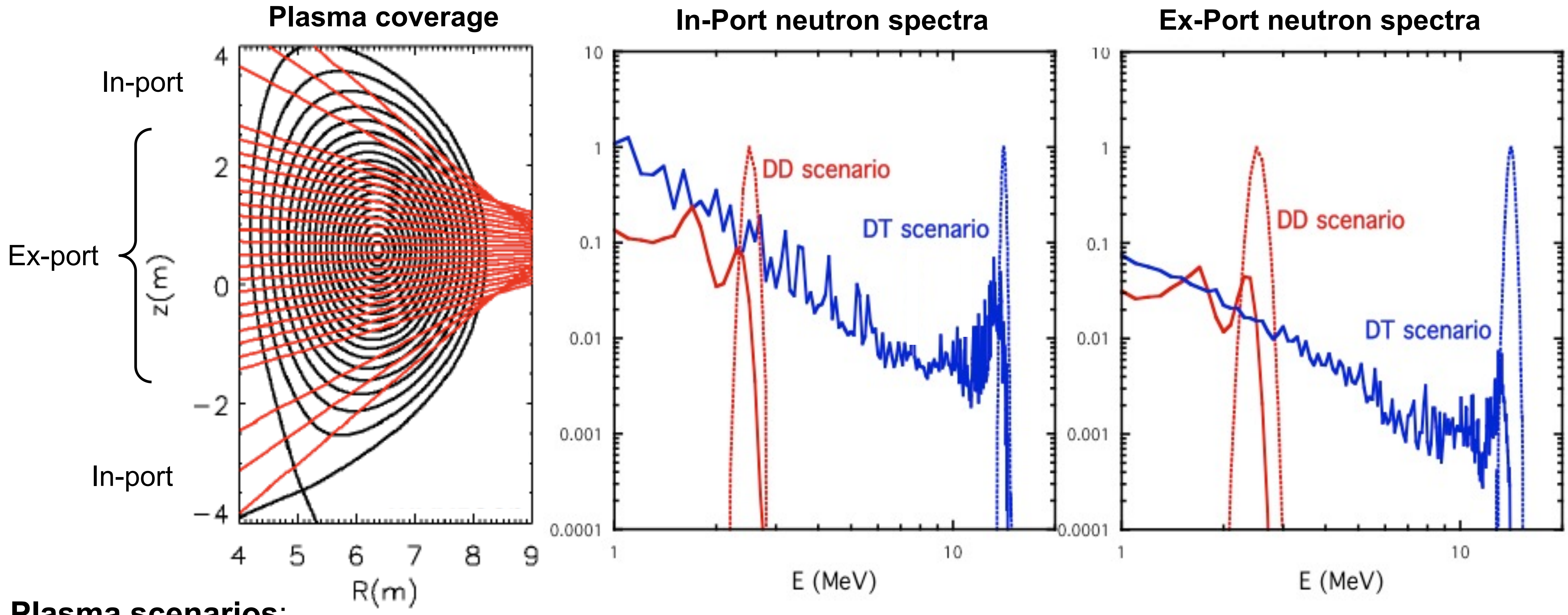
- **L = 1.4-3 m**
- **d = 1.1 cm**
- **Flux (500 MW scenario): ~ 0.85-2.3x10^8 n cm^{-2} s^{-1}**



^{4}He scintillator
(full power DT measurements)

- Massive **SWX-277Z-5** shielding block (high-temperature concrete-like material for gamma and neutron shielding applications, Boron content 5% by weight) extending from the port flange up to the Bioshield plug
- **Conical optical paths** hollowed out in the DFW and DSM
- **SS316L(N)-IG outer structure** and **inner stiffening plates and collimators**
- In-line detection system: a **single Crystal Diamond matrix , Plastic scintillator and ^{4}He scintillator**
- **B_4C beam dumps** inside the detector boxes

RNC plasma coverage & spectra



Plasma scenarios:

- ***DD** 15 MA L-mode NB-off-axis low power (**Y_n=1.9x10^{17} n/s**)*
- ***DT** 15 MA peaked density plasma scenario (**Y_n=1.83x10^{20} n/s**)*

RNC measurement & plasma parameters

RNC measurement

Line-integrated Neutron Fluxes

Spatial Inversion

Measurable Plasma Parameters:

- **Local profile of the neutron emission (emissivity profile,** (n $s^{-1}m^{-3}$))

Integration over the plasma volume

Neutron Yield (n s^{-1})

- **Alpha particle source profile** (D+T→α+n)
- **Fusion power density** (Wm^{-3})

Line-integrated Pulse Height Neutron Spectra

Spatial Inversion

Unfolding + Spatial Inversion

Line-integrated neutron spectra

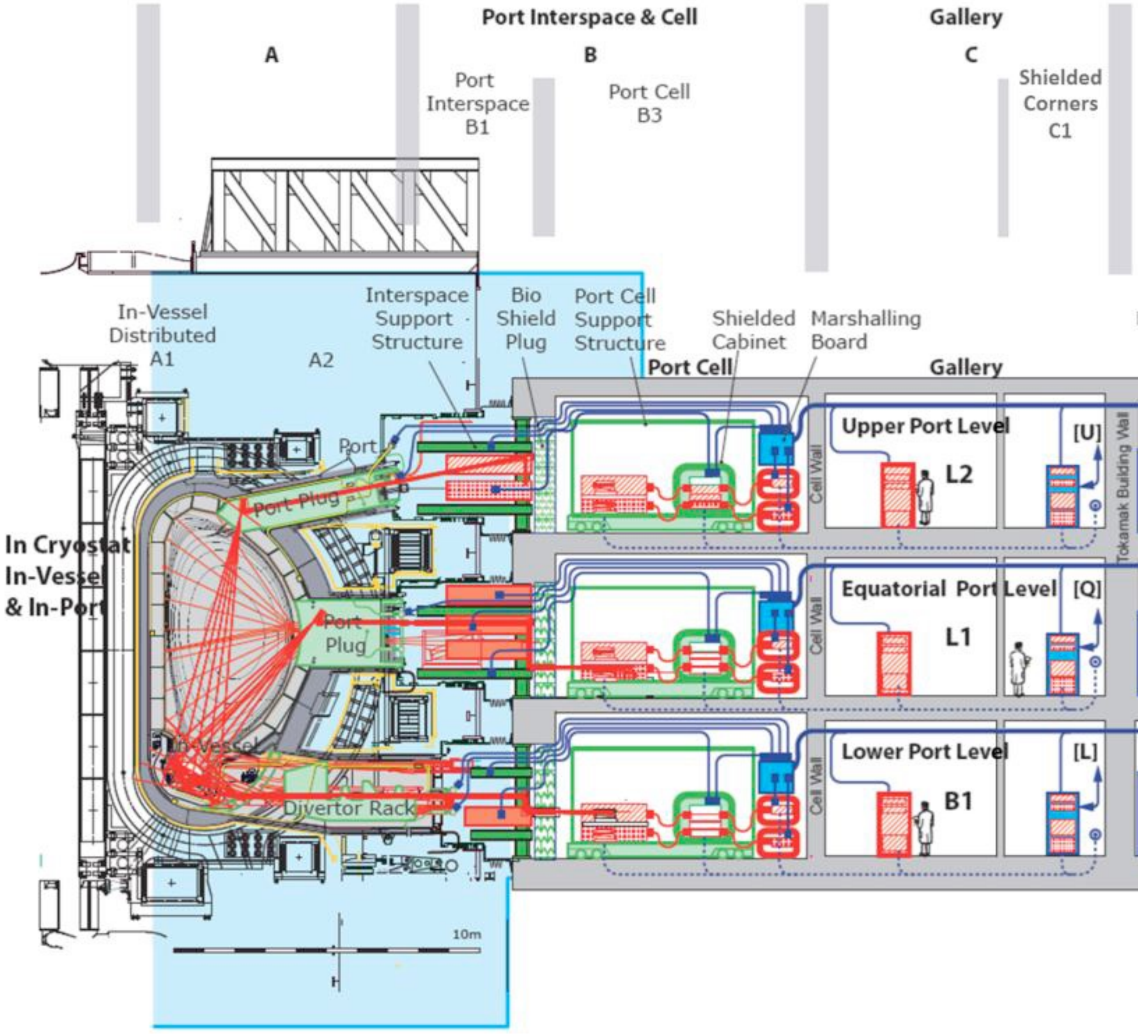
Local neutron spectra

Measurable Plasma Parameters:

- **Ion temperature profile**
- **Fast Ions profile** (density, energy)
- **Alpha particle profile** (density, energy)
- **Fuel ratio profile** (n_T/n_D)

Signals from RNC detectors need preamplification because of their low amplitude: front end electronics have to be as close as possible to the detectors **to minimize signal degradation**

Nuclear radiation environment in ITER



Level	Accumulated dose estimates (kGy)* * 4700 h ITER lifetime	Neutron flux estimates ($n/cm^2/s$)
Lower ports (B1)	50-500 (100 average)	10^5-10^6
Equatorial ports (L1)	1-10	10^5-10^6
Upper ports (L2)	5-50	10^5-10^6

Total ionizing dose and neutron fluence are higher than what commercial components can typically withstand: Potential damage caused by the nuclear radiation range from function degradation to component destruction.

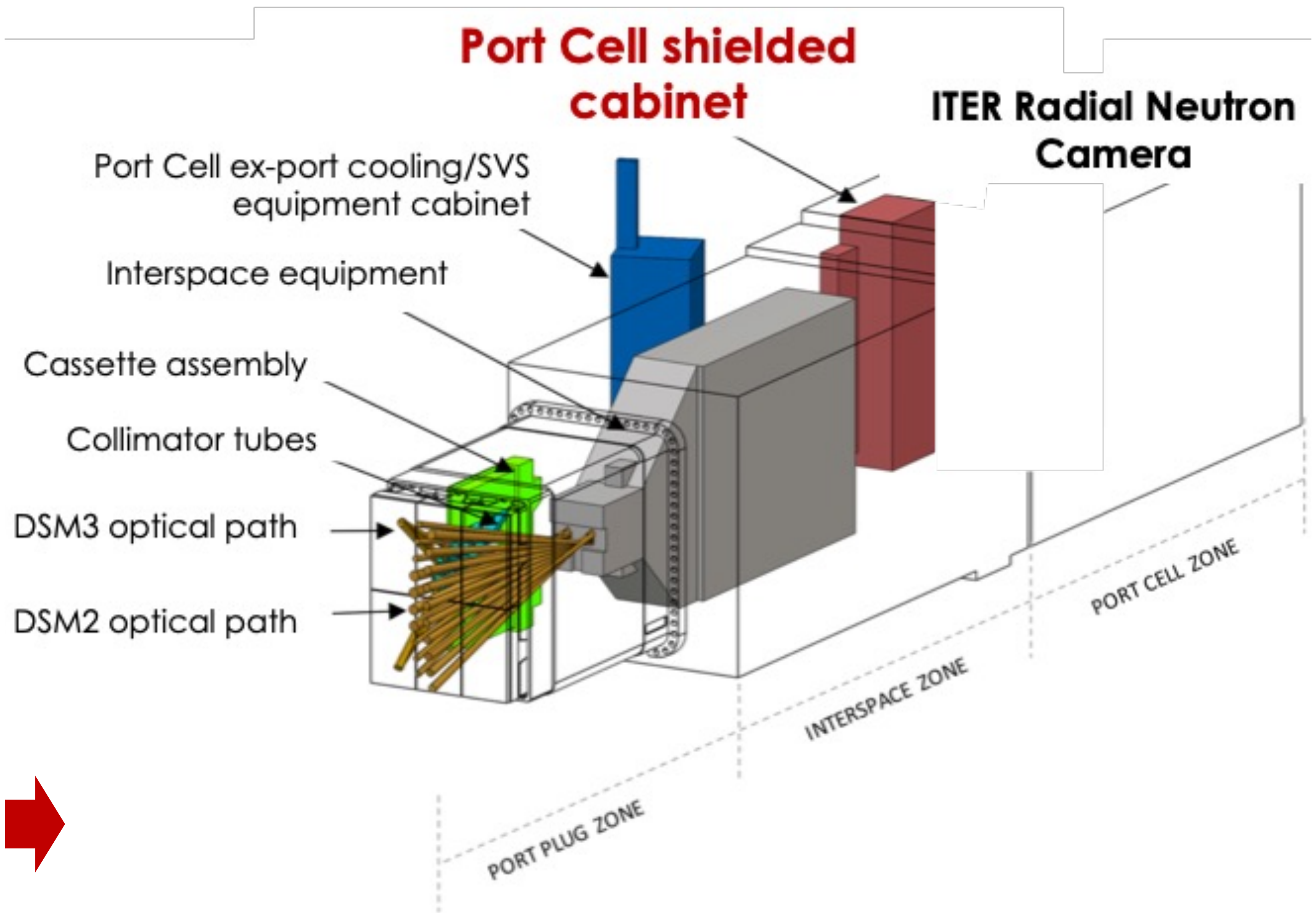
- **Progressive effect** due to accumulated ionization or atomic displacements
- **Instantaneous effect**, induced by an incoming neutron (SEE)

ITER policy on commercial electronics exposed to nuclear radiation: for the diagnostics electronics components (non-critical), the following alert thresholds have been proposed: **10 Gy for the accumulated dose and 100 $n/cm^2/s$ for the neutron flux**.

Mitigation strategy

the aim of radiation mitigation is to obtain mitigated radiation conditions As Low As Reasonably Achievable (ALARA principle).

- **Permanent change of functions** from active (with electronics) to passive (without electronics)
- **Periodical replacements of the irradiated electronic component**, when the cumulated radiation either reaches the alert thresholds, or reaches the maximum radiation conditions for which the component is qualified
- **Relocation of the electronic function in a remote area** with no radiation or with harmless residual radiation
- **Local shielding ensuring a reduced or harmless residual radiation environment** at the location of the electronic function

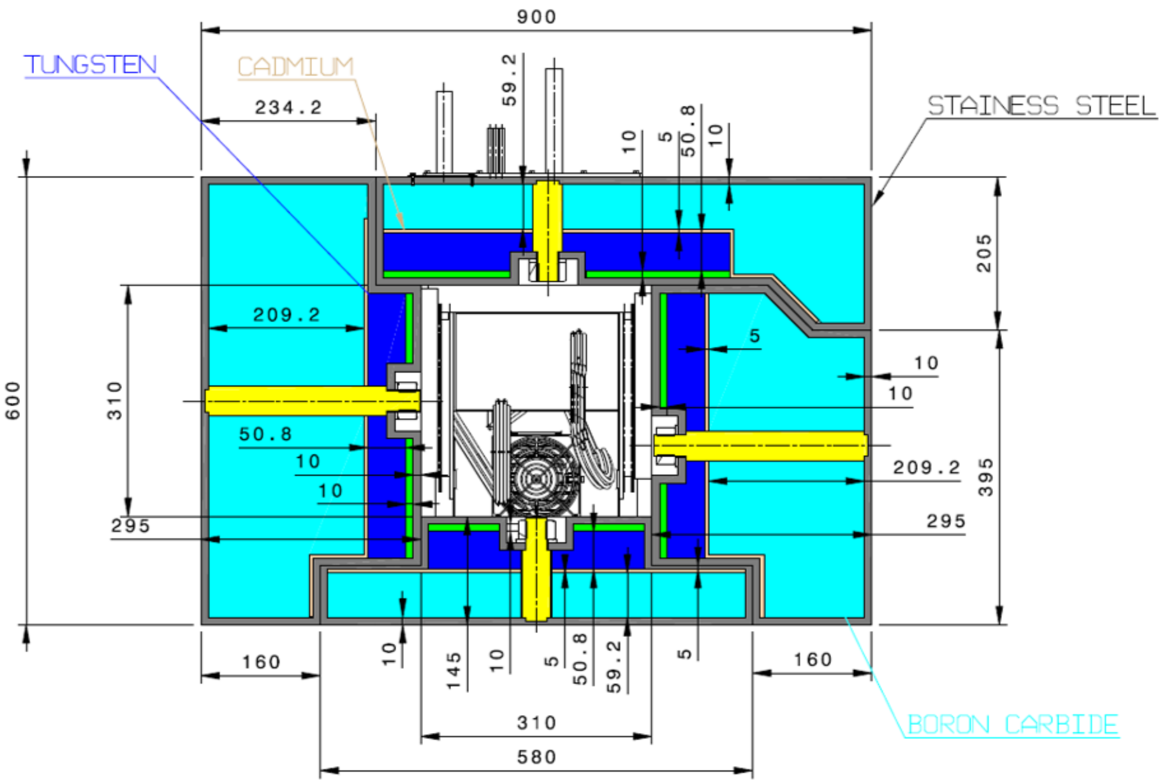


Shielded cabinet design

Shielded cabinet design driving criteria:

- Protect the inner electronics from **fast and thermal neutrons**
- Minimize the **gamma radiation field** in the inner cavity
- Provide protection from both the **static magnetic field** and the **transient electromagnetic fields** associated to events such as plasma disruptions, vertical displacements and magnet current discharges

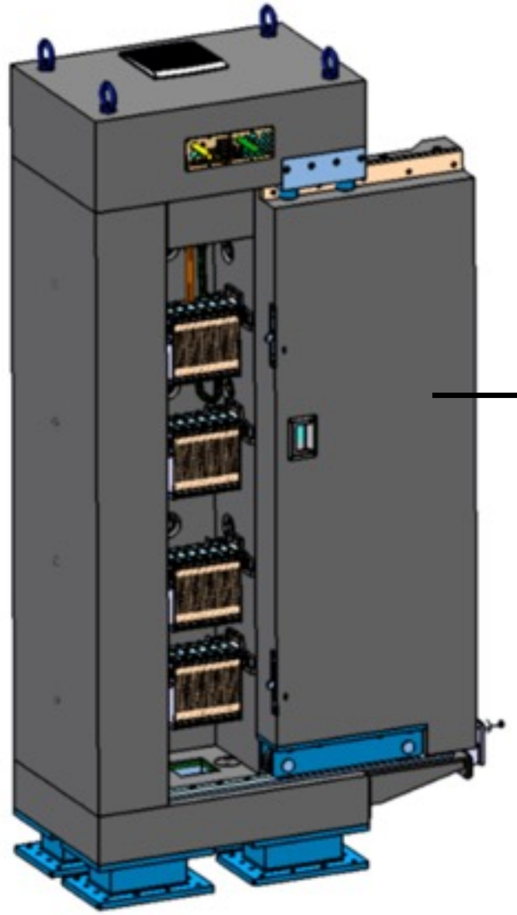
Cabinet side	Composition	Thickness (cm)	Role
Left hand side and right-hand side	Boron Carbide (B_4C)	5	Fast neutron moderator by neutron scattering
Front and back		20	
All sides	Cadmium (Cd)	0.5	Thermal neutrons absorber by capture reactions
All sides	Tungsten (W)	7	Gamma attenuation (environmental and due to neutron capture)
All sides	Iron (Fe)	2	Electromagnetic compatibility

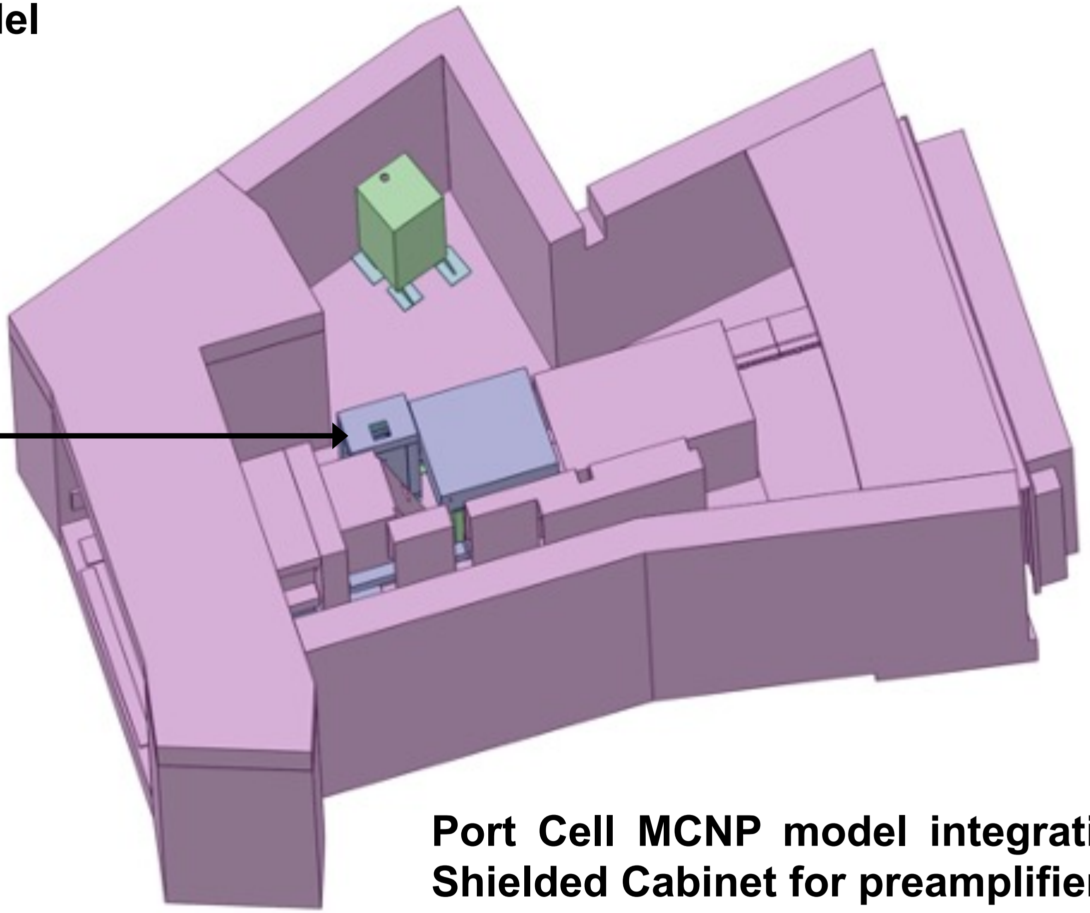


Nuclear analysis: MCNP modelling

The proposed layout for the electronics shielded cabinet underwent a **nuclear analysis** (**MCNP + FENDL-3.1d**) to verify its **reliability in protecting the enclosed preamplifiers**.

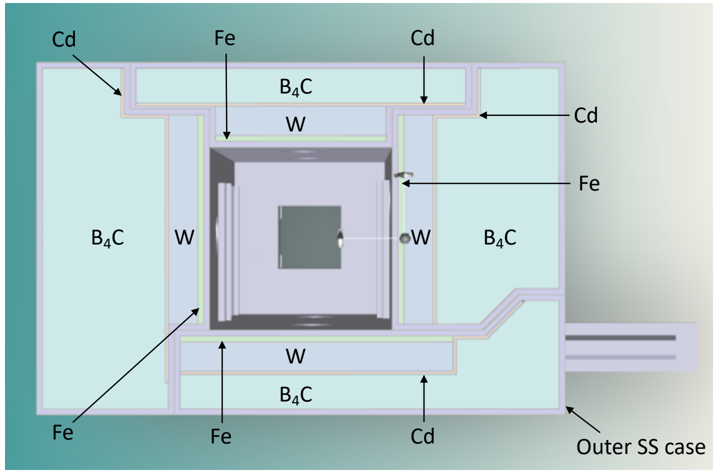
Shielded cabinet CAD model





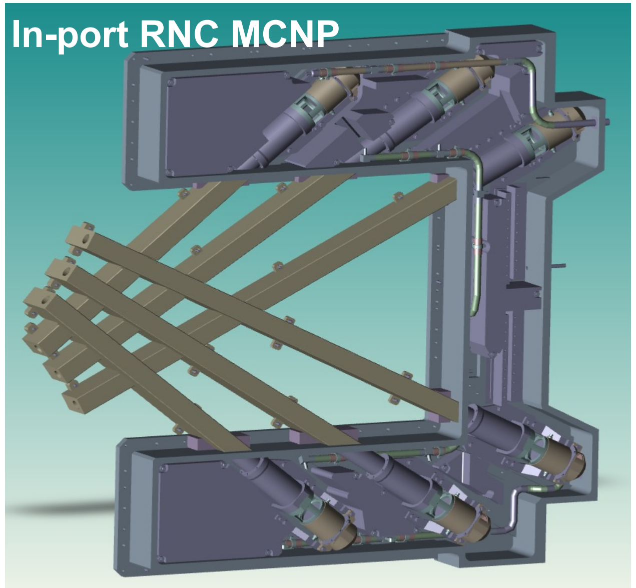
Port Cell MCNP model integrating the Shielded Cabinet for preamplifiers

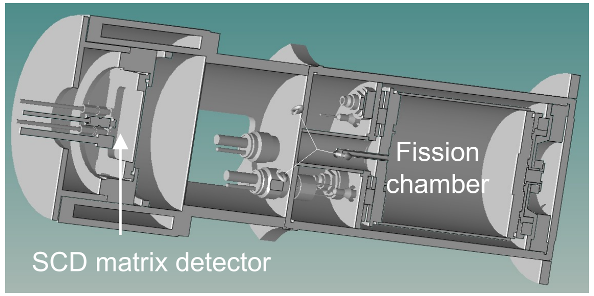
Shielded cabinet MCNP model

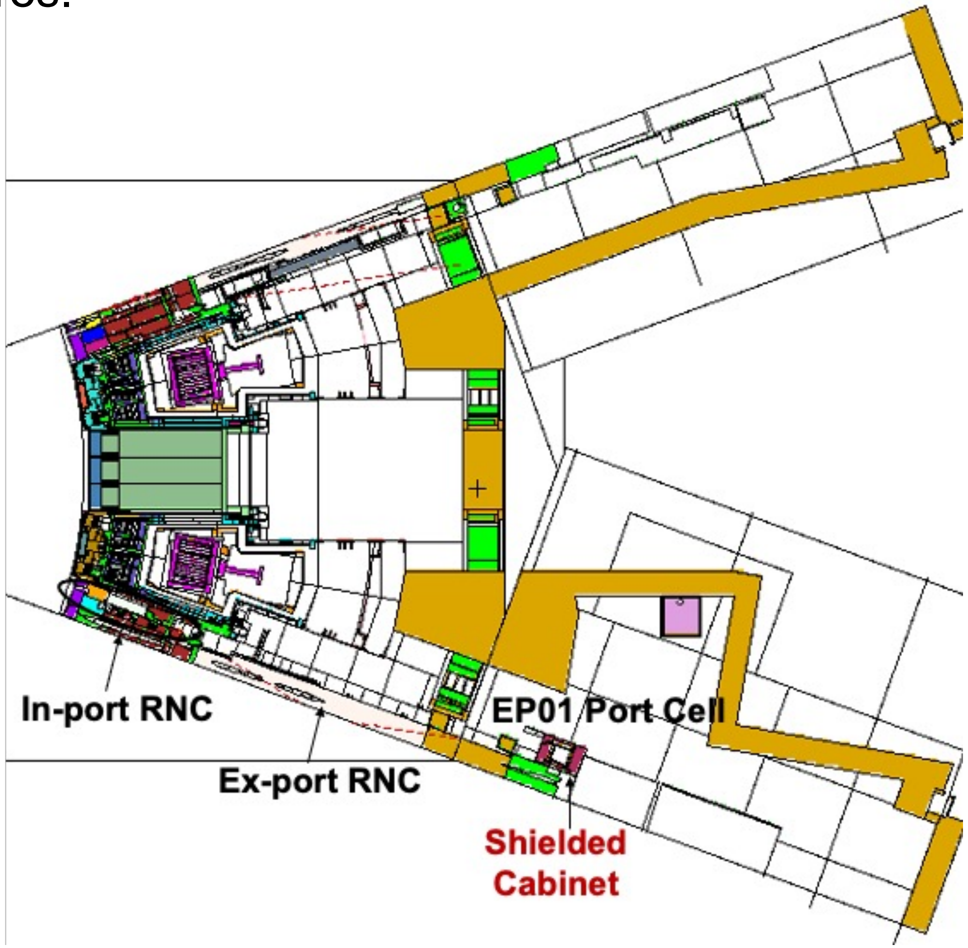


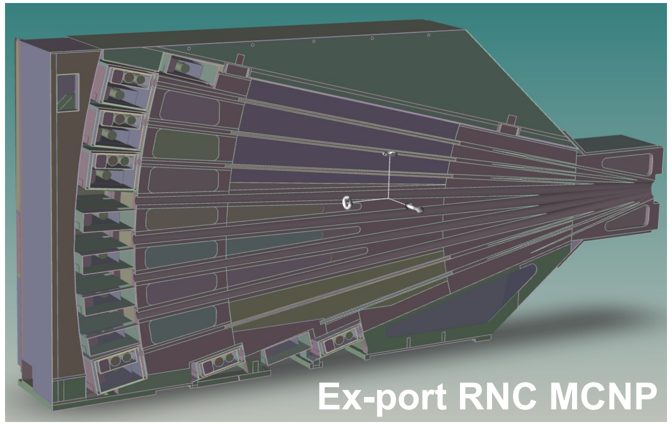
Nuclear analysis: model integration

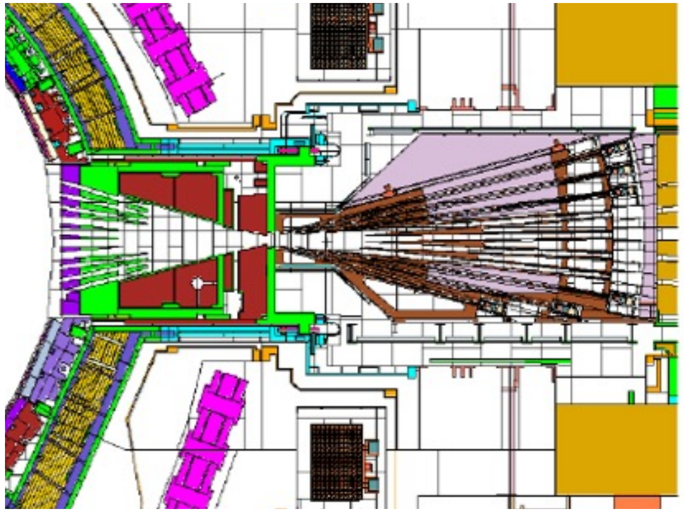
The MCNP model of the Shielded Cabinet has been integrated into an extended version of the **ITER MCNP C-model** (40° sector of the tokamak, with periodic boundary conditions) including the **EP01 components as well as the Port Cell structure** and features.











Nuclear analysis: variance reduction

Neutrons transport directly from the plasma source up to the Port Cell is a quite challenging task:

- source neutrons flux is strongly moderated by the ITER shielding components (Port Plug, Ex-port shielding block, Bioshield)
- substantial distance (~ 10 m) from the plasma source
- the cabinet prevents neutron from reaching the inner cavity where preamplifiers are located

Very few particles are likely to reach the scoring position

The reliability of the numerical results (e.g. convergence or fluctuation criteria), ensuring relevance for the objectives of the nuclear analysis, is achieved through the application of **proper variance reduction techniques (weight windows)**.

Automate**D** **VA**ria**N**ce Reduc**T**ion **G**enerator (**ADVANTG**): automatically generates space and energy dependent variance reduction parameters employing a deterministic transport solver. It enable MCNP simulations to obtain uniformly converged tallies over arbitrary regions of interest.

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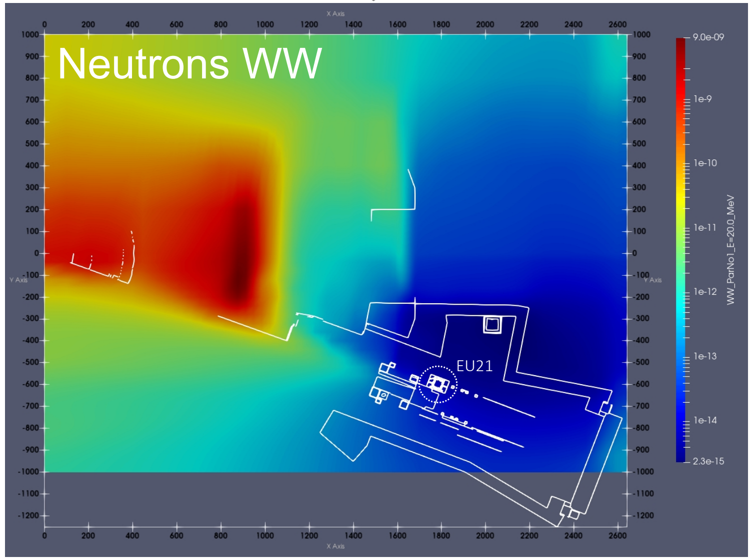
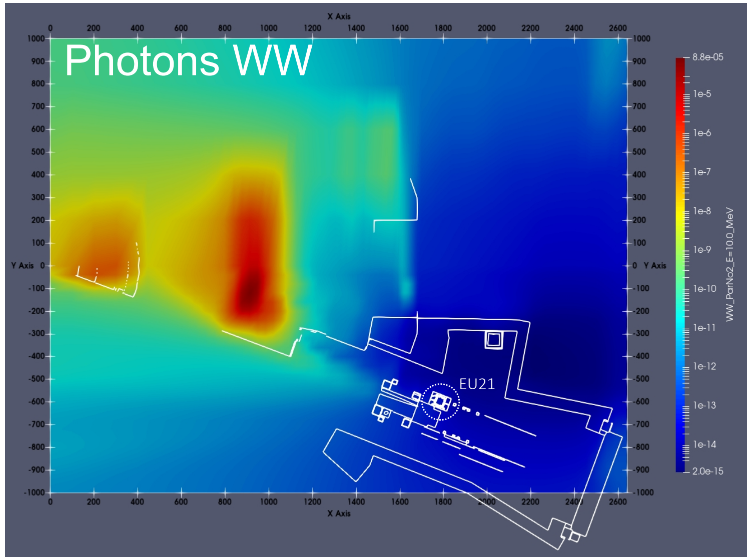


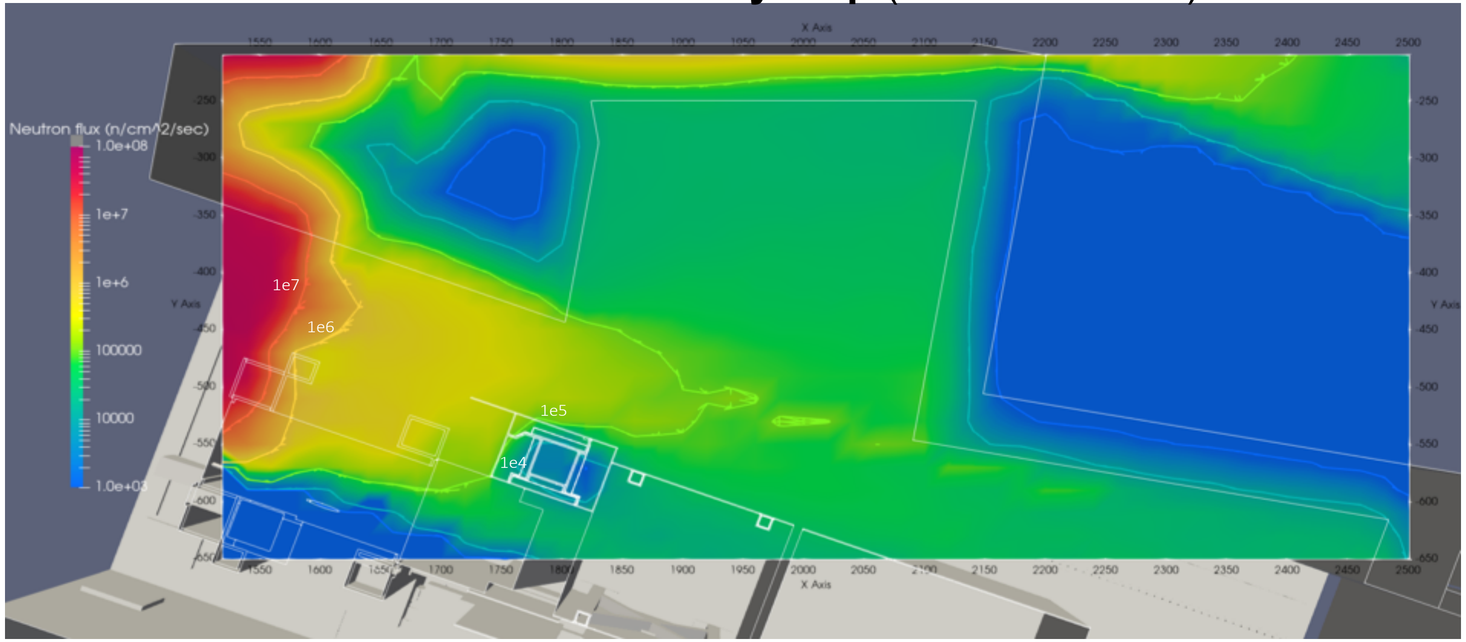


ENEA

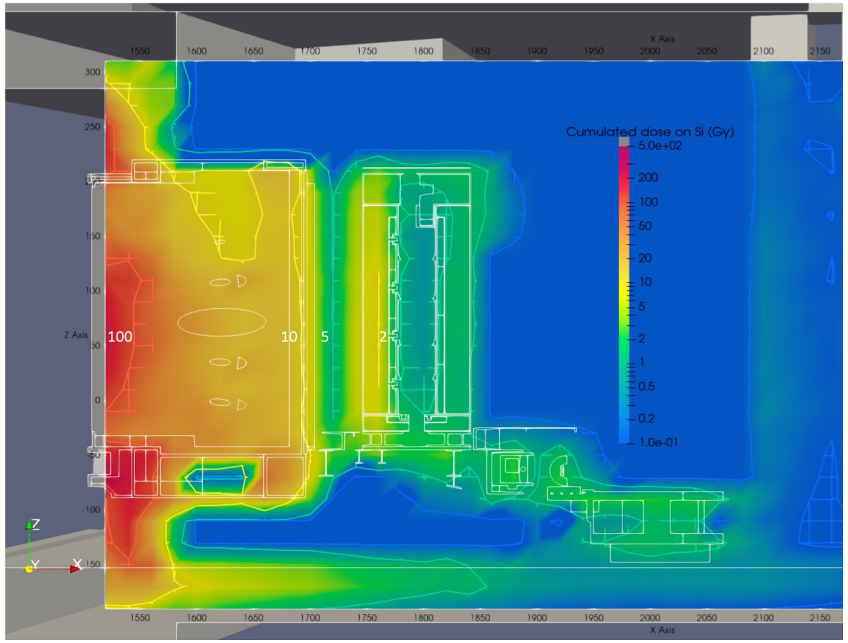
Nuclear analysis: results

DT inductive H-mode 10 MA plasma scenario, 500 MW fusion power (Y_n=1.77x10^{20} n/s)

Neutron flux density map (toroidal section)



Integrated dose to Silicon density map
(section along the cabinet longitudinal axis)



	Inside the cabinet	Outside the cabinet	Shielding factor
Neutron flux ($n/cm^2/s$)	3.6×10^3	3.8×10^5	1.06×10^2
Gamma flux ($\gamma/cm^2/sec$)	1.15×10^3	1.2×10^5	1.04×10^2
Integrated absorbed dose to Si (Gy)	1.5	N.A.	N.A.

Conclusions

- **The RNC shielded cabinet structure provides a substantial reduction of the nuclear loads** (about a factor 100 for neutron and gamma fluxes), with respect to the surrounding environment.
- **The neutron flux inside the cabinet (3.6×10^3 n/cm^2/s)** is still 2 orders of magnitude larger than the alert threshold for commercial electronics (10^2 n/cm^2/s) and therefore **the preamplifiers should be designed and tested for compliance with such neutron flux**
- **The absorbed dose to Si integrated over the ITER lifetime is 1.5 Gy, below the alert threshold for commercial electronics** (10 Gy)
- RNC detection chain components (detectors, electronics, feedthrough, cabling system) are undergoing experimental tests to verify their reliability in terms of:
  - **Measurement performances**
  - **Neutron/gamma radiation hardness** (cumulative effects: total ionizing dose, displacement; single event effect)
- Most of the above-mentioned tests are performed at the **Frascati Neutron Generator (FNG)** irradiation facility (see next presentation)

Thank you for your attention