Monte Carlo radiation transport parallel computations on Marconi-Fusion HPC for the IFMIF-DONES radiation shielding tasks

EUROfusion

Arkady Serikov[a], Yuefeng Qiu[a], Barbara Bienkowska[b]

[a] *Karlsruhe Institute of Technology (KIT), Institute for Neutron Physics and Reactor Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany*

[b]*Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland*

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Part I

Monte Carlo radiation transport massively parallel computations in the framework of the **MCHIFI** (Monte Carlo High Fidelity) project:

2012 – 2016: MCHIFI project foundation with the HPC resources of the F4E Broader Approach (BA) IFERC-CSC Helios supercomputer;

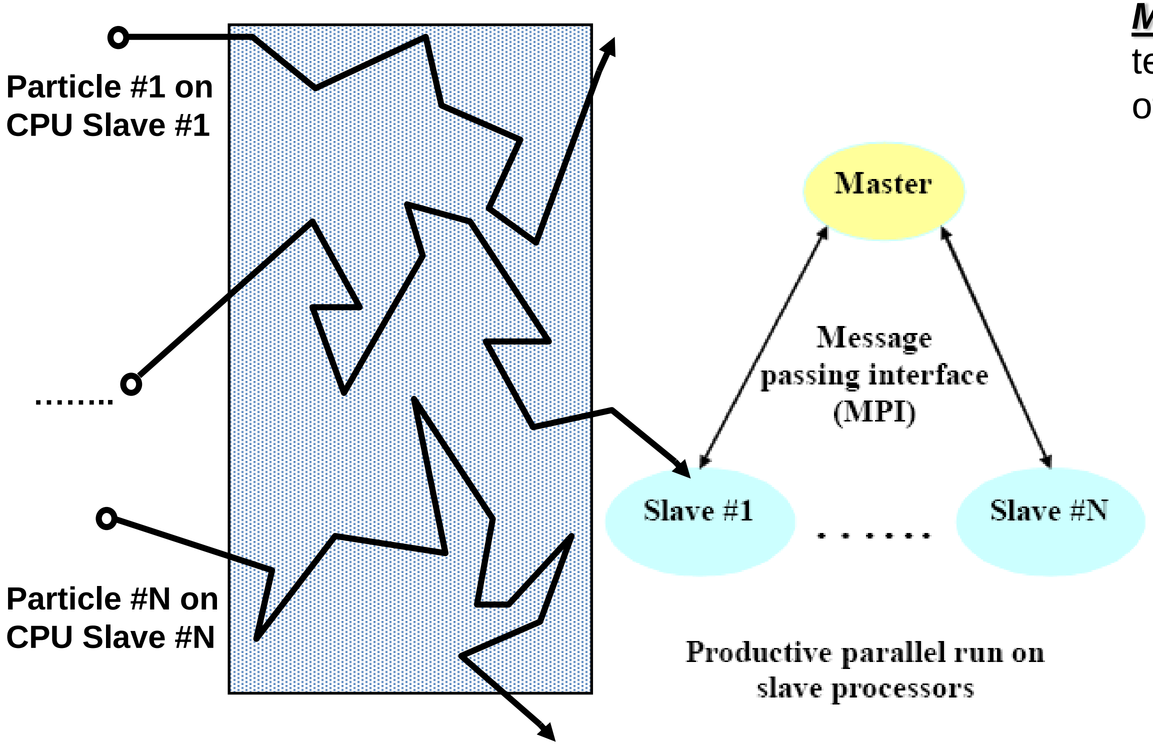
2016 – 2023: MCHIFI project continuation on the EUROfusion Marconi-Fusion HPC

Monte Carlo radiation transport parallel computations

Monte Carlo (MC) radiation transport runs on supercomputers

⇒ *Simulation of independent random pathways on microscopic level, i. e. tracking of individual particle histories from "birth" to "death"*

⇒ *Simulation can be computed on parallel multiprocessor systems*



Monte Carlo method is most suitable computational technique for nuclear fusion applications. That is because of the following reasons:

- ***Geometry***: complex fusion devices can be modelled in 3D geometry without major geometry approximations
- ***Data:*** continuous energy representation as stored on evaluated data files in ENDF format
- ***Calculation accuracy:*** only limited by statistics and data uncertainties (no numerical approximations)

Used supercomputers:

- Europe HPC-FF system at JSC (Germany);
- CampusGrid OpusIB, SCC-KIT (Germany);
- Europe HC3 at SCC-KIT (Germany);
- Europe BWGrid (Germany)
- IFERC-CSC Helios (Japan)
- **EUROfusion HPC Marconi-Fusion (Italy)**

The maximum speed-up was found on **EUROfusion HPC Marconi-Fusion** supercomputer with **OpenMP / MPI parallelization** for non-biased MCNP5 run equalled **2500 on 4096 cores** (or ~850 on 1024 cores, and ~450 on 512 cores) – because dependence of speed-up to number of cores is not linear due to overhead time spent for communications between computing nodes.

MCHIFI project: fusion neutronics computations on HPCs of F4E BA and EUROfusion

- **MCHIFI** (**M**onte **C**arlo **Hi**gh **Fi**delity) project has been organized for massively parallel computations on the EUROfusion Marconi-Fusion HPC for the most urgent and computationally demanded fusion neutronics tasks.
- The MCHIFI project was founded in 2012 to use the IFERC-CSC Helios supercomputer in the framework of the F4E Broader Approach (BA) to serve the ITER neutronics tasks.

- MCNP5 tested on the F4E Broader Approach IFERC-CSC Helios: 2x8 Intel Sandy-bridge EP processors with 2.7 Hz and 64 GB RAM per node:
  - Excellent scalability of MPI/OpenMP parallel runs of MCNP5 code up to 1024 cores in analogue runs, no variance reduction.
  - Speed-up equals ~450 on 512 cores, and ~850 of speed-up for 1024 cores.
  - OpenMP/MPI hybrid, the satisfactory speed-up of more than 2500 on 4096 cores was achieved for not-biased MCNP5 calculations, as it is illustrated in Figure 1

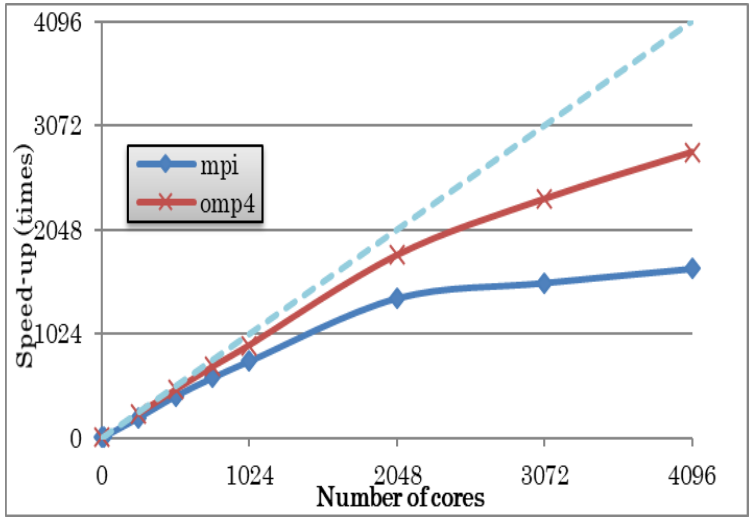


Figure 1. The MCNP5 speed-up on IFERC-CSC Helios supercomputer.

- McDeLicious tested on the EUROfusion HPC Marconi-Fusion with conventional partition (A3) based on INTEL Skylake with peak performance ~9.2 Pflops (2848 nodes). Each node is equipped with 2x24-cores Intel Xeon 8160 CPU (Skylake) at 2.10 GHz and 192 GB of RAM per node.
  - Speed-up MPI-parallel performance has been measured and presented in Figure 2 for the McDeLicious code for IFMIF-DONES radiation deep-penetration shielding tasks with variance reduction.

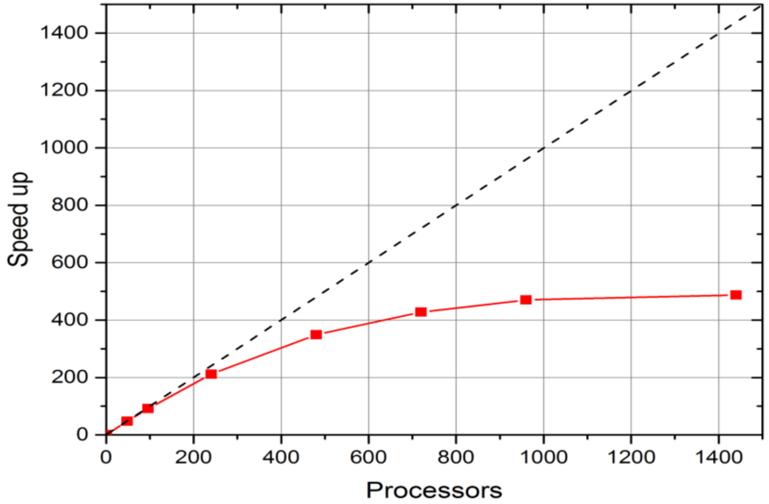


Figure 2. The speed-up of McDeLicious code on Marconi-Fusion HPC.

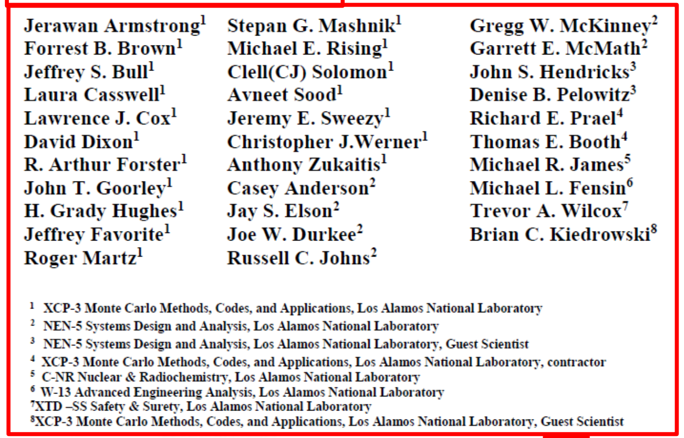
The optimal number of CPUs used in MCNP5/6 parallel calculations is dependent on complexity of the model. To improve the statistical errors of the MCNP5 results we are using the ADVANTG approach and the recently developed at KIT On-The-Fly (OTF) Monte Carlo variance reduction technique with dynamic Weight Window upper bounds, see Ref. [Yu Zheng, Y. Qiu, “Improvements of the on-the-fly MC variance reduction technique with dynamic WW upper bounds,” *Nuclear Fusion* **62** (2022) 086036, https://doi.org/10.1088/1741-4326/ac75fc]

Radiation transport with the MCNP code

MCNP is a code for radiation transport calculations in 3D geometry. The abbreviation is translated as **M**onte **C**arlo **N**-**P**article.

Neutron, photon, electron, or coupled neutron/photon/electron transport can be performed by MCNP. The MCNP code was developed by X-5 Monte Carlo Team in Los Alamos National Lab. (LANL), USA.

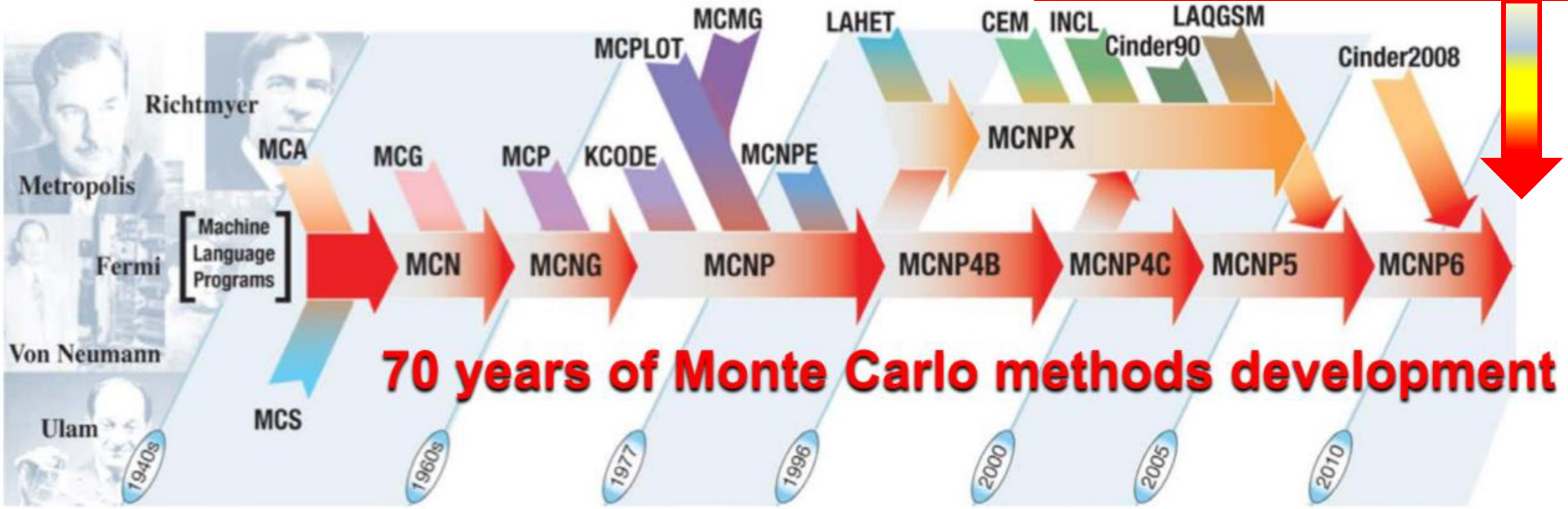
Contributors to MCNP6.2



Jerawan Armstrong[1]
Forrest B. Brown[1]
Jeffrey S. Bull[1]
Laura Casswell[1]
Lawrence J. Cox[1]
David Dixon[1]
R. Arthur Forster[1]
John T. Goorley[1]
H. Grady Hughes[1]
Jeffrey Favorite[1]
Roger Martz[1]
Stepan G. Mashnik[1]
Michael E. Rising[1]
Clell(CJ) Solomon[1]
Avneet Sood[1]
Jeremy E. Sweezy[1]
Christopher J.Werner[1]
Anthony Zukaitis[1]
Casey Anderson[2]
Jay S. Elson[2]
Joe W. Durkee[2]
Russell C. Johns[2]
Gregg W. McKinney[2]
Garrett E. McMath[2]
John S. Hendricks[3]
Denise B. Pelowitz[3]
Richard E. Prael[4]
Thomas E. Booth[4]
Michael R. James[5]
Michael L. Fensin[6]
Trevor A. Wilcox[7]
Brian C. Kiedrowski[8]

[1] XCP-3 Monte Carlo Methods, Codes, and Applications, Los Alamos National Laboratory
[2] NEN-5 Systems Design and Analysis, Los Alamos National Laboratory
[3] NEN-5 Systems Design and Analysis, Los Alamos National Laboratory, Guest Scientist
[4] XCP-3 Monte Carlo Methods, Codes, and Applications, Los Alamos National Laboratory, contractor
[5] C-NR Nuclear & Radiochemistry, Los Alamos National Laboratory
[6] W-13 Advanced Engineering Analysis, Los Alamos National Laboratory
[7] XTD –SS Safety & Surety, Los Alamos National Laboratory
[8] XCP-3 Monte Carlo Methods, Codes, and Applications, Los Alamos National Laboratory, Guest Scientist

History of the MCNP code development [1]



Reference:

[1] Avneet Sood, 2017. The Monte Carlo Method and MCNP-A Brief Review of Our 40 Year History, Presentation to the International Topical Meeting on Industrial Radiation and Radioisotope Measurement Applications Conference.

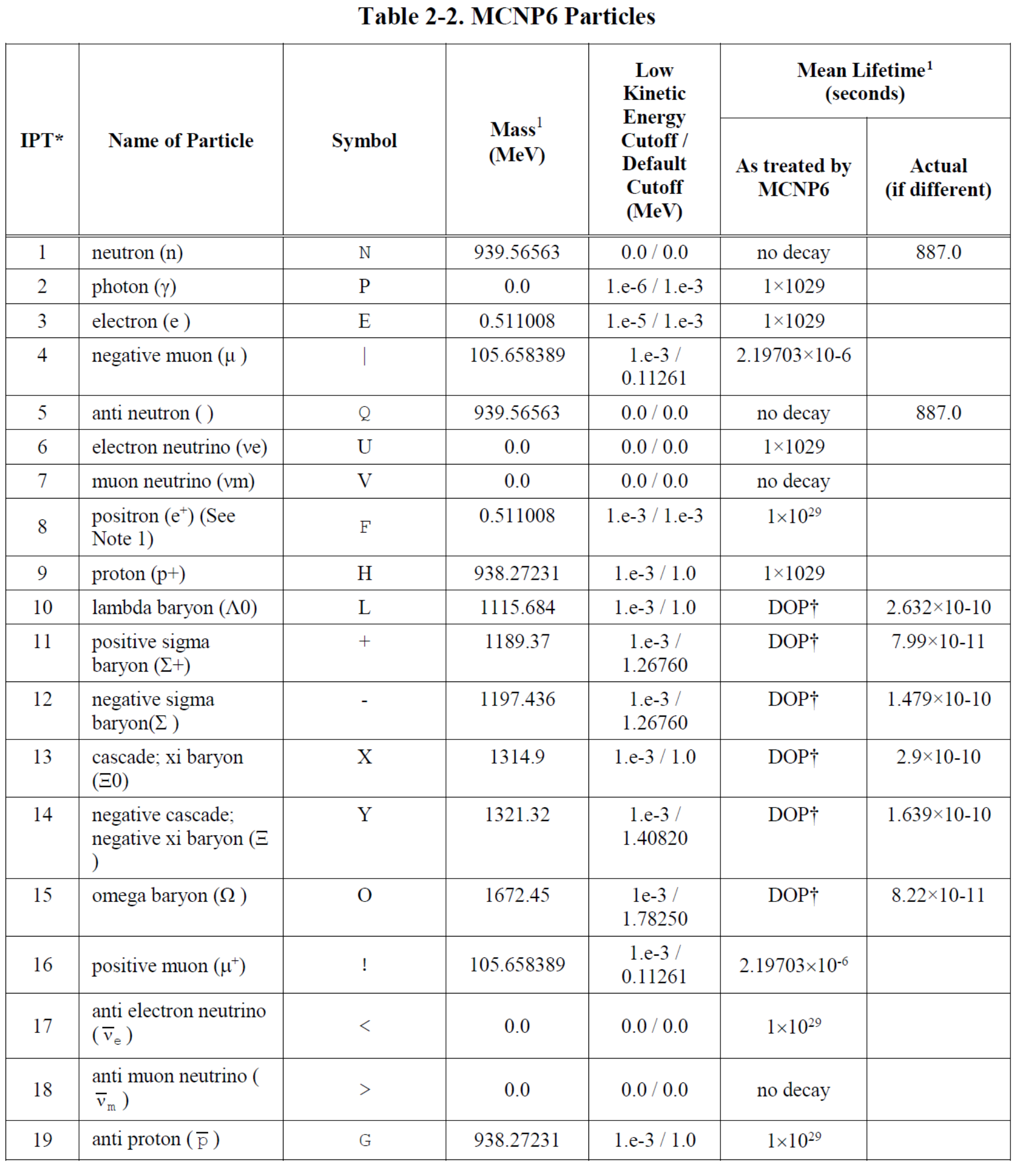
MCNP6 Versatility and Flexibility

- MCNP6 performs continuous-energy transport of 36 different particle types plus heavy-ion, fuel burnup, and high-fidelity delayed gamma emission. MCNP is written in Fortran 90, has been parallelized (OpenMP and MPI), and works on platforms including PCs, workstations, Linux clusters, and supercomputers.
- MCNP6 has thousands of MCNP users worldwide.

Examples of the MCNP6.2 applications:

- **Neutronics and nuclear reactor design**
- **Nuclear criticality safety**
- **Fusion neutronics**
- **Transmutation, activation, and burnup in reactor and other systems**
- Nuclear safeguards
- Medical physics, especially proton and neutron therapy
- Design of accelerator spallation targets, particularly for neutron scattering facilities
- Investigations for accelerator isotope production and destruction programs, including the transmutation of nuclear waste
- Research into accelerator-driven energy sources
- Accelerator based imaging technology such as neutron and proton radiography
- Detection technology using charged particles via active interrogation
- Design of shielding in accelerator facilities
- Activation of accelerator components and surrounding groundwater and air
- High-energy dosimetry and neutron detection
- Investigations of cosmic-ray radiation backgrounds and shielding for high altitude aircraft and spacecraft
- Single-event upset in semiconductors from cosmic rays in spacecraft or from the neutron component on the earth’s surface
- Analysis of cosmo-chemistry experiments, such as Mars Odyssey
- Charged-particle propulsion concepts for spaceflight
- Investigation of fully coupled neutron and charged-particle transport for lower-energy applications
- Nuclear material detection
- Design of neutrino experiments

Particles transported by MCNP6. As listed in Chapter 2 of the MCNP® 6.2 USER'S MANUAL, October 27, 2017



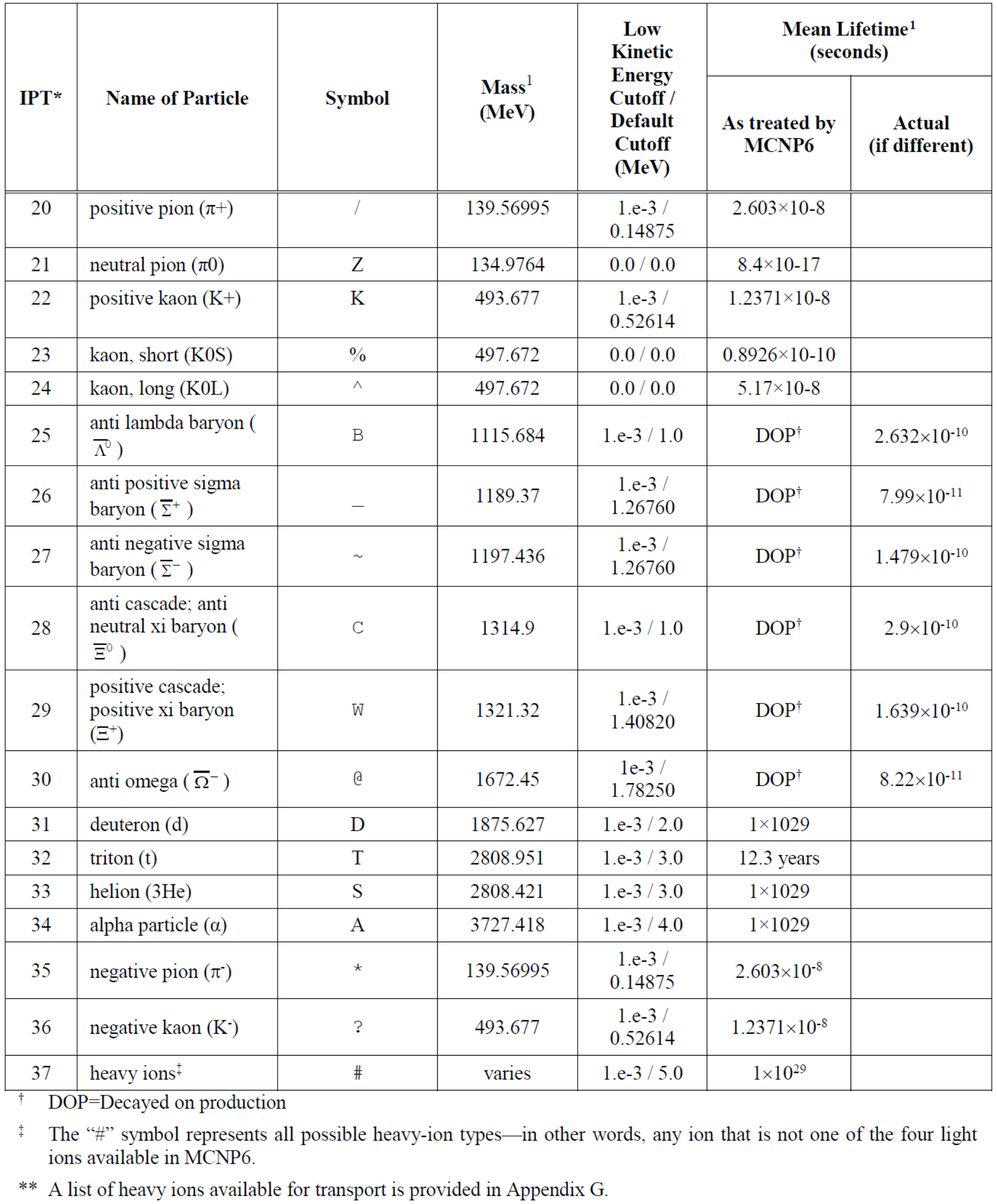


Table 2-2. MCNP6 Particles

IPT*	Name of Particle	Symbol	Mass[1] (MeV)	Low Kinetic Energy Cutoff / Default Cutoff (MeV)	Mean Lifetime[1] (seconds)	
					As treated by MCNP6	Actual (if different)
1	neutron (n)	N	939.56563	0.0 / 0.0	no decay	887.0
2	photon (γ)	P	0.0	1.e-6 / 1.e-3	1×1029	
3	electron (e)	E	0.511008	1.e-5 / 1.e-3	1×1029	
4	negative muon (μ)	|	105.658389	1.e-3 / 0.11261	2.19703×10-6	
5	anti neutron ( )	Q	939.56563	0.0 / 0.0	no decay	887.0
6	electron neutrino (νe)	U	0.0	0.0 / 0.0	1×1029	
7	muon neutrino (νm)	V	0.0	0.0 / 0.0	no decay	
8	positron (e^+) (See Note 1)	F	0.511008	1.e-3 / 1.e-3	1×10^{29}	
9	proton (p+)	H	938.27231	1.e-3 / 1.0	1×1029	
10	lambda baryon (Λ0)	L	1115.684	1.e-3 / 1.0	DOP†	2.632×10-10
11	positive sigma baryon (Σ+)	+	1189.37	1.e-3 / 1.26760	DOP†	7.99×10-11
12	negative sigma baryon(Σ)	-	1197.436	1.e-3 / 1.26760	DOP†	1.479×10-10
13	cascade; xi baryon (Ξ0)	X	1314.9	1.e-3 / 1.0	DOP†	2.9×10-10
14	negative cascade; negative xi baryon (Ξ)	Y	1321.32	1.e-3 / 1.40820	DOP†	1.639×10-10
15	omega baryon (Ω)	O	1672.45	1e-3 / 1.78250	DOP†	8.22×10-11
16	positive muon (μ^+)	!	105.658389	1.e-3 / 0.11261	2.19703×10^{-6}	
17	anti electron neutrino ($\overline{\nu}_e$)	<	0.0	0.0 / 0.0	1×10^{29}	
18	anti muon neutrino ($\overline{\nu}_m$)	>	0.0	0.0 / 0.0	no decay	
19	anti proton ($\overline{p}$)	G	938.27231	1.e-3 / 1.0	1×10^{29}	
20	positive pion (π+)	/	139.56995	1.e-3 / 0.14875	2.603×10-8	
21	neutral pion (π0)	Z	134.9764	0.0 / 0.0	8.4×10-17	
22	positive kaon (K+)	K	493.677	1.e-3 / 0.52614	1.2371×10-8	
23	kaon, short (K0S)	%	497.672	0.0 / 0.0	0.8926×10-10	
24	kaon, long (K0L)	^	497.672	0.0 / 0.0	5.17×10-8	
25	anti lambda baryon ($\overline{\Lambda}^0$)	B	1115.684	1.e-3 / 1.0	DOP†	2.632×10^{-10}
26	anti positive sigma baryon ($\overline{\Sigma}^+$)	_	1189.37	1.e-3 / 1.26760	DOP†	7.99×10^{-11}
27	anti negative sigma baryon ($\overline{\Sigma}^-$)	~	1197.436	1.e-3 / 1.26760	DOP†	1.479×10^{-10}
28	anti cascade; anti neutral xi baryon ($\overline{\Xi}^0$)	C	1314.9	1.e-3 / 1.0	DOP†	2.9×10^{-10}
29	positive cascade; positive xi baryon (Ξ^+)	W	1321.32	1.e-3 / 1.40820	DOP†	1.639×10^{-10}
30	anti omega ($\overline{\Omega}^-$)	@	1672.45	1e-3 / 1.78250	DOP†	8.22×10^{-11}
31	deuteron (d)	D	1875.627	1.e-3 / 2.0	1×1029	
32	triton (t)	T	2808.951	1.e-3 / 3.0	12.3 years	
33	helion (3He)	S	2808.421	1.e-3 / 3.0	1×1029	
34	alpha particle (α)	A	3727.418	1.e-3 / 4.0	1×1029	
35	negative pion (π^-)	*	139.56995	1.e-3 / 0.14875	2.603×10^{-8}	
36	negative kaon (K^-)	?	493.677	1.e-3 / 0.52614	1.2371×10^{-8}	
37	heavy ions‡	#	varies	1.e-3 / 5.0	1×10^{29}	

† DOP=Decayed on production

‡ The "#" symbol represents all possible heavy-ion types—in other words, any ion that is not one of the four light ions available in MCNP6.

** A list of heavy ions available for transport is provided in Appendix G.

MCHIFI: Development of the On-The-Fly (OTF) MC variance reduction technique

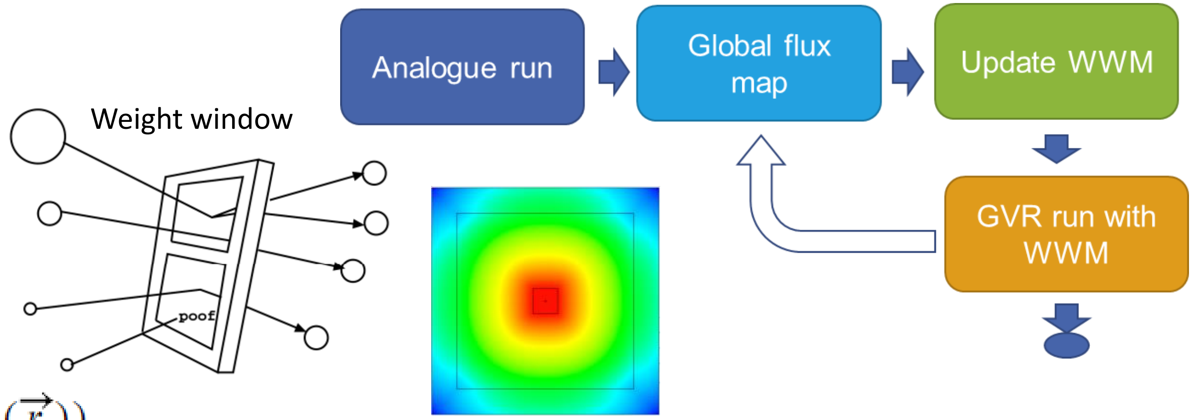
- **OTF-GVR**: On-The-Fly Global Variance Reduction:
  - Weight windows mesh (WWM) is a common method used for MC shielding calculation.
  - OTF performs “on-the-fly” iterations to get a global flux map and a weight-window mesh (WWM).
  - OTF uses novel dynamic WW upper bound method to solve the neutron streaming and “long-history” particles
  - Compared with ADVANTG, the Figure-of-Merit in OTF is raised by a **factor of 20**

OTF-GVR:

$$n(\vec{r}) \approx m(\vec{r})\bar{w}(\vec{r})$$

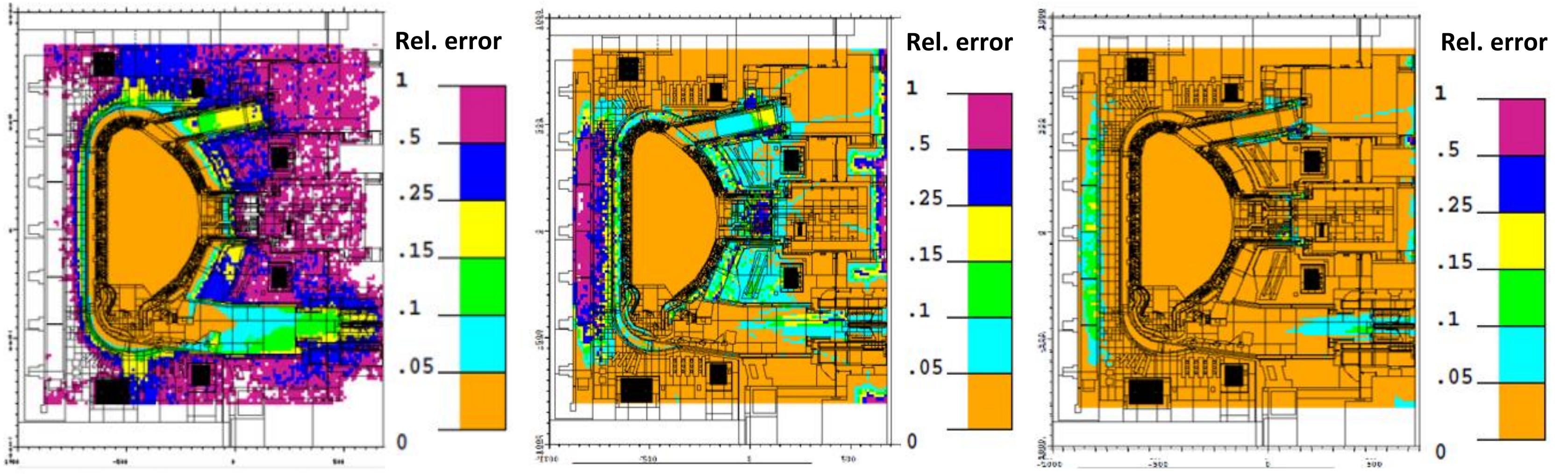
$$\bar{w}(\vec{r}) = \phi(\vec{r})/\max(\phi(\vec{r})) \Rightarrow \bar{w}(\vec{r}) = c \times \phi(\vec{r})/\max(\phi(\vec{r}))$$

Definition of “c” to avoid “long-history” by limiting the n, p particles splitting in the OTF run in Ref. [Yu Zheng, Yuefeng Qiu, et al., “An improved on-the-fly global variance reduction technique by automatically updating weight window values for Monte Carlo shielding calculation”, Fusion Eng. Des. 147 (2019) 111238, https://doi.org/10.1016/j.fusengdes.2019.06.011]

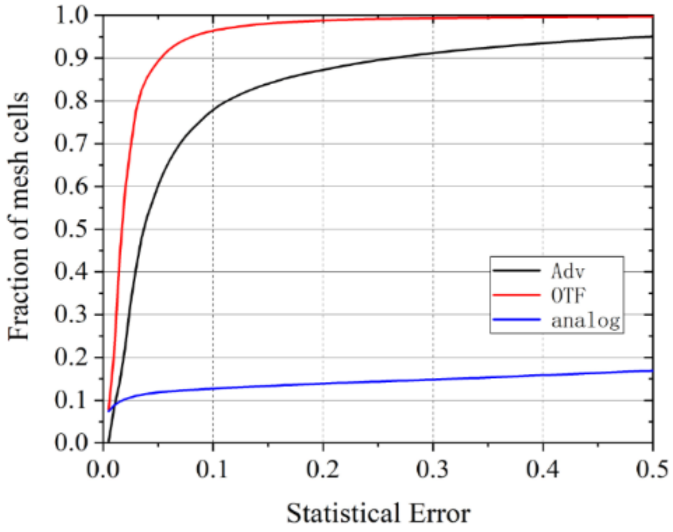


On-the-fly Global weight window mesh generation

Comparison of the MC statistical precision of the neutronics results indicated by relative error maps: MCNP vs. OTF



Analogue MCNP **MCNP - ADVANTG (ORNL) WWM** **OTF-GVR**



Percentage of mesh cells and rel. error

Ref.: [Yu Zheng et al 2022 Nucl. Fusion 62 086036, https://doi.org/10.1088/1741-4326/ac75fc]

Part II

Application of the EUROfusion Marconi-Fusion HPC **MCHIFI** project for solving the IFMIF-DONES radiation shielding tasks

DONES Working Group, IFMIF-DONES España to build the DONES facility

The International Fusion Materials Irradiation Facility – DEMO Oriented NEutron Source (IFMIF-DONES). DEMO is a demonstration fusion reactor prototype. In relation to this international project, in Dec. 2017, Fusion for Energy (F4E) evaluated positively the joint Spain-Croatia proposal **to site the IFMIF-DONES in Granada, Spain.**

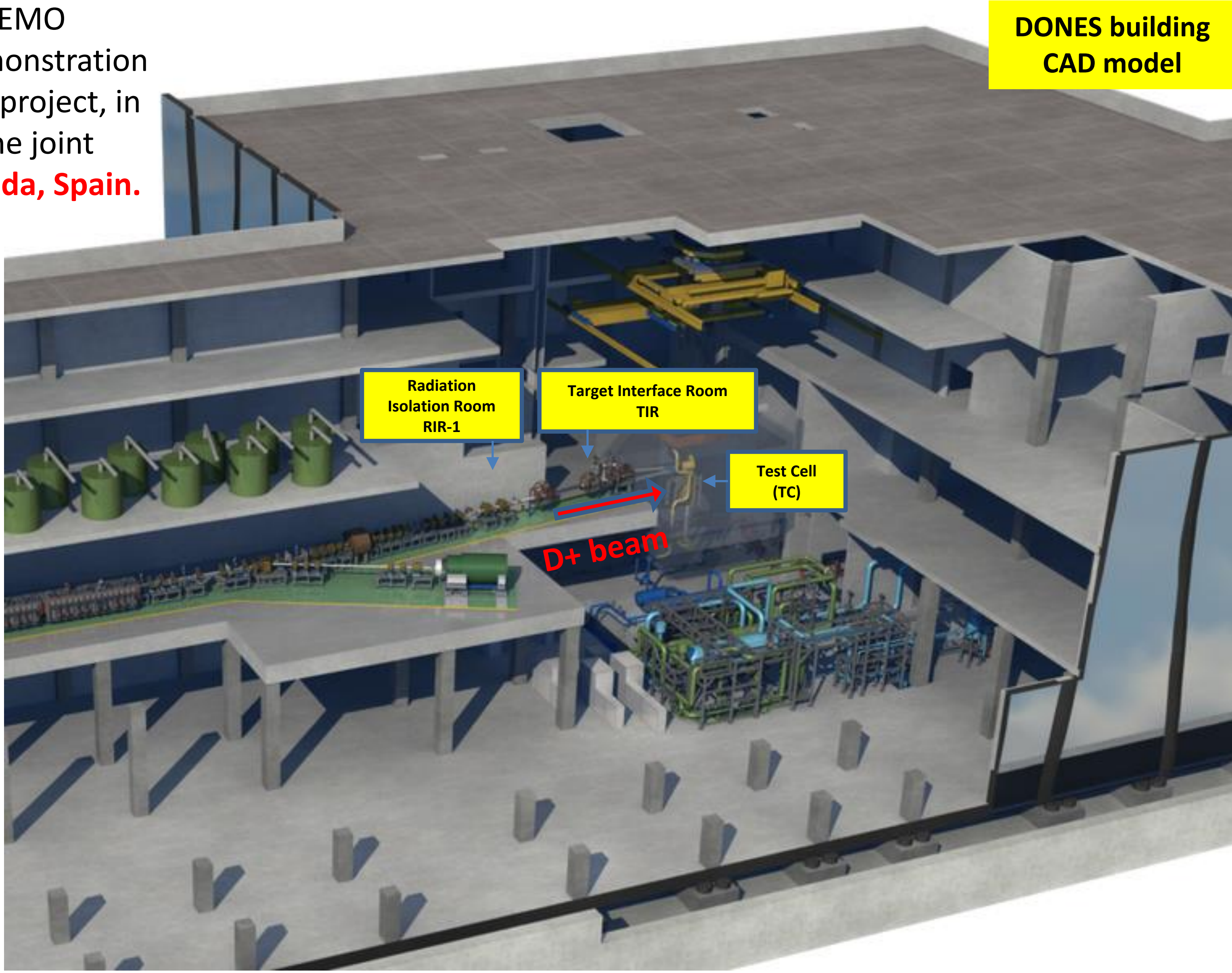
Countries and Organizations involved in the DONES Working Group
Hungary
Croatia
Italy
Spain
Germany
Slovenia
Denmark
Greece
Finland
Sweden
Lithuania
Estonia
France
F4E - Support
EUROfusion - Observer
DG-ENER - Lead
DG-RTD - Observer

EURATOM (DG-ENER) organized a Working Group with Spain, Croatia and other EU countries supported by F4E to initiate the IFMIF-DONES project. Updates of the IFMIF-DONES: https://ifmif-dones.es/

In 2021 the **IFMIF-DONES España** consortium of the Spain General State Administration and the Autonomous Community of Andalusia established to provide the IFMIF-DONES facility design, construction, and operation.

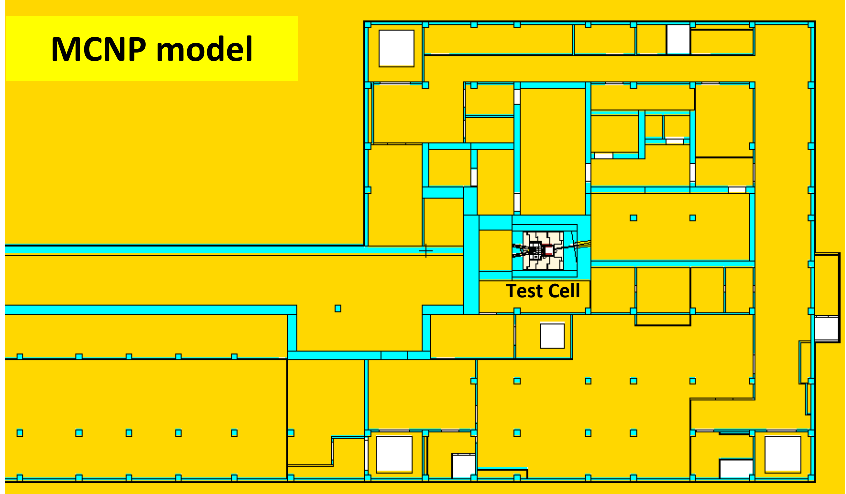
The IFMIF-DONES facility **construction began in 2022**, its commissioning is planned for 2029, and the first results are expected to be obtained in 2035.

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
+
Junta de Andalucía
→
IFMIF-DONES ESPAÑA

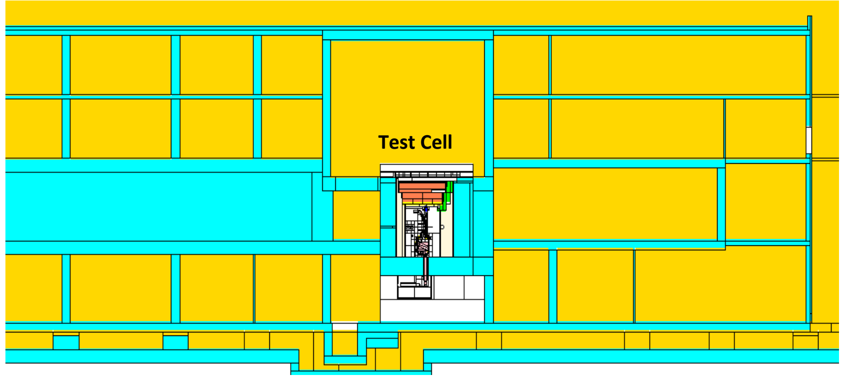


IFMIF-DONES geometry CAD-to-MCNP conversion

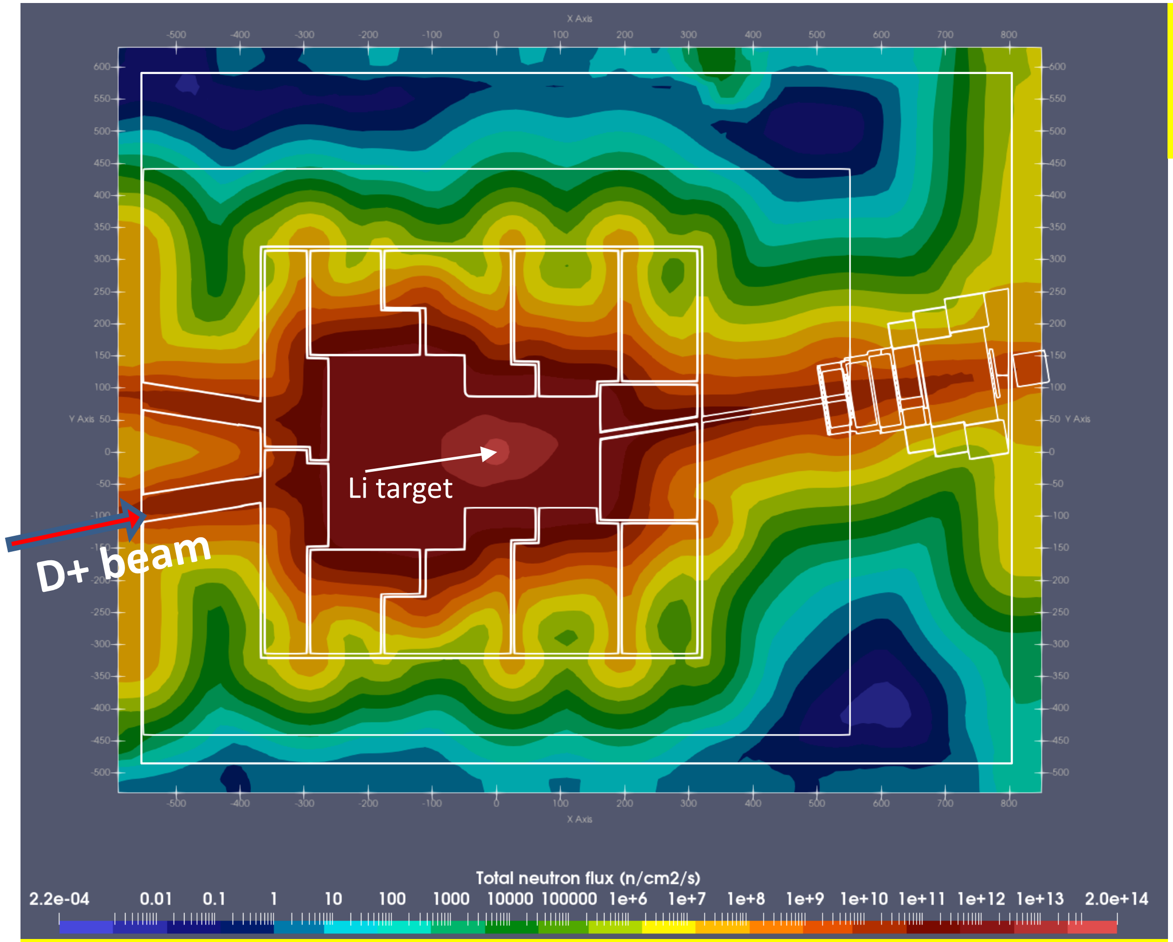
- The CAD model of IFMIF-DONES building is properly prepared to be used with the MCNP code. The geometry of each component of the building was simplified and decomposed into a number of simple primitive blocks. Then the CAD model is converted into MCNP model and fill into the separate envelope using the MCNP universe card. The CAD-to-MCNP conversion is performed using **McCad and SuperMC programs.**



DONES building model horizontal cut at the beam level



DONES building model vertical cut at the target center

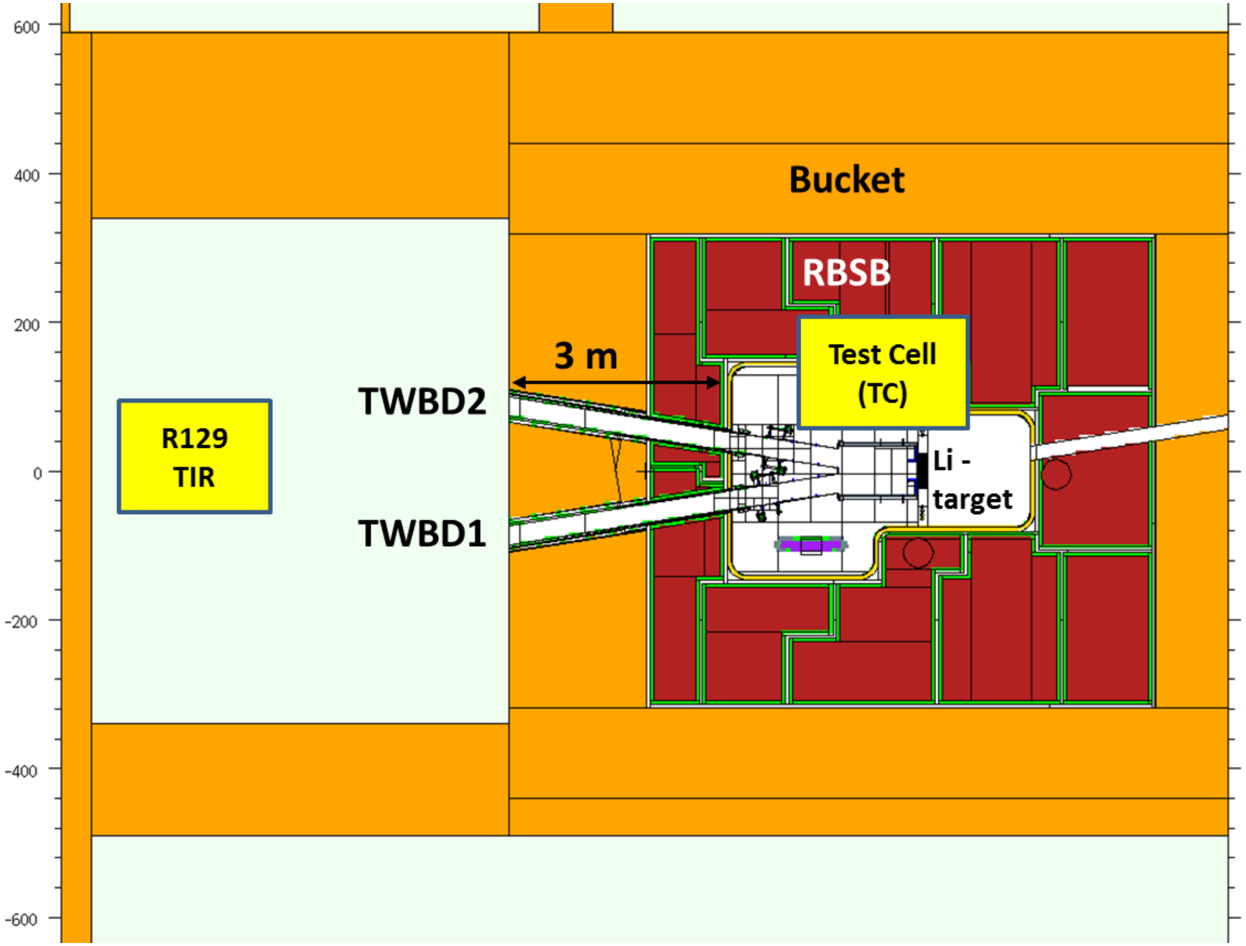


MCNP model of the DONES Test Cell

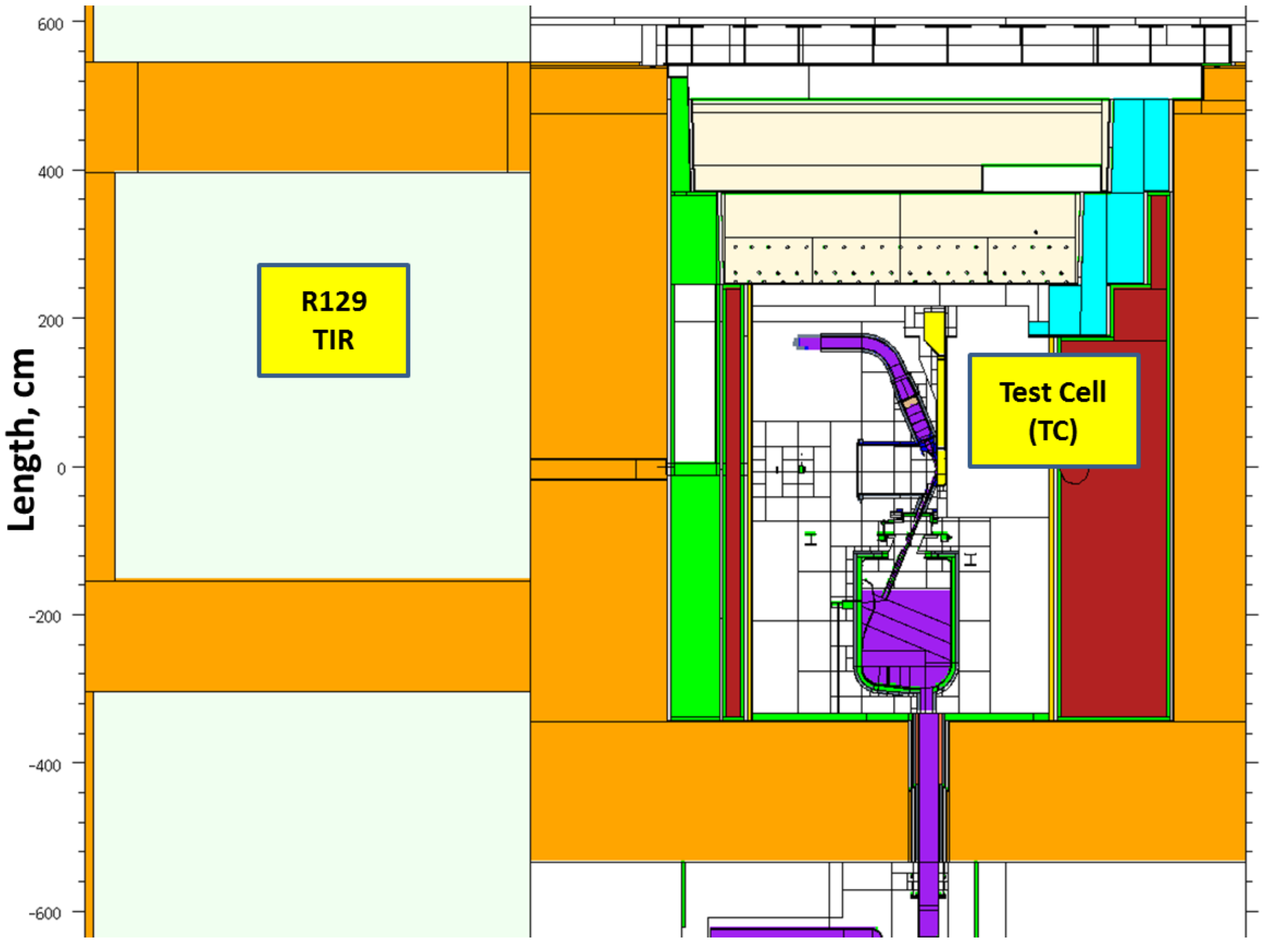
Total n-flux mapped at the horizontal cut of the DONES Test Cell

Neutronics modeling of the IFMIF-DONES

The neutron and photon radiation transport was performed by the **McDeLicious** code package – an **MCNP** source extension that simulates the deuteron-lithium (d-Li) nuclear reactions in Li of Test Cell. The neutron cross-sections library FENDL-3.1d used in calculations. The neutronics results were normalized to a 125 mA deuteron beam of 40 MeV deuterons impinging the Li target.

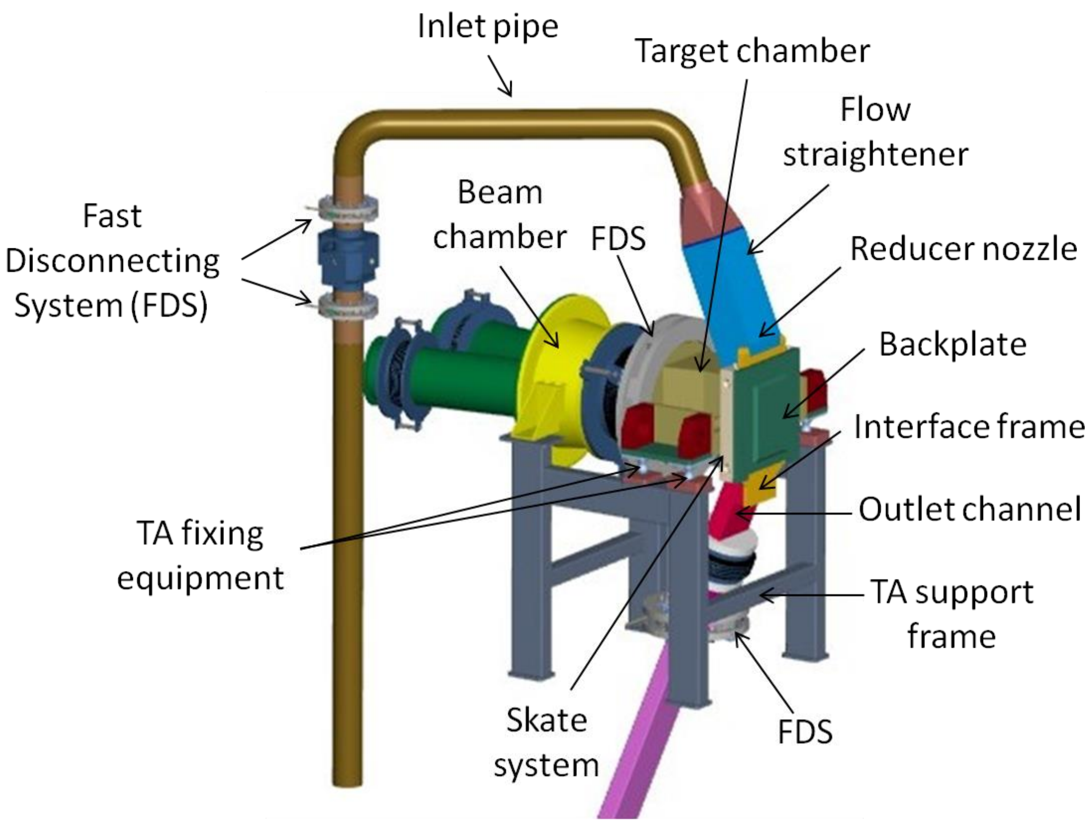


MCNP model horizontal cut at the center of the Li target and two TWBD beam ducts.

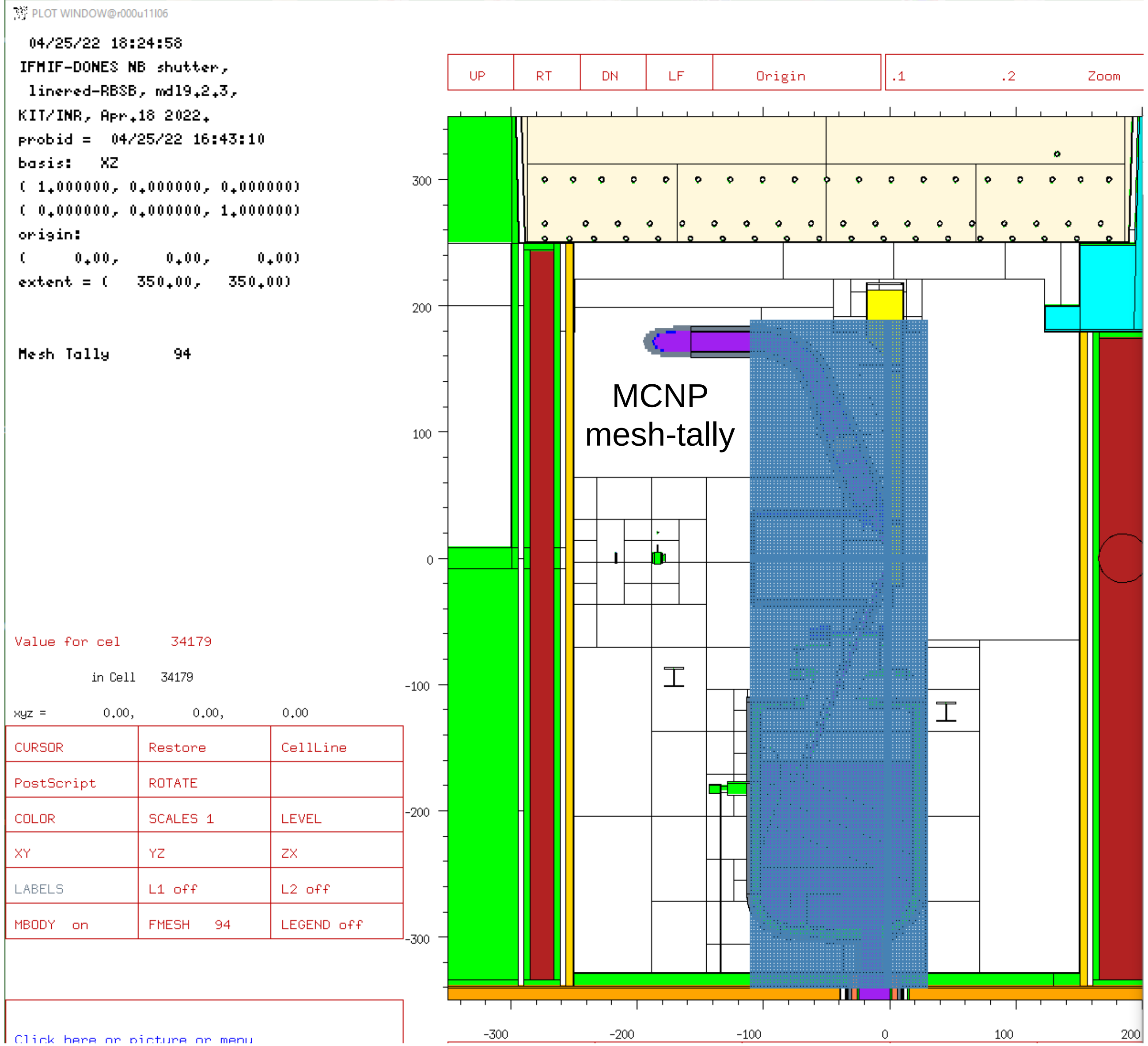


MCNP model vertical cut throught the center of the Li target.
The spacial dimension of the model is given in the length scale [cm].

MCNP modeling of the d-Li source Target Assembly (TA) in DONES



DONES Target Assembly (TA) components



```
 04/25/22 18:24:58
IFMIF-DONES NB shutter,
 linered-RBSB, md19.2.3,
KIT/INR, Apr.18 2022.
probid =  04/25/22 16:43:10
basis:   XZ
( 1.000000, 0.000000, 0.000000)
( 0.000000, 0.000000, 1.000000)
origin:
(      0.00,      0.00,      0.00)
extent = (    350.00,    350.00)


Mesh Tally       94
```

```
Value for cel       34179

           in Cell     34179

xyz =          0.00,          0.00,          0.00
```

MCNP model vertical cut of the DONES TA covered with mesh-tally

Nuclear heat density (W/cc) in the TA materials of the MCNP model

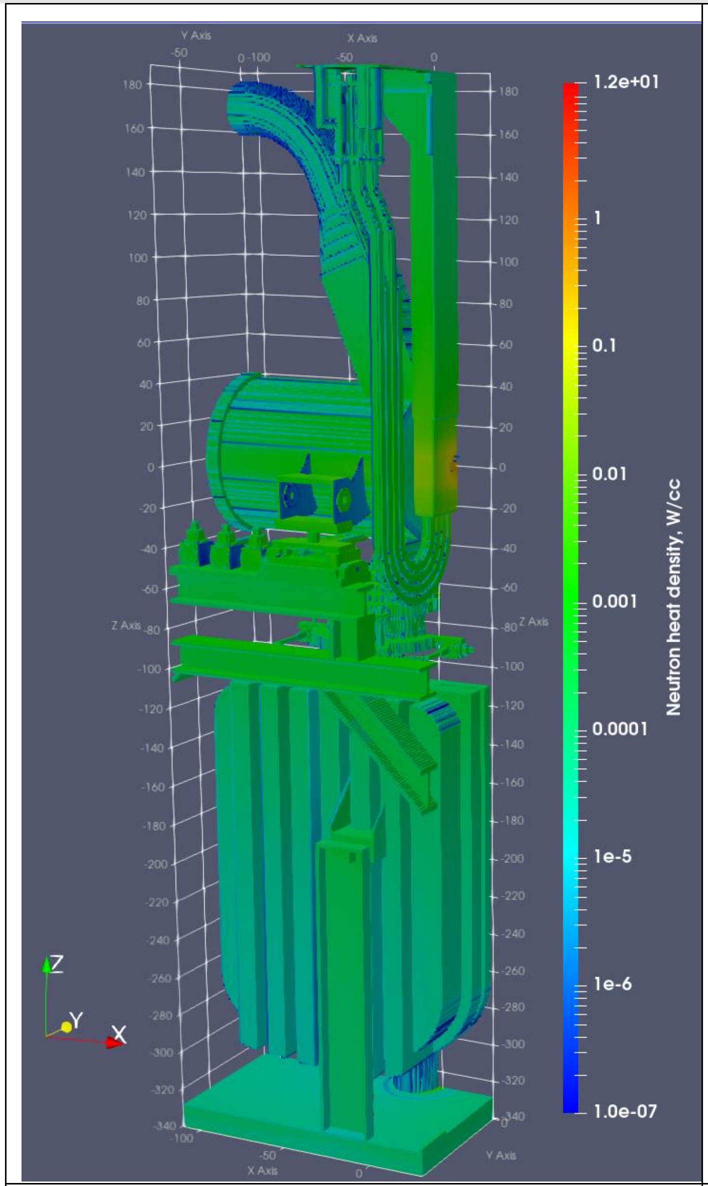


Fig. 1. Neutron heat density (W/cc) in actual materials of the MCNP model – look from the outside.

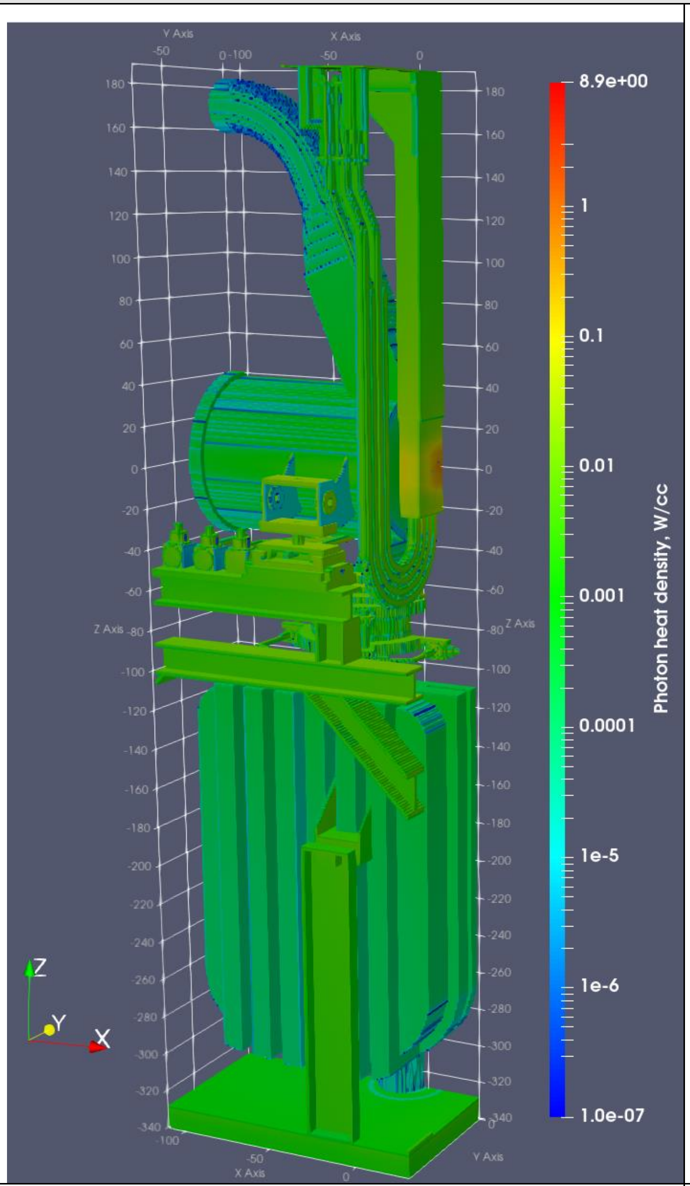


Fig. 2. Photon heat density (W/cc) in actual materials of the MCNP model – look from the outside.

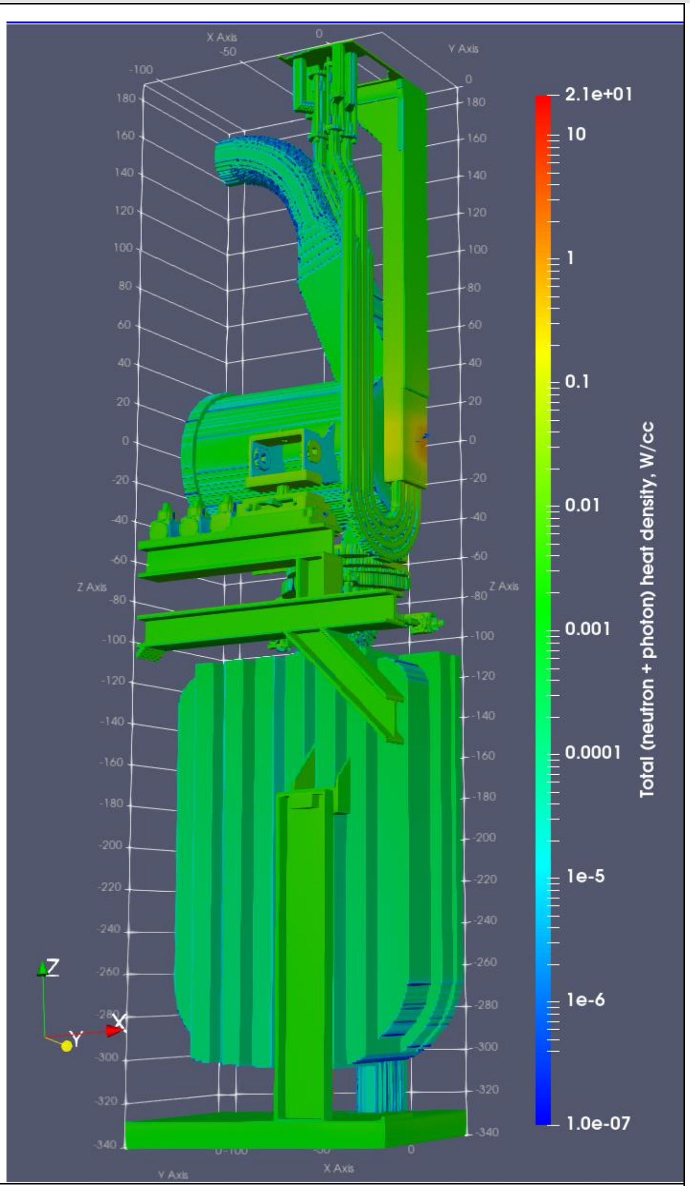


Fig. 3. Total (neutron + photon) heat density (W/cc) in actual materials of the model – look from the outside.

TA materials:

Steel SS316L material density 7.93 g/cc

EUROFER steel with density 7.87 g/cc

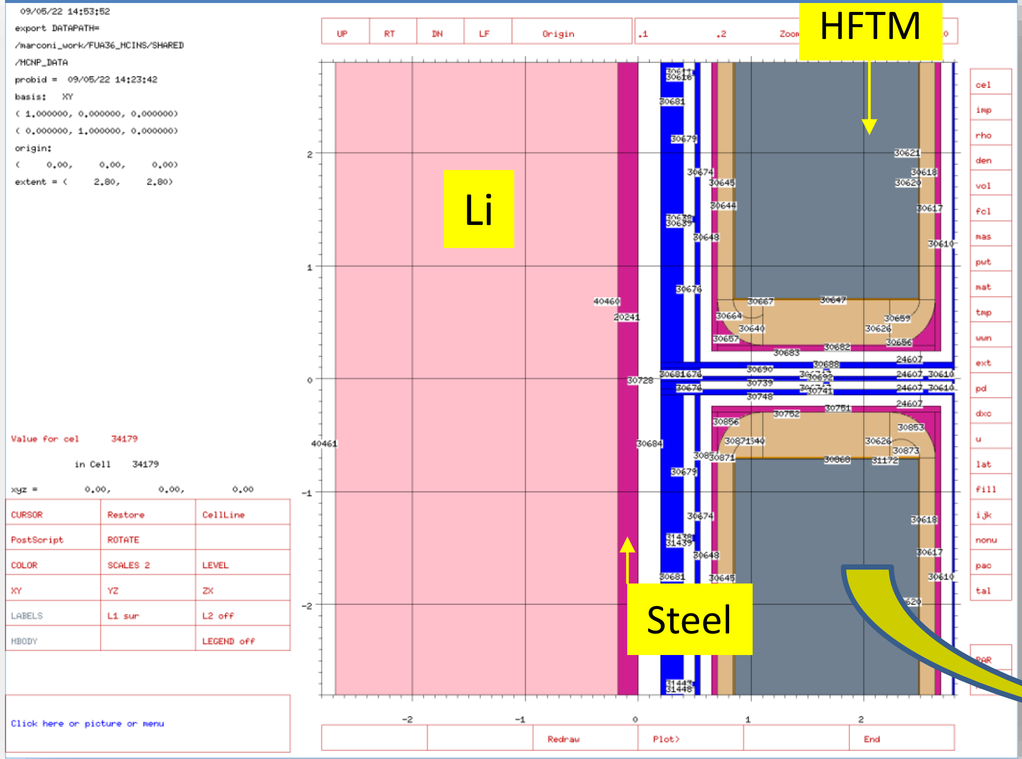
Lithium (Li) with impurities, its density is 0.512 g/cc.

Heating in Li jet at the area of deuteron footprint requires inclusion of the heat contributions of charged particles.

Deuteron beam energy deposition in the Li jet at the TA d-Li footprint area

- D+ ion beam stops in the lithium jet delivering a total power of 5 MW on a volume of 5×20×2.5 cm^3, with d-Li footprint area of 5x20 cm^2.
- Deuterons lose their energy in Li by interactions with Li electron clouds and nuclei – all the processes have been taken into account in the MCNP6 energy deposition calculations with the TMESH card.
- For calculation of deuteron beam energy deposition in Li at the d-Li footprint area, **transport of neutrons, photons, deuterons, and protons** – 4 particles have been transported with the MCNP6 mode **n p d h**

Horizontal cut of the MCNP6 geometry at d-Li footprint



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/MCNP_DATA
probid =  09/05/22 14:23:42
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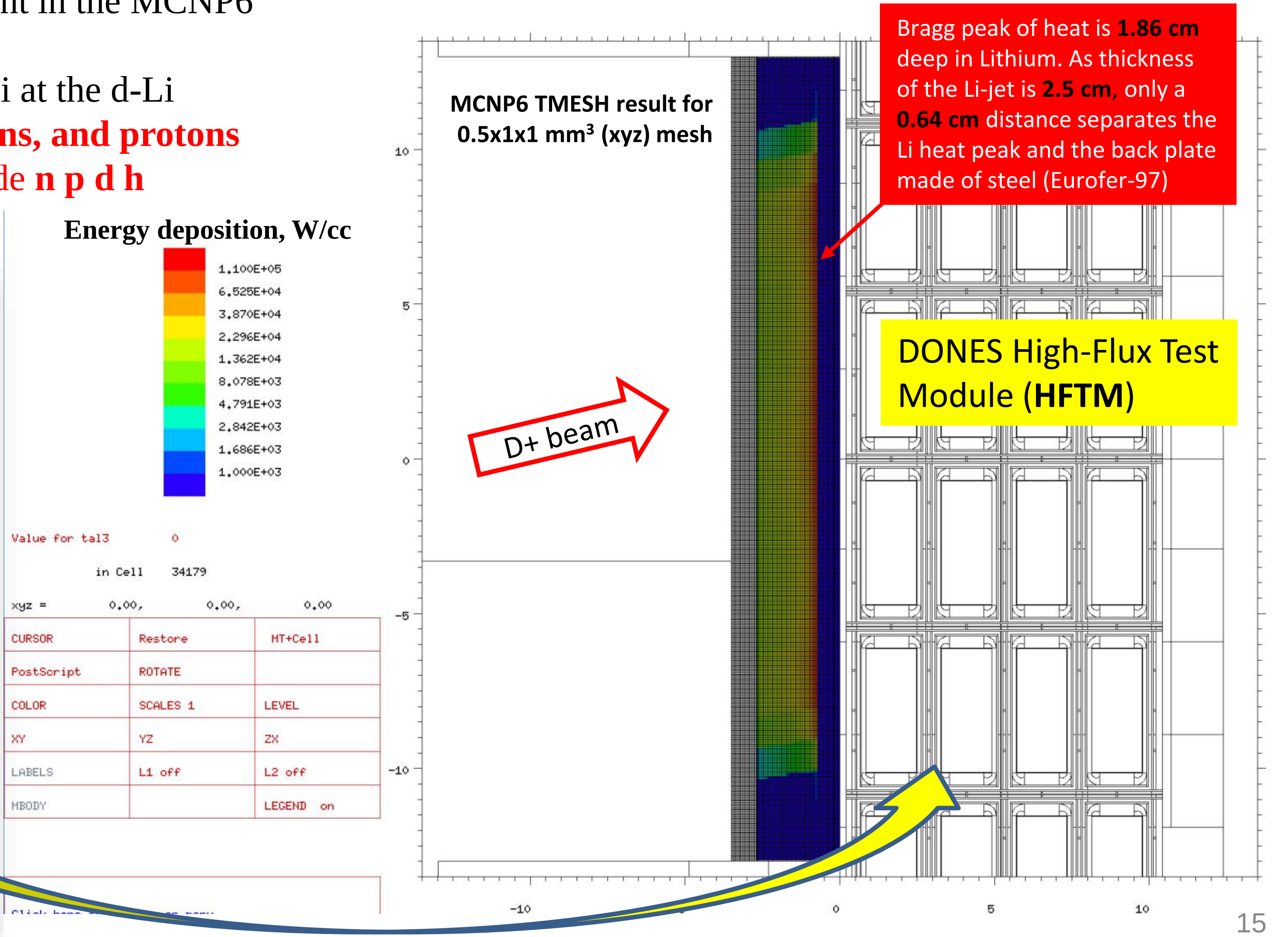
( 1.000000, 0.000000, 0.000000)
( 0.000000, 1.000000, 0.000000)
origin:
(     0.00,     0.00,     0.00)
extent = (     2.80,     2.80)

Value for cel      34179
          in Cell    34179
xyz =      0.00,      0.00,      0.00
```

MCNP6 horizontal cut of the D+ beam energy deposition at the d-Li footprint area with heat peak of 110 kW/cc



Energy deposition, W/cc

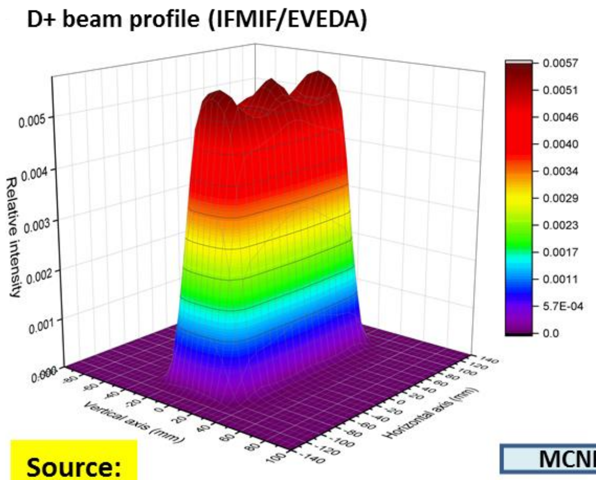
```
Value for tal3        0
          in Cell    34179
xyz =      0.00,      0.00,      0.00
```

MCNP6 TMESH result for 0.5x1x1 mm^3 (xyz) mesh

Bragg peak of heat is **1.86 cm** deep in Lithium. As thickness of the Li-jet is **2.5 cm**, only a **0.64 cm** distance separates the Li heat peak and the back plate made of steel (Eurofer-97)

DONES High-Flux Test Module (**HFTM**)

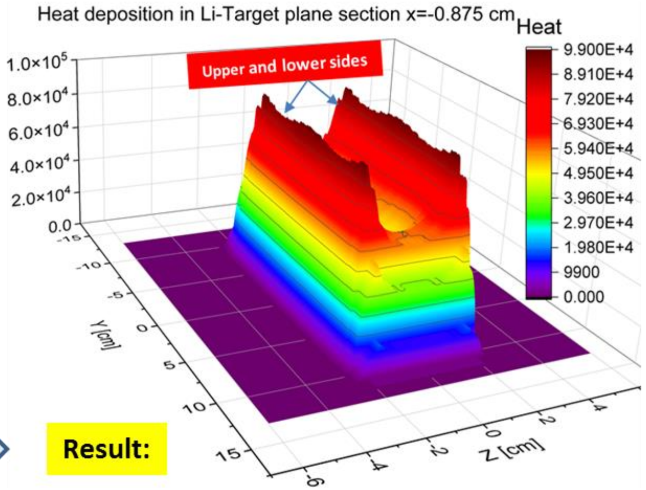
Deuteron beam energy deposition in the Lithium jet at the d-Li 20×5 cm^2 footprint area

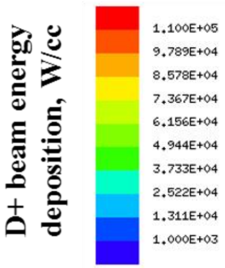


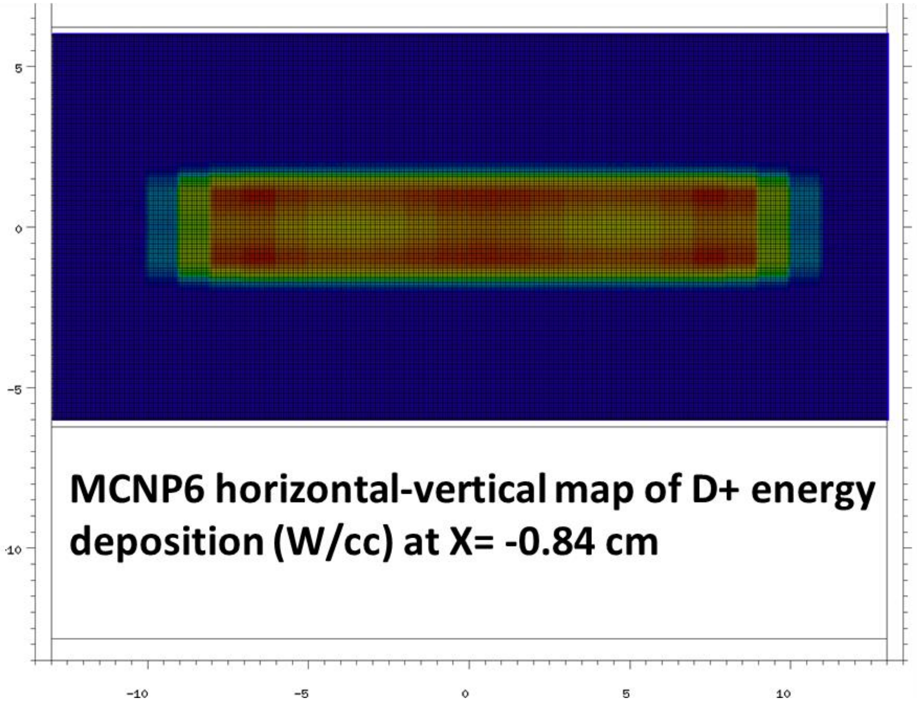
Source:

MCNP6 transport

Result:



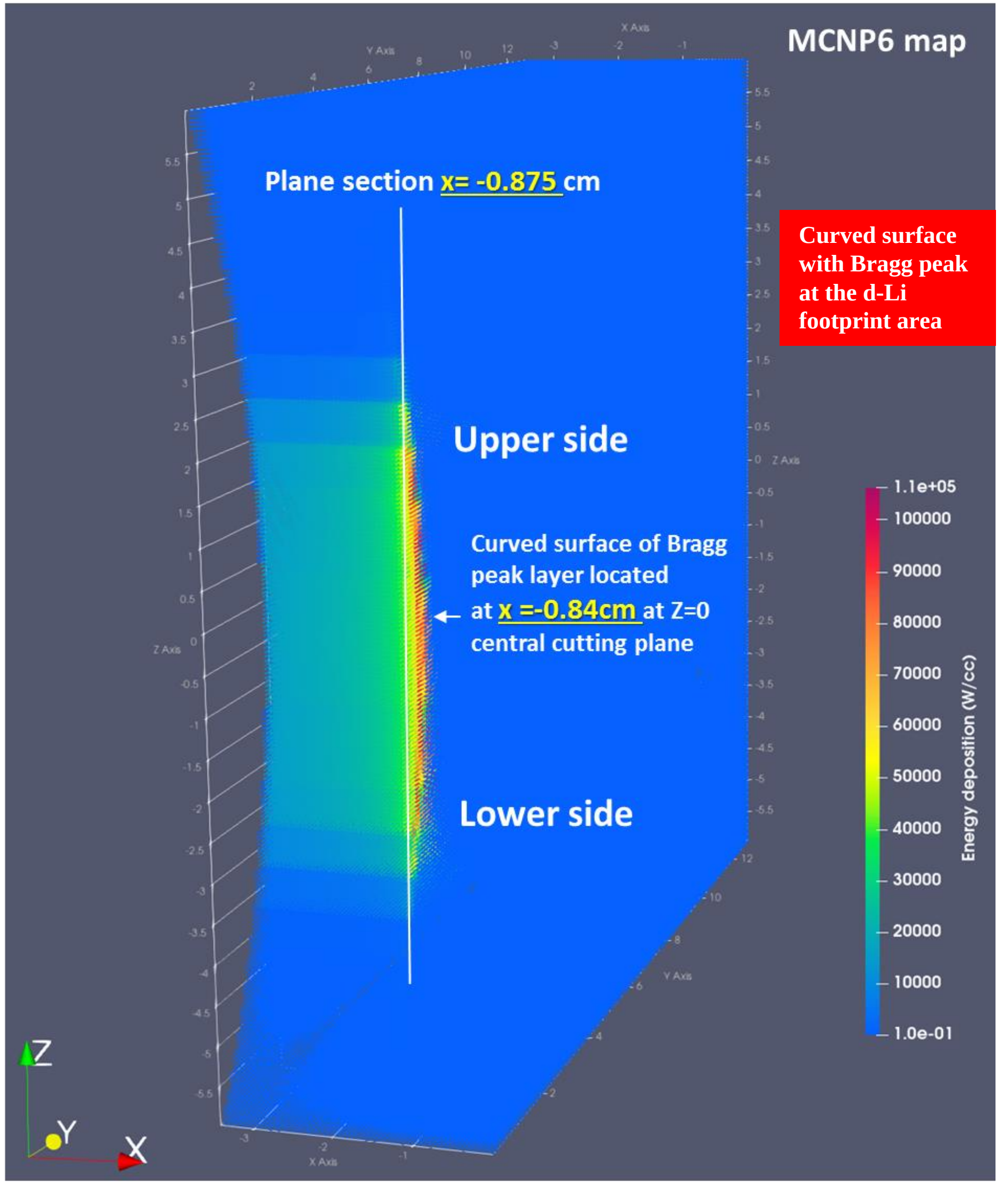




MCNP6 horizontal-vertical map of D+ energy deposition (W/cc) at X= -0.84 cm

Heat at peak is 110 kW/cc
Integral D+ heat 4.8 MW

Notice: Bragg peak at Lithium thickness of **1.86 cm** corresponds to **-0.84 cm** coordinate in the MCNP model geometry with X=0 at the TA back plate and X=-2.7cm is the front point of Li at Z=0 central plane: **1.86cm - 2.7cm = -0.84cm**



MCNP6 map

Plane section x= -0.875 cm

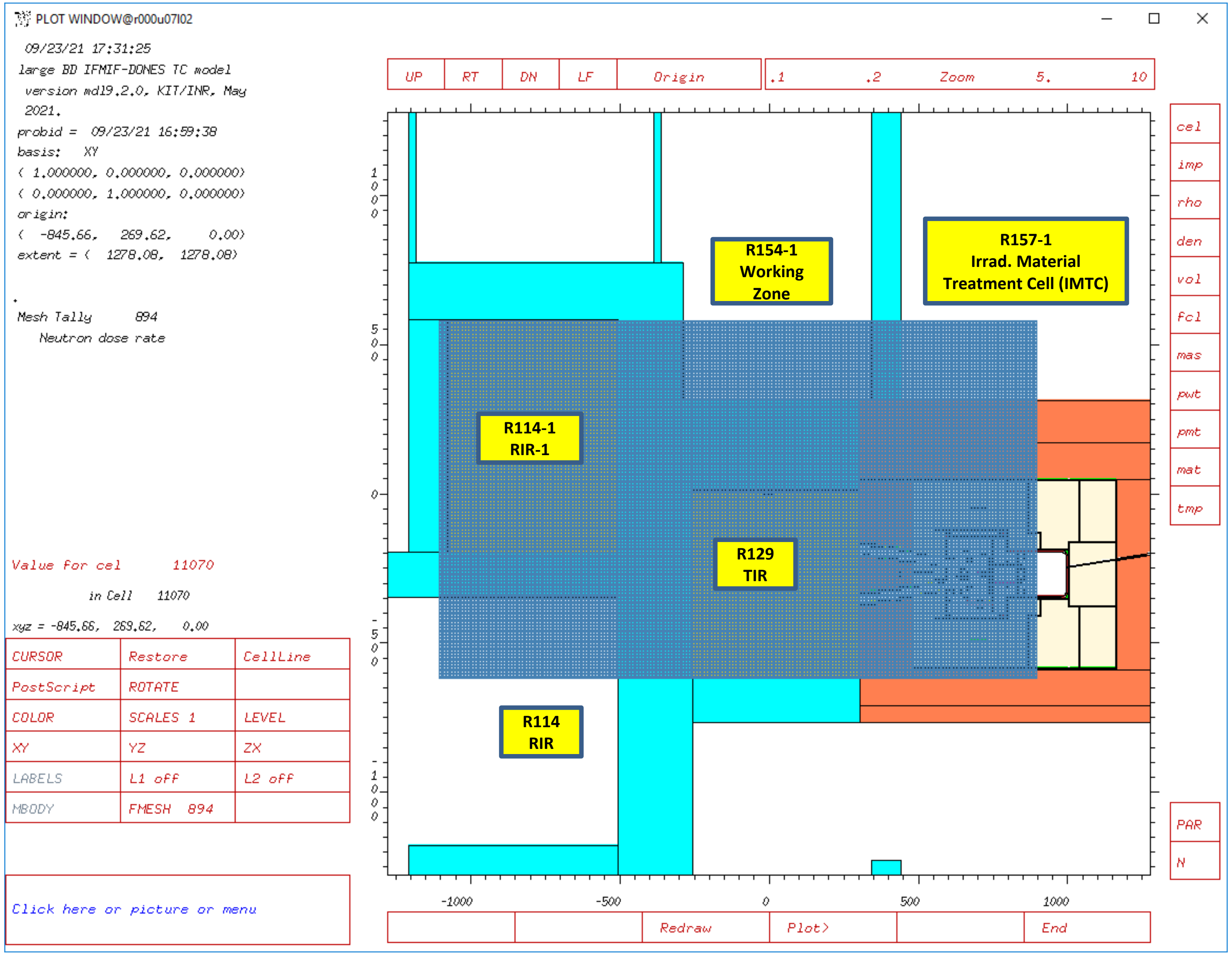
Upper side

Curved surface of Bragg peak layer located at x =-0.84cm at Z=0 central cutting plane

Lower side

Curved surface with Bragg peak at the d-Li footprint area

MCNP model mesh-tally for TIR and adjacent rooms



PLOT WINDOW@r000u07l02

```
 09/23/21 17:31:25
large BD IFMIF-DONES TC model
 version md19.2.0, KIT/INR, May
 2021.
probid =  09/23/21 16:59:38
basis:   XY
( 1.000000, 0.000000, 0.000000)
( 0.000000, 1.000000, 0.000000)
origin:
(  -845.66,   269.62,     0.00)
extent = (  1278.08,  1278.08)

Mesh Tally      894
   Neutron dose rate

Value for cel      11070

           in Cell    11070

xyz = -845.66,  269.62,    0.00
```

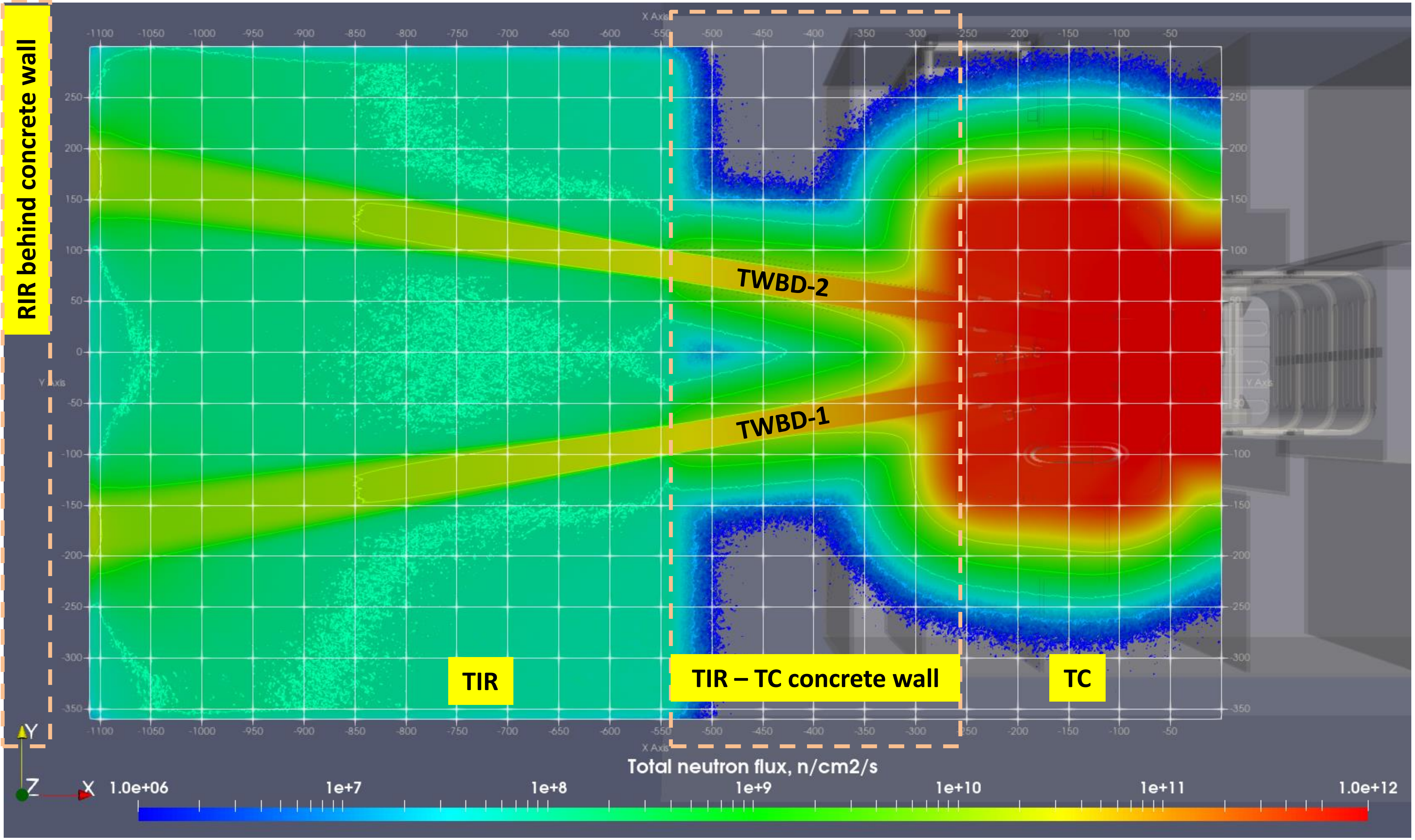
- In distributed memory MPI-jobs, simple MCNP models must fit in 4 GB RAM memory per each Marconi core: 4 GB/core * 48 cores/node = 192 GB/node of A3-SKL (Skylake) conventional partition.

- The reduced numbers of cores per node (~20 cores/node) must be set in the MPI MCNP runs due to the high memory consumption of the complex models with large mesh-tallies.

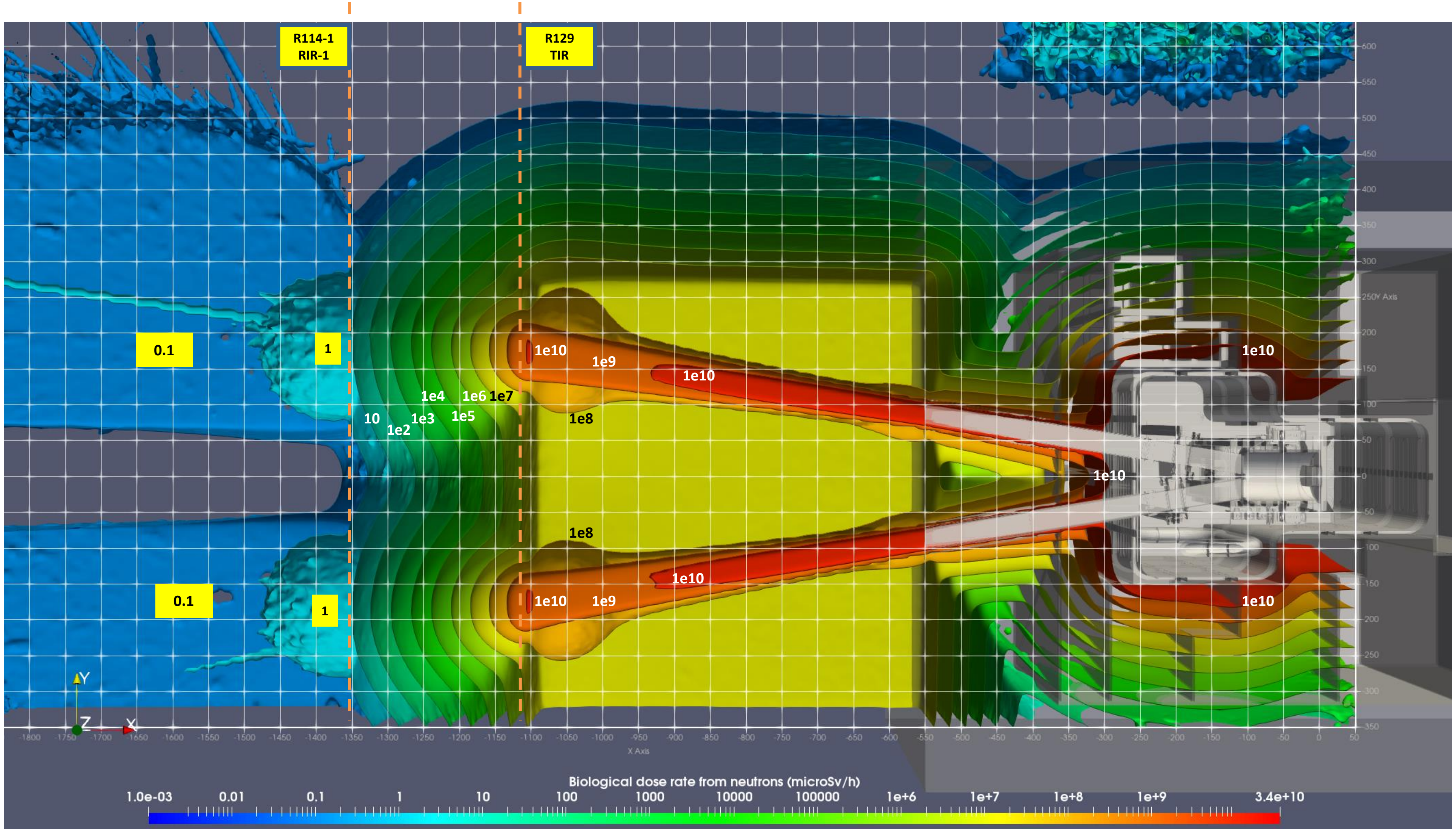
- For the results production we assumed middle-size MCNP model with averaged use of 10 nodes with 48 cores/node equalled to 480 cores of A3-SKL.

Total n-flux distribution in TC and empty TIR thresholded scale

Total n-flux calculated with d-Li source on scale from 1e6 to 1e12, with flux threshold at 1e6 n/cm2/s

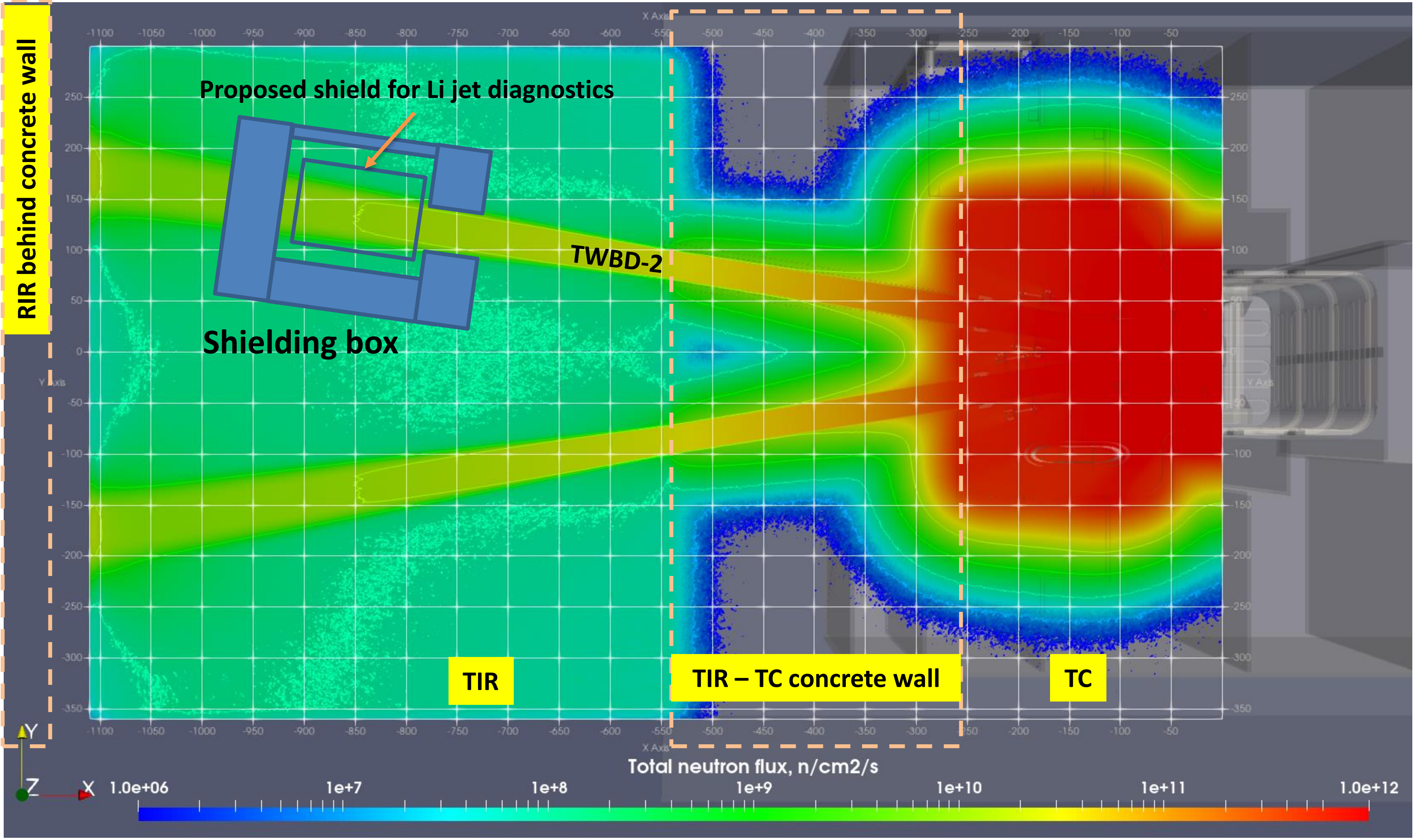


Empty TIR: map of biological dose rate (microSv/h) from neutrons. Top view.



Total n-flux distribution in TC and TIR – proposed shielding box

Total n-flux calculated with d-Li source on scale from 1e6 to 1e12, with flux threshold at 1e6 n/cm2/s


RIR behind concrete wall

Proposed shield for Li jet diagnostics

Shielding box

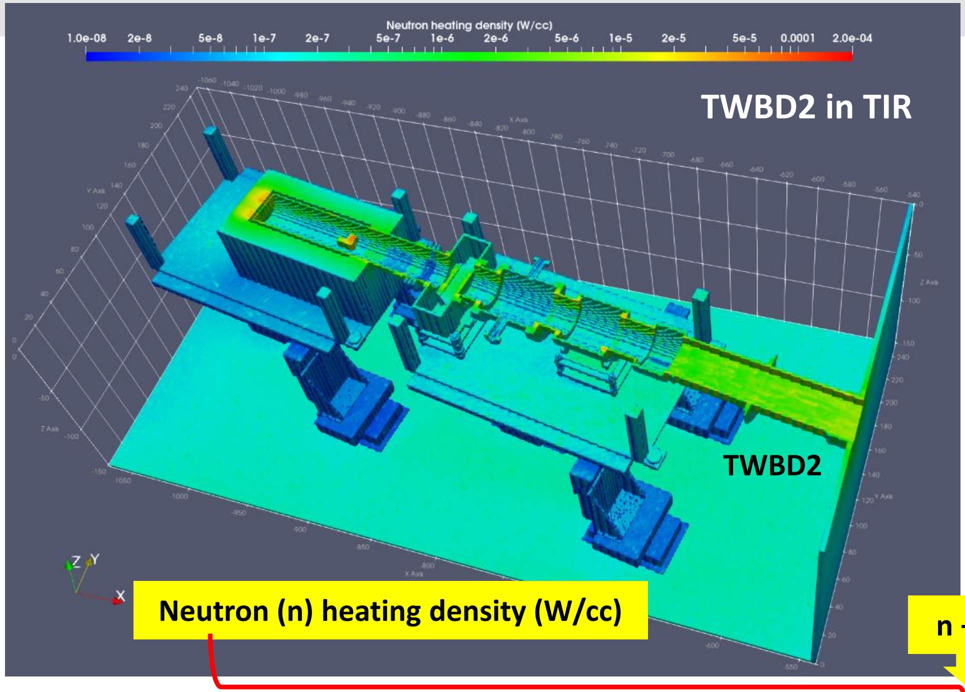
TWBD-2

TIR

TIR – TC concrete wall

TC

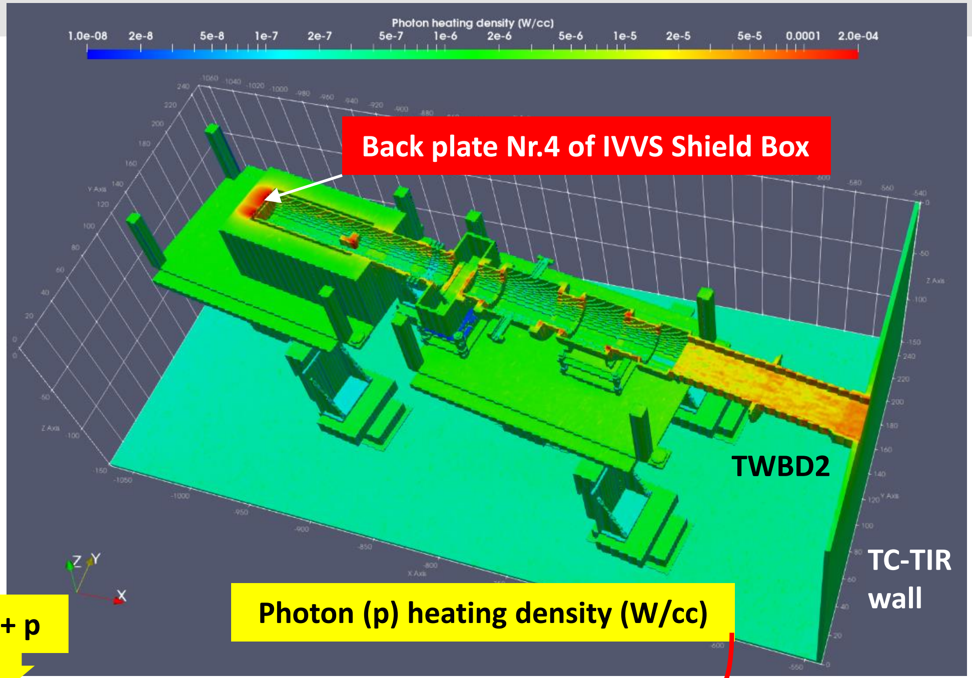
Neutron and photon heating contributors to nuclear heat density (W/cc)



TWBD2 in TIR

TWBD2

Neutron (n) heating density (W/cc)



Back plate Nr.4 of IVVS Shield Box

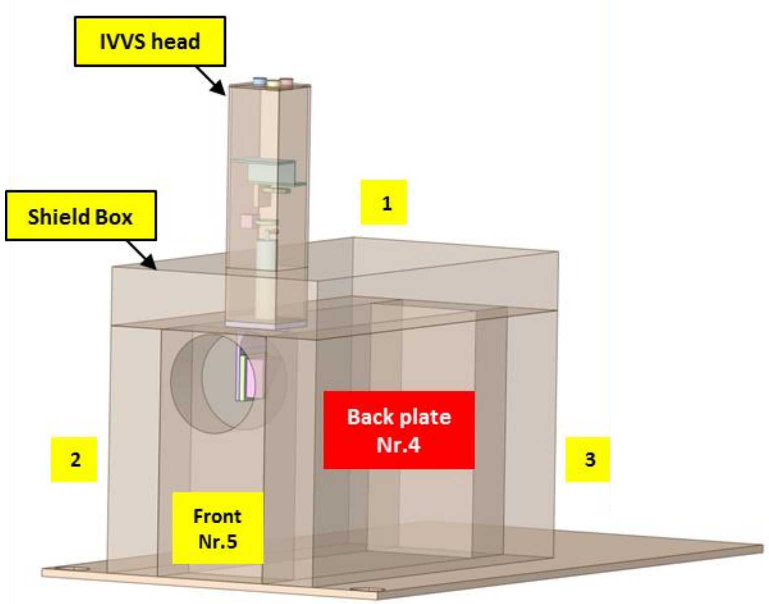
TWBD2

TC-TIR wall

Photon (p) heating density (W/cc)

n + p

Thickness of the Shield Box plates = 15 cm



IVVS head

Shield Box

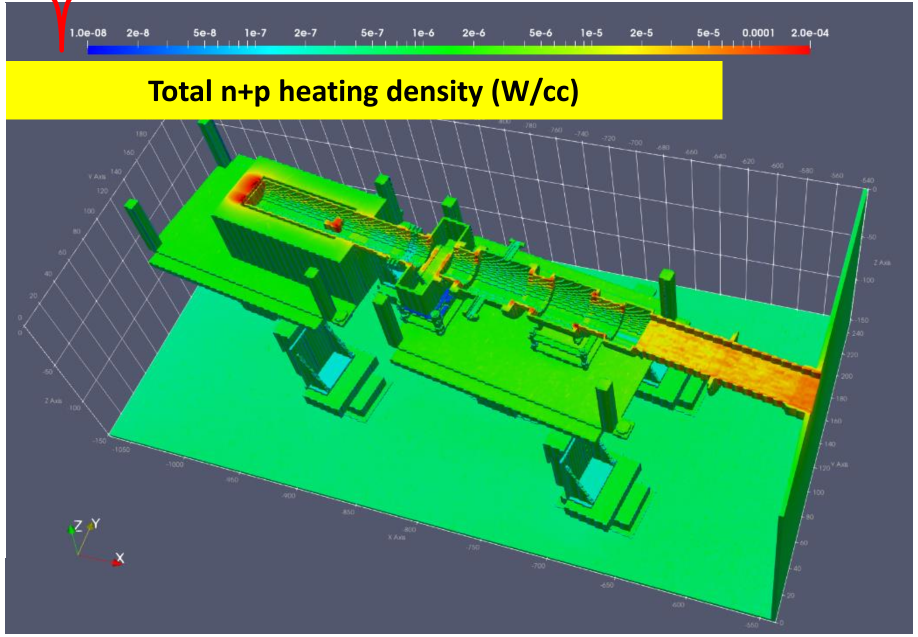
1

2

3

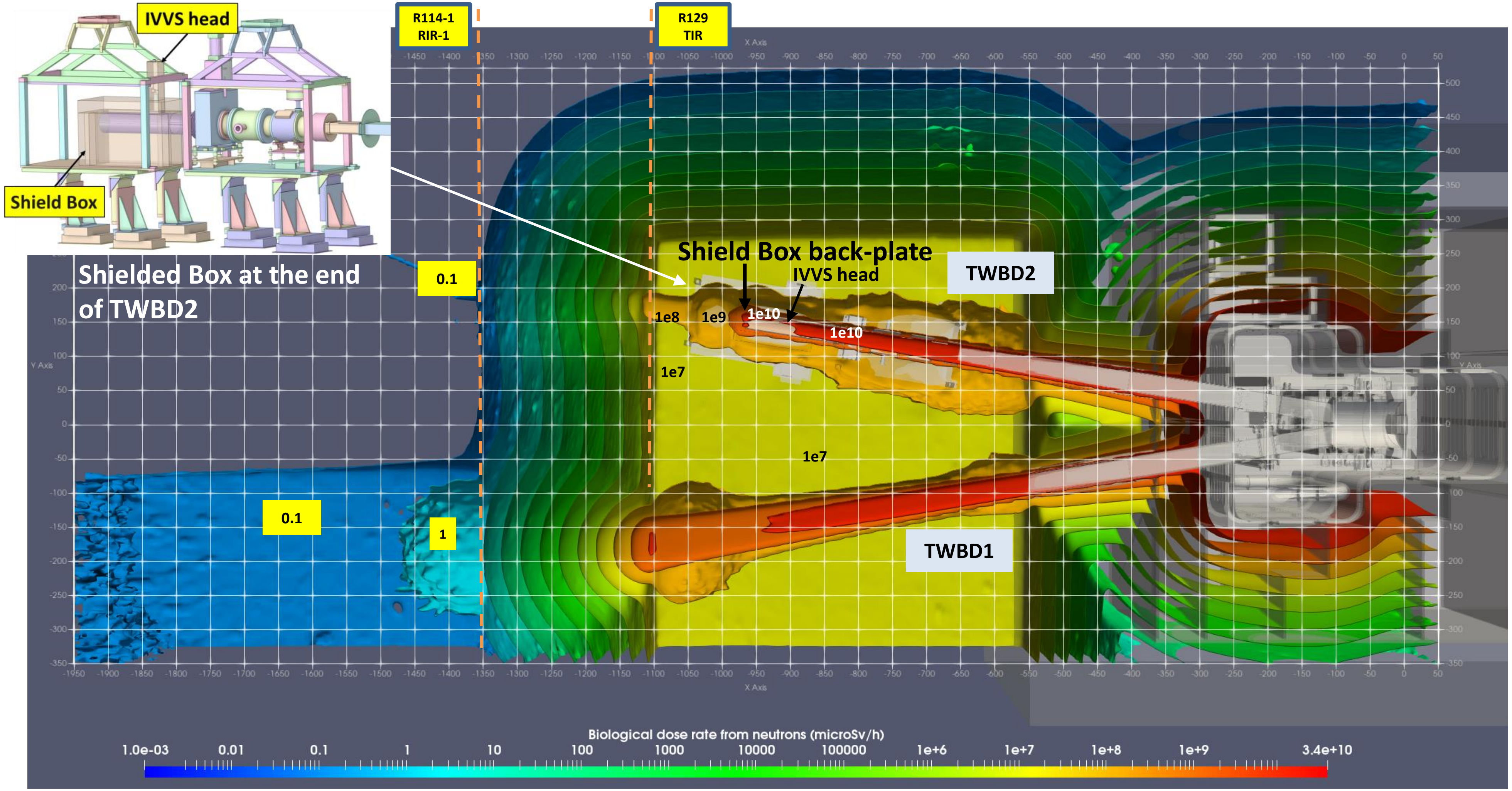
Back plate Nr.4

Front Nr.5



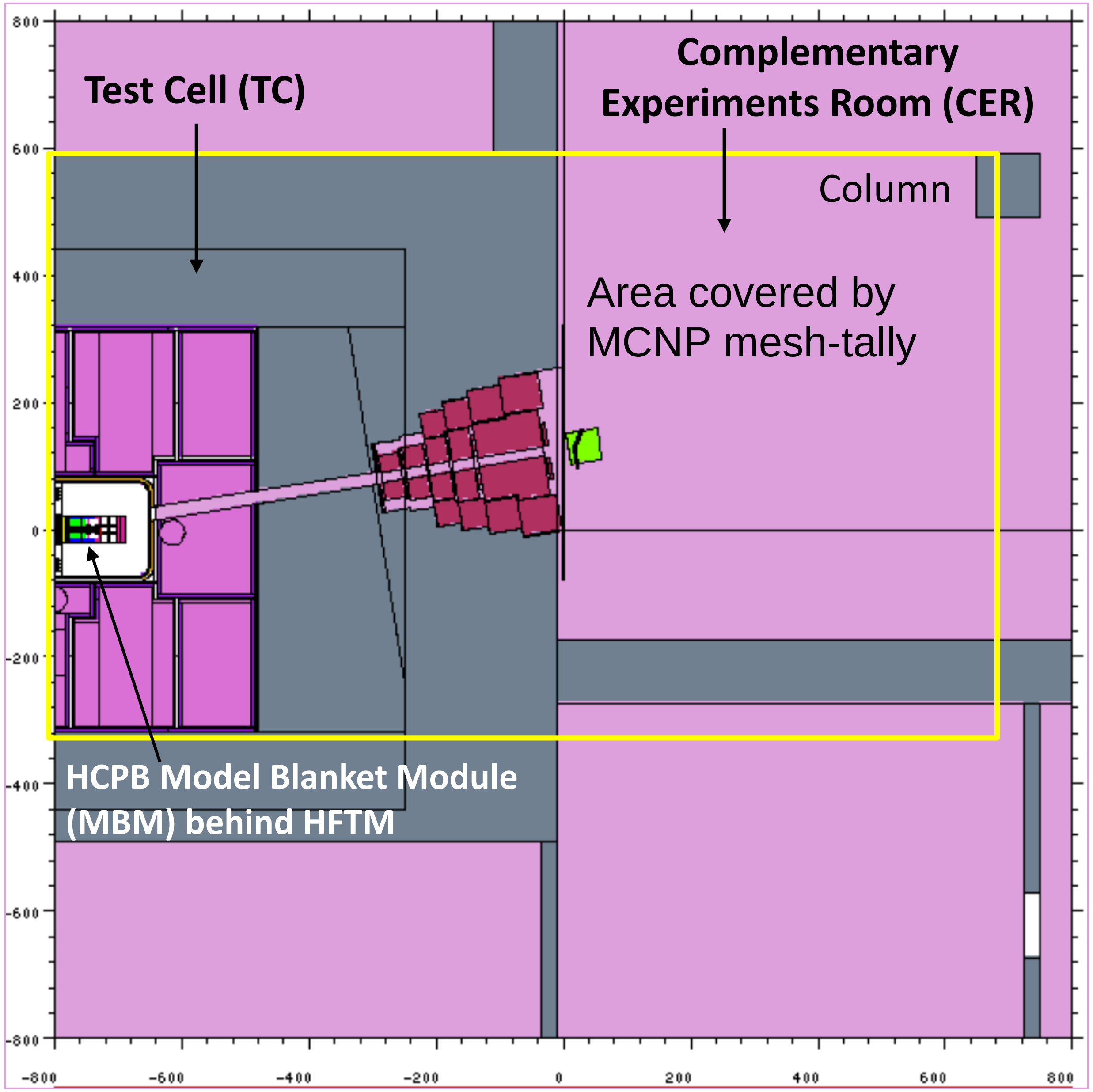
Total n+p heating density (W/cc)

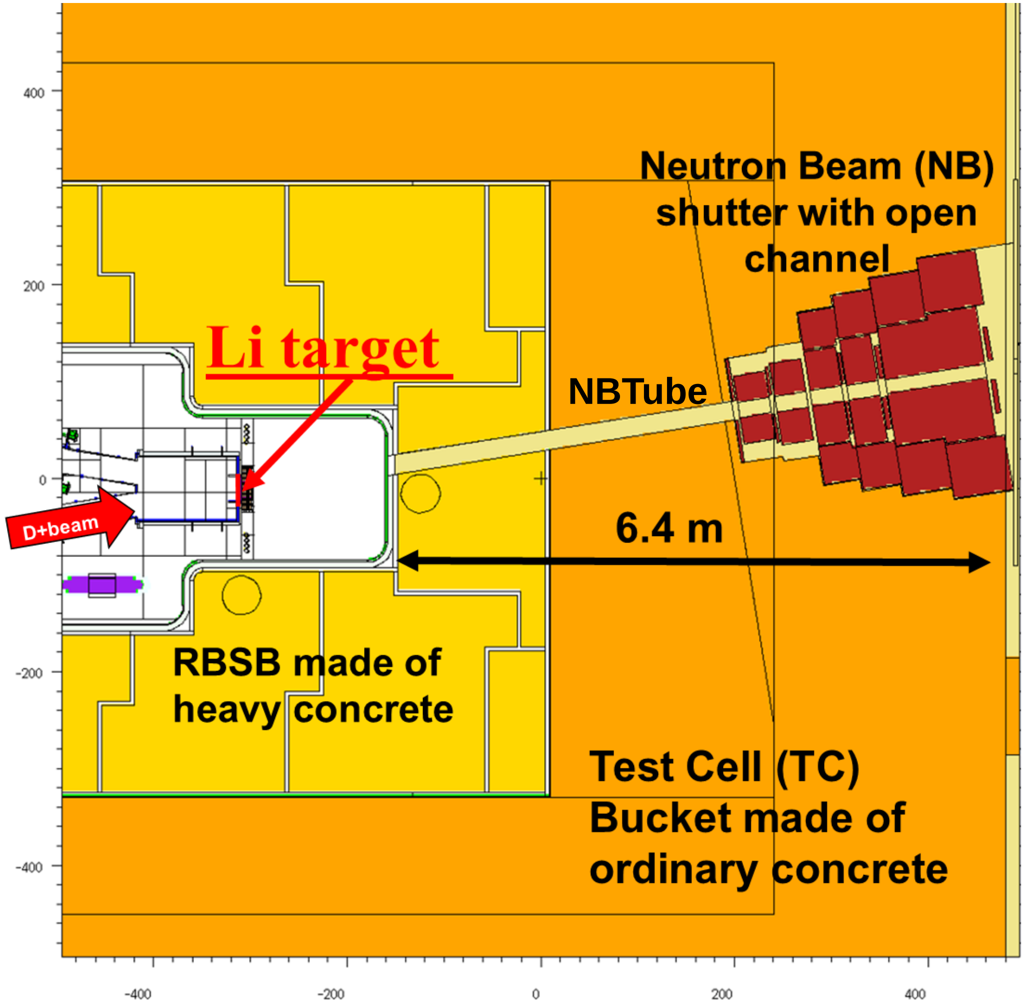
Comparison of two BDs: Shielded BD2 vs. Empty BD1:
View from the top on the map of biological dose rate (microSv/h) from neutrons



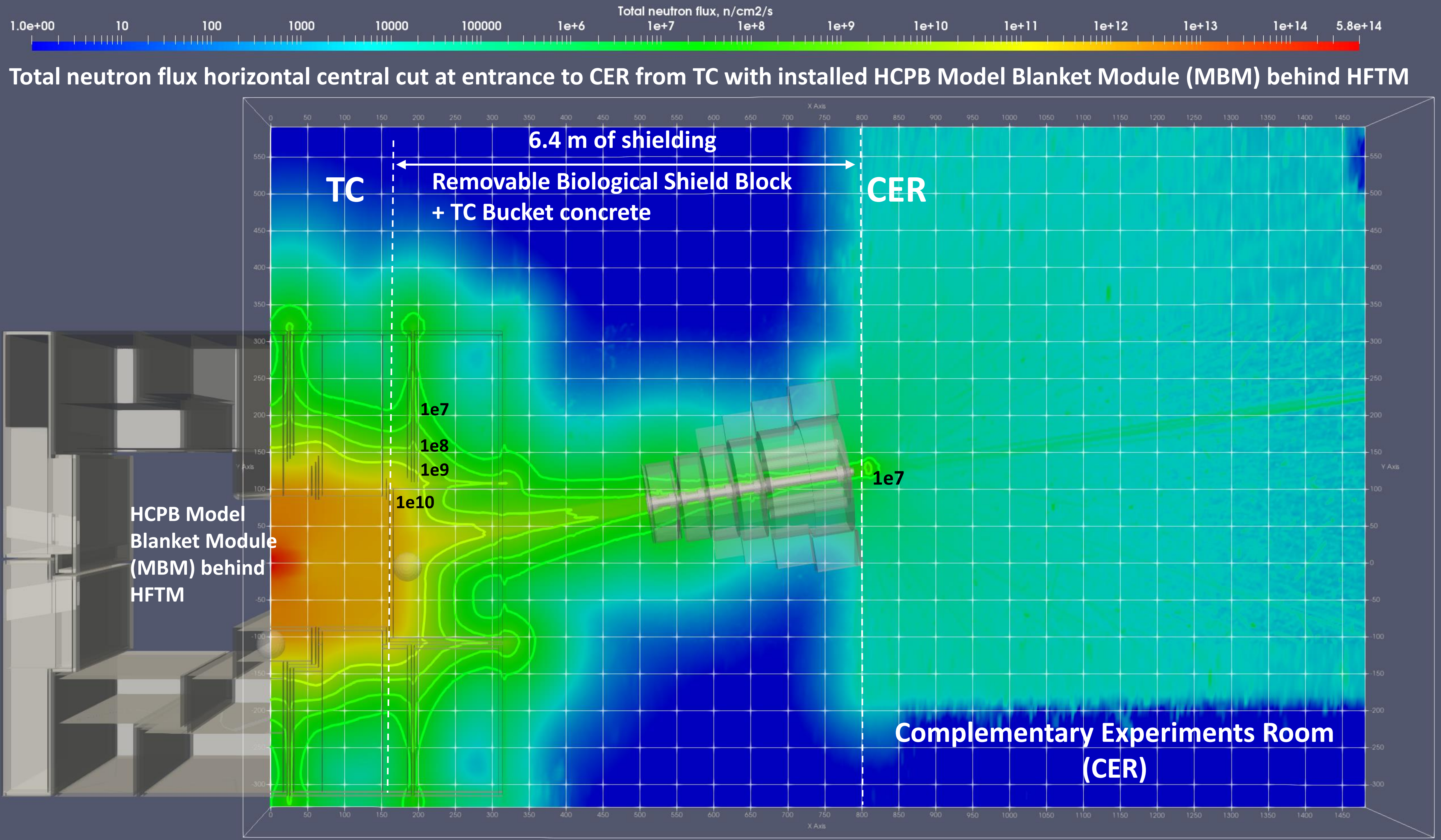
Neutron flux computations in TC-CER using the MCNP mesh-tallies

Mapping of neutrons streaming from Test Cell (TC) through the Neutron Beam Tube and Shutter (NBT & S) system to CER. The collimated neutrons will be supplied to conduct variety neutronics experiments inside CER.



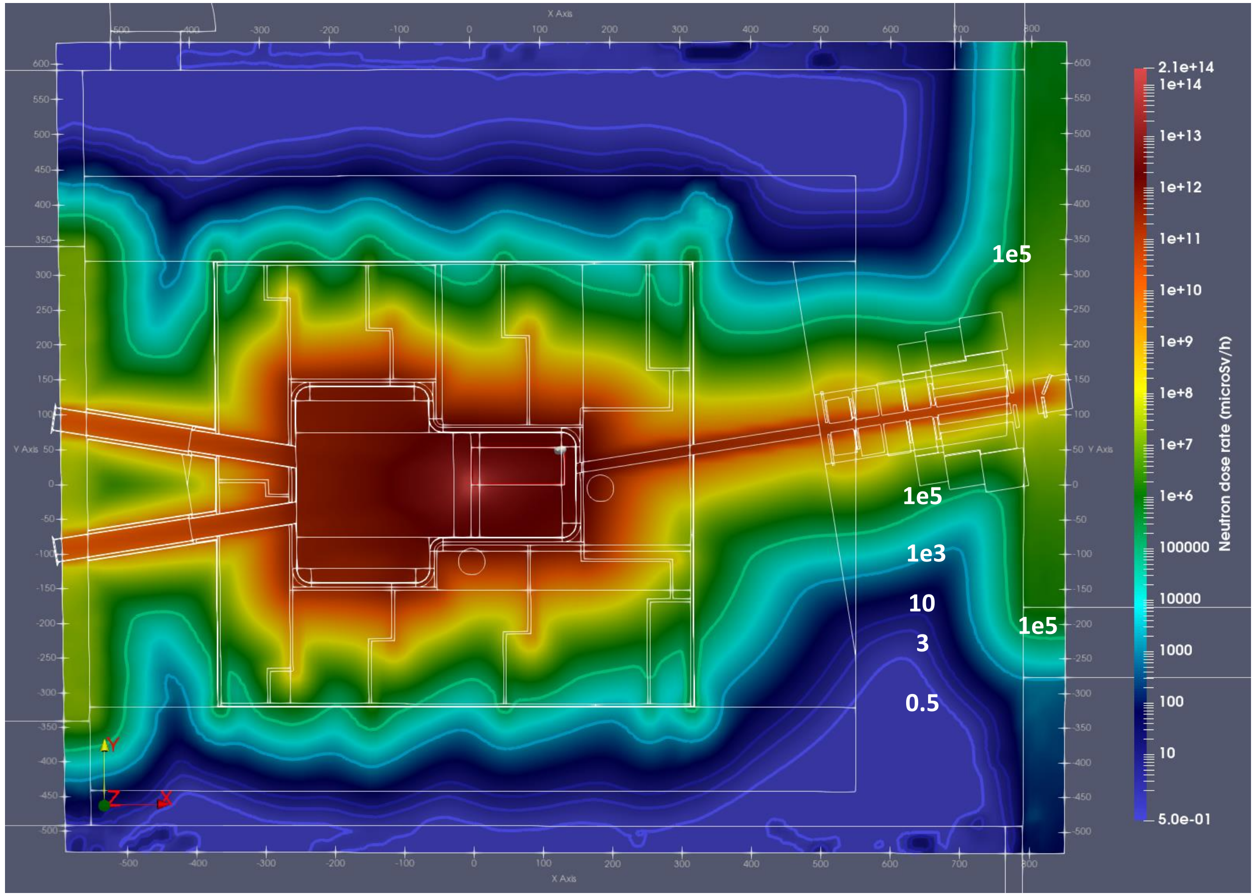


Total neutron flux horizontal central cut at entrance to CER from TC with installed HCPB Model Blanket Module (MBM) behind HFTM



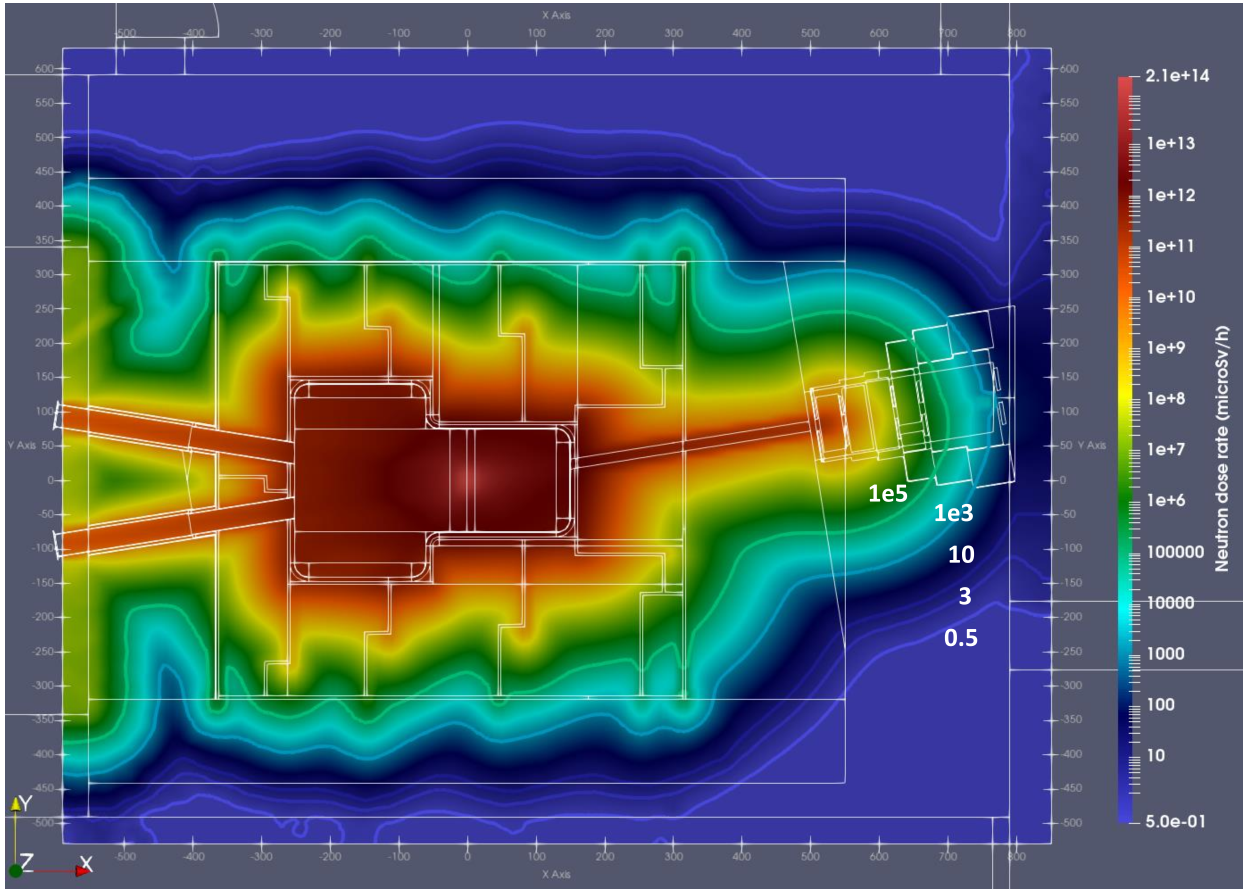
Neutron dose rate maps for two positions of the NB shutter, with only the High-Flux Test Module (HFTM) in TC

<u>Position #1: Open</u> NB shutter



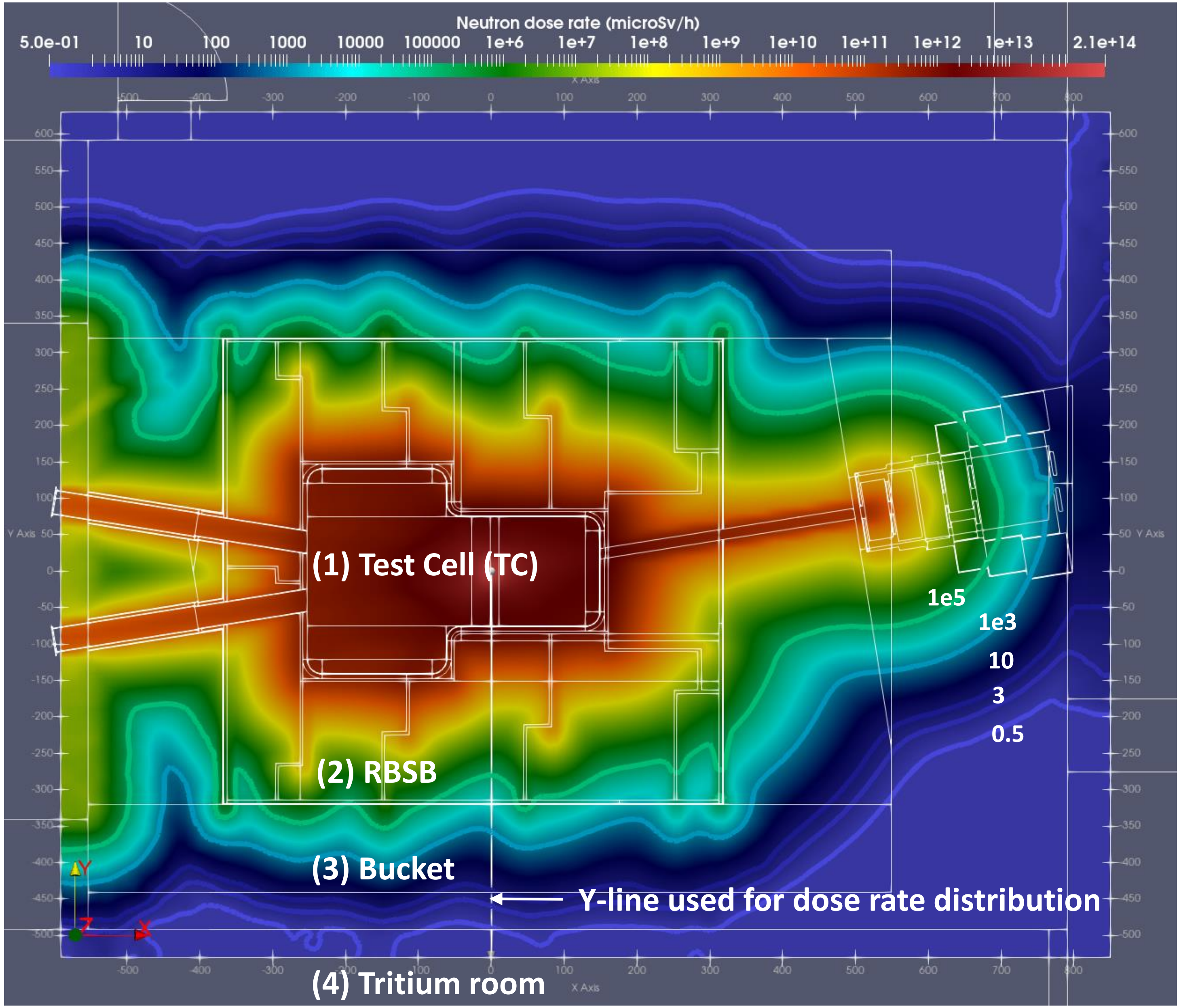
CER is Red (forbidden) radiation zone: DR>1e5 microSv/h

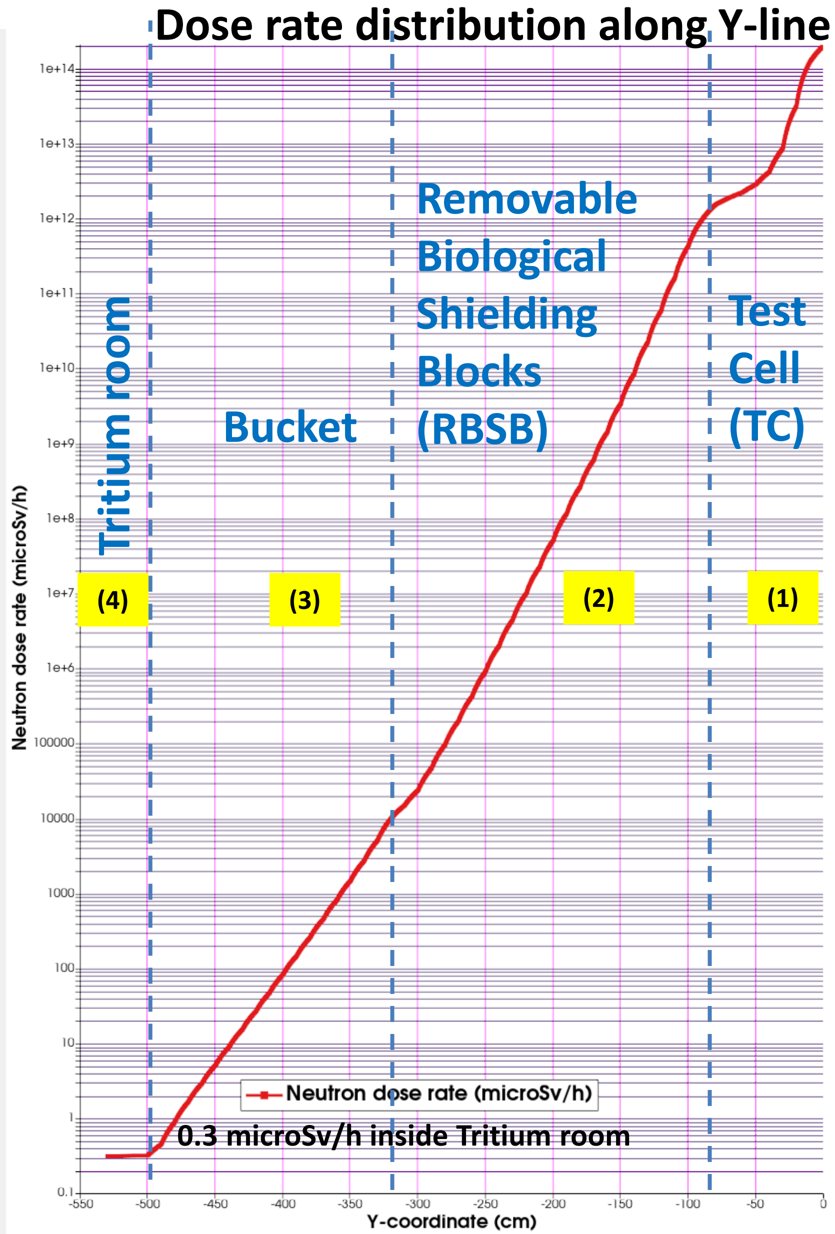
<u>Position #2: Closed</u> NB shutter



CER is Yellow (limited regulated) rad. zone: (10<DR<1e3) microSv/h

Ultimate proof of solving the IFMIF-DONES radiation shielding task: Biological dose rate (microSv/h) from neutrons, with 15 orders of magnitude dose attenuation along the Y-line distribution





Conclusions

- **Serving most demanded Monte Carlo radiation transport computations for fusion large facilities, the MCHIFI (Monte Carlo High Fidelity) HPC** project has been established in 2012 to use the IFERC-CSC Helios supercomputer in the framework of the F4E Broader Approach (BA) for ITER neutronics tasks.
- Since 2016, MCHIFI project was deployed on the computational resources of the Marconi-Fusion HPC facility offered by EUROfusion and operated by ENEA/CINECA. At this moment, MCHIFI is running on 7th cycle of Marconi-Fusion HPC. In our application for the 8th cycle, we have justified the number of core-hours requested to fulfill not only the IFMIF-DONES shielding tasks, but also numerous Shutdown Dose Rate (SDR) calculations for the JET NEXP SDR experiment of the C38 2019-2020 DD and the C41 2021 DT2 campaigns of JET, and using the data of JET DT3 campaign to be available at the end of 2023.
- A large number of the Marconi-Fusion HPC nodes are needed in the for the IFMIF-DONES large-scale complicated models to run the Monte Carlo (MC) radiation transport parallel computations with the MCNP and McDeLicious codes.
- The methodology improvement is demonstrated in the recent development of the On-The-Fly (OTF) modification of the MCNP code. The OTF Global Variance Reduction (OTF-GVR) is the state-of-the-art code for the IFMIF-DONES radiation shielding tasks characterized by neutrons deep penetration. We have used OTF-GVR for radiation transport through the 6.4 m shielding between the IFMIF-DONES Test Cell and its Complementary Experiments Room (CER).
- **Developed at KIT Monte Carlo radiation transport CAD-based methodology** can reproduce the d-Li neutron & photon source at the Li target and extremely strong radiation attenuation in heterogeneous IFMIF-DONES geometry:
  - Neutron flux attenuation by 18 orders of magnitude (from 2e14 to 2e-4 n/cm^2/s inside Tritium room);
  - Biological dose rate from neutrons attenuation by 15 orders of magnitude (from 2e14 to 0.3 microSv/h inside Tritium room);
  - Radiation energy deposition attenuation by 11 orders of magnitude (heat at peak of 110 kW/cc in d-Li footprint to ~ 1 microW/cc inside steel of the IVVS shielding box inside the Target Interface Room -TIR).
  - The MCNP mesh-tally reveled the dominancy of fast neutrons in the total neutron flux at the exit from Neutron Beam (NB) shutter to CER.