Neutronics Analysis for the Edge Charge Exchange Recombination Spectroscopy in Equatorial Port of ITER

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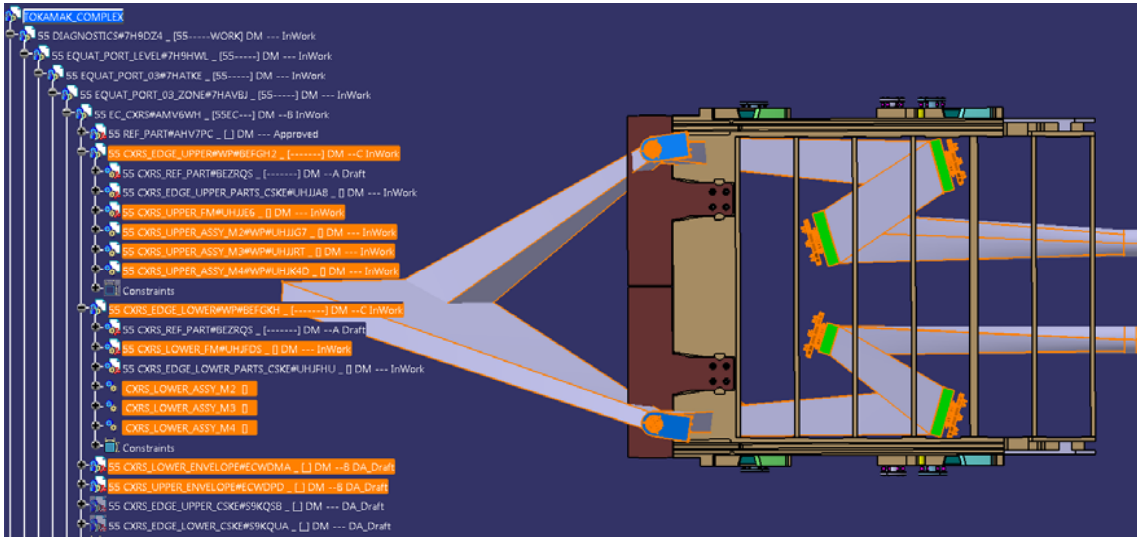
Introduction (Edge CXRS)

– The Charge Exchange Recombination Spectroscopy (**CXRS**) is a type of active beam spectroscopy developed over the last three decades into a mature tool for fusion plasmas diagnostic. The edge CXRS (55.EC according to the ITER PBS) is used for the measurement of the main impurity ion densities (including helium ash), ion temperatures and toroidal as well as poloidal plasma rotation. The edge CXRS views the ITER edge plasma from Equatorial Port 3 (EP#3).

– The update of the CXRS optical design is devised by the RF-DA to match the modular DSM design and position the dogleg more towards the middle of the port.

Diagnostics PBS 55 structure of **Edge CXRS:**



– KIT provided neutronics analysis as part of the IO service contract IO/17/CT/4300001478:

• **Local neutronics analysis** with just CXRS channels in generic modular DSMs and neighbouring DSMs fully closed:

  – **Radiation fluxes and Nuclear heat loads on FM, M2, M3 and M4**

  – **Indication on suitability of CXRS Edge doglegs by means of SDDR analysis**

– **Global analysis** could be performed if detailed CAD design of the neighbouring diagnostics (MSE, GDC, and VisIR) will be available before the time of 55.EC CXRS Edge PDR.

CAD geometry of the Edge CXRS in EP3

ITER_D_79SL6Y v3.2

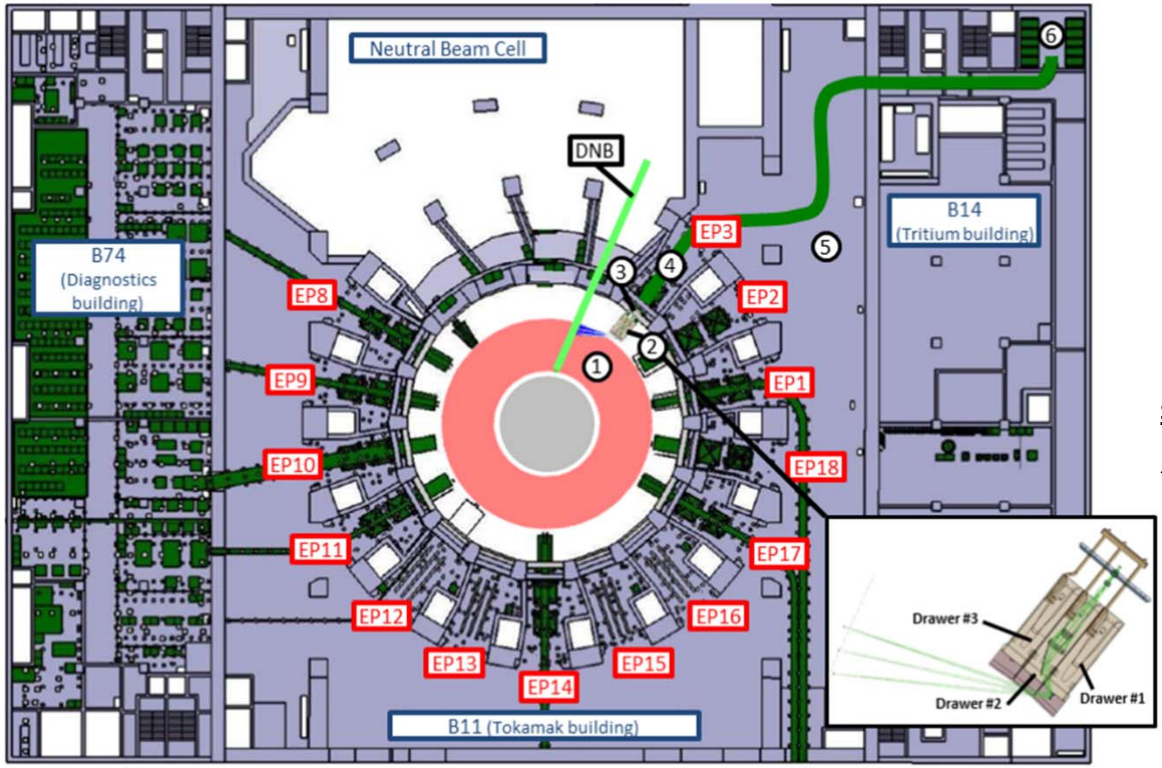
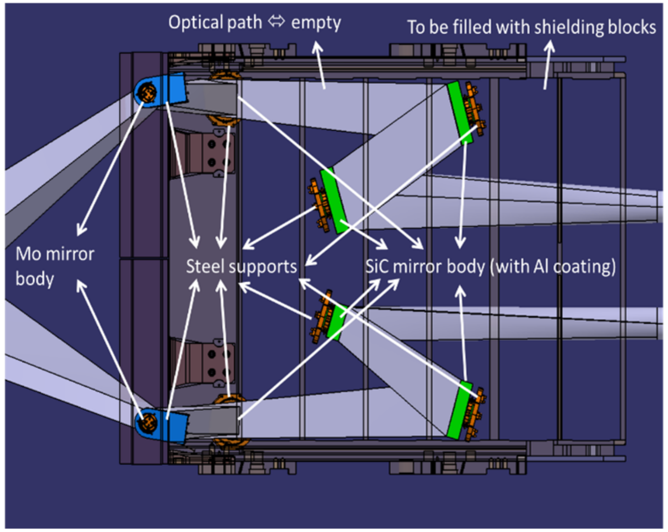
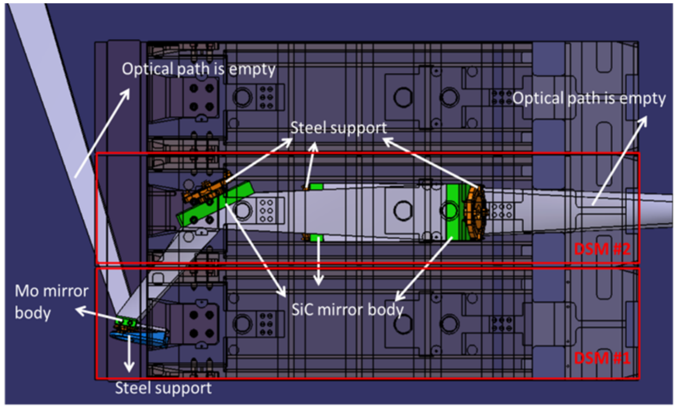


Figure 7 – A top view of the complete CXRS-edge system:

(1)Plasma, (2) Equatorial Port Plug 3 with FM assembly in Drawer #1 and remaining optics in Drawer #2, (3) Interspace, (4) Port Cell, (5) Gallery, (6) Active Beam Spectroscopy Diagnostic Area in Building 14 (Tritium building).



Side view of CAD model of the EPP3 CXRS Edge assembly with mirrors made of molybdenum (Mo) and silicon carbide (SiC), their holders, and optical pathways



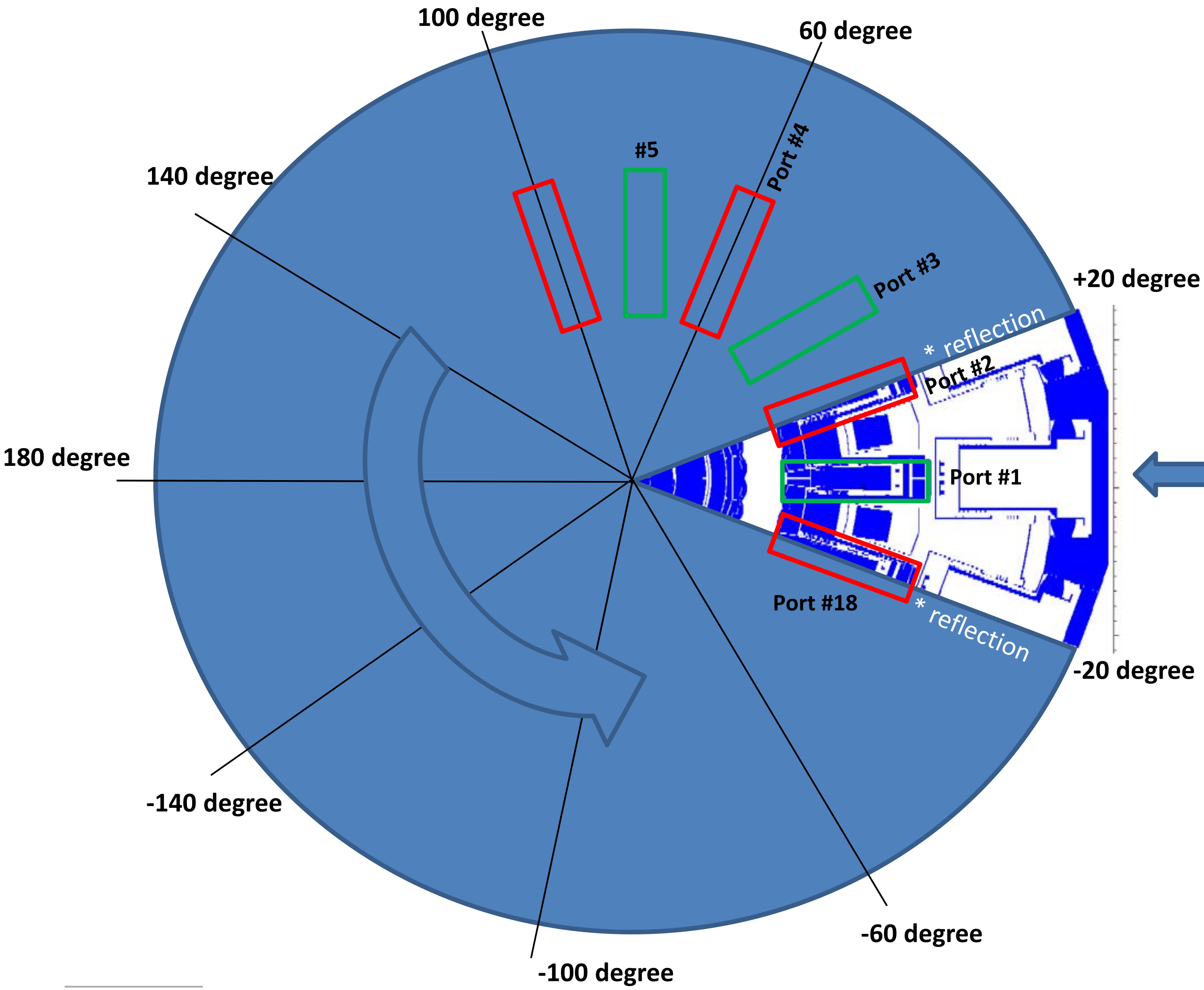
Top view CAD model of the EPP3 CXRS Edge assembly - to show only the upper optical path

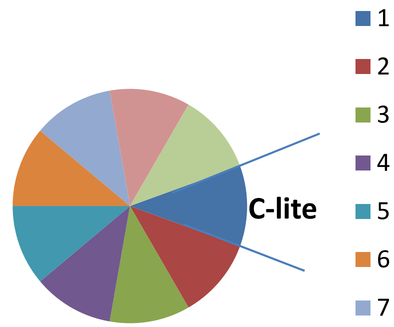
Fusion Neutronics Methodology: Codes, Tools, Nuclear Data

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

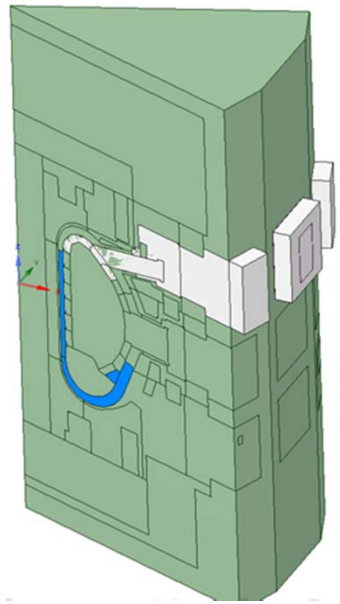
- **SpaceClaim** software reads CAD models, solves geometry problems, allows to work in 3D without having to be a CAD expert.
- **CAD-to-MCNP conversion tools:**
  - **SuperMC3.2.0 (FDS Team, China)**
  - **McCad (KIT, Germany)**
- **Radiation transport calculations (n/gamma fluxes, nuclear heat, gas production):**
  - Monte Carlo code **MCNP5 v1.60, MCNP6 v1.0 (LANL)**
  - **FENDL-3.1 (IAEA)** neutron cross-section library
  - **MCNP model of ITER tokamak (IO): C-Model R180430 -** 40 tor-degree with all the major components of ITER.
- **Activation and Shut-Down Dose Rate (SDDR) calculations:**
  - **FISPACT-II (CCFE)** inventory code and **EAF-2010 (EU)**
  - **D1S-UNED v3.1.2 code (UNED)**
  - **R2Smesh v2.2 code (KIT)**
- **Vizualisation: Paraview** (Kitware) in vtk-format

- 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 symmetrical 9 times by using the reflective boundary conditions.



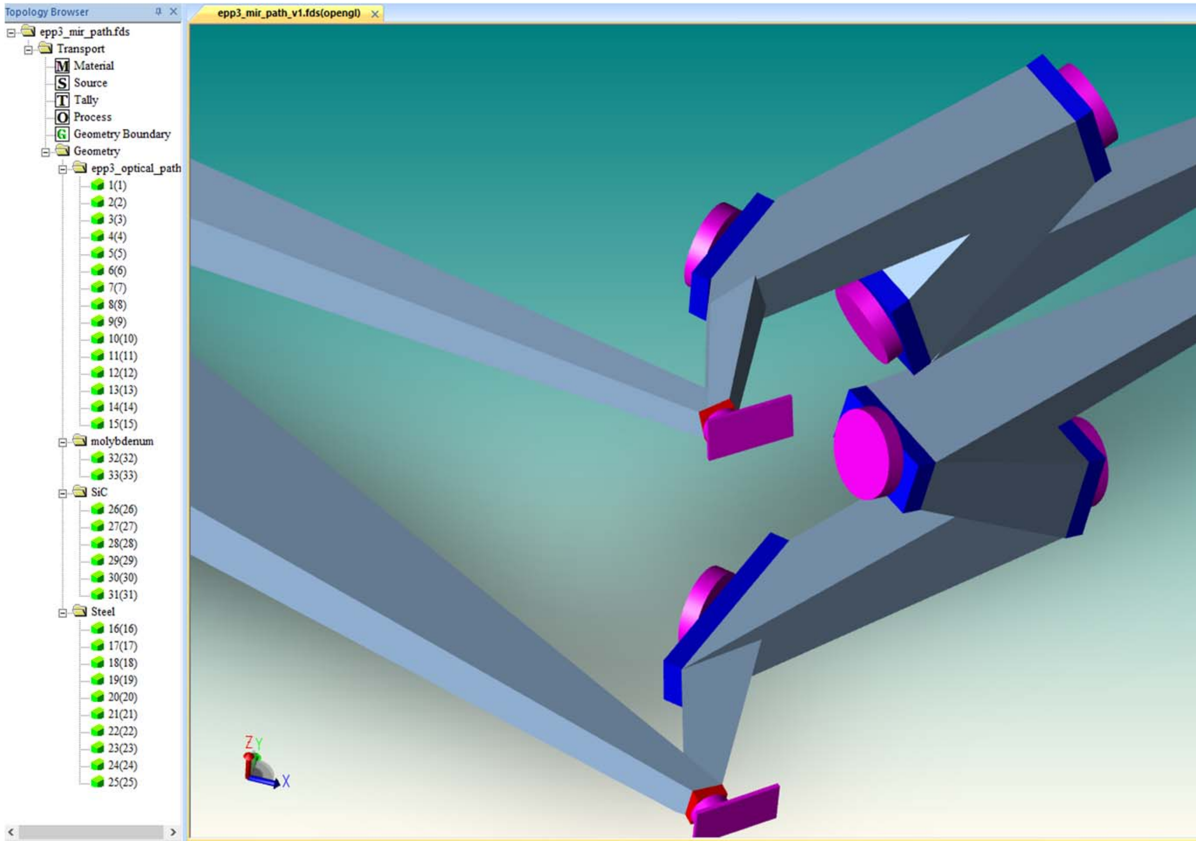


9x40 degree identical toroidal sectors

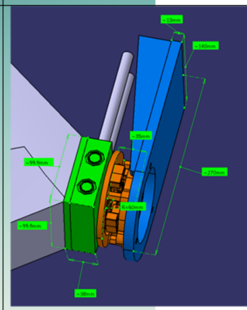
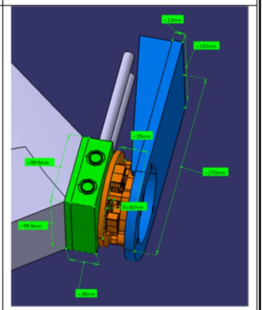
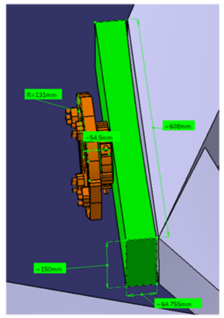
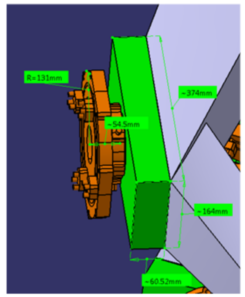


In C-lite baseline model DGEP design of 2015 and Cryopump LP were used.

Development of the CXRS-edge MCNP model, integration into the EP#3 of C-Model 2018

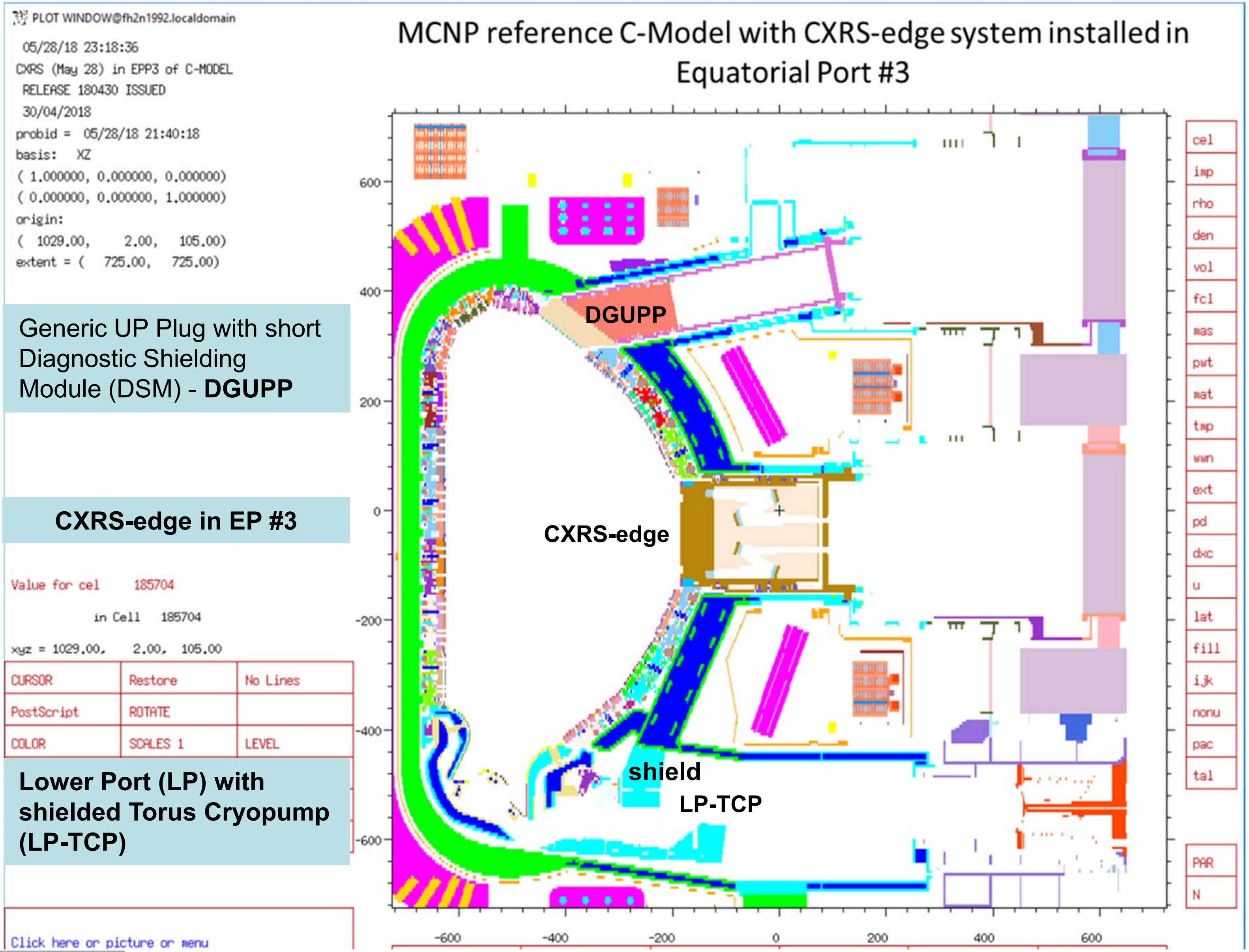


Dimensioning of the Edge CXRS-Edge mirrors and holders

Mirror parts	Lower optical pathway	Upper optical pathway
M1-lower & upper mirror and holder dimensions **Green: Molybdenum: 100mm x 100mm x 38mm** **Orange: Steel 'disc': Ø120mm x 35mm** **Blue: Steel 'plate': 140mm x 270mm x 13mm**		
M2: SiC and steel	**M2-lower** mirror and holder dimensions: **Green: SiC: 608mm x 150mm x 65mm** **Orange: Steel 'disc': Ø260mm x 55mm** 	**M2-upper** mirror and holder dimensions: **Green: SiC:374mm x 164mm x 60mm** **Orange: Steel 'disc': Ø260mm x 55mm** 

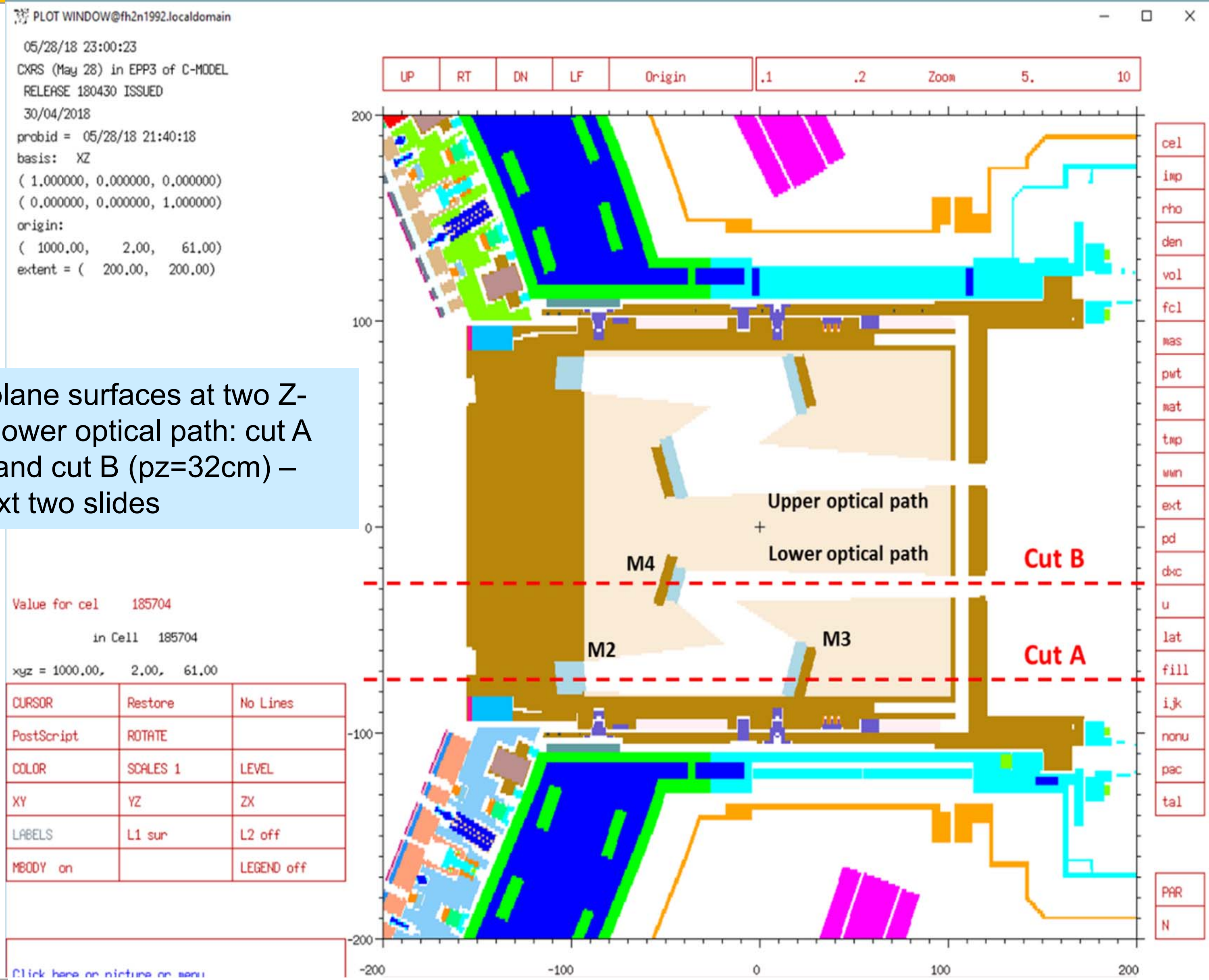
MCNP cell numbers in four material groups shown in the legend of the CXRS neutronics model "epp3-mir_path.fds" prepared with the ANSYS SpaceClaim and SuperMC codes for conversion to MCNP. The legend shows cell numbers of the model grouped by four materials: "epp3_optical_path" - void cells; "molybdenum" – mirror Mo-layer of M1 of first mirrors at the lower and upper pathways; "SiC" –SiC-layer of the M2-M4 mirrors in the lower and upper pathways, "Steel" – SS316L(N)-IG steel of the disks and plates of the simplified mirror's holders.

MCNP C-MODEL RELEASE 180430 ISSUED 30/04/2018 with integrated CXRS-edge in EP #3

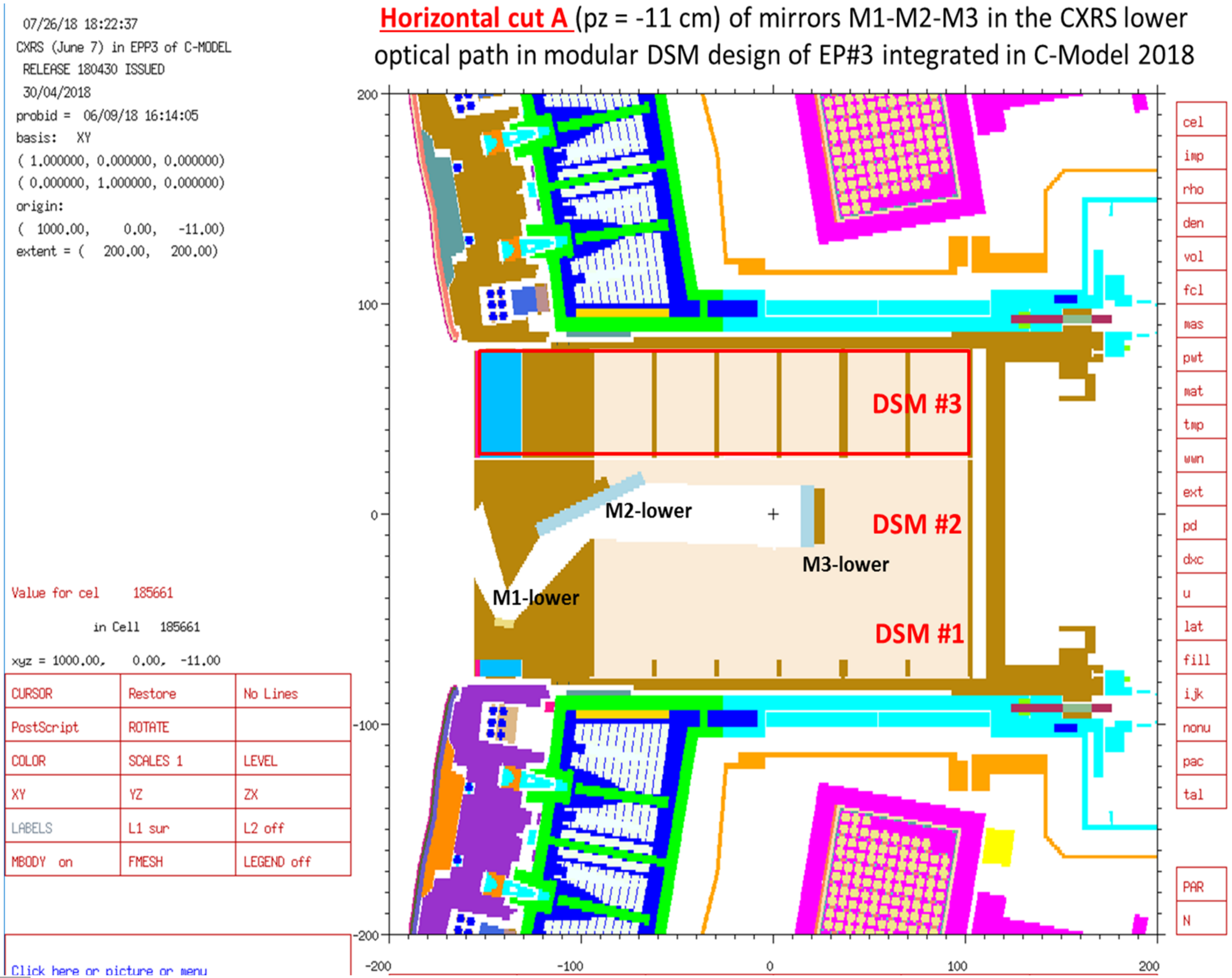


Vertical central cut (py= 2cm) of the MCNP model of CXRS-edge in EP#3 plug

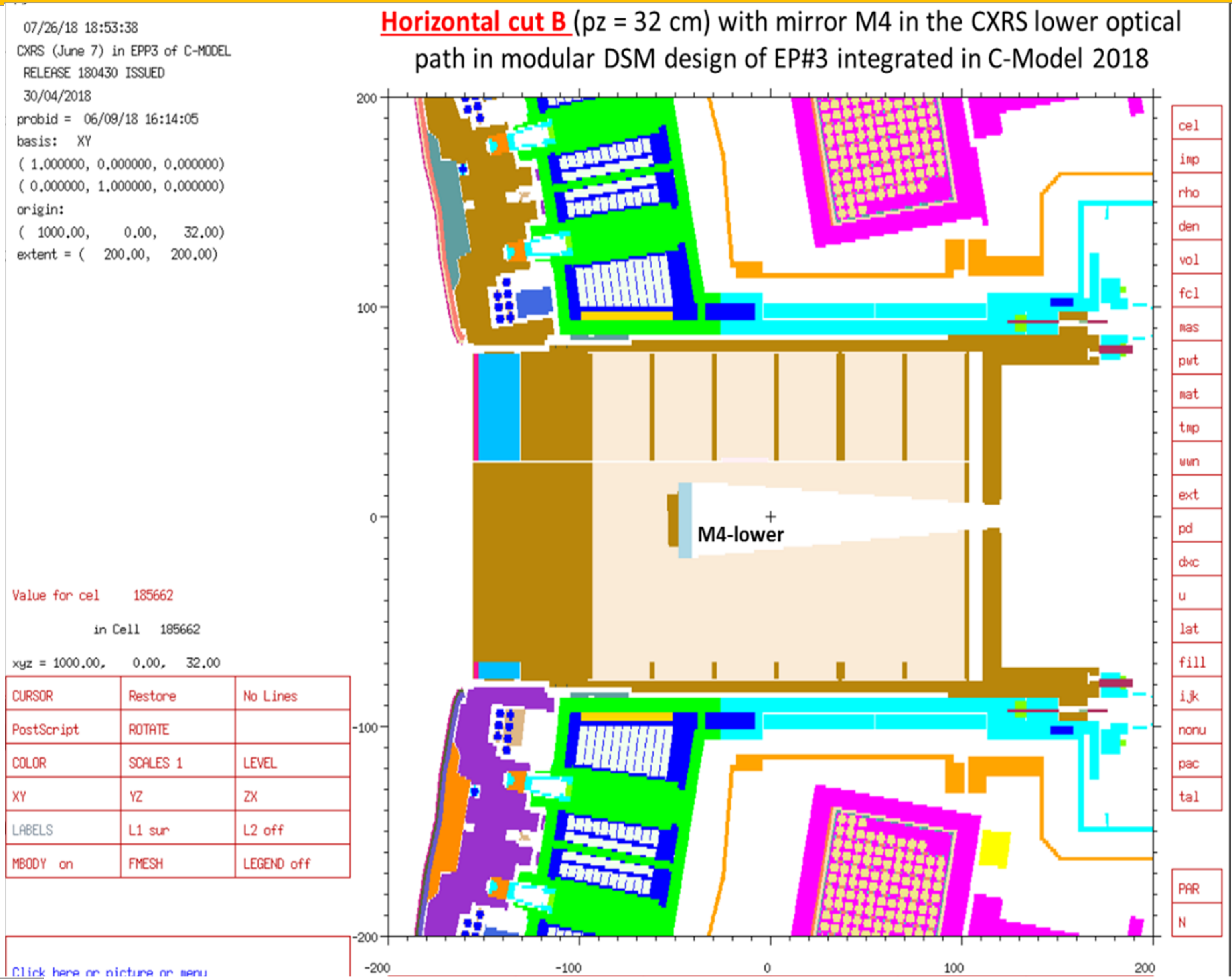
Two cutting plane surfaces at two Z-levels at the lower optical path: cut A (pz= -11cm) and cut B (pz=32cm) – shown on next two slides

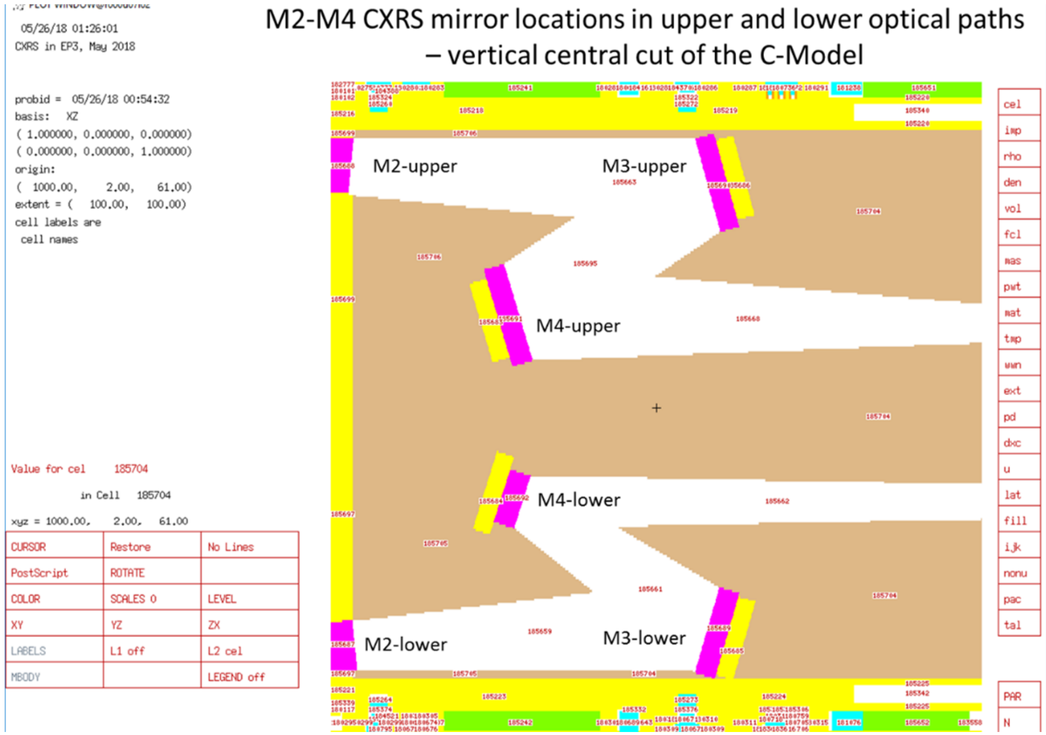


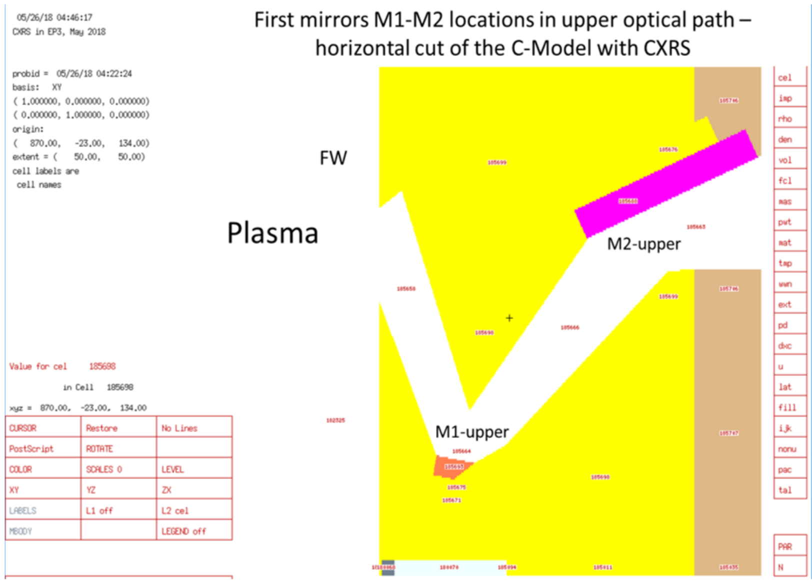
Horizontal cut A (pz=-11cm) of the MCNP model of CXRS-edge specified in Slide 9

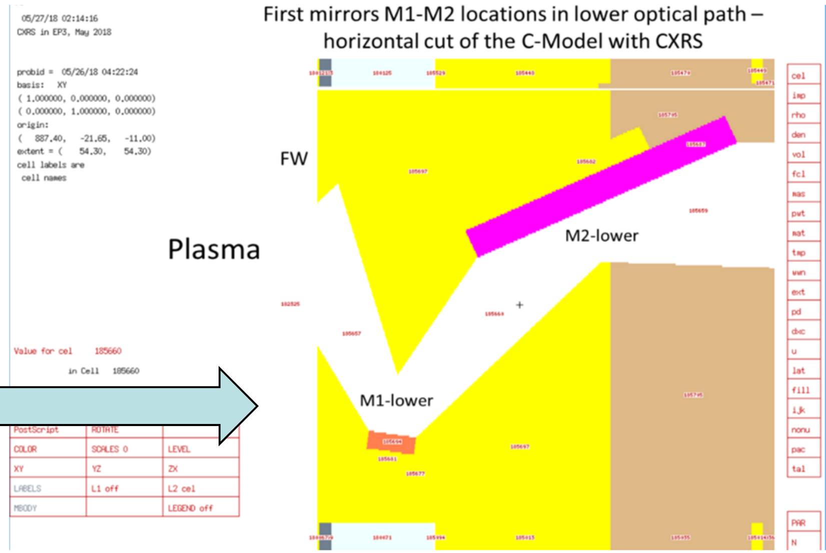


Horizontal cut B (pz= 32cm) of the MCNP model of CXRS-edge specified in Slide 9









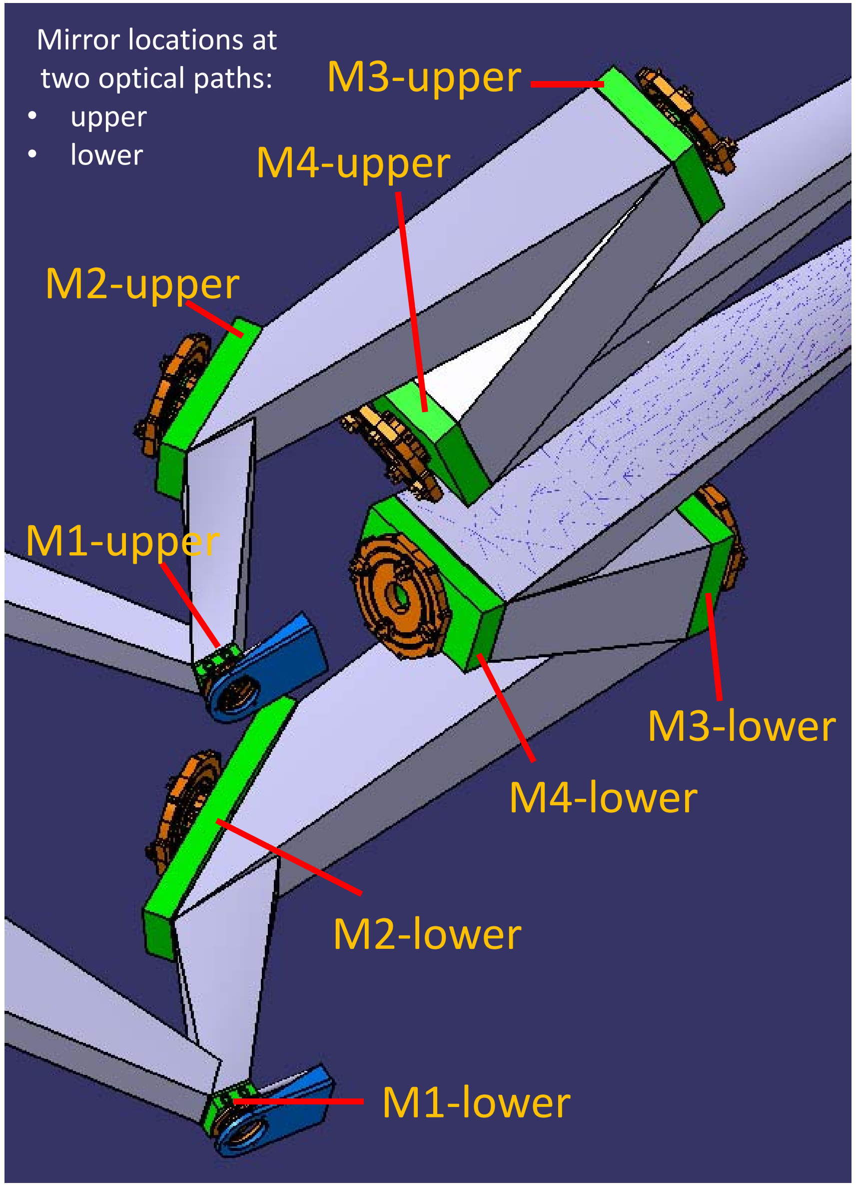
Disposition of mirrors M2-M4 (magenta color) with their holders in two (upper and lower) optical pathways of CXRS in DSM#2 of EP#3 on the vertical central cut py=2cm.

Horizontal cut (pz = -11 cm) through the mirrors close to the EP#3 first wall First Mirror (FM or M1-lower Mo-layer colored in orange) and M2-lower (SiC is magenta color) arranged in horizontal dogleg in first wall panel of DSMs #1 and #2 in the lower optical pathway of CXRS. The SiC layer of the M2 mirror is modeled as one volume of the MCNP cell # 185687

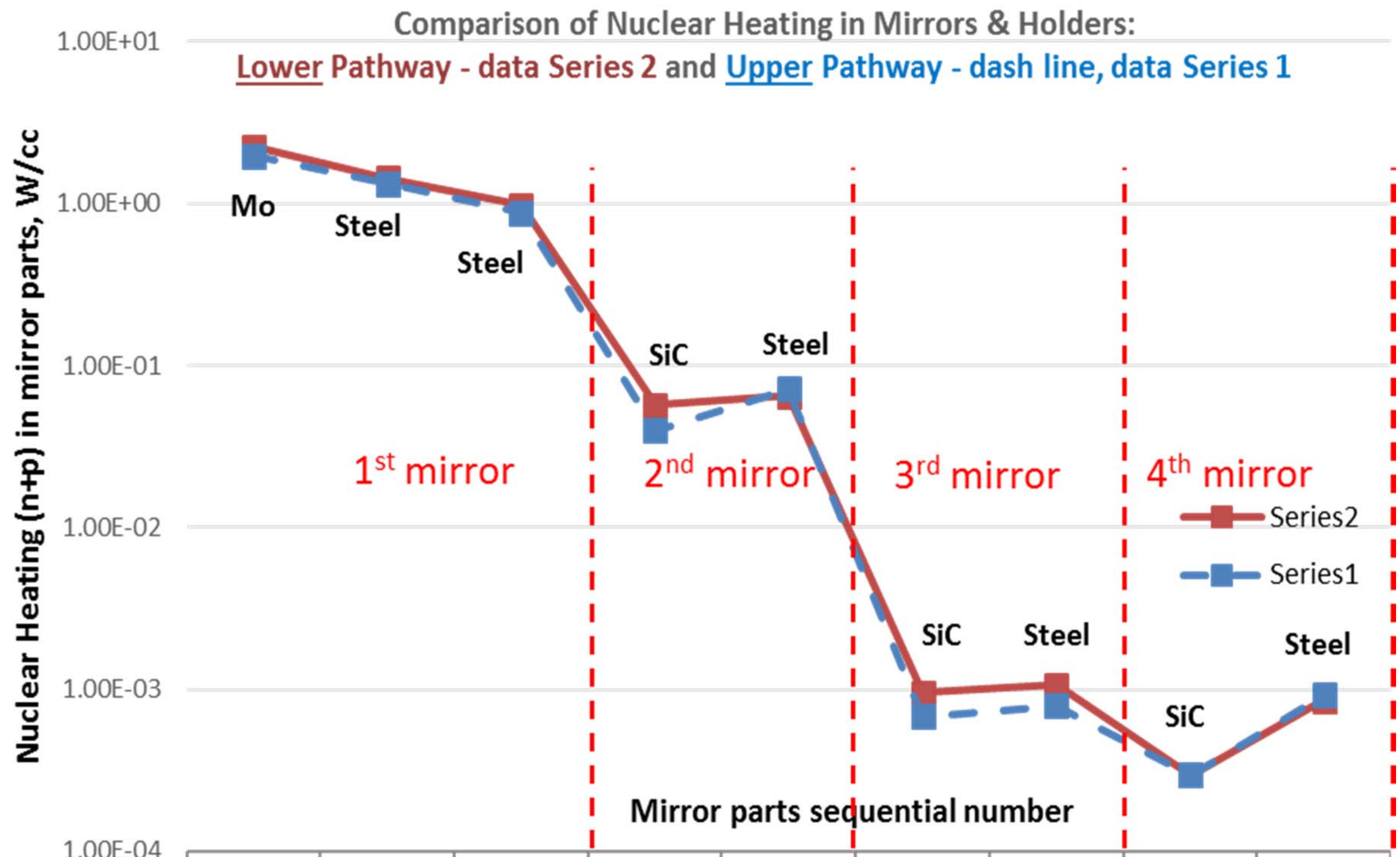
Radiation (n+p) heating loads on Edge CXRS mirrors

<u>Total (neutron + photon) and partial heating contributions</u>
from photons and neutrons in materials of the CXRS mirrors and their holders

MCNP	Material	Heating (n+p) per cell volumes, W/cc	Photon heating per cell volumes, W/cc	Neutron heating per cell volumes, W/cc
M1 upper	Molybdenum mirror	1.96E+00	1.86E+00	1.01E-01
	steel disk	1.33E+00	1.14E+00	1.83E-01
	steel plate	8.77E-01	7.62E-01	1.16E-01
M1 lower	Molybdenum mirror	2.25E+00	2.12E+00	1.24E-01
	steel disk	1.43E+00	1.23E+00	1.99E-01
	steel plate	9.76E-01	8.44E-01	1.31E-01
M2 upper	SiC mirror	3.95E-02	2.36E-02	1.59E-02
	steel disk	7.17E-02	6.75E-02	4.22E-03
M2 lower	**SiC mirror**	**5.66E-02**	3.29E-02	2.38E-02
	steel disk	6.52E-02	6.15E-02	3.71E-03
M3 upper	SiC mirror	6.80E-04	4.47E-04	2.33E-04
	steel disk	7.88E-04	7.40E-04	4.84E-05
M3 lower	SiC mirror	9.57E-04	5.98E-04	3.59E-04
	steel disk	1.06E-03	9.83E-04	7.72E-05
M4 upper	SiC mirror	2.95E-04	2.71E-04	2.45E-05
	steel disk	9.22E-04	9.13E-04	9.01E-06
M4 lower	SiC mirror	2.97E-04	2.67E-04	3.02E-05
	steel disk	8.50E-04	8.38E-04	1.19E-05

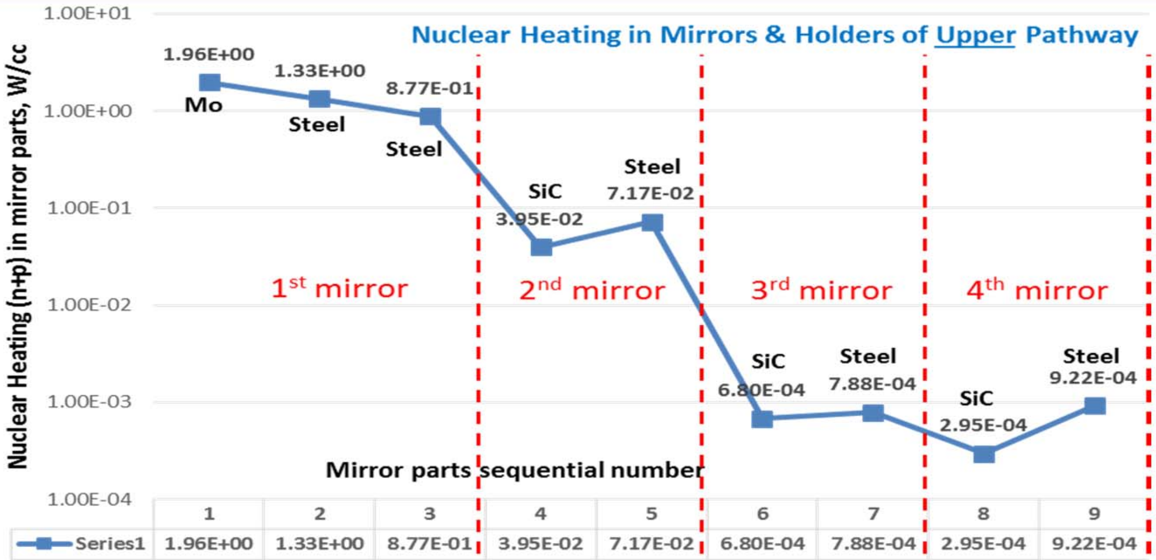


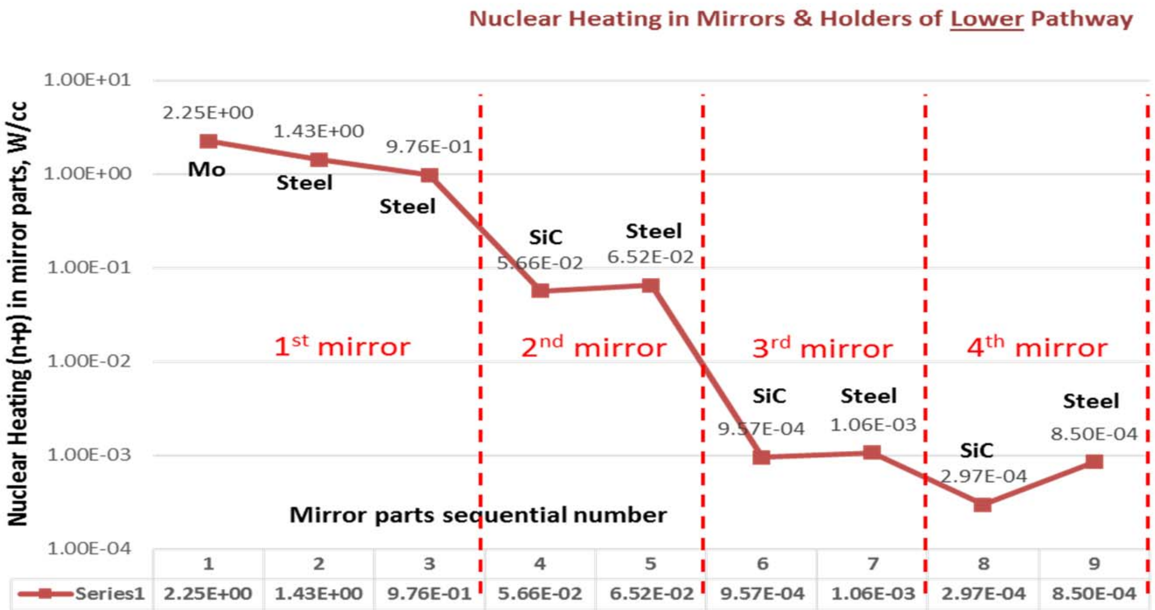
Comparison of total (neutron + photon) nuclear heating density (W/cm³) distributions in materials of mirrors and their holders in the Lower and Upper CXRS optical pathways



	1	2	3	4	5	6	7	8	9
Series2	2.25E+00	1.43E+00	9.76E-01	5.66E-02	6.52E-02	9.57E-04	1.06E-03	2.97E-04	8.50E-04
Series1	1.96E+00	1.33E+00	8.77E-01	3.95E-02	7.17E-02	6.80E-04	7.88E-04	2.95E-04	9.22E-04

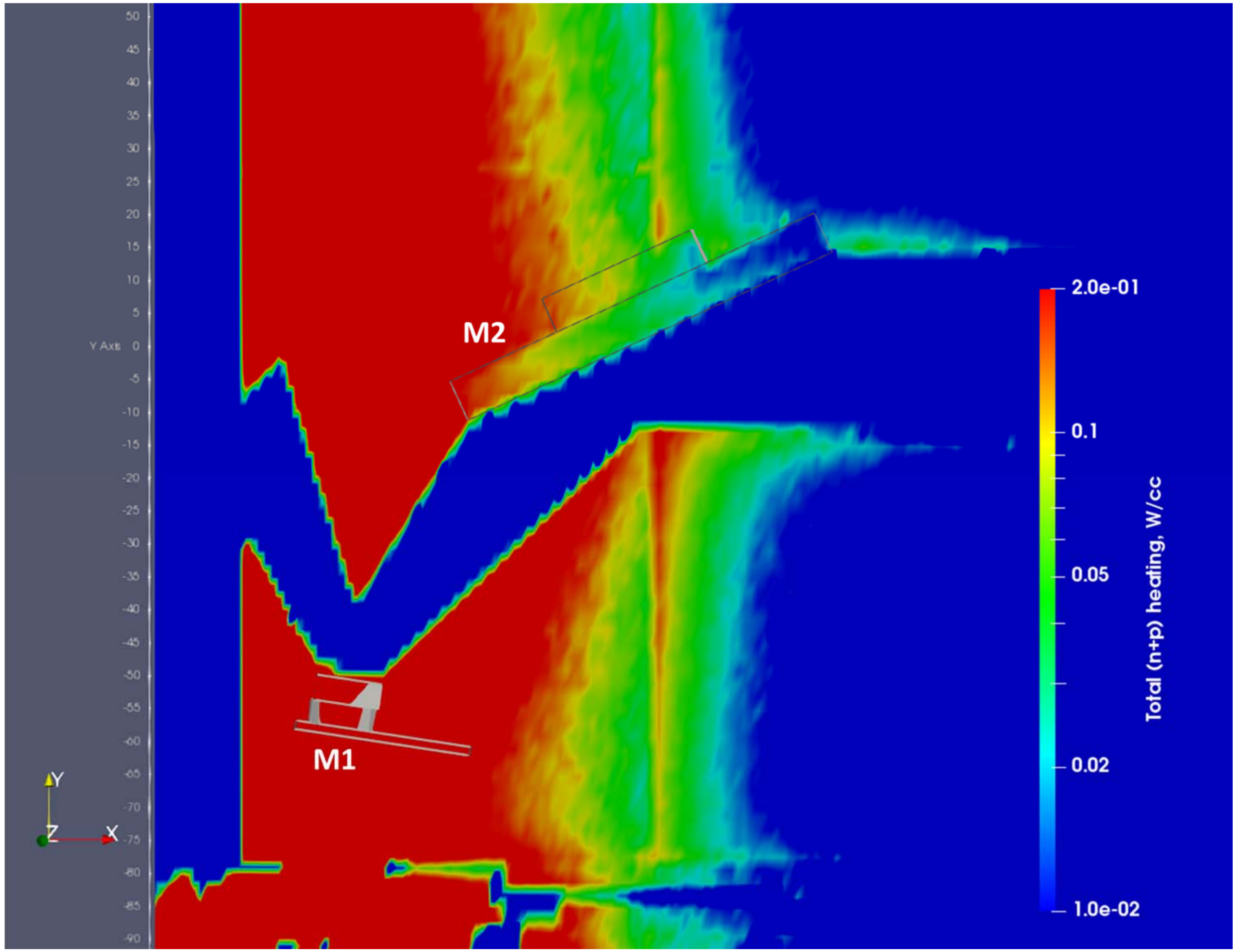
Detailed nuclear heating distributions inside the mirrors of Lower and Upper pathways





- The maximum heating in the M1 made of molybdenum is **2.25 W/cc** at the lower optical path, and **1.96 W/cc** in molybdenum M1 of the upper path.
- The heating deposition was dominated by the contribution coming from secondary photons produced on nuclear reactions with neutrons.
- **The problem of small thermal conductivity of silicon carbide (SiC)** motivated us to study nuclear heating gradients in mirrors M2-M4 with SiC layers. Among all the SiC mirrors, the peak nuclear heating load was detected on M2 mirror arranged in the CXRS lower optical pathway, in so-called M2-lower mirror.

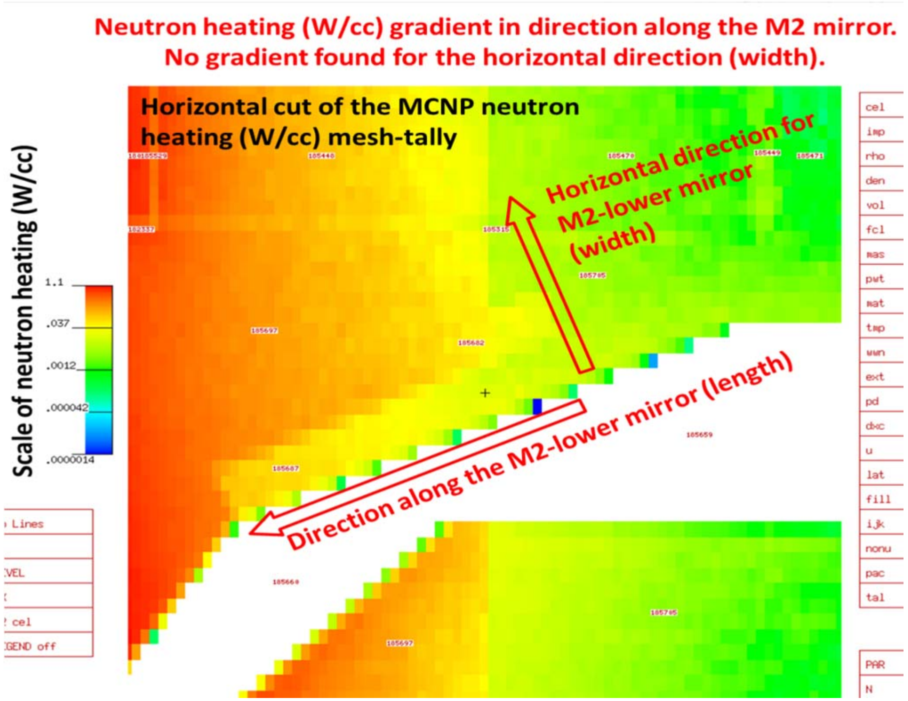
Nuclear heating gradient along the SiC mirror M2 in lower optical path

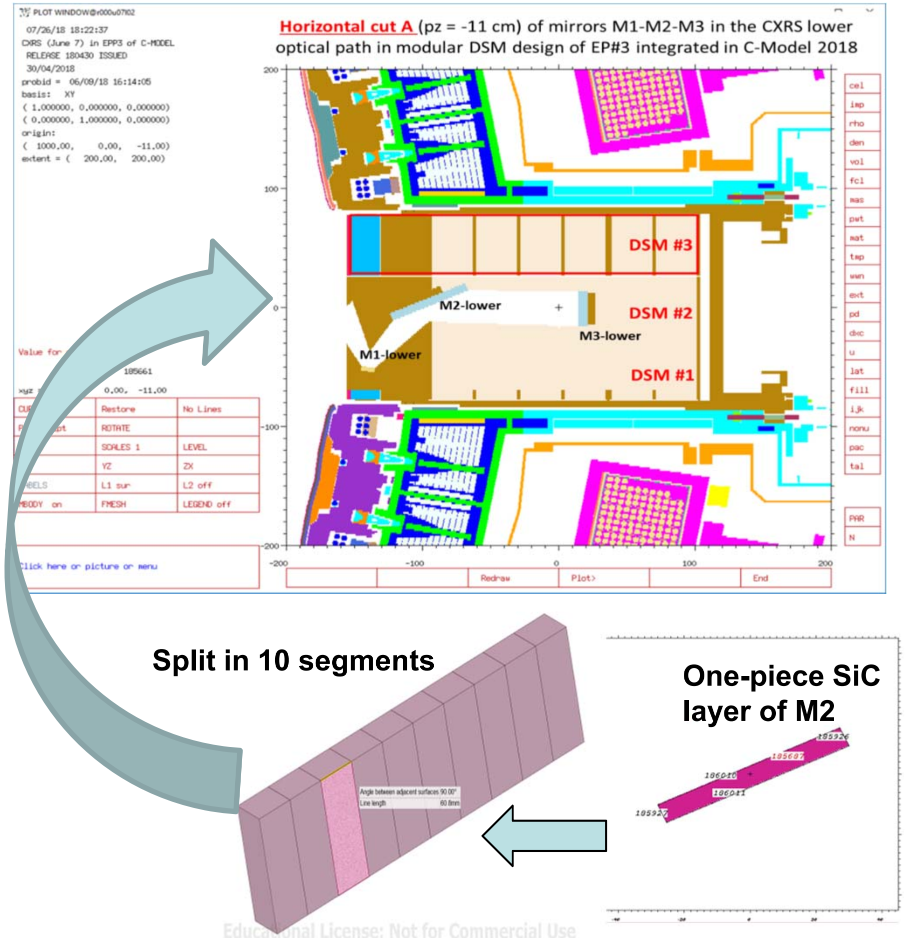


We have found nuclear heat gradient of one order of magnitude on the level of 0.2 W/cc – 0.01 W/cc in the SiC layer of M2-lower mirror, while averaged heat in SiC of M2 is 5.66e-2 W/cc averaged value over the SiC layer of that particular mirror M2.

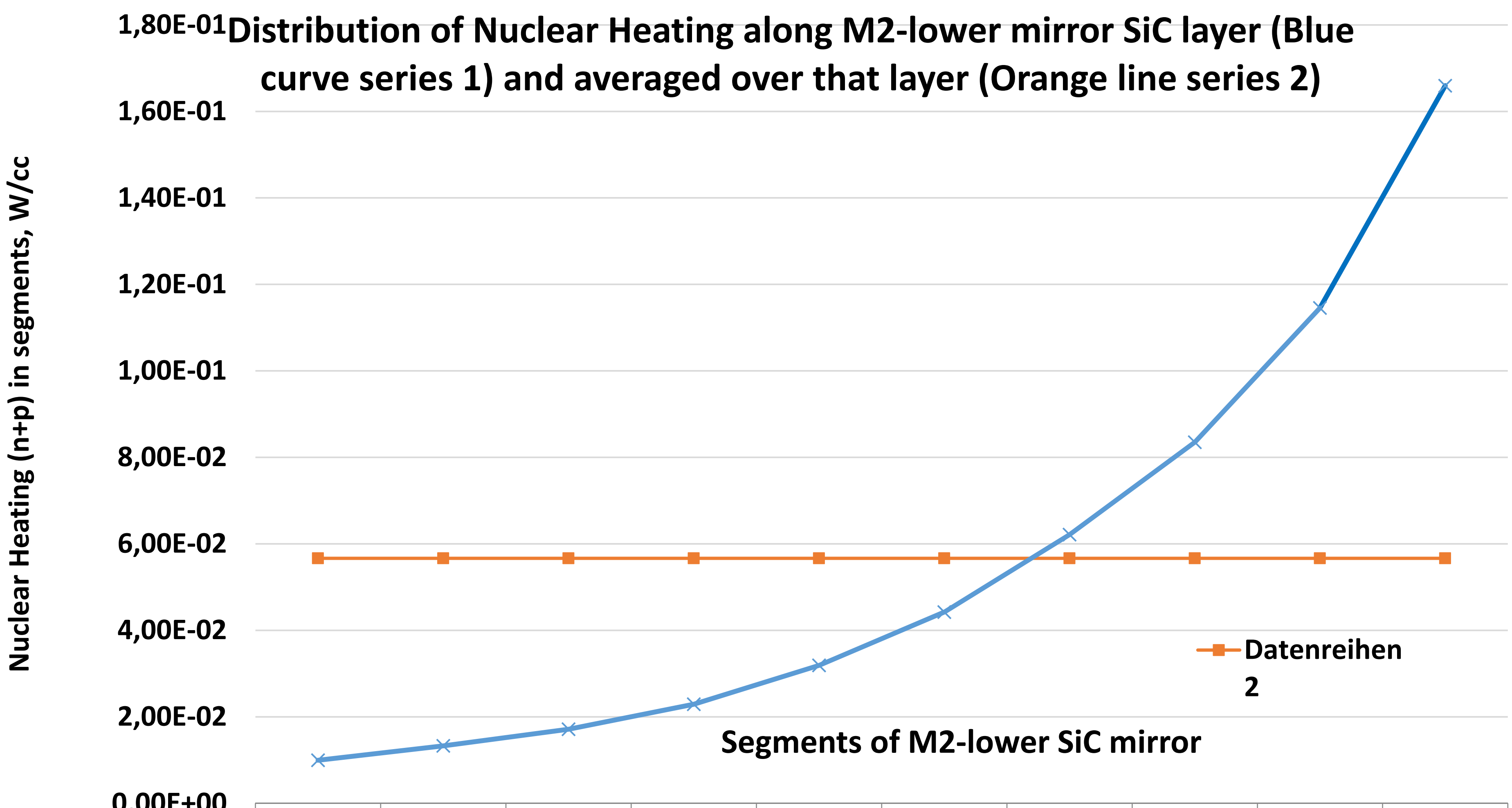
Distribution along the SiC layer of the M2-lower mirror: split it by 10 segments

- The length of SiC layer of the M2 mirror is 608 mm. In order to study the heat distribution along its length, it was split by 10 segments – by 6-cm elements of SiC-layer of the M2-lower mirror. In other two dimensions of the SiC M2-lower mirror, its width and height, no any noticeable heating gradients were found.
- The mesh-tally maps with fine distributions of 2-cm resolution reveled adequacy of the segmentation to be used as nuclear volumetric sources in the subsequent thermo-hydraulic analysis.



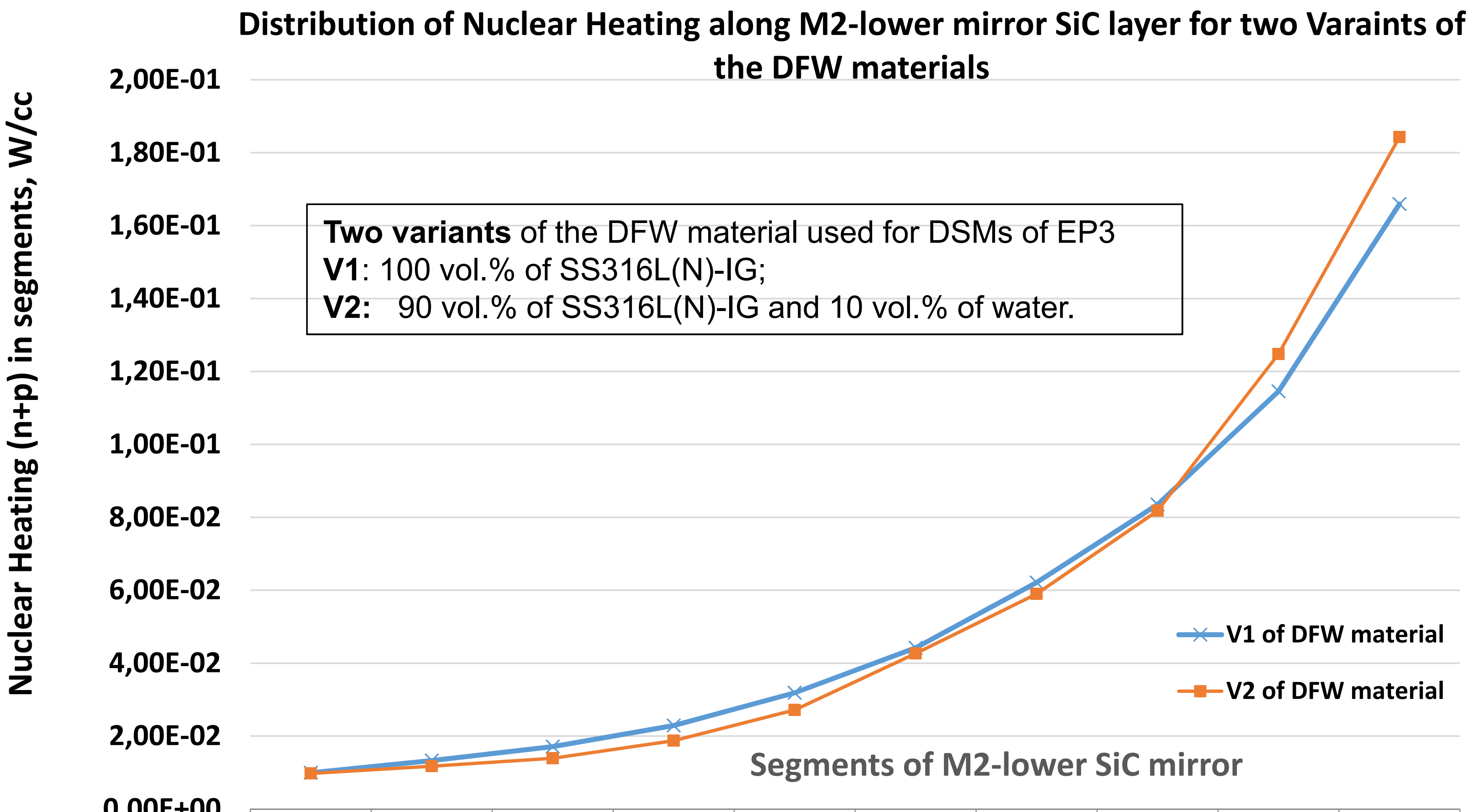


Nuclear heating (W/cc) averaged and distributed along the SiC layer of the M2 length



	1	2	3	4	5	6	7	8	9	10
Datenreihen2	5,66E-02	5,66E-02	5,66E-02	5,66E-02	5,66E-02	5,66E-02	5,66E-02	5,66E-02	5,66E-02	5,66E-02
Datenreihen1	9,97E-03	1,33E-02	1,71E-02	2,29E-02	3,19E-02	4,42E-02	6,21E-02	8,35E-02	1,15E-01	1,66E-01

Dependence of the nuclear heating distribution on the materials of the DFW panel

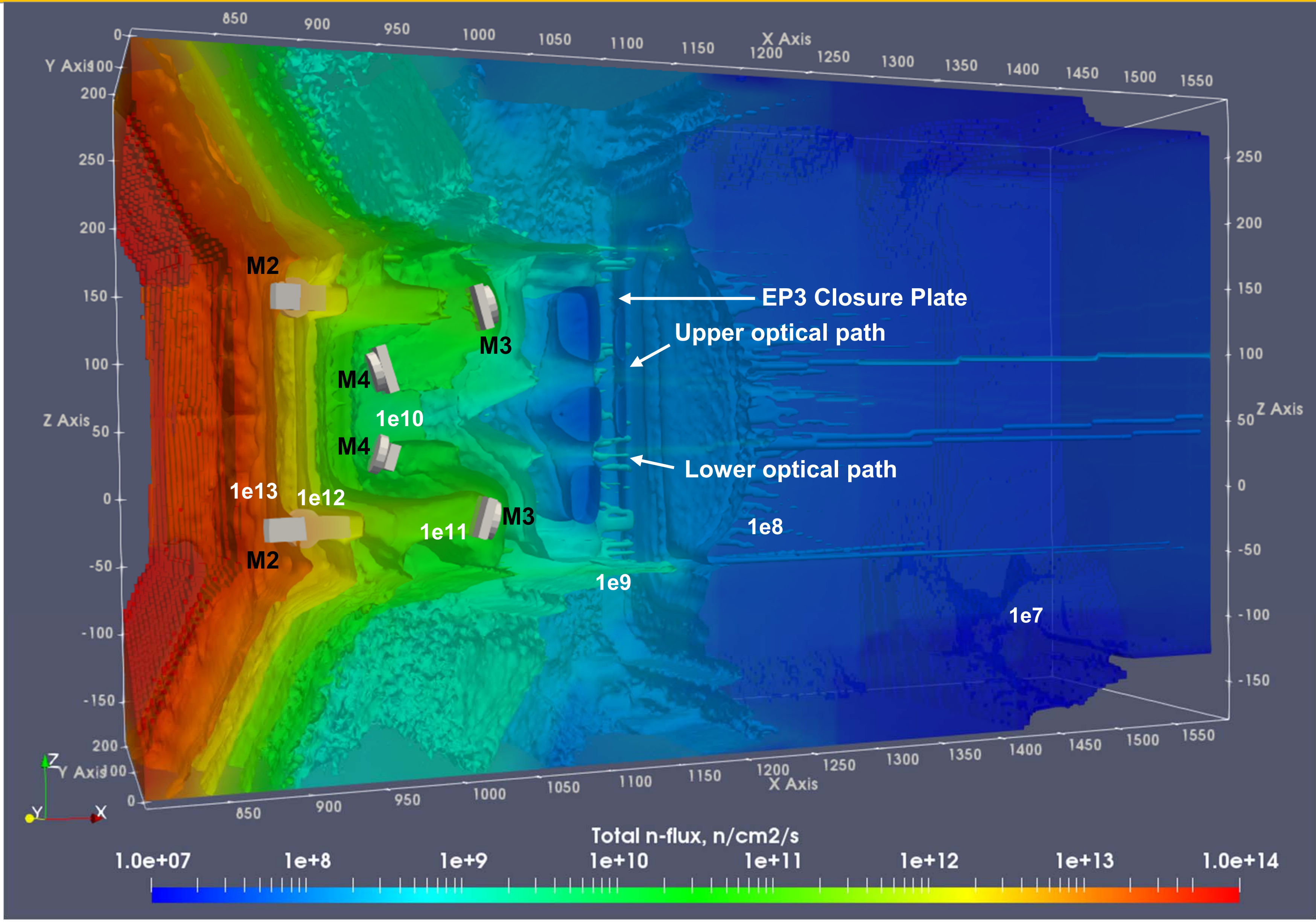


	1	2	3	4	5	6	7	8	9	10
V1 of DFW material	9,97E-03	1,33E-02	1,71E-02	2,29E-02	3,19E-02	4,42E-02	6,21E-02	8,35E-02	1,15E-01	1,66E-01
V2 of DFW material	9,77E-03	1,18E-02	1,39E-02	1,87E-02	2,72E-02	4,27E-02	5,90E-02	8,18E-02	1,25E-01	1,84E-01

Neutron and photon fluxes in Edge CXRS mirrors in EP#3 of C-Model R180430

CXRS Mirror	Material	C-Model cell number	Thermal and Epithermal neutron flux in cells, n/cm2/s	Fast neutron flux in cells, n/cm2/s	Total neutron flux in cells, n/cm2/s	Total photon flux in cells, n/cm2/s
M1 upper	Molybdenum mirror	185693	**3.88E+13**	**7.61E+13**	**1.15E+14**	**3.17E+13**
	steel disk	185675	**4.03E+13**	**7.45E+13**	**1.15E+14**	**2.99E+13**
	steel plate	185671	**3.40E+13**	**5.15E+13**	**8.55E+13**	**1.91E+13**
M1 lower	Molybdenum mirror	185694	**4.24E+13**	**8.37E+13**	**1.26E+14**	**3.63E+13**
	steel disk	185681	**4.31E+13**	**7.96E+13**	**1.23E+14**	**3.22E+13**
	steel plate	185677	**3.68E+13**	**5.64E+13**	**9.32E+13**	**2.12E+13**
M2 upper	SiC mirror	185688	**1.13E+13**	**6.51E+12**	**1.79E+13**	**2.15E+12**
	steel disk	185676	**1.07E+13**	**6.29E+12**	**1.70E+13**	**1.50E+12**
M2 lower	SiC mirror	185687	**1.28E+13**	**8.01E+12**	**2.08E+13**	**2.87E+12**
	steel disk	185682	**9.03E+12**	**5.11E+12**	**1.41E+13**	**1.42E+12**
M3 upper	SiC mirror	185690	**1.52E+11**	**7.49E+10**	**2.27E+11**	**6.22E+10**
	steel disk	185686	**8.57E+10**	**3.66E+10**	**1.22E+11**	**1.96E+10**
M3 lower	SiC mirror	185689	**1.74E+11**	**9.07E+10**	**2.65E+11**	**8.11E+10**
	steel disk	185685	**9.70E+10**	**4.43E+10**	**1.41E+11**	**2.74E+10**
M4 upper	SiC mirror	185691	**1.73E+10**	**7.39E+09**	**2.47E+10**	**3.06E+10**
	steel disk	185683	**1.10E+10**	**5.83E+09**	**1.69E+10**	**2.38E+10**
M4 lower	SiC mirror	185692	**1.62E+10**	**8.02E+09**	**2.42E+10**	**2.90E+10**
	steel disk	185684	**1.09E+10**	**7.23E+09**	**1.81E+10**	**2.35E+10**

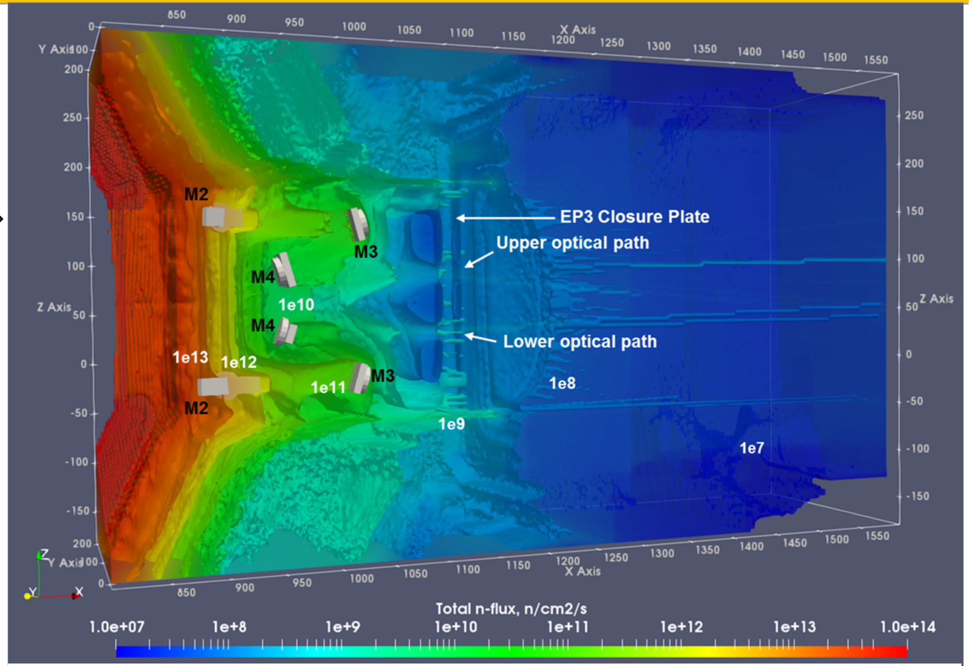
Total neutron flux in EP3 with Edge CXRS integrated in C-Model 180430



Total neutron flux in EP3 with Edge CXRS or generic DGEPP in C-Model 180430

EP3 with Edge CXRS integrated in C-Model 180430:

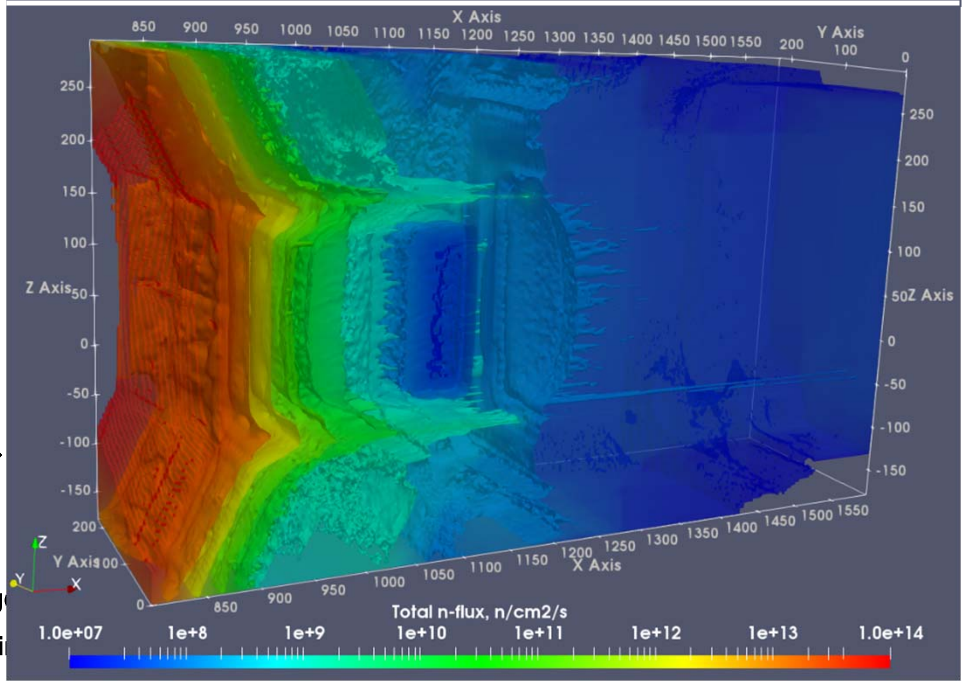
Neutron streaming for 3 pathways:
1. Gaps all-round the DGEPP
2. CXRS upper optical path
3. CXRS lower optical path



Edge CXRS Mirrors in EP3	Total neutron flux in cells, n/cm2/s	Total photon flux in cells, n/cm2/s
M1 upper	1.15E+14	3.17E+13
M1 lower	1.26E+14	3.63E+13
M2 upper	1.79E+13	2.15E+12
M2 lower	2.08E+13	2.87E+12
M3 upper	2.27E+11	6.22E+10
M3 lower	2.65E+11	8.11E+10
M4 upper	2.47E+10	3.06E+10
M4 lower	2.42E+10	2.90E+10

Generic DGEPP in C-Model 180430:

Neutron streaming for 1 pathway:
1. Gaps all-round the DGEPP



N-flux comparison for ***Edge CXRS in EP3*** vs. ***Core CXRS in UP3***

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

Core CXRS in UP3

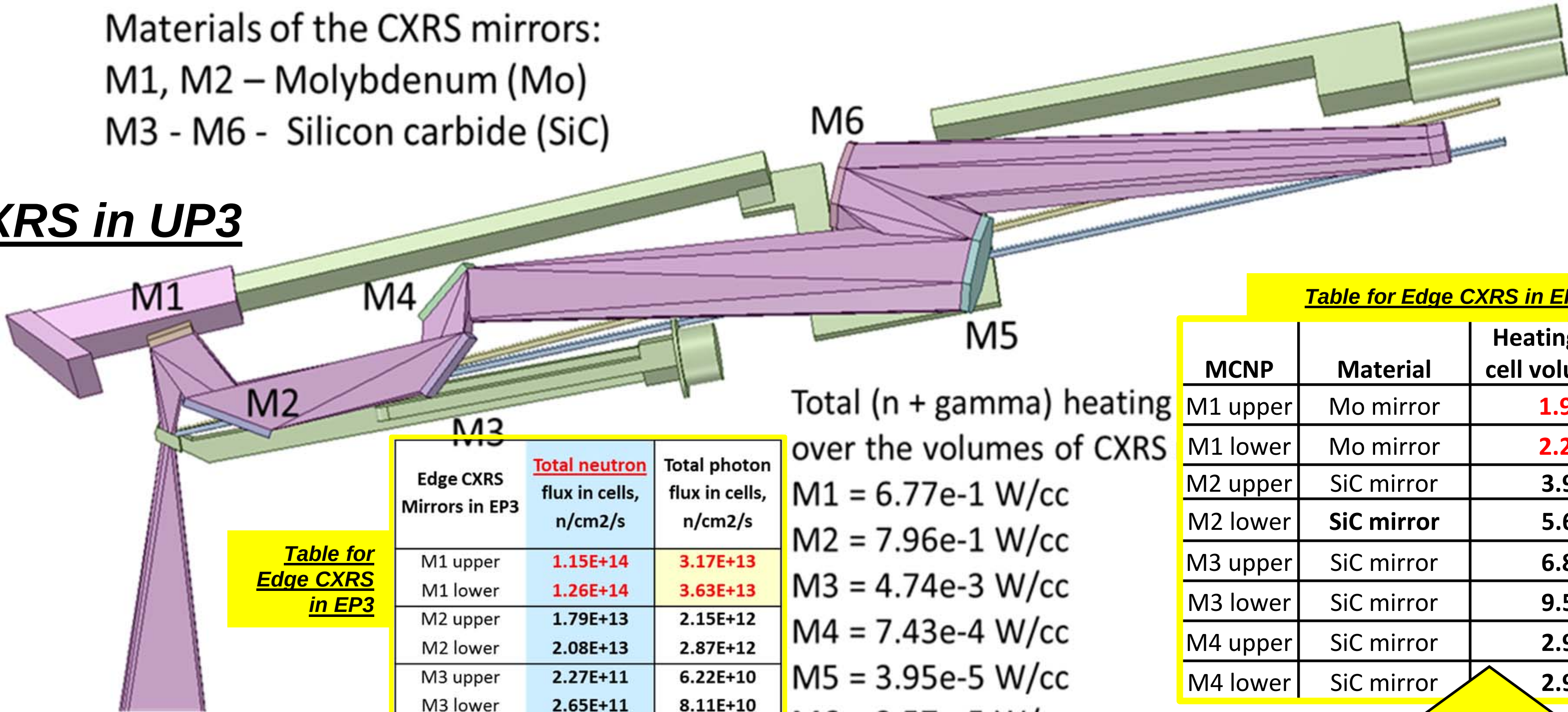


Table for Edge CXRS in EP3

Edge CXRS Mirrors in EP3	Total neutron flux in cells, n/cm2/s	Total photon flux in cells, n/cm2/s
M1 upper	1.15E+14	3.17E+13
M1 lower	1.26E+14	3.63E+13
M2 upper	1.79E+13	2.15E+12
M2 lower	2.08E+13	2.87E+12
M3 upper	2.27E+11	6.22E+10
M3 lower	2.65E+11	8.11E+10
M4 upper	2.47E+10	3.06E+10
M4 lower	2.42E+10	2.90E+10

Total (n + gamma) heating over the volumes of CXRS
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

Table for Edge CXRS in EP3

MCNP	Material	Heating (n+p) per cell volumes, W/cc
M1 upper	Mo mirror	**1.96E+00**
M1 lower	Mo mirror	**2.25E+00**
M2 upper	SiC mirror	**3.95E-02**
M2 lower	**SiC mirror**	**5.66E-02**
M3 upper	SiC mirror	**6.80E-04**
M3 lower	SiC mirror	**9.57E-04**
M4 upper	SiC mirror	**2.95E-04**
M4 lower	SiC mirror	**2.97E-04**

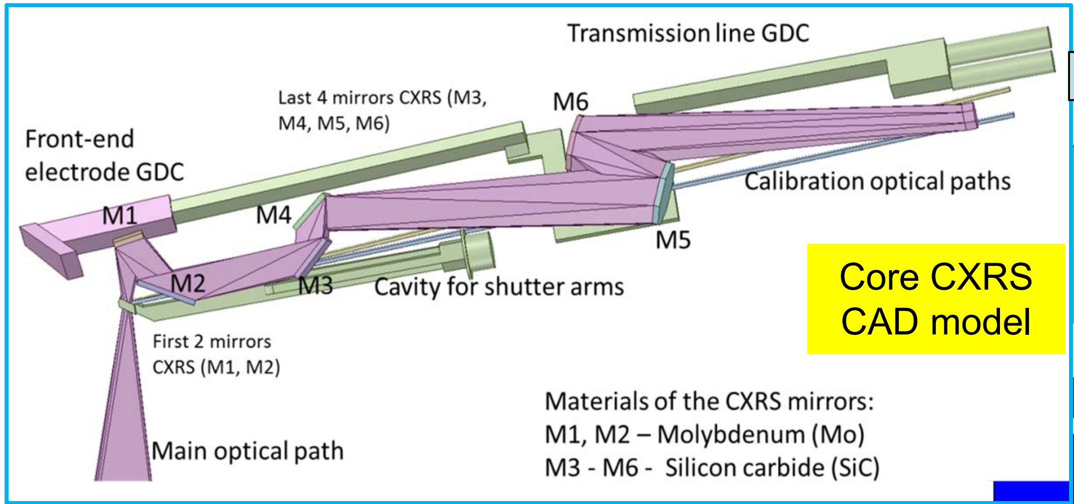
Vs.

Table for Core CXRS in UP3

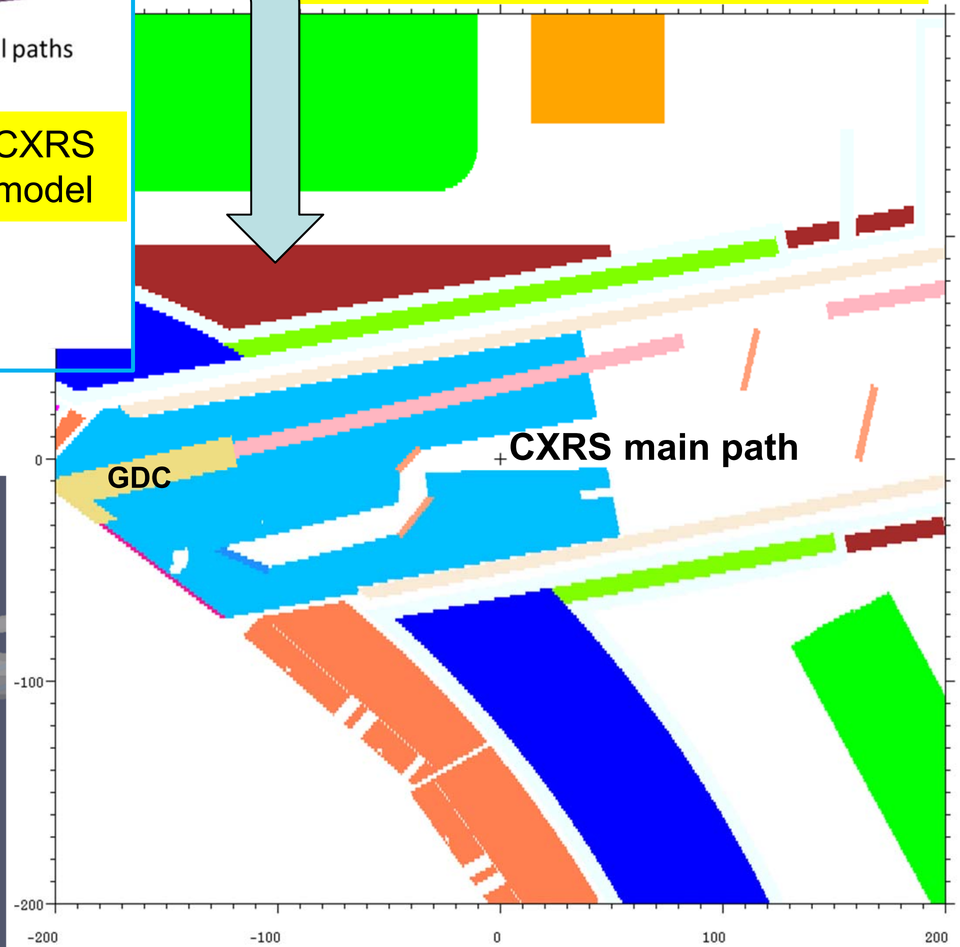
vs.

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

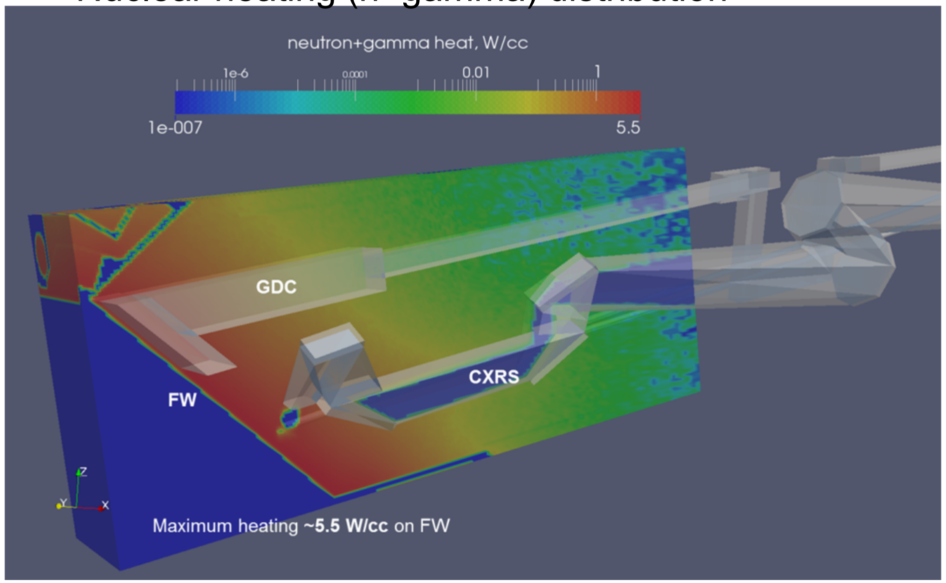
Core CXRS: CAD-to-MCNP model geometry conversion with SuperMC code



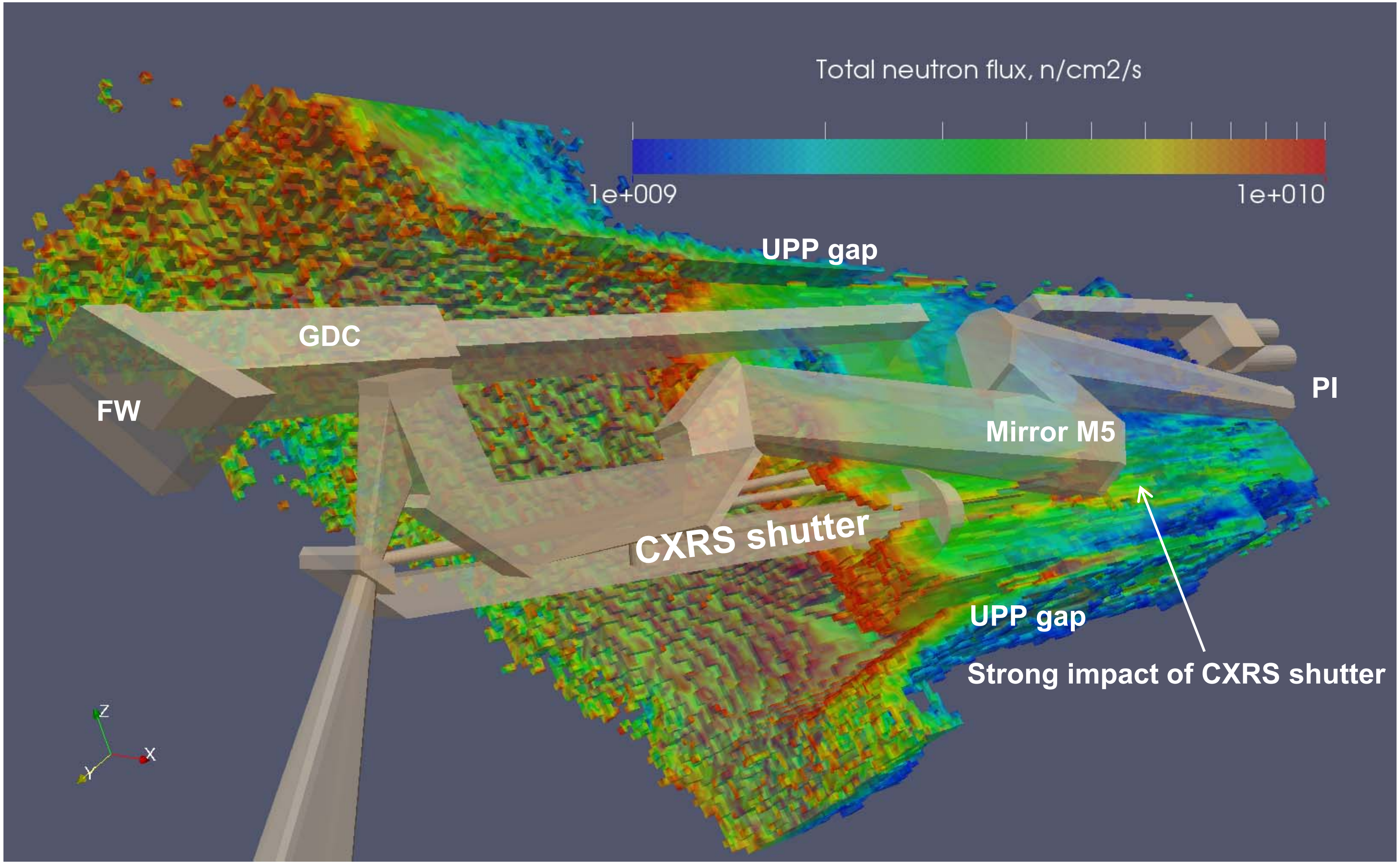
Integration of Core CXRS into UP3 of MCNP neutronic model



Nuclear heating (n+gamma) distribution



Impact of Core CXRS shutter – on neutron flux streaming in UP3 *



* **Ref.: A. Serikov et al., "Neutronics for Diagnostic Systems of ITER Port Plugs"**, Transactions of the American Nuclear Society, **Vol. 113**, pp. 1005-1008.

Shielding design improvement of *Core CXRS in UP3:* comparison n-fluxes in interspace

UPP interspace control volumes **F3&F4** of Ref. [1, 2] are equivalent to Volumes 1 and 2 of **Ref. [3]**

UPP interspace control volumes F3 & F4

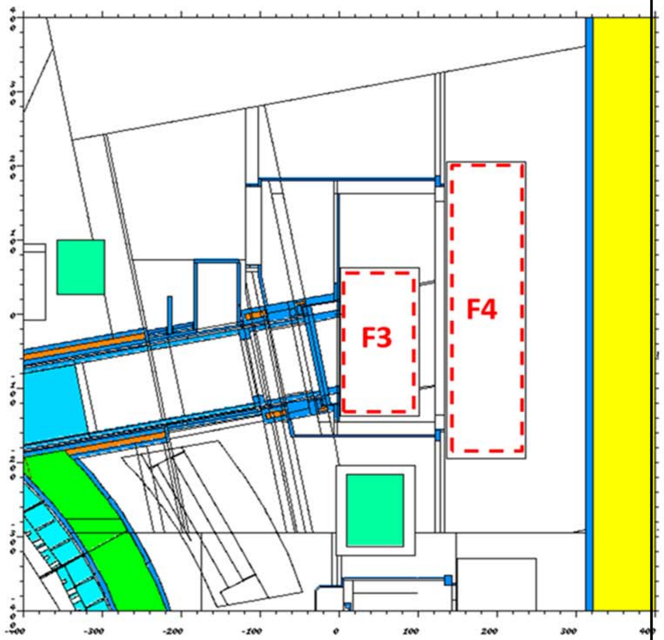


Table 5. Total neutron and gamma fluxes inside the Port Interspace (PI) control volumes F3 & F4 for the 3 cases of UPP-CXRS

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

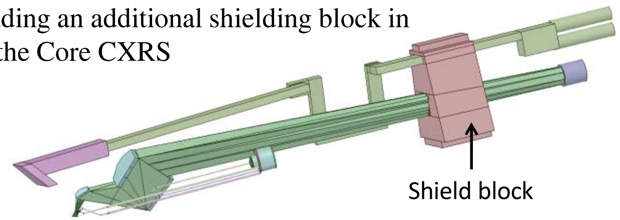
Case 3: Generic UPP	Neutron flux, n/cm2/s	Gamma flux, gamma/cm2/s
F3	7.61E+07	1.09E+07
F4	5.82E+07	8.54E+06

References:
[1] A. Serikov, "Task Report on Nuclear Shielding Assessment for 55.E1 CXRS-core Diagnostic System", ITER_D_Q97EAD, https://user.iter.org/?uid=Q97EAD
[2] A. Serikov, Serikov A. et al Radiation in-port cross-talks for ITER port diagnostics Fusion Sci. Technol. **Vol.72,** pp.559–65, https://doi.org/10.1080/15361055.2017.1347470

Table 1 Cited from Ref. [3]
Neutron fluxes in the interspace control volumes for all 10 design setups.

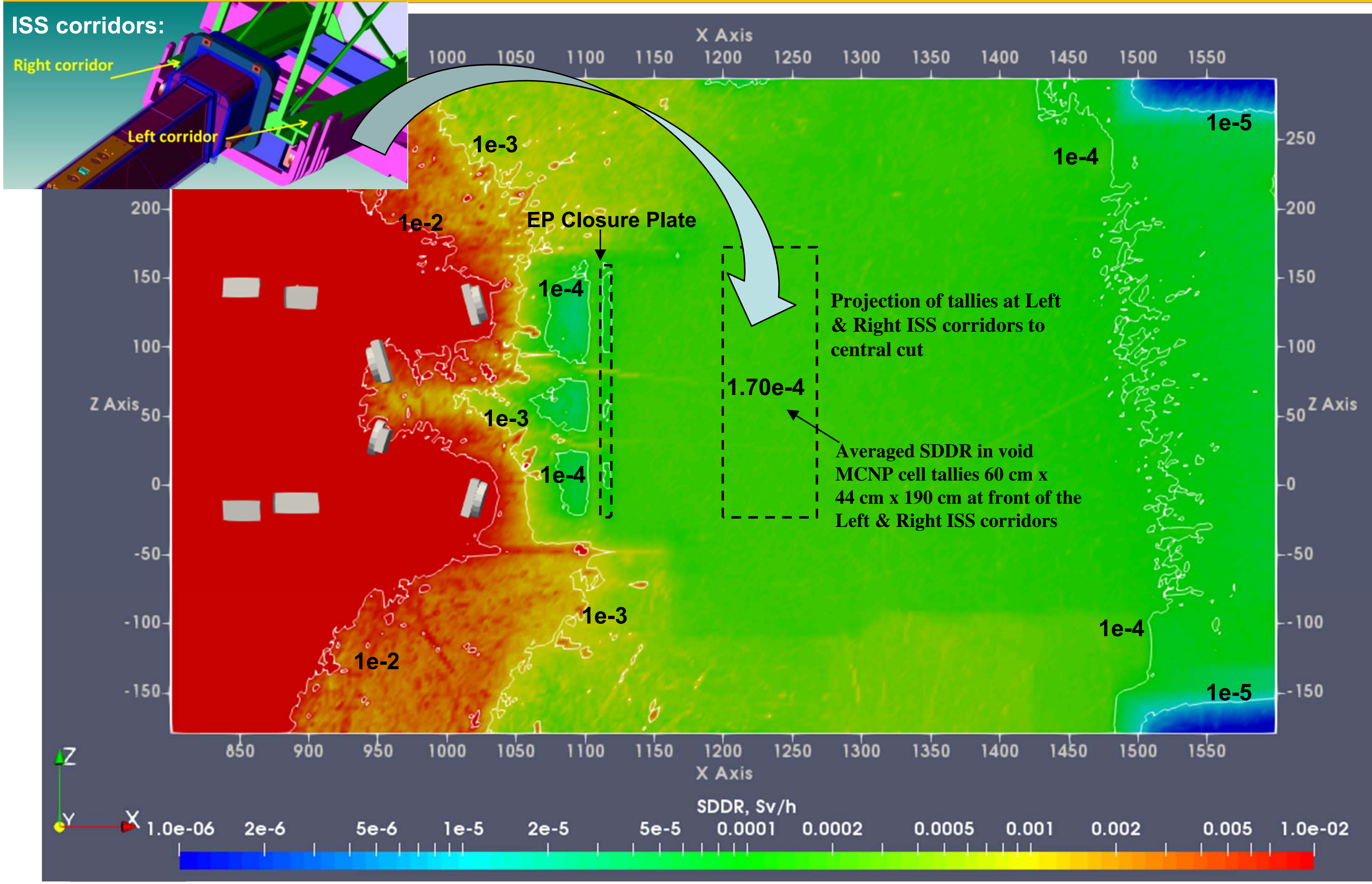
Design setup	Volume 1 [E+07 n/cm²/s]	Volume 2 [E+07 n/cm²/s]
#1 with shutter	7.14 ± 0.36	5.31 ± 0.34
#1 without shutter	7.05 ± 0.36	5.22 ± 0.34
#2 with shutter	15.0 ± 0.9	8.48 ± 0.55
#2 without shutter	14.3 ± 0.9	7.95 ± 0.52
#3 with shutter	8.62 ± 0.43	5.91 ± 0.35
#3 without shutter	8.73 ± 0.43	5.91 ± 0.35
#3 + shield with shutter	7.07 ± 0.36	5.45 ± 0.35
#3 + shield without shutter	7.55 ± 0.36	5.47 ± 0.35
#4 with shutter	7.15 ± 0.36	5.32 ± 0.34
#4 without shutter	6.86 ± 0.35	5.15 ± 0.34

Design #3 including an additional shielding block in the rear part of the Core CXRS

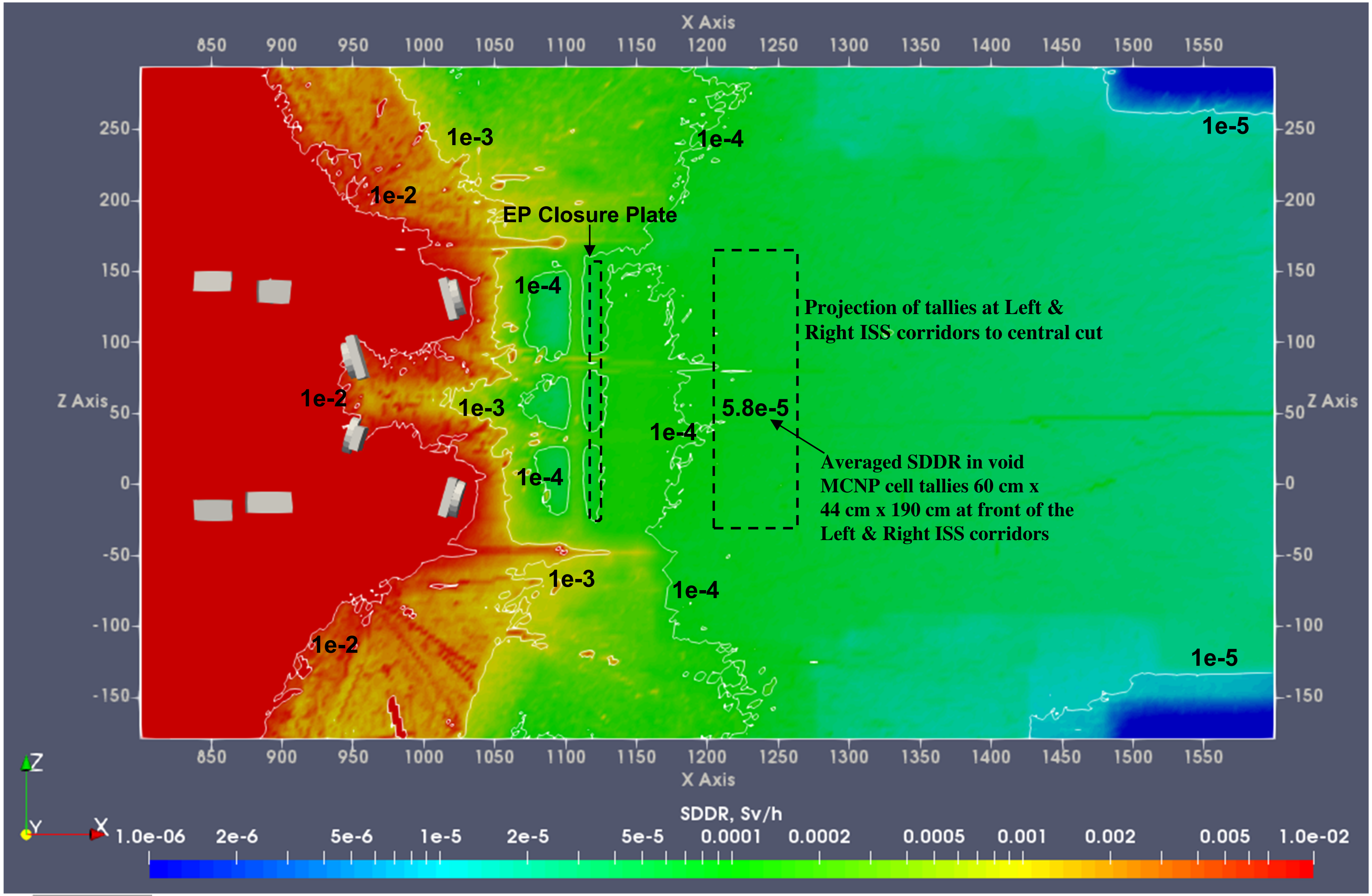


Ref. [3] B.Weinhorst, et al., "ITER core CXRS diagnostic: Assessment of different optical designs with respect to neutronics criteria", Fusion Engineering and Design **123** (2017) pp. 927–931, https://doi.org/10.1016/j.fusengdes.2017.03.061

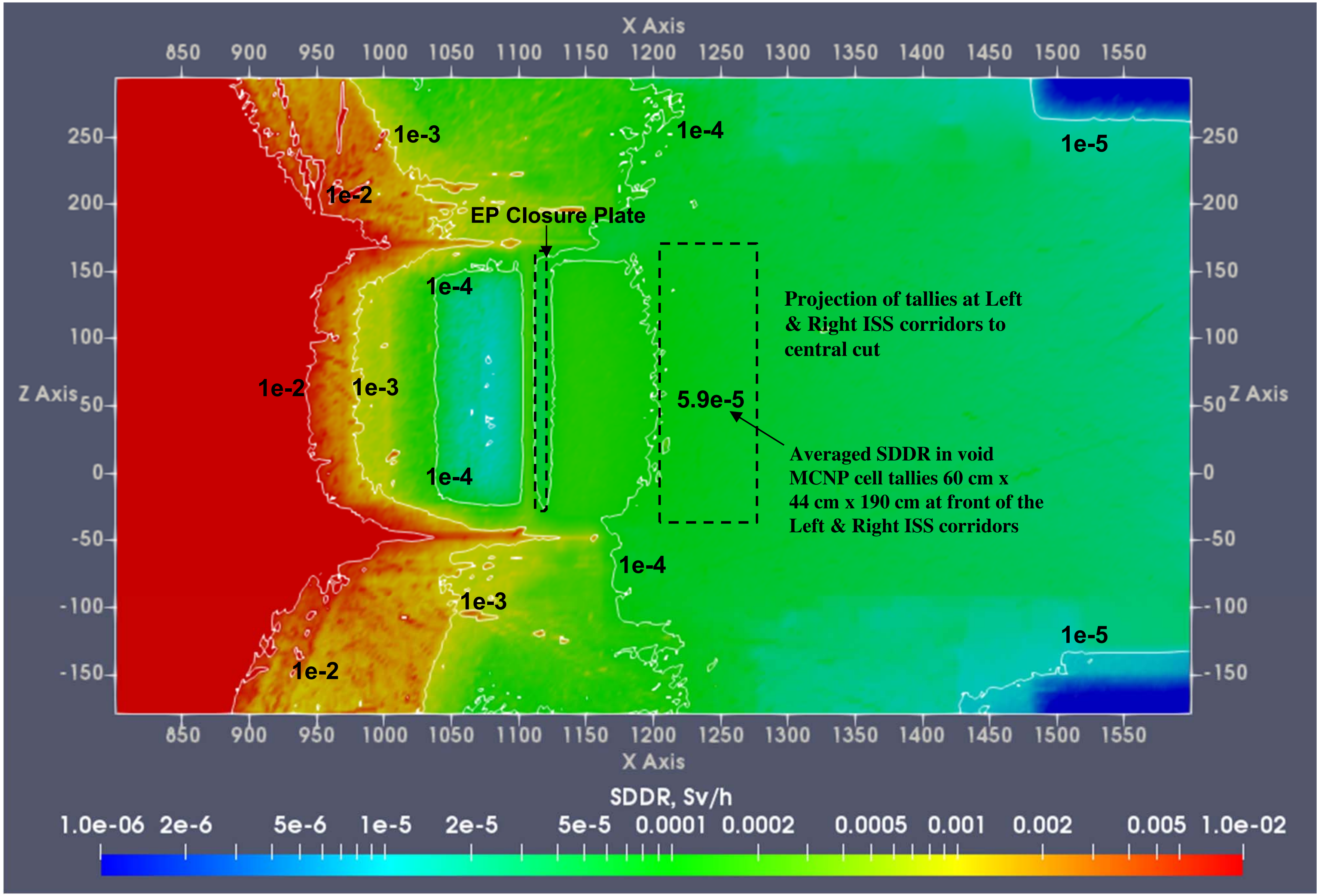
SDDR (Sv/h) for the Edge CXRS in EP#3: whole C-model with central cut py=2cm



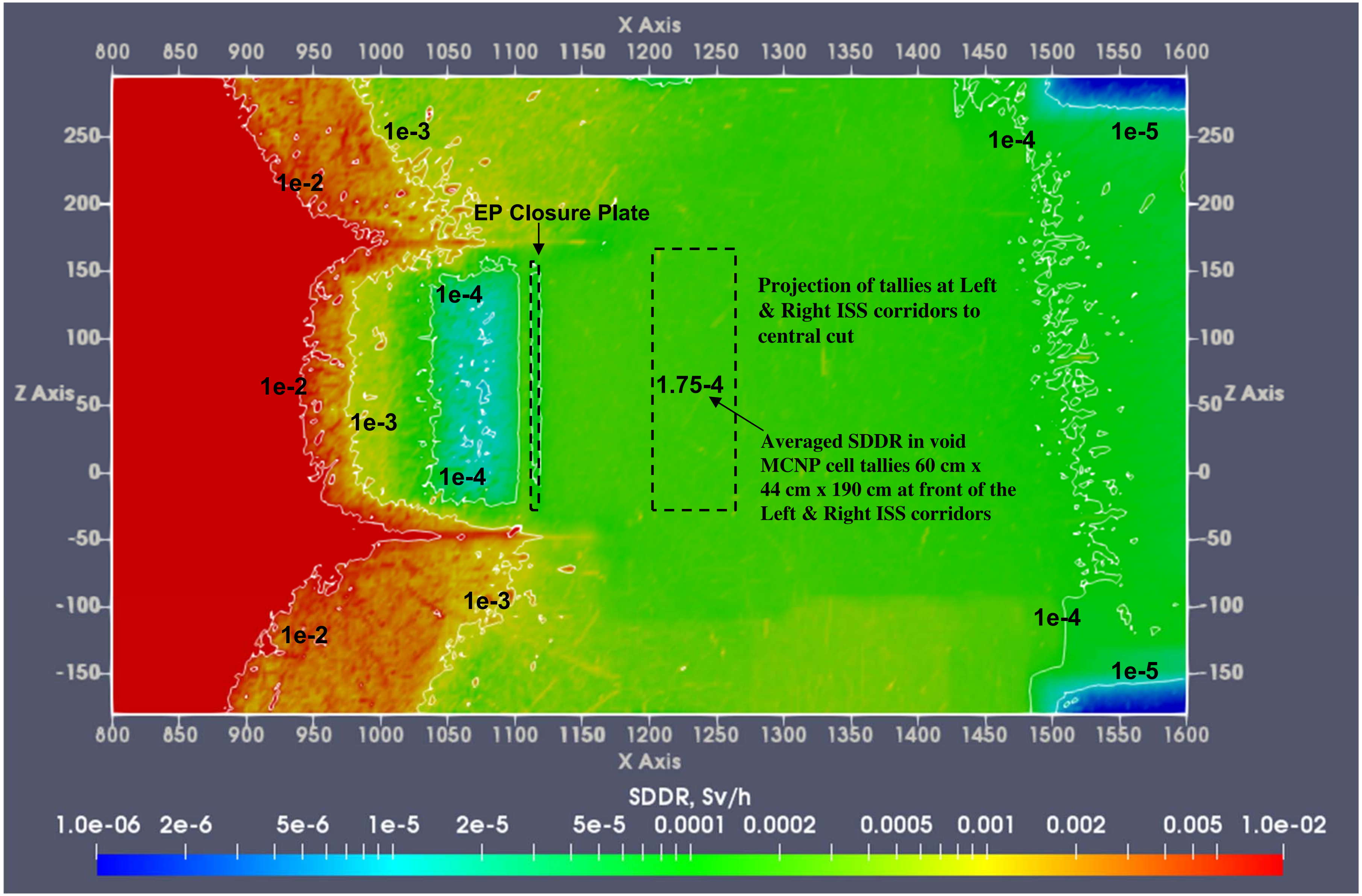
SDDR (Sv/h) for the Edge CXRS in EP#3: local model with central cut py=2cm



SDDR (Sv/h) for the DGEPP: whole C-model model with central cut py=2cm



SDDR (Sv/h) for the DGEPP: whole C-model model with central cut py=2cm



Conclusions

- Design development of the Edge CXRS in EP3, Core CXRS in UP3 is still in progress. The presented scoping results have a relative character.
- 3D maps of neutron fluxes and Shut-Down Dose Rate (SDDR) with isosurfaces allowed to find the radiation pathways, hot spots - most critical areas from neutronics perspectives.
- N-flux and nuclear heat comparisons for Edge CXRS in EP3 vs. Core CXRS in UP3 demonstrated 3-4 times higher values for the Edge CXRS in EP3.
- The dominancy of neutron and gamma radiation streaming along the gaps around the EP plug has been confirmed, the streaming in optical pathways was substantially mitigated by the labyrinths.
- SDDR at the ISS corridors of port interspace of EP3 in local and whole C-Model does not reveal contribution from Edge CXRS, indicated of suitability of the doglegs and labyrinths of the Edge CXRS optical pathways and sufficiency of the EP3 performance.
- Local SDDR in EP3 ISS corridors is 58 microSv/h, whole SDDR is 170 microSv/h, that means 66% of SDDR is coming from the EPP environment.