Super Monte Carlo Program for Nuclear and Radiation Simulation

SuperMC Tutorial

Application of Monte Carlo code SuperMC at KIT for fusion neutronics modelling

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Outline

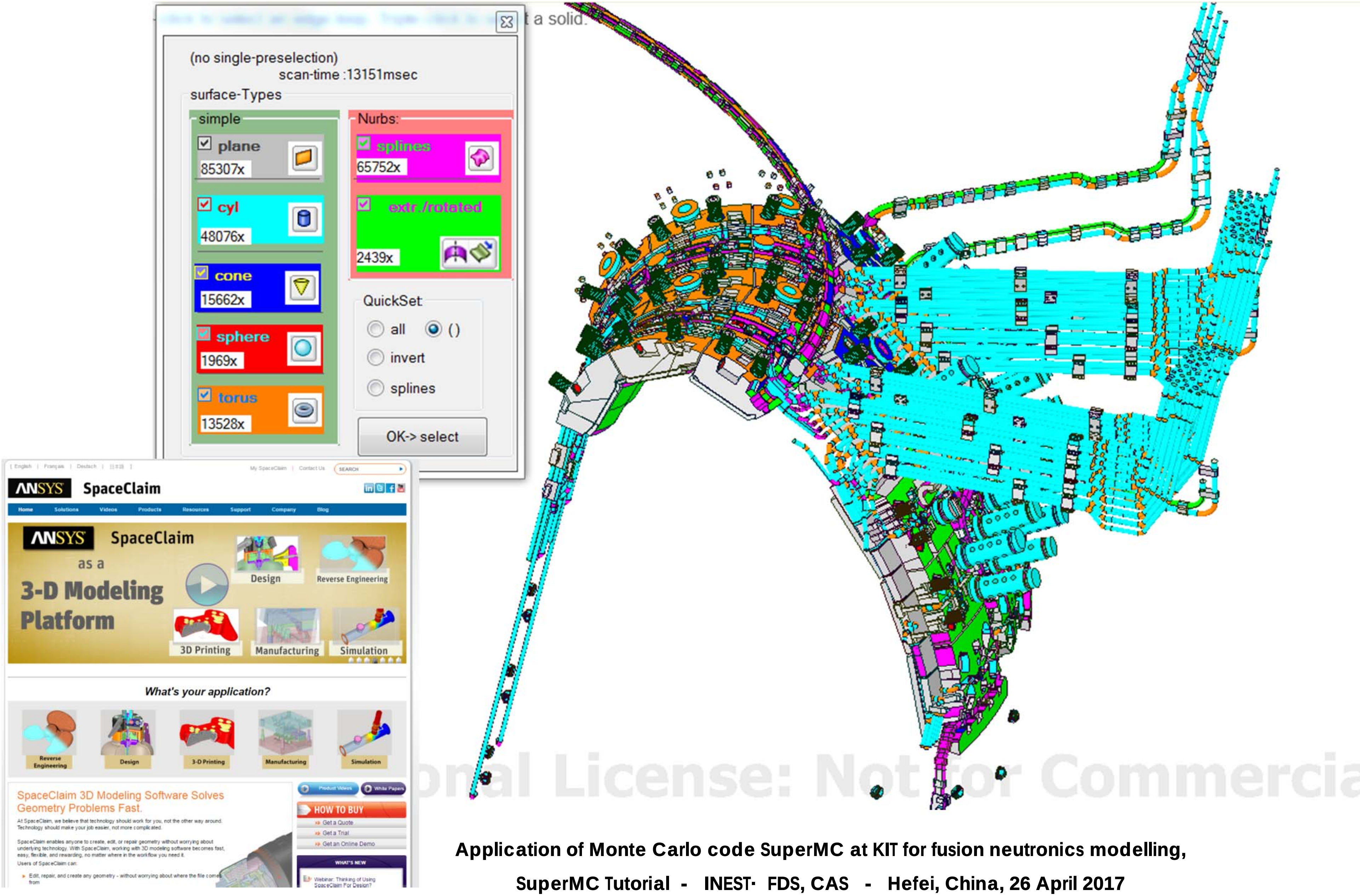
- **Fusion Neutronics Methodology: Codes, Tools, Nuclear Data**
- **Geometry modelling principles** available in CAD-based Monte Carlo (MC) transport simulations
- **Challenges & problems of CAD conversion** for MC models with Constructive Solid Geometry (CSG) definition.
- **Examples of SuperMC successful applications** for MC CSG modeling
- **Suggestions for SuperMC further improvement**

Fusion Neutronics Methodology: Codes, Tools, Nuclear Data

➧ To reach the objectives, **we used the state-of-the-art codes and interfaces** approved for ITER neutronics applications:

- **SpaceClaim** software reads CAD models, solves geometry problems, allows to work in 3D without having to be a CAD expert
- **CAD-to-MCNP conversion tools:**
  - **MCAM & SuperMC (FDS Team, China)**
  - **McCad (KIT, Germany)**
- **Radiation transport calculations (n/gamma fluxes, nuclear heat, gas production):**
  - Monte Carlo code **MCNP5 v1.60, MCNP6 (LANL)**
  - **FENDL-2.1 (IAEA)** neutron cross-section library
  - **B-lite MCNP model (IO)** 40 tor-degree with all the components of ITER with modifications for the Upper Port area. C-lite model is not ready for Upper Port.
- **Activation and Shut-Down Dose Rate (SDDR) calculations:**
  - **FISPACT-2007 (CCFE)** inventory code and **EAF-2007 (EU)**
  - **D1S code (ENEA)**
  - **R2Smesh (KIT)**
- **Vizualisation: Paraview** (Kitware) in vtk-format

Challenges & problems of CAD conversion: CAD file of the ITER in-vessel components with surfaces color codes – visualized with ANSYS SpaceClaim software



CAD-Based Monte Carlo Rad. Transport

Three modelling approaches of CAD-based Monte Carlo transport simulations:

1. **Constructive Solid Geometry (CSG)** – traditional approach with **CAD to Monte Carlo models conversion codes**:
   - SuperMC (FDS team, China);
   - McCad (KIT fusion neutronics group, Germany).
2. Unstructured Mesh (UM) geometry in MCNP6 (LANL, USA);
3. Direct particle tracking technique with Direct Accelerated Geometry Monte Carlo (DAGMC) library – MCNP patch developed by University of Wisconsin–Madison, USA.

Three stages of CAD (CSG) – to – MC models geometry conversion:

1) Geometry simplification – remove the unnecessary details;
2) Approximation of free-form and spline surfaces to 1st and 2nd order surfaces accepted of MCNP;
3) Material definition with homogenization setting up the material mixtures for the simplified cells, such as steel-water shielding composition of 60 vol.% steel – 40 vol.% water.

Problems with CAD (CSG) – to – MC models geometry conversion

- In the original CAD engineering model there are too many spline surfaces.
- MC codes with the CSG approach for modeling geometry do not support splines.

- Therefore, splines should be substituted with other surface types, e.g. cylinders and planes.
- There is no automatic algorithm exist for surface substitution. Splines substitution is the most challenging problem we encounter in geometry preparation for CAD-to-MC conversion.
- It takes time for manual labor for changing splines to the acceptable surfaces.
- Geometry editing is conducted in CAD programs such as SpaceClaim.

- After all necessary manipulations with CAD geometry, the model is saved in CAD formats such as STEP, SAT for model transferring to MC format by using converters such as SuperMC and McCad.
- The strategic idea is to couple as close as possible these two parts of CAD editing and CAD conversion.
- McCad converter has been integrated inside the SpaceClaim, now in **one program** we can work simultaneously with **CAD for editing and conversion.**

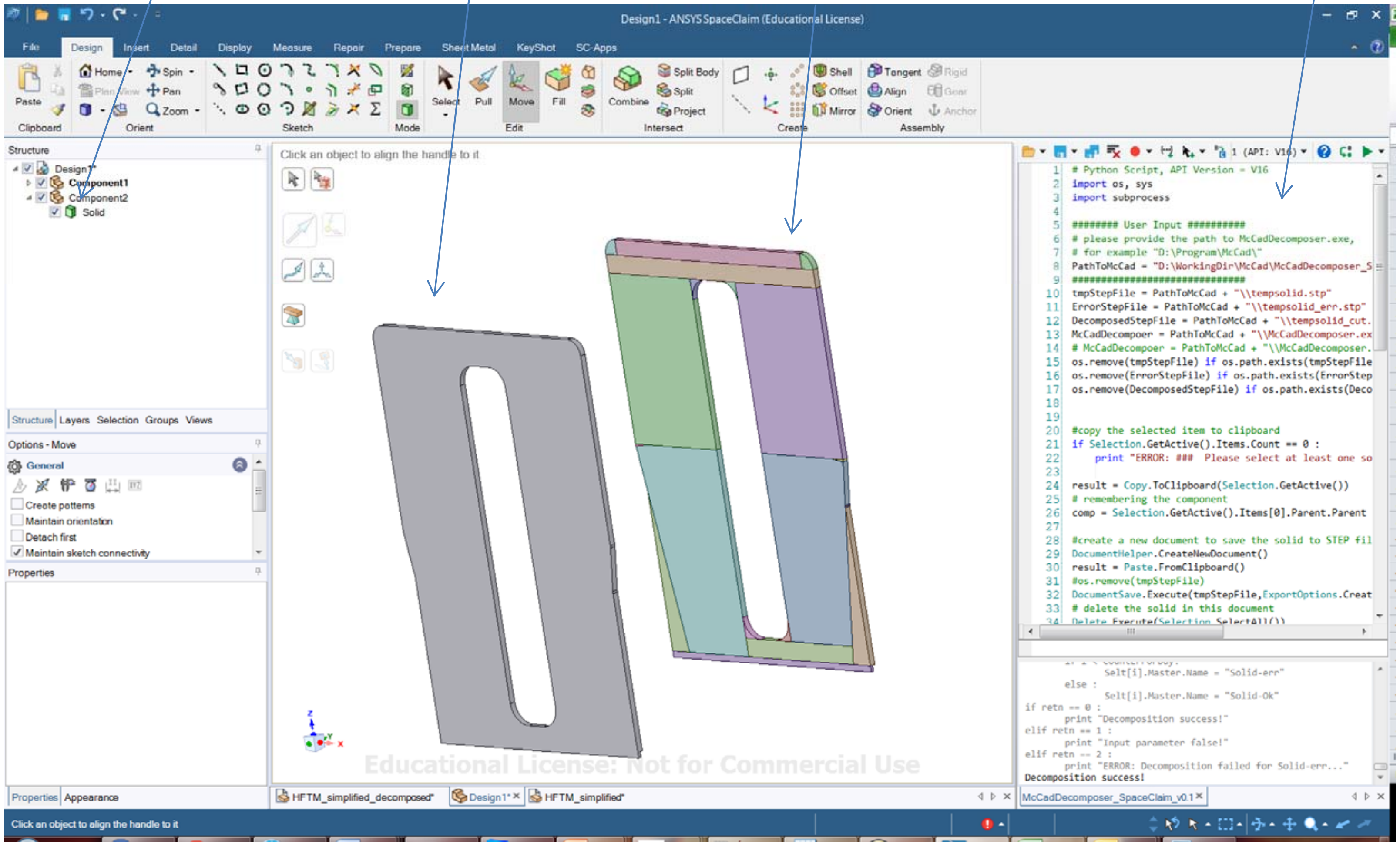
Integration of McCad inside the ANSYS SpaceClaim

Interactive decomposition, Can recover if McCad failed

Before decomposition

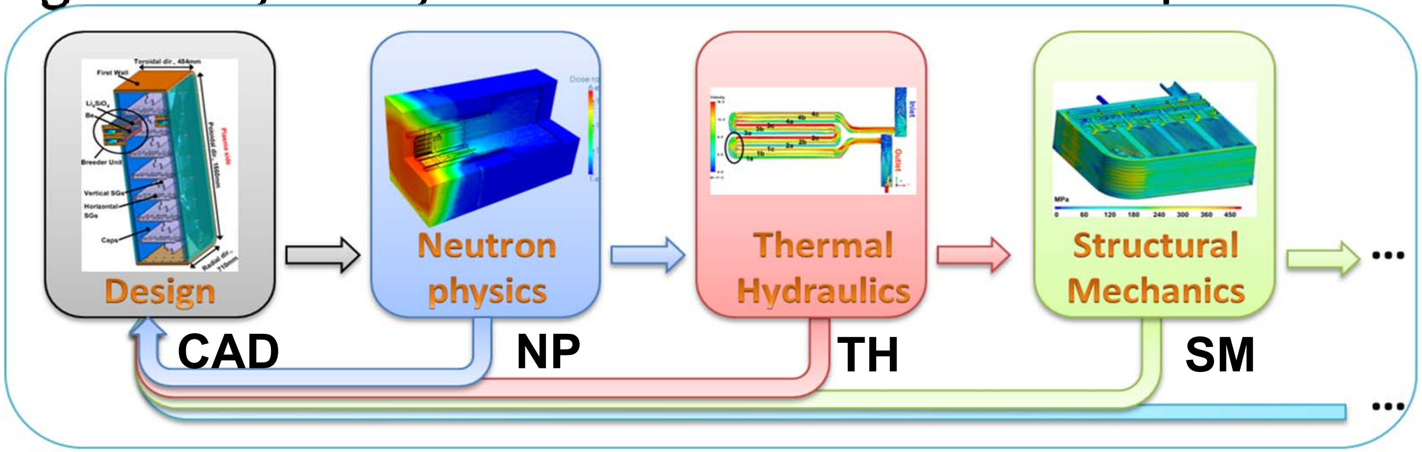
After McCad decomposition

Python script to run McCad



Integration of McCad in SALOME platform

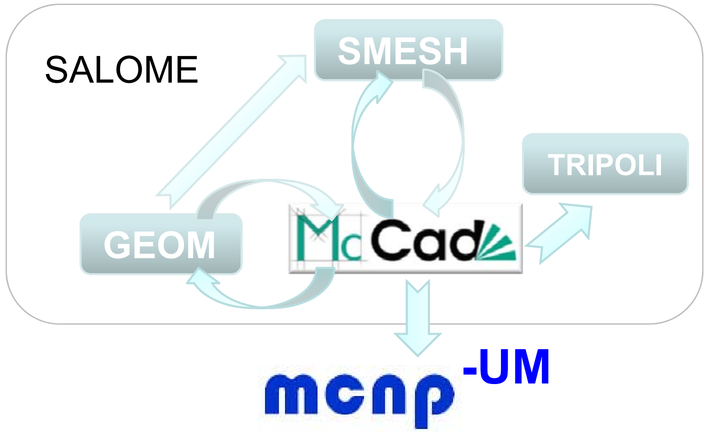
- Design analysis cycle for fusion reactor components



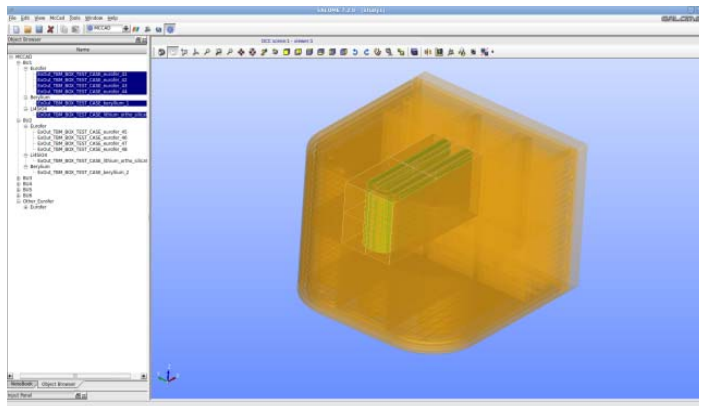
- Characteristics
  - Design often change → based on CAD and mesh geometry;
  - Various computation codes → suitable data transfer scheme;
  - Frequently coupled → integrating into a suitable platform

CAD/Mesh conversion

- McCad – a geometry conversion tool for MC codes
  - McCad conversion kernel already developed at INR-KIT

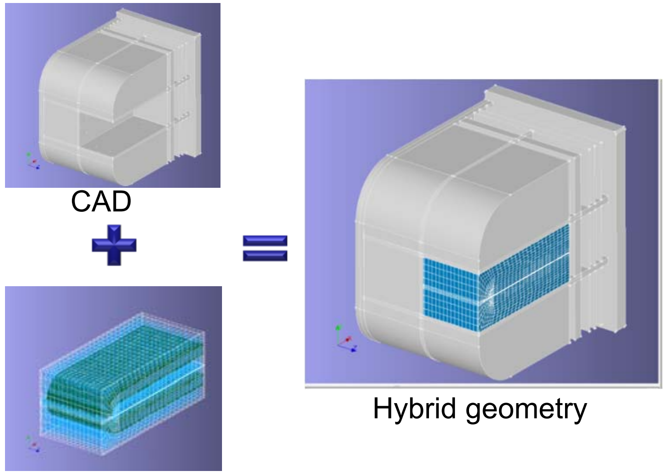


- McCad integration in SALOME
  - New McCad in SALOME platform
    - User friendly for managing models and assigning properties;
    - Model persistency using a portable project file;
    - One-click automatic conversion;
  - Interaction with SALOME geometry module
    - Bi-directional CAD data communications;
    - Creating/modifying model in SALOME geometry module

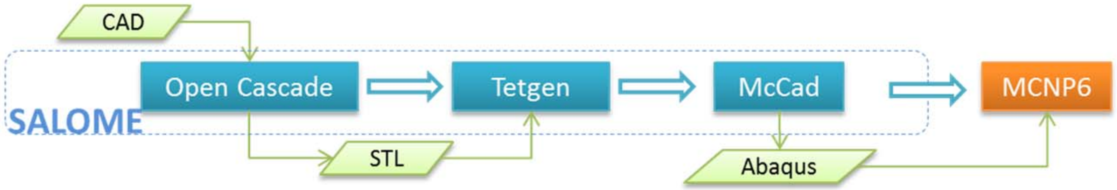


CAD/Mesh conversion

- Upgrading McCad to support hybrid geometry
  - Interface for MCNP6
    - Managing CAD and mesh together in one GUI;
    - Converting meshes to MCNP6 support format;
  - Interaction with SALOME meshing module
    - Bi-directional mesh data communication;
    - Creating/import mesh using SALOME meshing module.

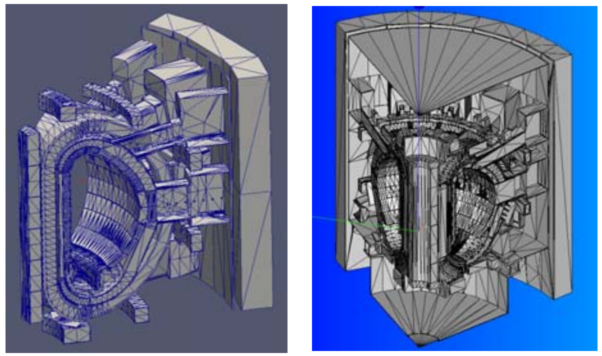


- Fast tetrahedral meshing



- Fast tetrahedralization;
- Geometry adaptive meshing, reduce overlapping;
- Less mesh cell, but high geometry fidelity.

	ITER Benchmark	Alite-80°
CAD solids	934	4296
Mesh cells	1.51E5	4.48E5
CPU time (s)	25	98
Volume diff	0.11%	-
Lost particles (per 1E8 NPS)	33	2



ITER Benchmark Alite-80°

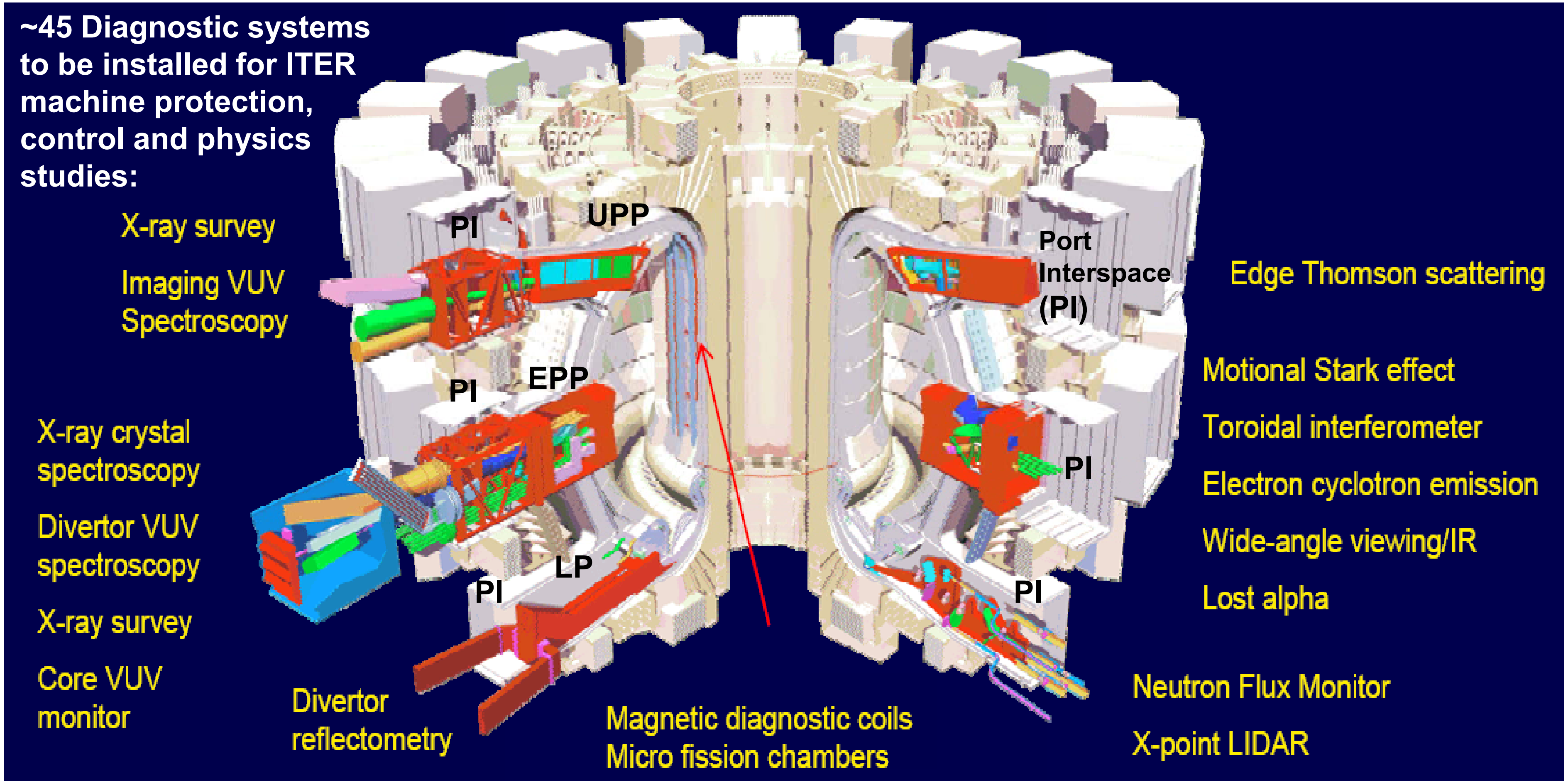
Tetrahedral mesh generated by McCad

Examples of SuperMC successful applications for MC CSG modeling

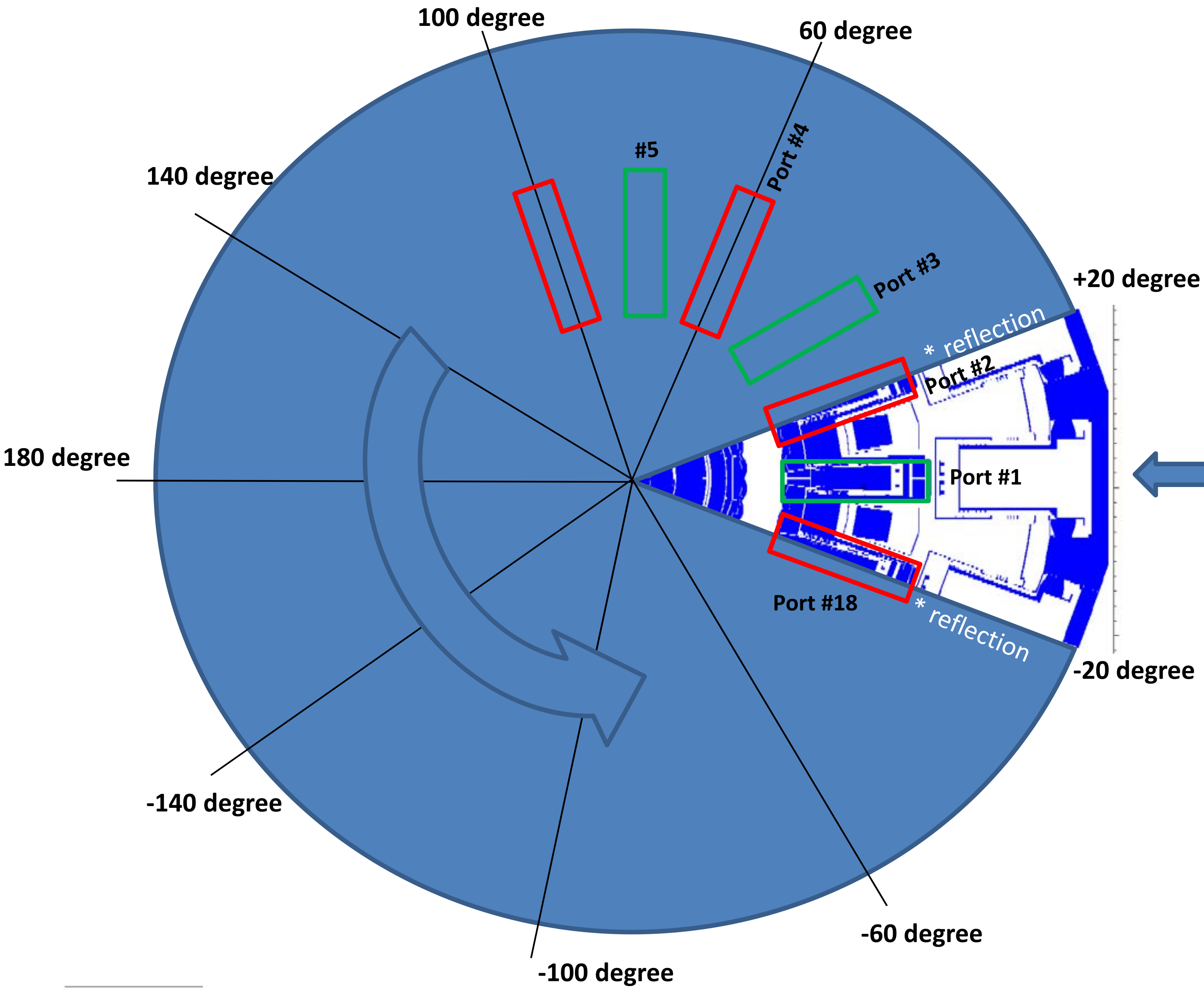
Introduction

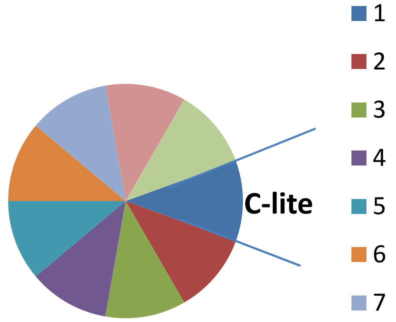
<u>Objectives</u> – CAD-based neutronics computational support for design development of the ITER Diagnostic Generic Upper Port Plug (DGUPP) which will host many Diagnostic systems.

<u>The objectives have been reached</u> by Monte Carlo (MCNP) radiation transport and activation analyses resulting in developing new 3D MCNP model and studying potential design improvements for radiation shielding of the Port Interspace (PI) where personnel access is planned for Upper Port maintenance.

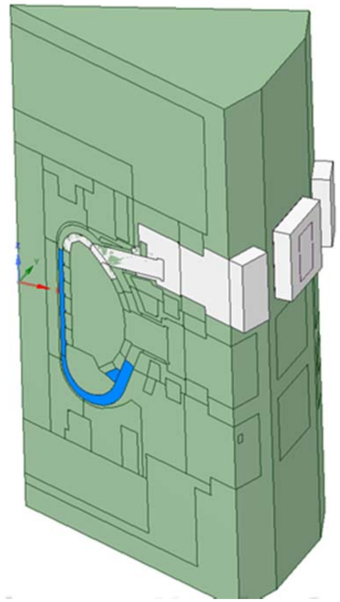


- MCNP models called “C-lite” or “C-Model” in 40 degree toroidal sector symmetrically represents the whole 360 degree of ITER machine;
- 40 degree is copying simmetricall 9 times by using the reflective boundary conditions.





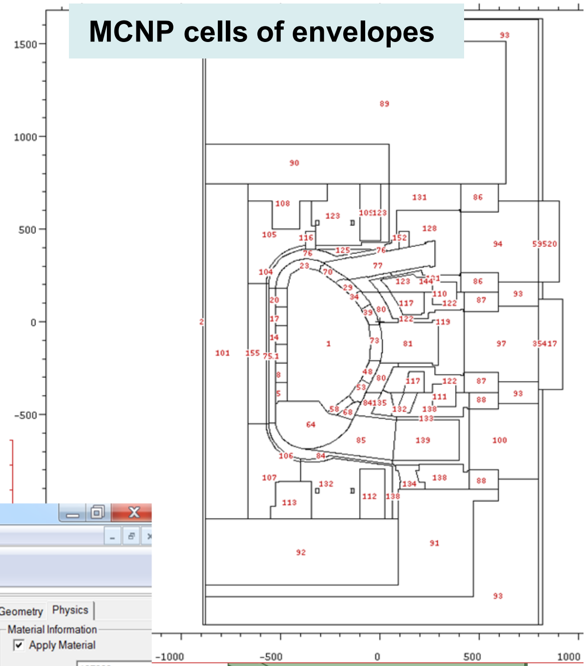
9x40 degree identical toroidal sectors



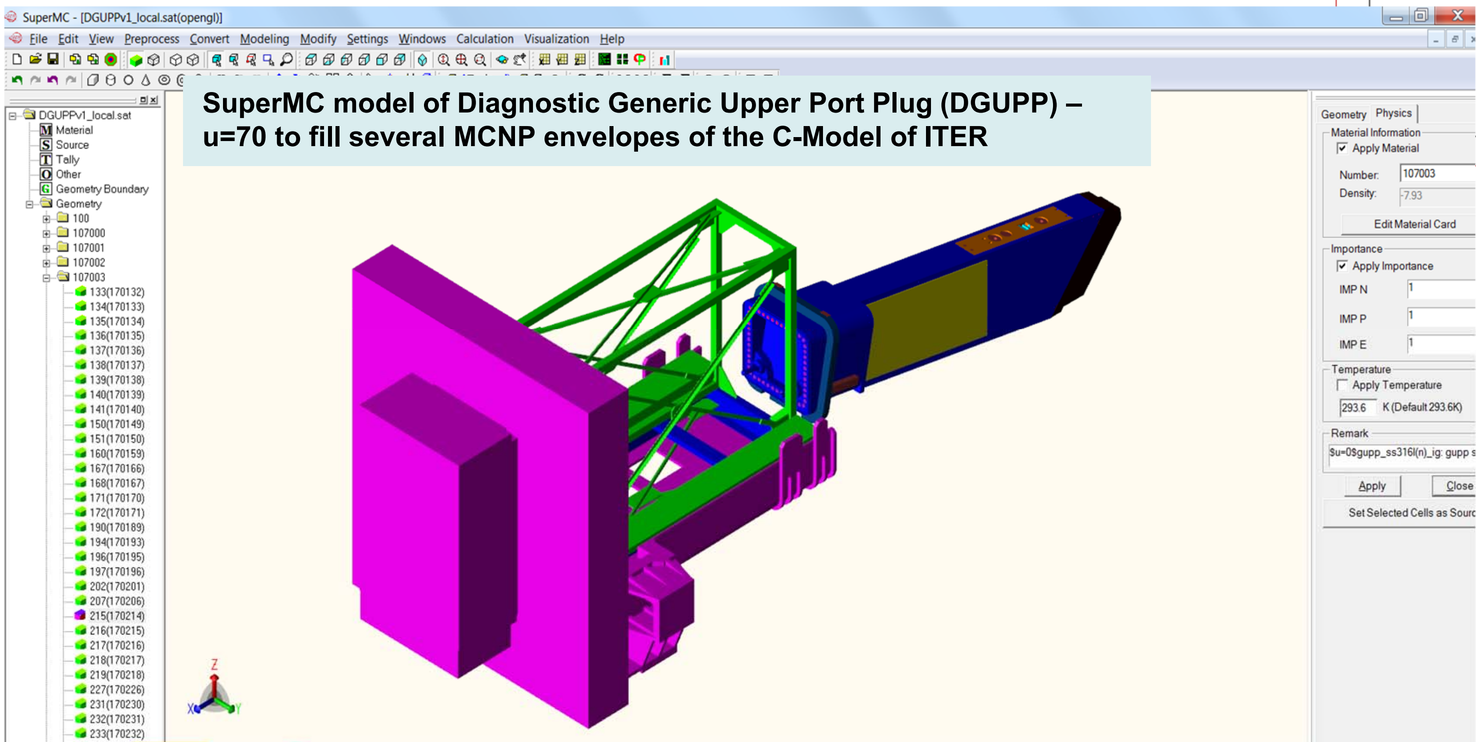
40 degree sector of C-Model

Module structure of ITER C-Model

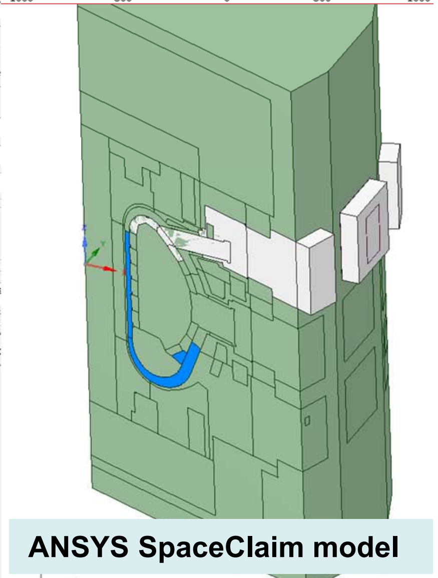
- **ANSYS SpaceClaim** graphical code was used for most model preparation (simplification and approximation) of the CAD model. Because the original CAD engineering models have inadequate quality for geometry conversion to MCNP models.
- **SuperMC** capabilities of geometry converting and inverting **CAD⟷MCNP** was used for conversion CAD to MCNP, then manual fixing geometry errors in MCNP if necessary (coincide surfaces, undefined gaps or overlaps) – found as **lost particles** and then returning back from MCNP into CAD.



MCNP cells of envelopes



SuperMC model of Diagnostic Generic Upper Port Plug (DGUPP) – u=70 to fill several MCNP envelopes of the C-Model of ITER

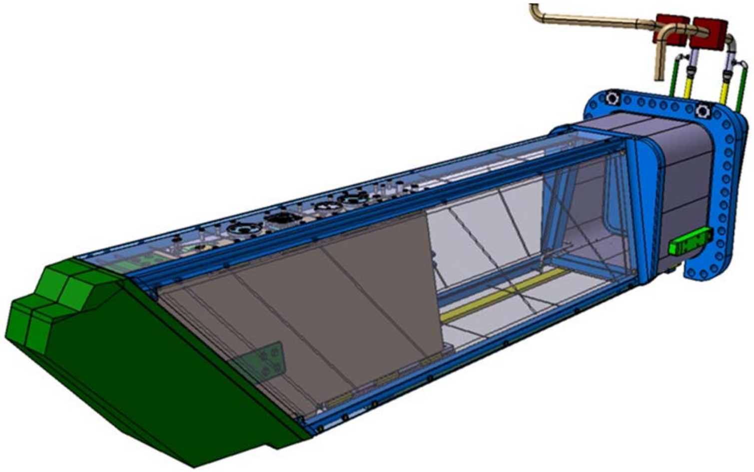


ANSYS SpaceClaim model

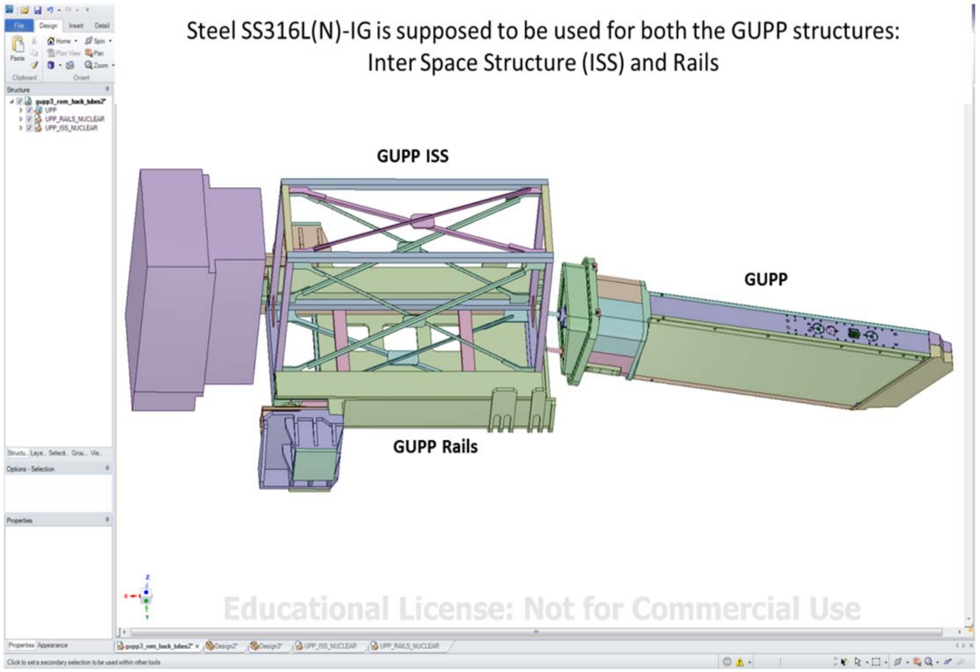
Example of SuperMC application

Diagnostics Generic Upper Port Plug
(DGUPP)

MCNP neutronics model development of the Diagnostics Generic Upper Port Plug (DGUPP) in 3D geometry based on the original engineering CAD model

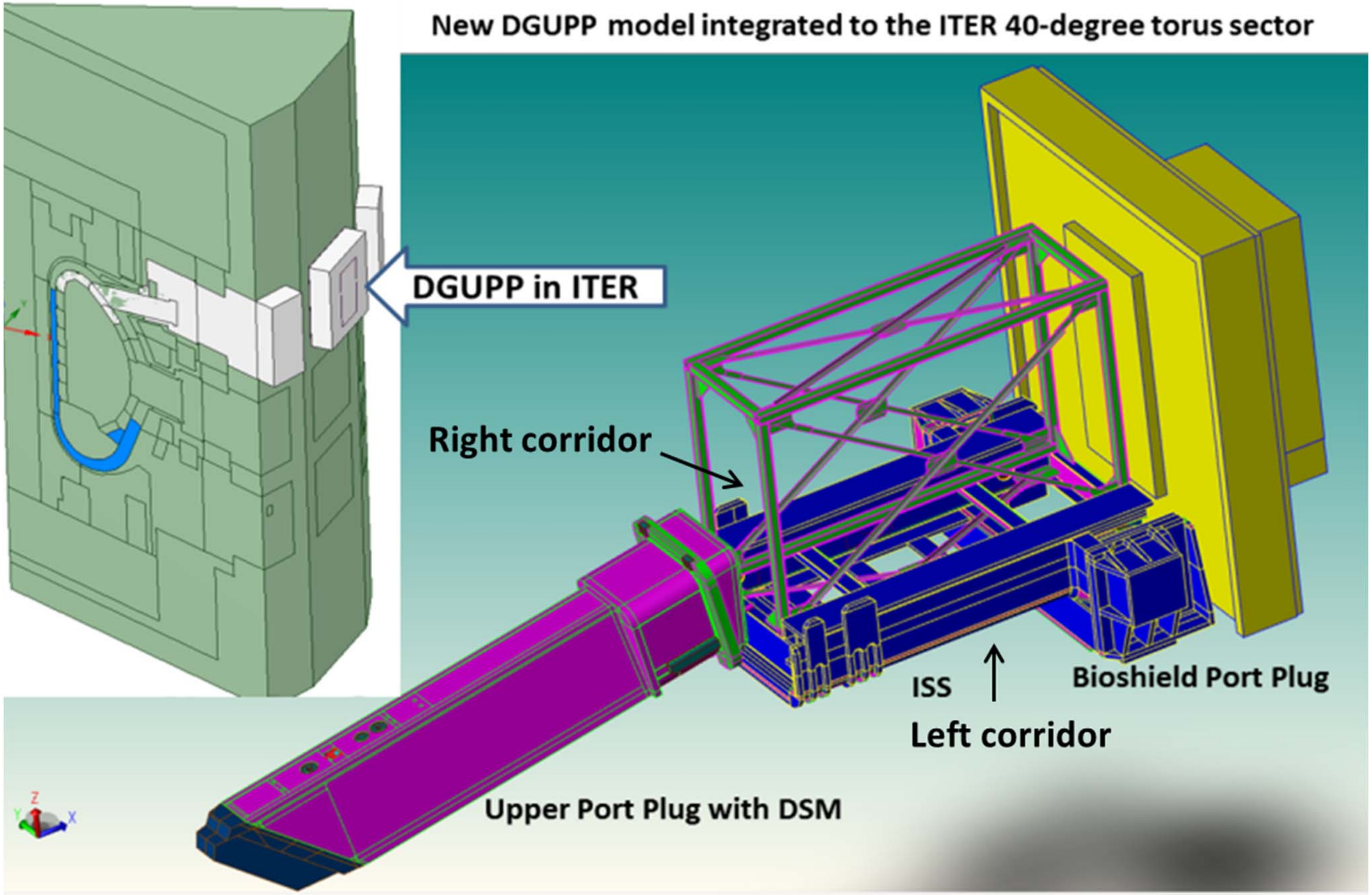


Original engineering CAD model

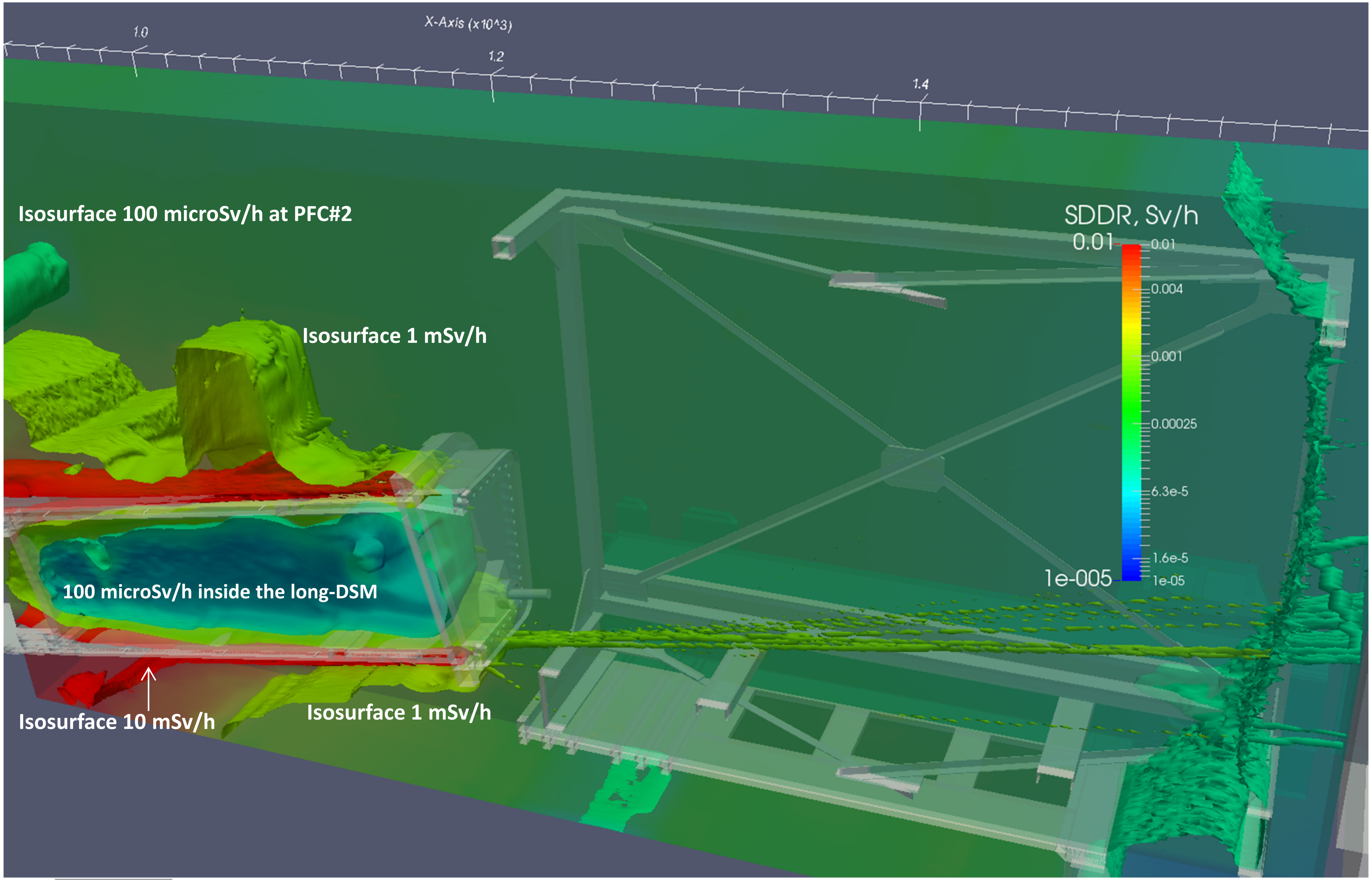


Simplified CAD model applicable for CAD-to MCNP conversion by SuperMC

MCNP model of ITER Diagnostic Generic Upper Port Plug (DGUPP)



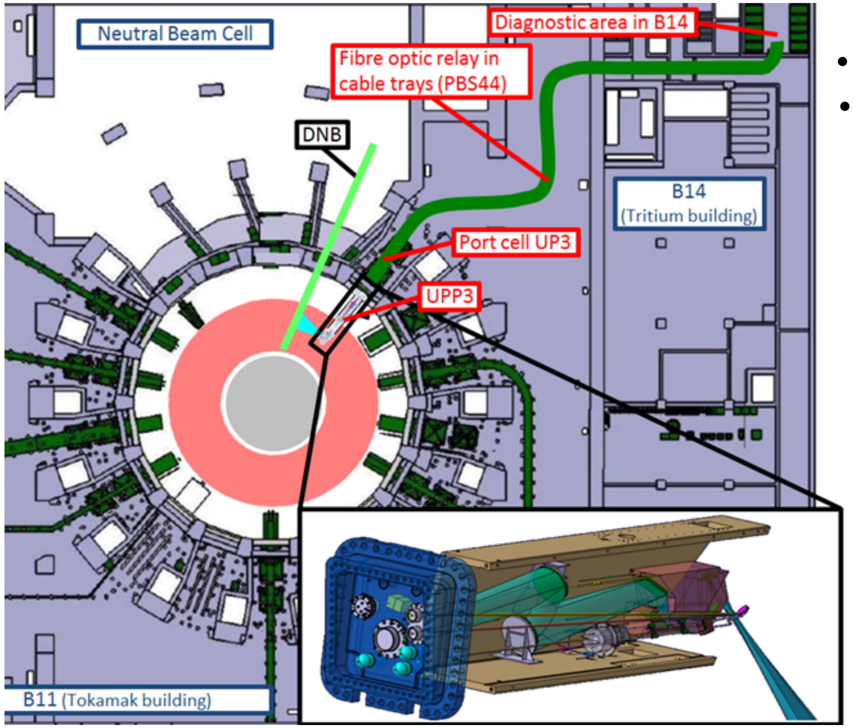
Shut-Down Dose Rare (SDDR) isosurfaces in DGUPP



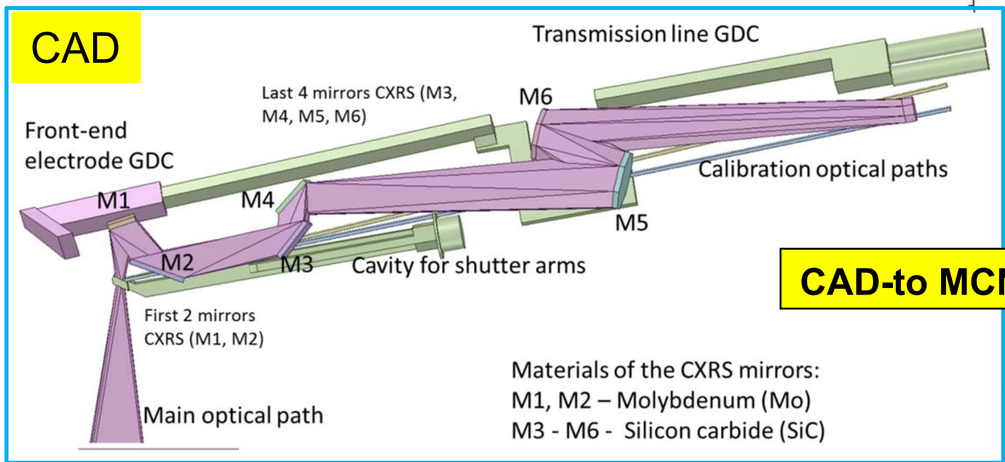
Example of SuperMC application

Charge eXchange Recombination Spectroscopy
(CXRS)

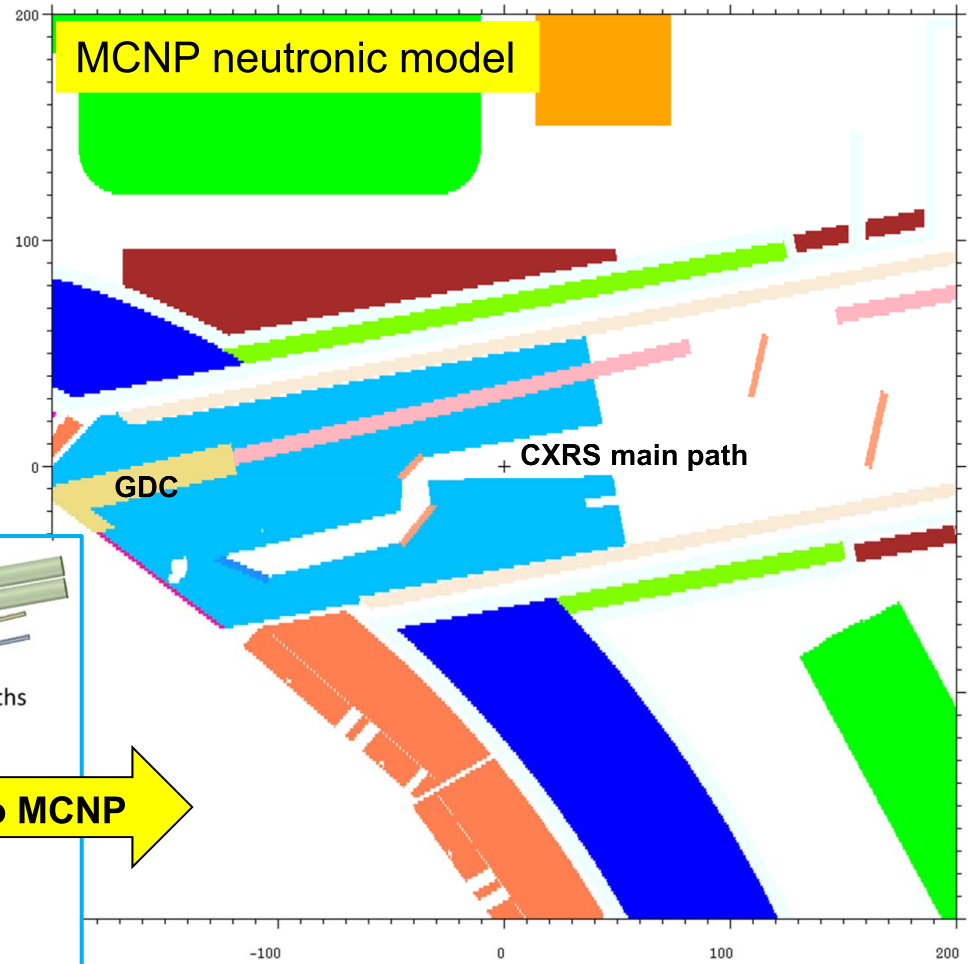
UPP#3 with Charge eXchange Recombination Spectroscopy (CXRS)



- Collects visible light emitted by Diag. Neutral Beam (DNB)
- Analyses the light ➔ Ion Temp., Plasma Rotation, Impurities

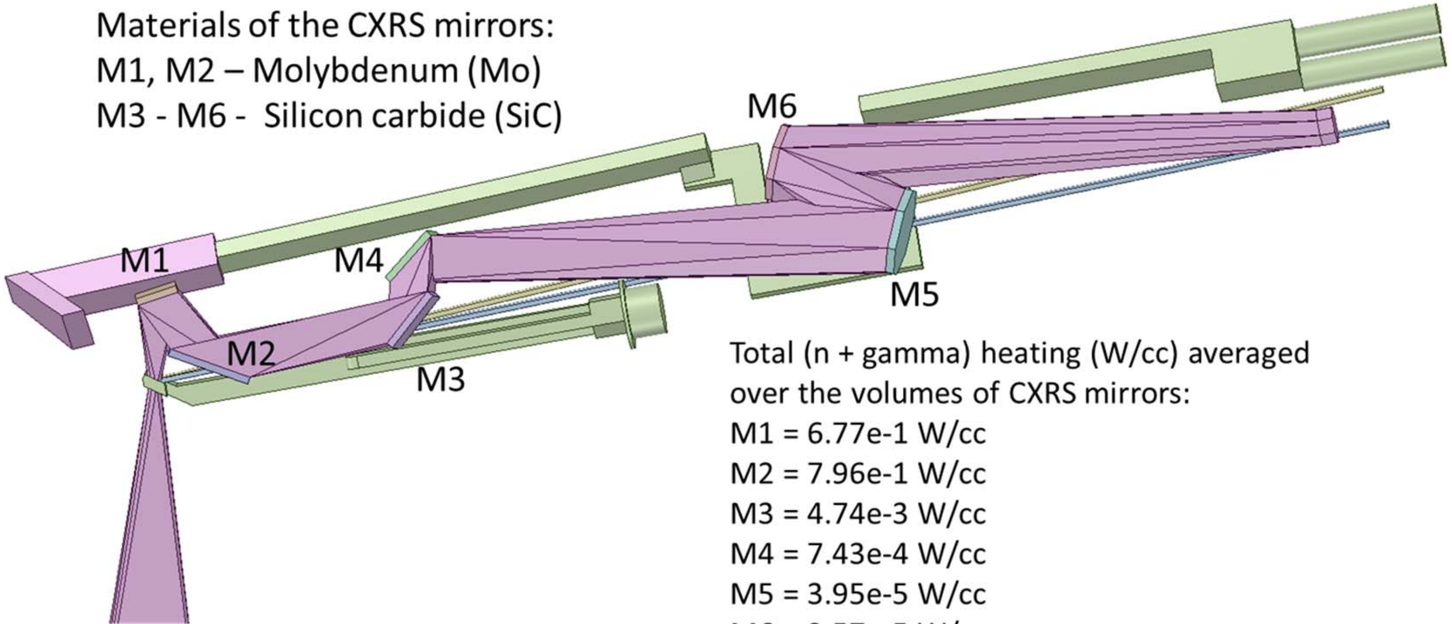


CAD-to MCNP



Neutron and gamma loads on the CXRS mirrors

Materials of the CXRS mirrors:
M1, M2 – Molybdenum (Mo)
M3 - M6 - Silicon carbide (SiC)

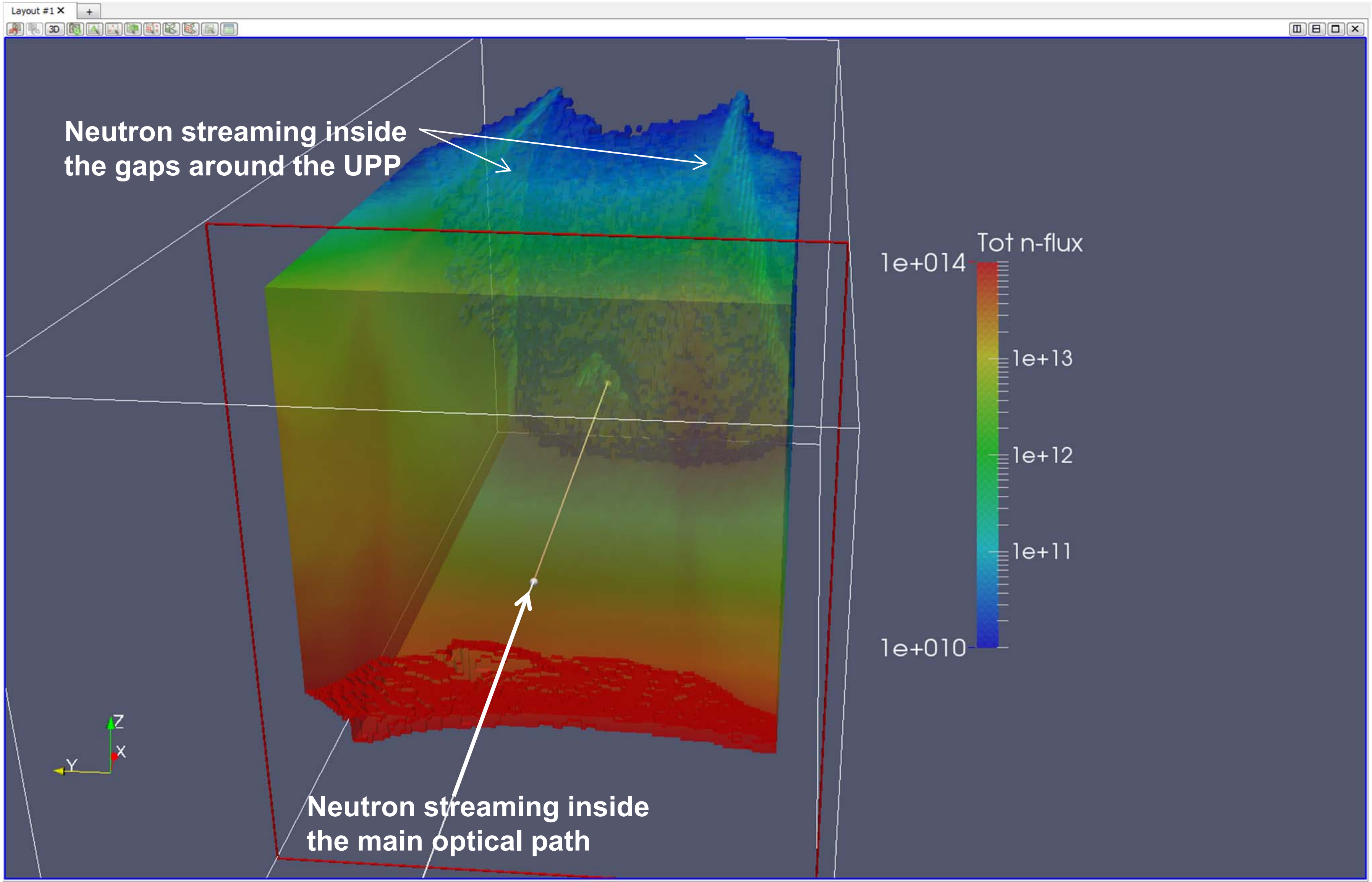


Total (n + gamma) heating (W/cc) averaged over the volumes of CXRS mirrors:
M1 = 6.77e-1 W/cc
M2 = 7.96e-1 W/cc
M3 = 4.74e-3 W/cc
M4 = 7.43e-4 W/cc
M5 = 3.95e-5 W/cc
M6 = 2.57e-5 W/cc

MCNP cell number	Mirror number	Material	Volume, cm3	Neutron flux, n/cm2/s	Gamma flux, gamma/ cm2/s	Neutron heating, W/cm3	Gamma heating, W/cm3	Total (n+gamma) heating, W/cm3
Cell 17500	M1	Molybdenum (Mo)	469.8000	2.50E+13	1.03E+13	1.48E-02	6.62E-01	6.77E-01
Cell 17512	M2	Molybdenum (Mo)	945.0000	3.04E+13	1.20E+13	1.79E-02	7.78E-01	7.96E-01
Cell 17502	M3	Silicon carbide (SiC)	907.5000	7.24E+11	2.89E+11	5.89E-04	4.15E-03	4.74E-03
Cell 17530	M4	Silicon carbide (SiC)	1061.1000	1.40E+11	5.03E+10	5.87E-05	6.84E-04	7.43E-04
Cell 17529	M5	Silicon carbide (SiC)	2748.0950	7.31E+09	2.91E+09	8.29E-06	3.13E-05	3.95E-05
Cell 17501	M6	Silicon carbide (SiC)	2150.2000	4.69E+09	1.47E+09	3.13E-06	2.26E-05	2.57E-05

For the interval of the MCNP statistical uncertainty (5%), the neutron and photon fluxes averaged for the 6 mirrors are the same for the UPP-CXRS with or without GDC.

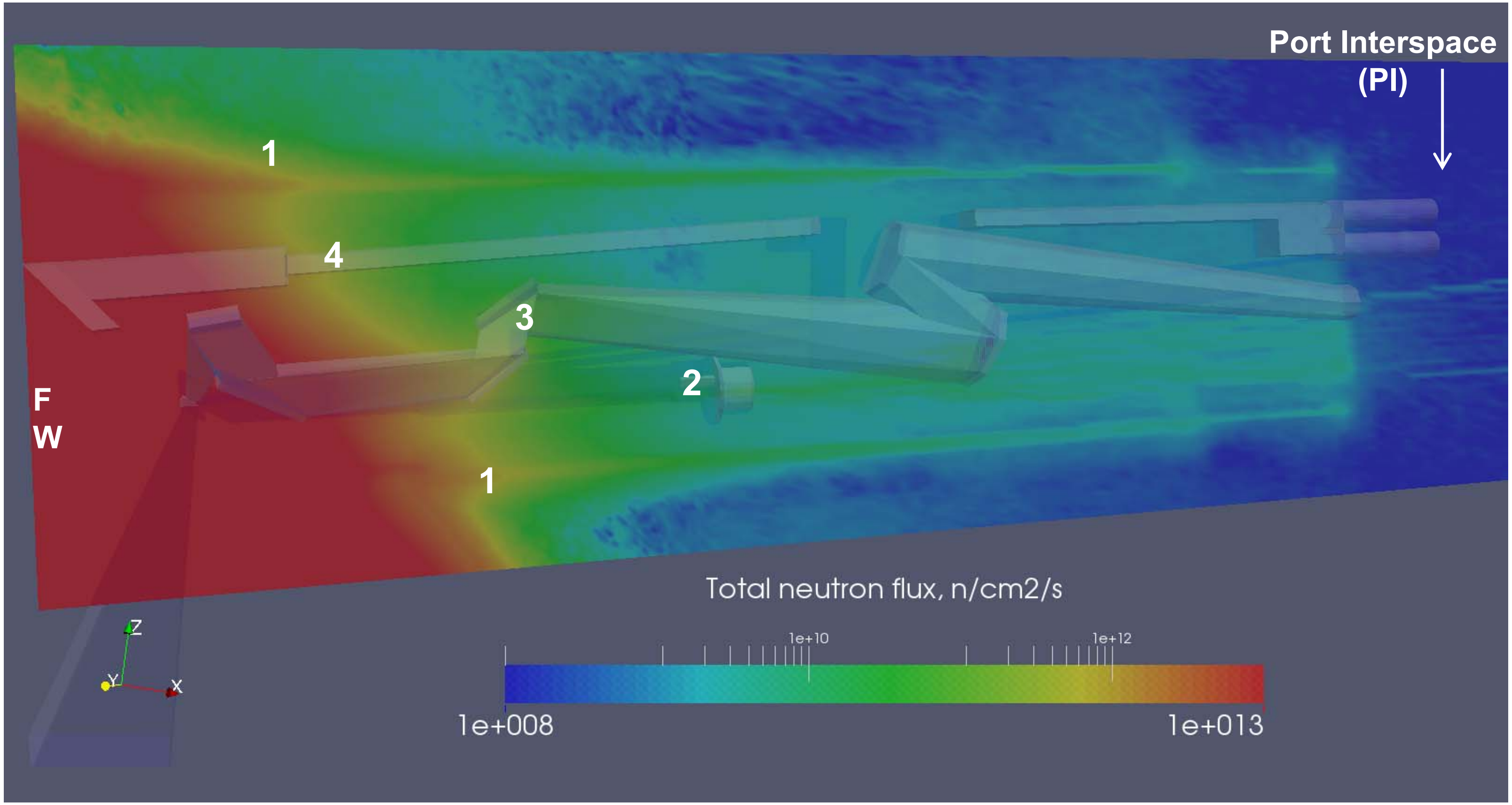
Total neutron flux (n/cm2/s) distribution thresholded between 1e14 and 1e10 n/cm2/s



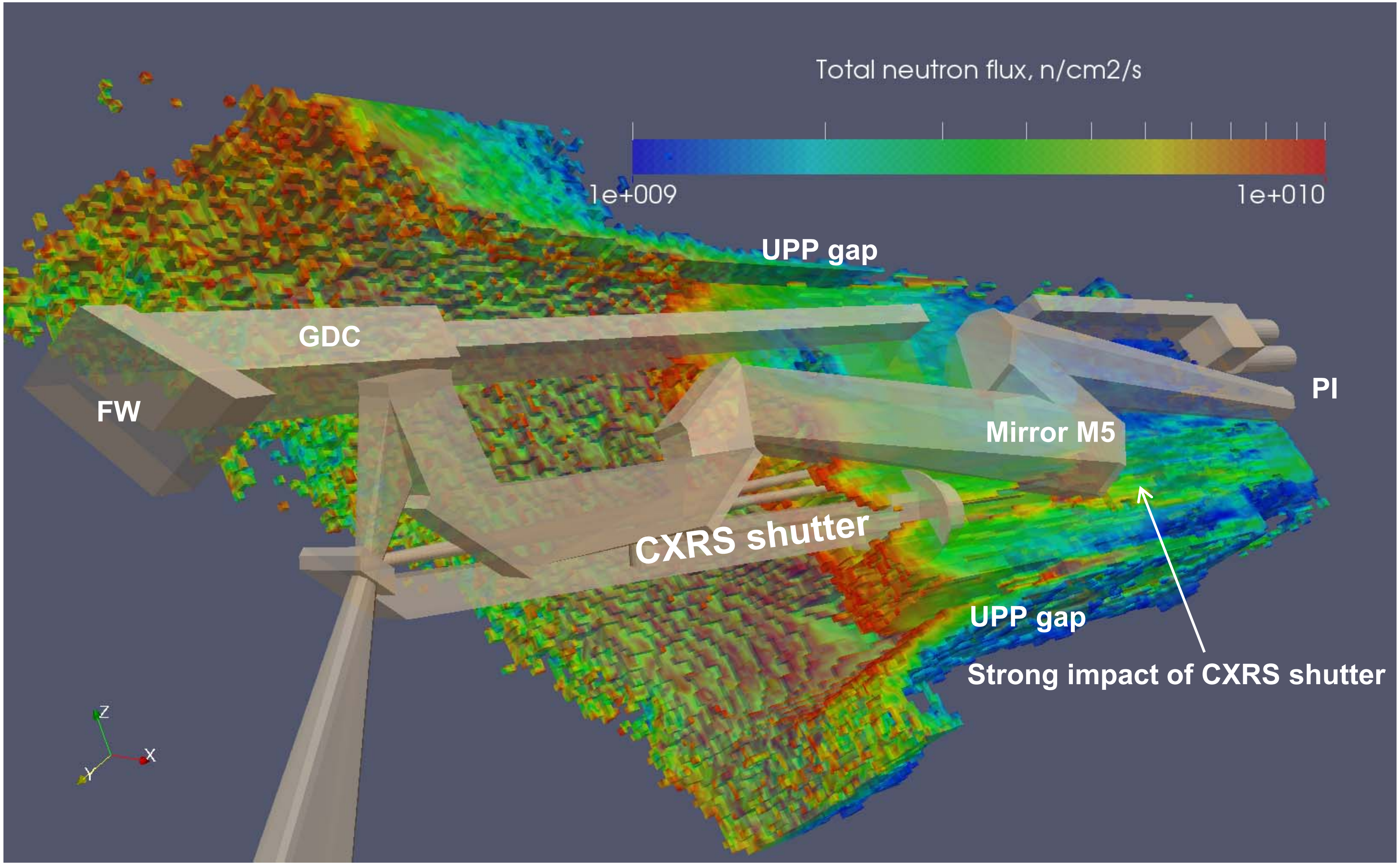
Total neutron flux (n/cm2/s) mapped over **UPP with CXRS and GDC**

4 neutron streaming pathways:

1 – Gaps all-round the UPP
2 – CXRS shutter
3 – CXRS main optical path
4 – GDC electrode

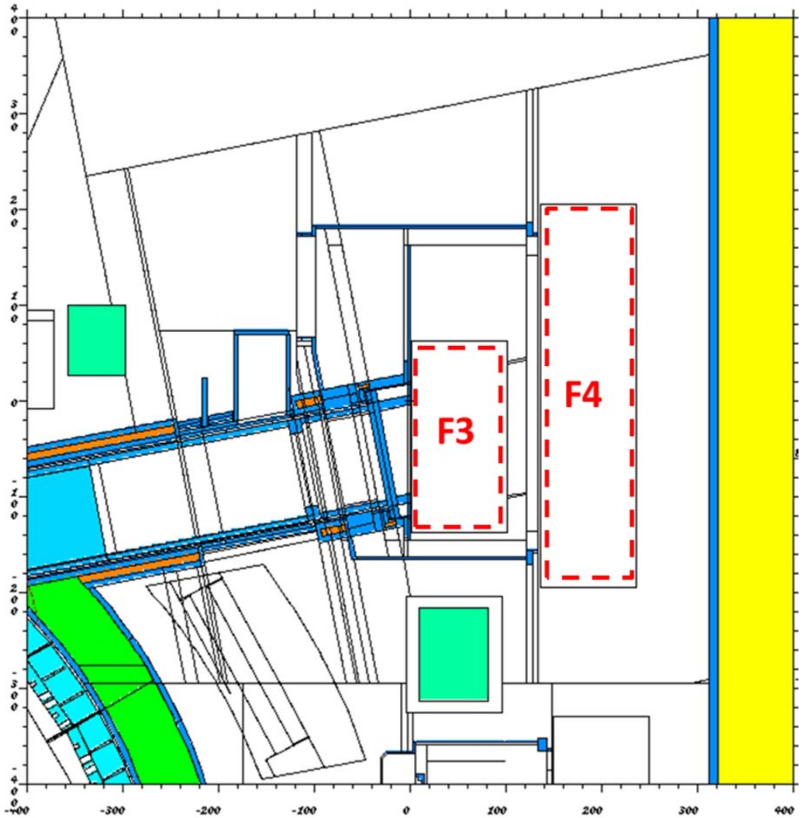


Impact of CXRS shutter – on neutron flux streaming



Total neutron & gamma fluxes inside Port Interspace (PI) volumes F3 & F4 for the 3 cases of UPP-CXRS

UPP interspace control volumes F3 & F4



Case 1: UPP-CXRS with GDC	Neutron flux, n/cm2/s	Gamma flux, gamma/cm2/s
F3	9.48E+07	1.35E+07
F4	6.52E+07	9.42E+06

Case 2: UPP-CXRS except GDC	Neutron flux, n/cm2/s	Gamma flux, gamma/cm2/s
F3	9.65E+07	1.15E+07
F4	6.64E+07	8.64E+06

Case 3: Generic UPP	Neutron flux, n/cm2/s	Gamma flux, gamma/cm2/s
F3	7.61E+07	1.09E+07
F4	5.82E+07	8.54E+06

Conclusion: for the range of the MCNP statistical uncertainty (2%), neutron fluxes in Cases 1 & 2 are identical: in PI volume F3: **9.5e7 n/cm2/s**, in PI volume F4: **6.6e7 n/cm2/s**. For the Generic UPP with bulk shield plug, the neutron fluxes are lower: 7.6e7 n/cm2/s in F3, and 5.8e7 n/cm2/s in F4. That means the GDC system does not affect the SDDR in PI.

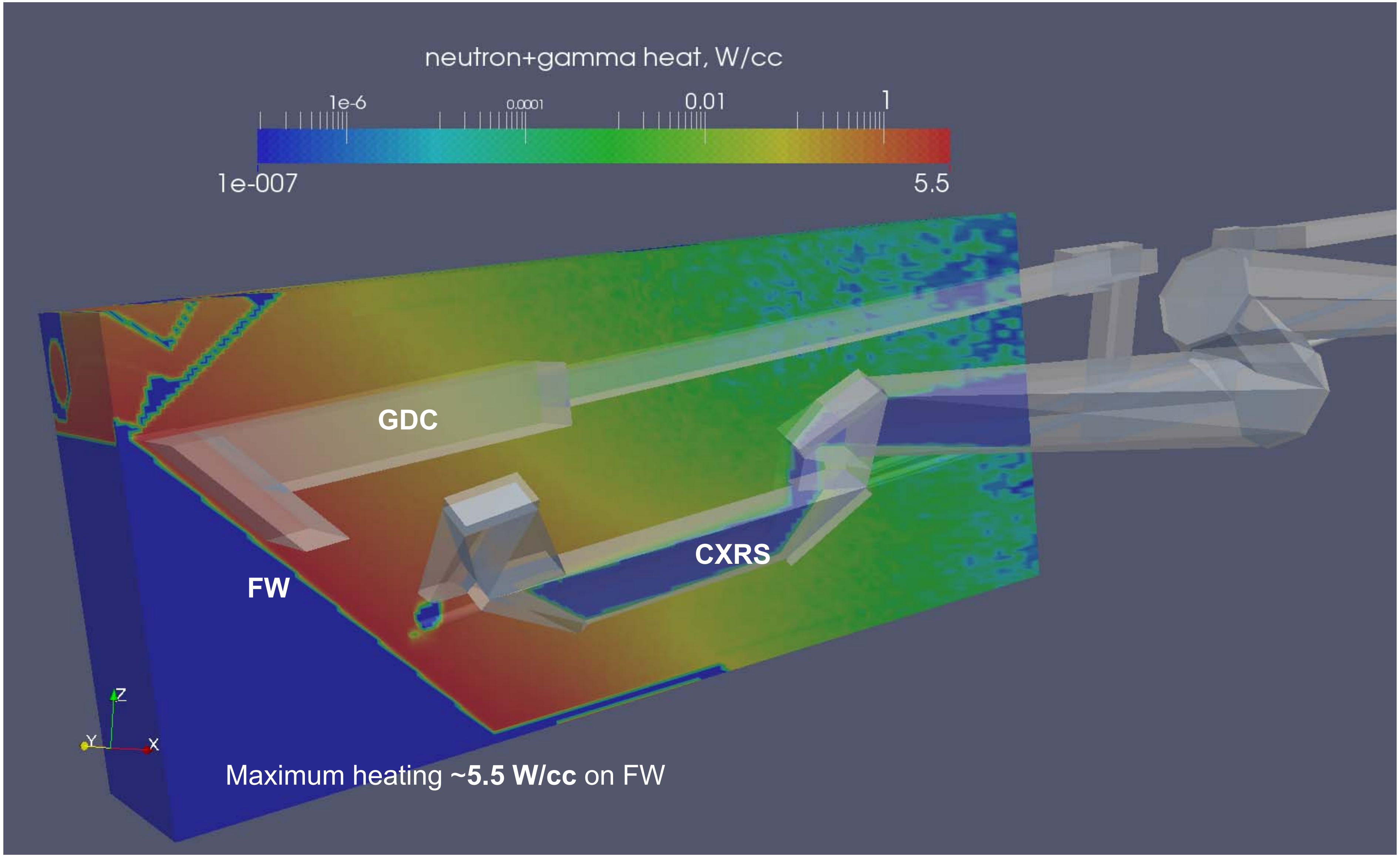
For the gamma fluxes the MCNP statistical uncertainty is higher – reaching 10%-15% of relative statistical error, where gamma fluxes are the following: 1.3e7 gamma/cm2/s in F3 and 9.0e6 gamma/cm2/s in F4.

SDDR at 12 days cooling time inside the PI-control volumes F3 & F4 for the 3 cases of UPP-CXRS configurations

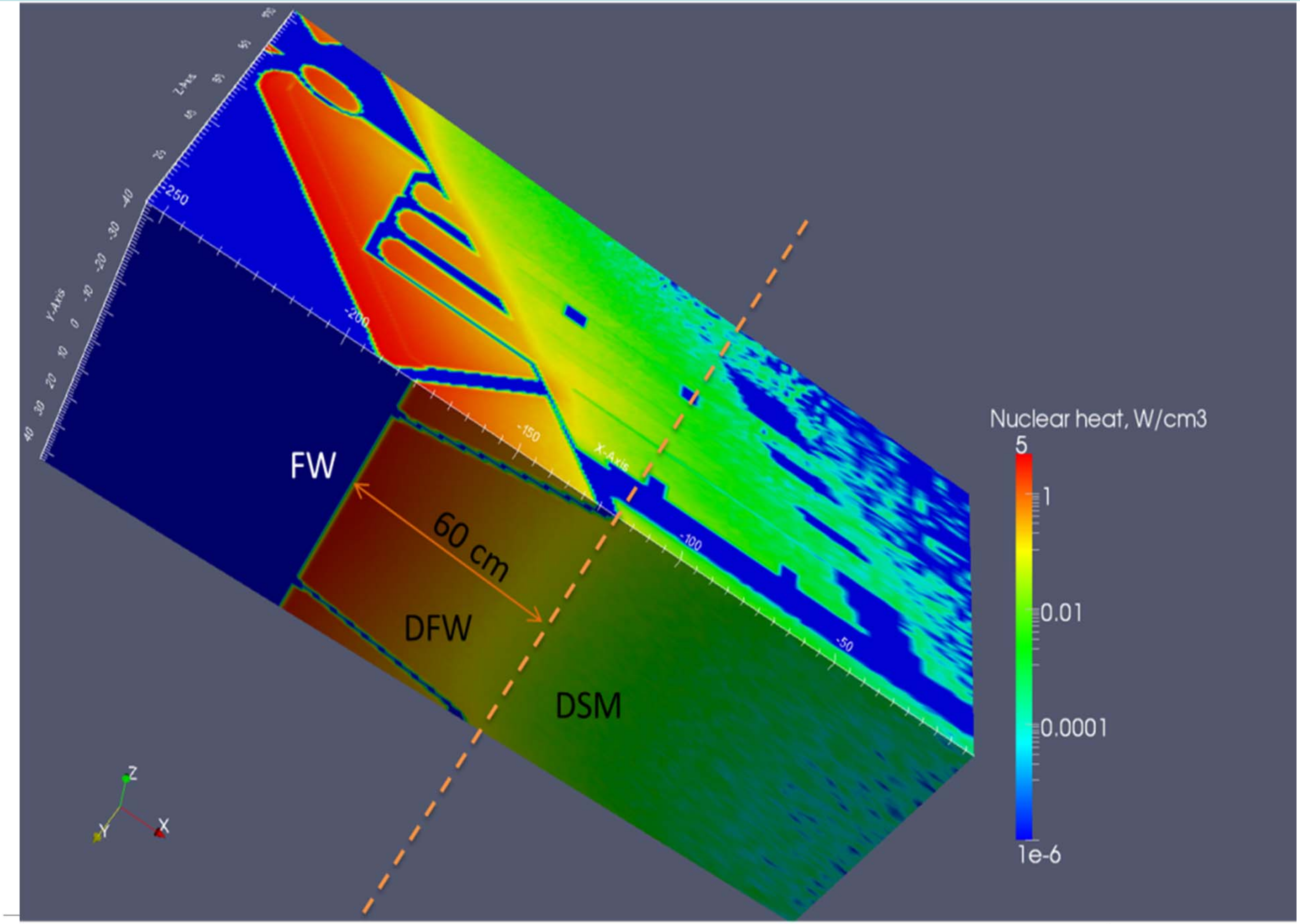
Radioactive isotope	Case 1 of UPP-CXRS with GDC, microSv/h in F3	Case 1 of UPP-CXRS with GDC, microSv/h in F4	Case 2 of UPP-CXRS except GDC, microSv/h in F3	Case 2 of UPP-CXRS except GDC, microSv/h in F4	Case 3 of Generic UPP, microSv/h in F3	Case 3 of Generic UPP, microSv/h in F4
Cr 51	9.76E-01	6.96E-01	9.18E-01	6.70E-01	7.27E-01	6.00E-01
Mn 53						
Mn 54	4.76E+00	4.05E+00	3.53E+00	3.65E+00	2.01E+00	3.22E+00
Fe 55	1.44E+00	1.22E+00	1.21E+00	1.11E+00	6.45E-01	1.14E+00
Fe 59	3.76E+00	2.50E+00	3.67E+00	2.47E+00	3.28E+00	2.07E+00
Co 57						
Co 58	**1.79E+01**	**1.21E+01**	**2.09E+01**	**1.43E+01**	**1.44E+01**	**1.08E+01**
Co 60	**6.79E+01**	**5.23E+01**	**6.62E+01**	**5.19E+01**	**5.76E+01**	**4.90E+01**
Ni 58						
Ni 59						
Ni 63						
Zn 64						
Zr 93						
Nb 92						
Nb 92m						
Nb 93m						
Nb 94	7.84E-04	9.70E-04	7.54E-04	9.10E-04	7.81E-04	8.81E-04
Hf181						
Ta179						
Ta180m						
Ta182	**2.71E+01**	**1.80E+01**	**2.59E+01**	**1.78E+01**	**2.04E+01**	**1.43E+01**
Total dose	**1.24E+02**	**9.09E+01**	**1.22E+02**	**9.19E+01**	**9.90E+01**	**8.11E+01**

Conclusion: for the range of the statistical uncertainty (3%), the **SDDR results in Cases 1 & 2 are identical**: in PI volume **F3: 124 microSv/h**, in PI volume **F4: 92 microSv/h**. That means the GDC system does not affect the SDDR in PI. Comparison with the GUPP shows the contribution of CXRS system is **25 microSv/h in F3** and **10 microSv/h in F4**

Nuclear heating (n+gamma) distribution in 100% steel for the Case #1 of CXRS-GDC



Total (n+p) nuclear heat density (W/cm³) with strong attenuation from FW at 60 cm distance deep in DSM: from 5 W/cm³ to 0.06 W/cm³



Summary for UPP#3 CXRS-core neutronics analysis

- **Neutron flux** in Port Interspace (PI) of UPP#3 with CXRS-core between **9.5e7 n/cm^2/s** (for F3 control volume in PI) and 6.5e7 n/cm^2/s (for F4). The neutron streaming is mainly through the gaps around the UPP and through the CXRS-core shutter cavity.

- **Shut-Down Dose Rate (SDDR)** is between **124 microSv/h** (for F3 in PI) and 91 microSv/h (for F4 in PI) with a contribution from CXRS-core of 25 microSv/h in F3 and 10 microSv/h in F4, and no signification contribution from GDC.

- **Nuclear heating** is highest at the front of the UPP with **0.8 W/cm^3 for mirror M2** and 0.7 W/cm^3 for mirror M1, and it is dropping rapidly for the mirrors deeper inside the port. The nuclear heating is dominated by the gamma heating.

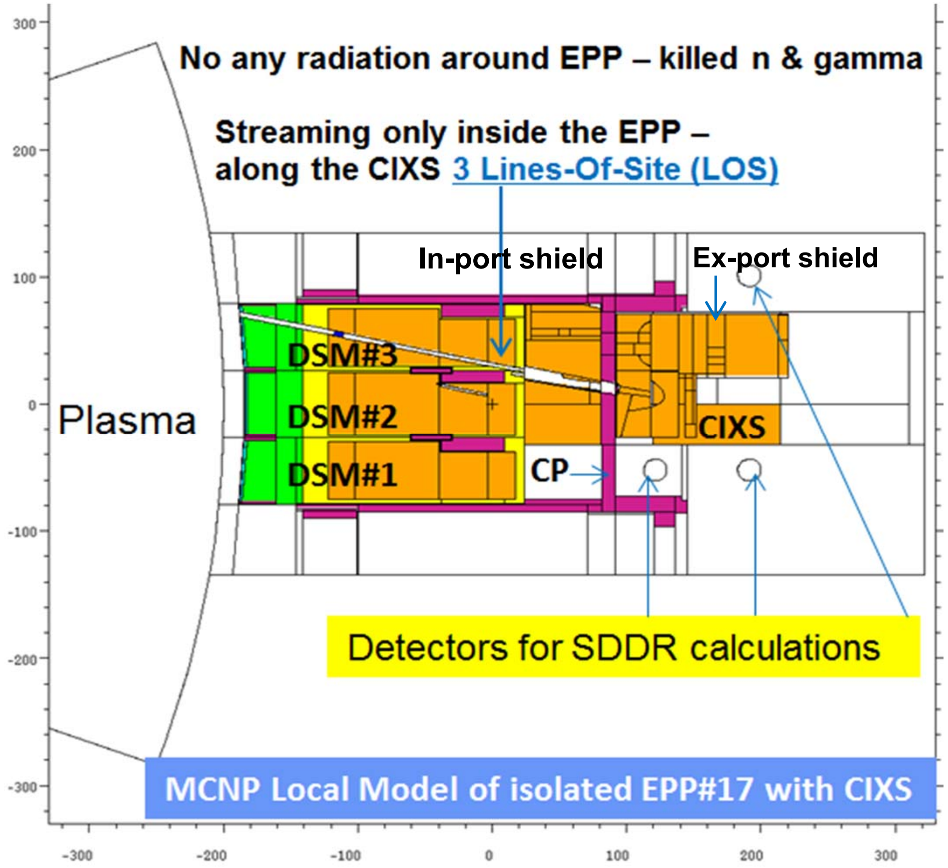
- Based on the obtained results, it was recommended to add shield block behind the shatter cavity.

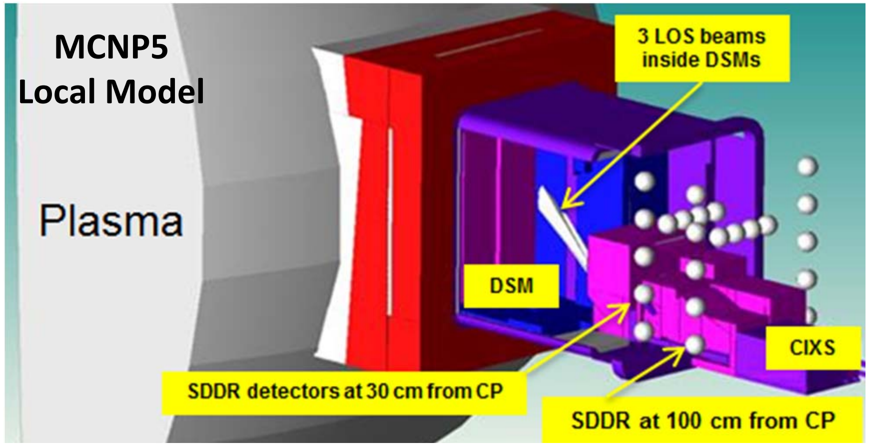
Core Imaging X-Ray Spectrometer (CIXS)

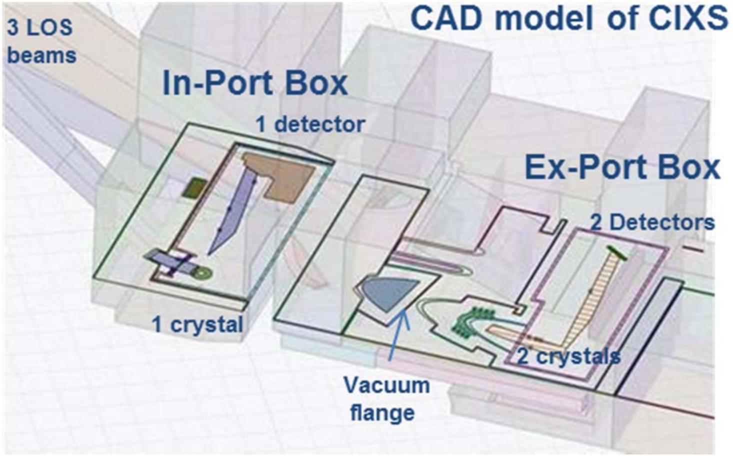
Core Imaging X-Ray Spectrometer (CIXS): MCNP5 Local Model

CIXS with straight 3 Line-of-Site (LOS) apertures in DSMs #2 and #3

1) Radiation shielding optimization - Shut-Down Dose Rate (SDDR) as the target parameter
2) Reducing the fluence levels on the detectors to minimize the number of their changes





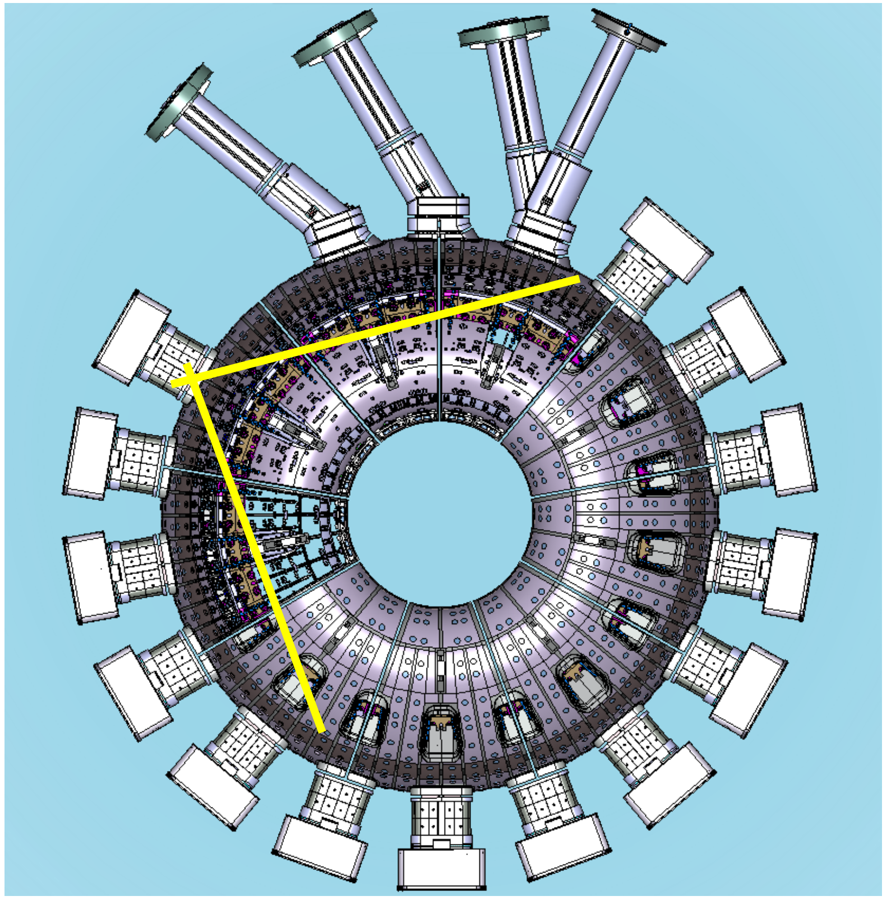


Example of SuperMC application

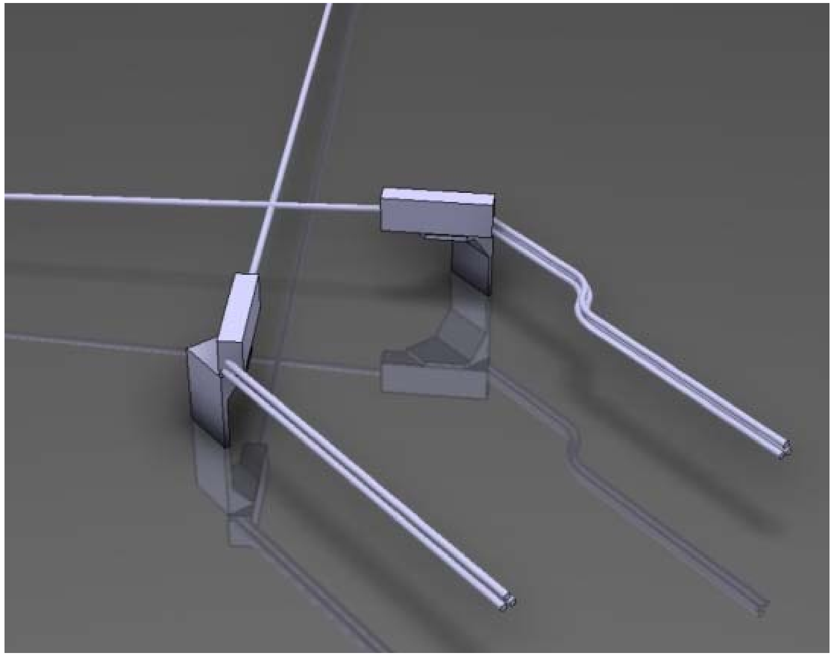
Diagnostics Equatorial Port Plug (EPP) #8 with Tangential Neutron Spectrometer (TNS)

Tangential Neutron Spectrometer (TNS) integrated inside the Diagnostic Equatorial Port Plug (EPP) #8

Diamond detectors and fission chambers are installed in TNS as neutron detectors. High fluxes (10^9 n/cm^{2}s – 10^{10} n/cm^{2}s) will allow at least 100 ms spectroscopy time resolution.



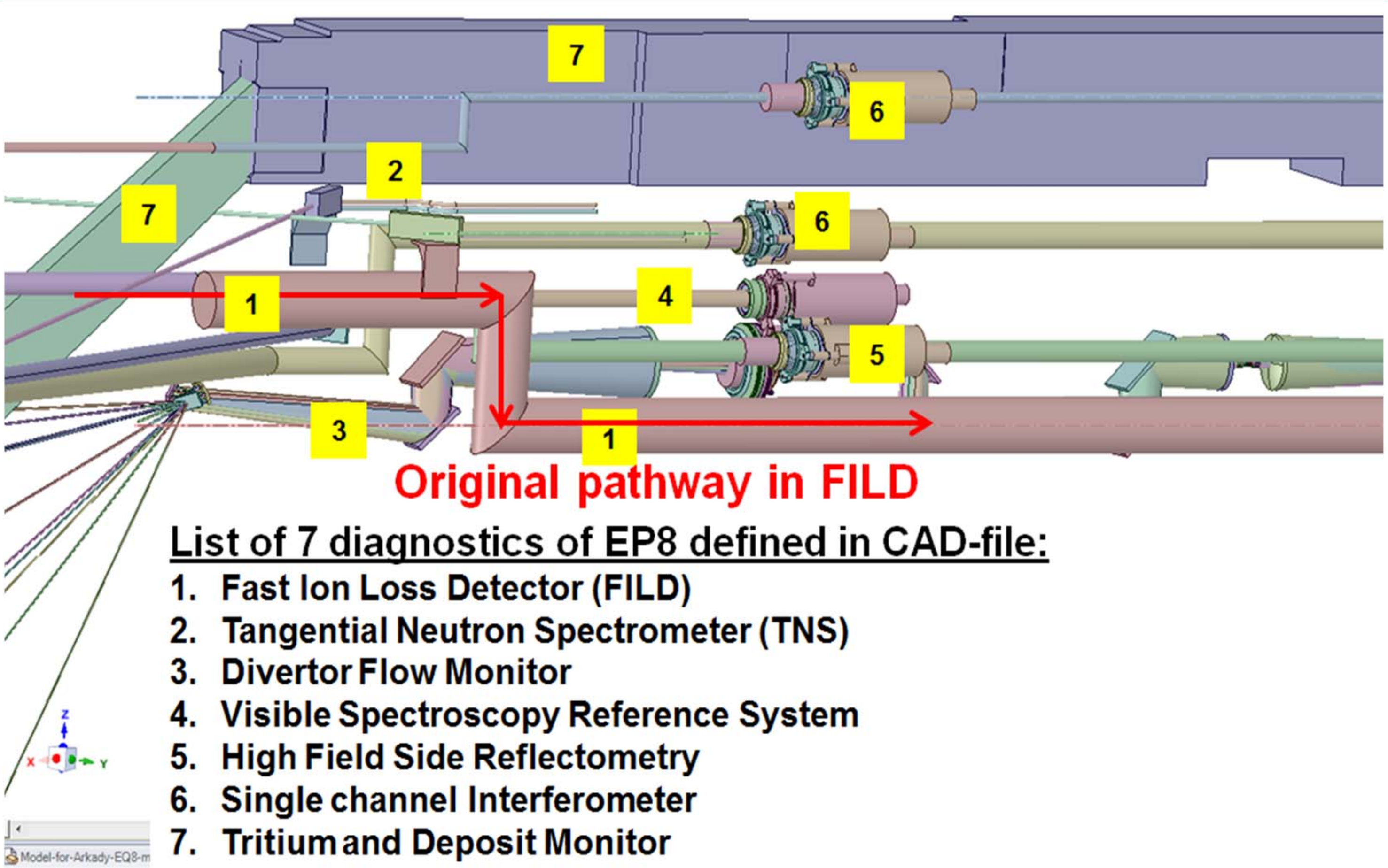
Top view on ITER vacuum vessel



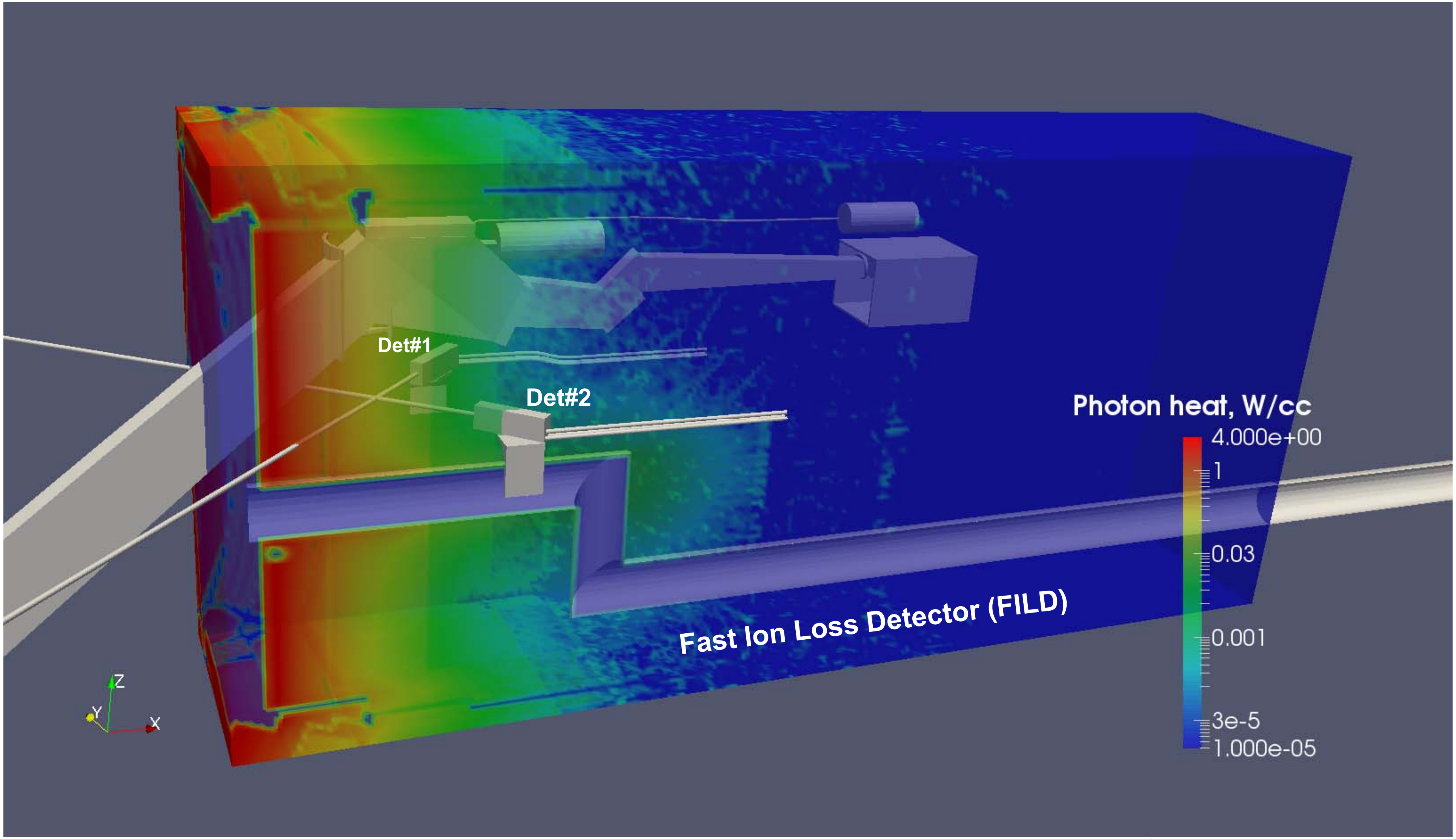
2 neutron detectors of Tangential Neutron Spectrometer (TNS)

Example: In-port radiation cross-talks

The purpose of TNS spectrometer is to measure spectra of neutrons flying in tangential direction as a collective D-T plasma rotation. In result to estimate the Doppler energy shift of the neutron spectrum emission. **Problem** was noise of neutrons coming from other Diagnostics.



Photon heating (W/cm^3) for EPP8 (7 diagnostics included in EPP#8) – impact of Lost Alpha Monitor (LAM) on neutron energy spectrum in two Detectors of TNS



Suggestions for SuperMC Further Improvement

- To improve the SuperMC/MCAM compatibility with other graphic codes (SpaceClaim) and platforms such as SALOME.
- Practically, it would be a great success of the SuperMC code if the information about the MCNP cells will be kept after saving the models from FDS-format to CAD formats (STP and SAT). We need to keep properties of the MCNP cells: cell number, its material number, material density specified for the cell. This information about the MCNP cells is important to preserve during the designing work with several iterations of the models conversion & inversion (MCNP←→CAD).
- Capability of SuperMC to check lost MC particles. Problem of geometry errors (overlaps and gaps) is recognized, leading to lost particles in the MC radiation transport and wrong final results of neutron & photon fluxes and nuclear responses (nuclear heating, gas production, and so on).
- In addition to CSG modeling in SuperMC, it is proposed to develop farther meshing (faceting) for MC geometry definition. Meshing save MC modeling time.