Neutronics of the IFMIF-DONES irradiation facility

U. Fischer, KIT

Co-ordinator PPPT Neutronics & Nuclear Data

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Contributors

B. Bienkowska - IPPLM, Warsaw, Poland

K. Drozdowicz – IFJ PAN, Cracow, Poland

M. Frisoni - ENEA, Bologna, Italy

F. Mota - ECIEMAT, Madrid, Spain

F. Ogando - UNED, Madrid, Spain

Y. Qiu - KIT, Karlsruhe, Germany

G. Stankunas - LEI, Kaunas, Lithuania

G. Tracz – IFJ PAN, Cracow, Poland

Outline

- **Introduction**
- **Computational Approaches, Tools & Data**
  - Neutron, photon & deuteron transport
  - Geometry modelling
  - Nuclear cross-section data
- **Nuclear analyses – major results**
  - Accelerator Facility
  - Test Cell & Test Systems
  - Activation & Radiation Loads
- **Conclusions**

IFMIF-DONES Neutron Source

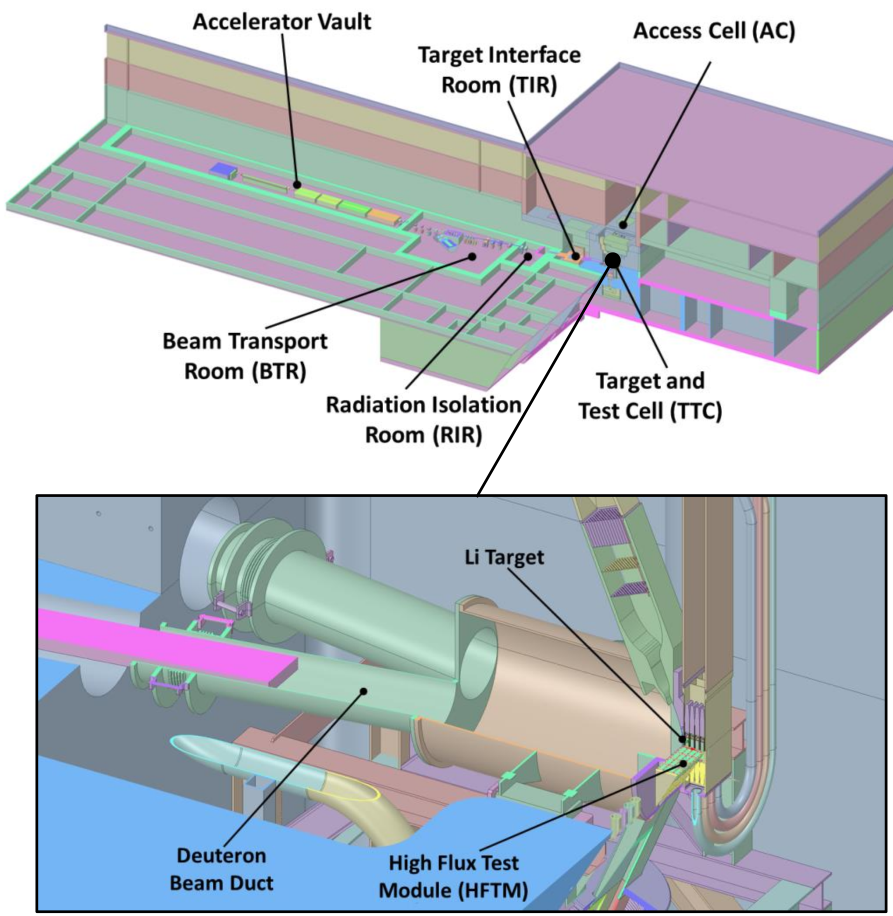
<u>I</u>nternational <u>F</u>usion <u>M</u>aterial <u>I</u>rradiation <u>F</u>acility
<u>D</u>emo <u>O</u>riented <u>Ne</u>utron <u>S</u>ource

- **Early Neutron Source (ENS)** project of **EUROfusion** for a D-Li neutron source for material irradiations

⇒ ***Main mission***: *To provide irradiation data for the construction of DEMO*

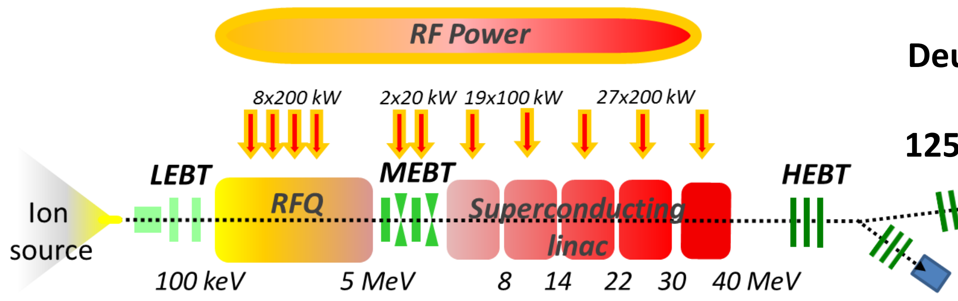
- Design based on IFMIF using only one deuteron accelerator (125 mA, 40 MeV)
- Lithium target, Test Cell and HFTM, etc. are (almost) identical, no other modules

⇒ ***Neutronics key issue:*** *Essential data to be provided for design, optimization, performance and safety evaluation*



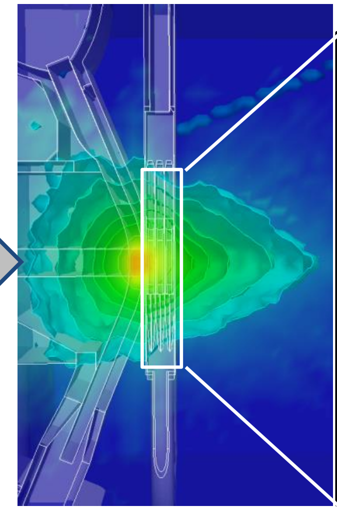
IFMIF-DONES Neutron Source

Accelerator System



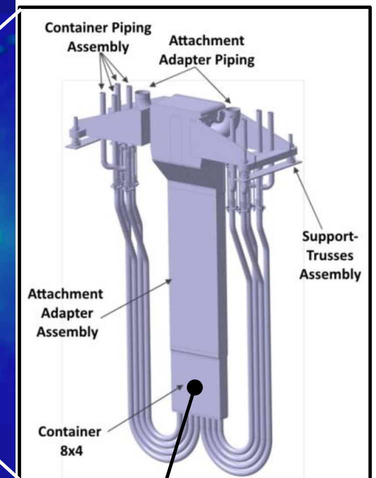
Deuteron beam @ target: 125 mA, 40 MeV

~ $5 \cdot 10^{16}$ neutrons/s

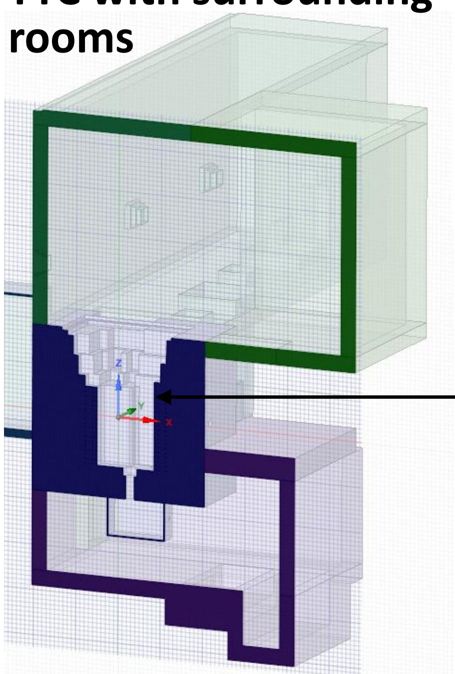


Neutron flux ~ $5 \cdot 10^{14}$ $cm^{-2}s^{-1}$

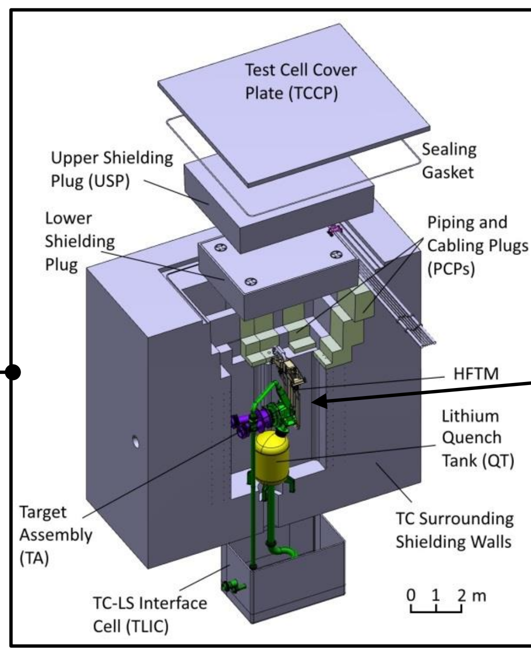
HFTM

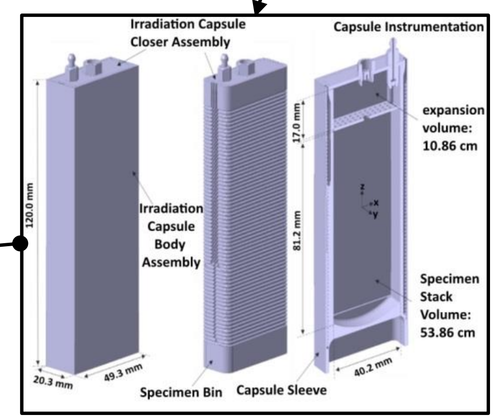


TTC with surrounding rooms



Target and Test Cell (TTC)





Irradiation Capsule

Required nuclear analyses

- **Layout and optimisation**
  - **Accelerator Facilities (AF)** with RFQ, SC Linac, beam transport systems, …
    - Radiation shielding (n + γ radiation), heating
  - **Target Facility (TF)** with Li target assembly and Li loop,
    - Issues: Heating, damage, activation, shielding
  - **Test Cell (TC)** with irradiation modules
    - Issues: HFTM performance under irradiation (damage, gas production, nuclear heating, neutron flux, …)
    - Issues: Bioshield performance (TC walls with liner)
- **Safety, radiation protection, waste**
  - Activation of components (AF, TF, TC)
  - Radiation dose fields “beam-on” and “beam off”

⇒ ***Dedicated computational tools & data required: neutron, photon & deuteron transport, activation & resulting radiation loads***

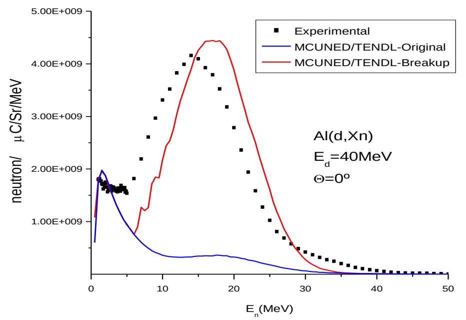
- Introduction
- **Computational Approaches, Tools & Data**
- Nuclear Analyses
- Conclusions & Outlook

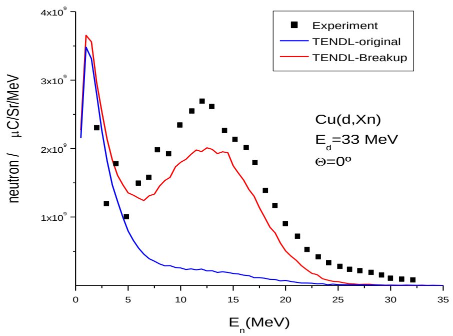
Computational Tools - MCUNED code

Deuteron transport simulation

- Extension to MCNPX with ability to handle in transport simulations light ions (p, d, t, He-3, α) using evaluated nuclear cross-section data, e.g. from TENDL data library
- Dedicated variance reduction technique for production of secondary particles $\Rightarrow$ drastic reduction of computing time
- Developed by UNED, Madrid, available as patch to MCNPX form NEA Data Bank, Paris
- Extensively benchmarked and applied for IFMIF accelerator nuclear analyse
- Standard for AF nuclear analyses in ENS project

MCUNED with deuteron break-up





$\Rightarrow$ ***Used to produce neutron and gamma sources from deuteron interactions with accelerator materials, for use with MCNP5 & RS2UNED to obtain radiation fields, activation and shut-down dose rate maps***

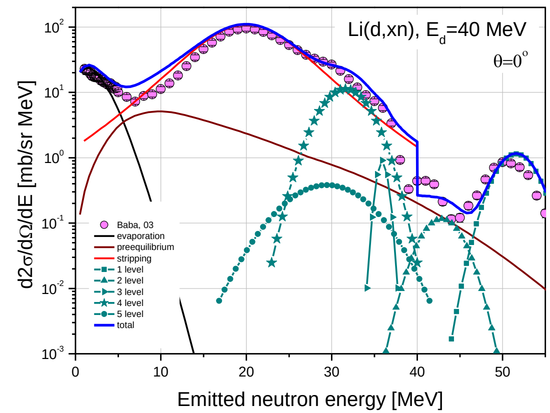
Computational Tools - McDeLicious code

D-Li neutron generation, n and γ transport simulation

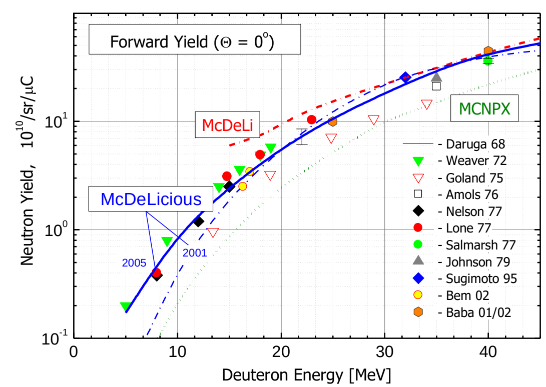
- Extension to MCNP with ability to simulate generation (d-Li) source neutrons (and photons)
- Based on ad-hoc evaluated d + ^{6,7}Li cross-section data for neutron (and photon) generation
- Deuteron beam footprint based on beam dynamics simulations
- Developed by KIT, Karlsruhe, as patch to MCNP-5, -6
- Extensively benchmarked against thin and thick Li target neutron yield measurements
- Standard for IFMIF and DONES TTC nuclear analyses

$\Rightarrow$ ***Used to provide n + γ sources in Li target, simulate n + γ transport across TTC and surroundings, provide nuclear responses & radiation fields***

D(Li, xn) cross-section data



Thick Li-target neutron yields

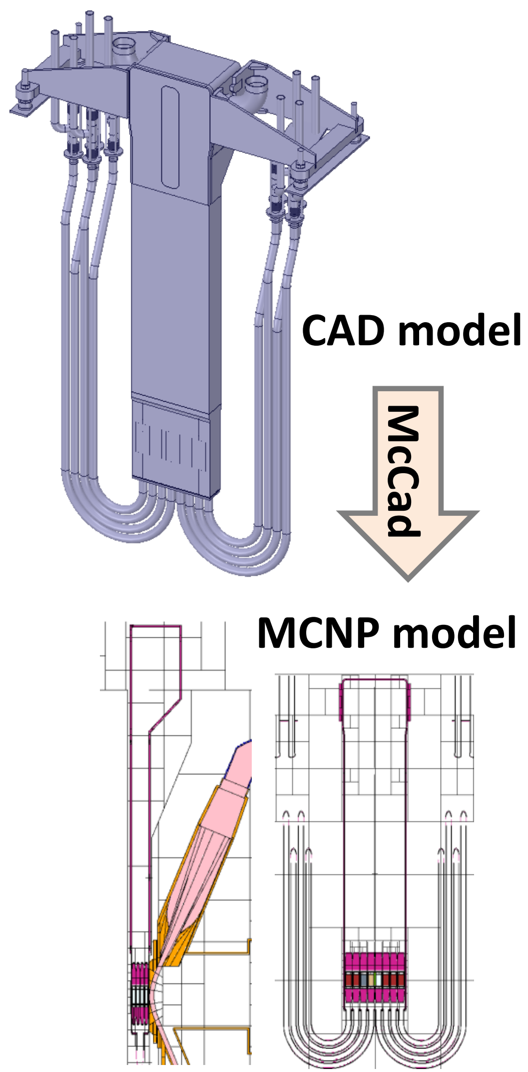


Computational Tools - McCad

Generation of MC simulation models

- Software tool to enable the automatic conversion of CAD models into representation of Monte Carlo codes - MCNP/ McDeLicious, Tripoli, GEANT4
- Developed by KIT, Karlsruhe, as open source software, freely available at https:/github.com/inr-kit.
- Runs under Linux and Windows, implemented into SALOME simulation platform.
- Additional tools for processing high resolution mesh tally data and visualization on the CAD geometry
- Extensively used in fusion appliacations (ITER, DEMO,
- EUROfusion/PPPT, IFMIF/DONES)

⇒ *McCad main tool for generating TTC simulation model of IFMIF-DONES starting from engineering CAD models*

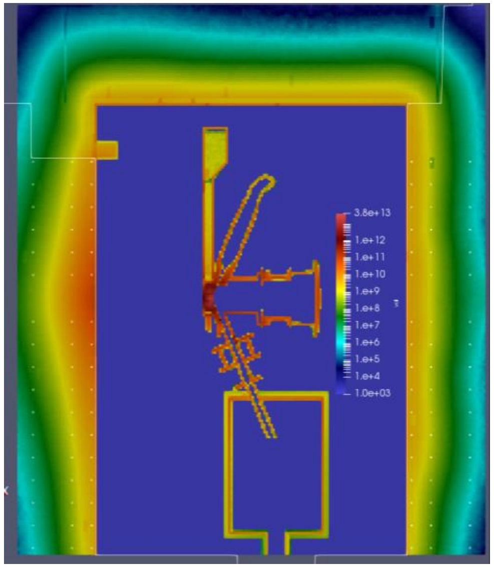


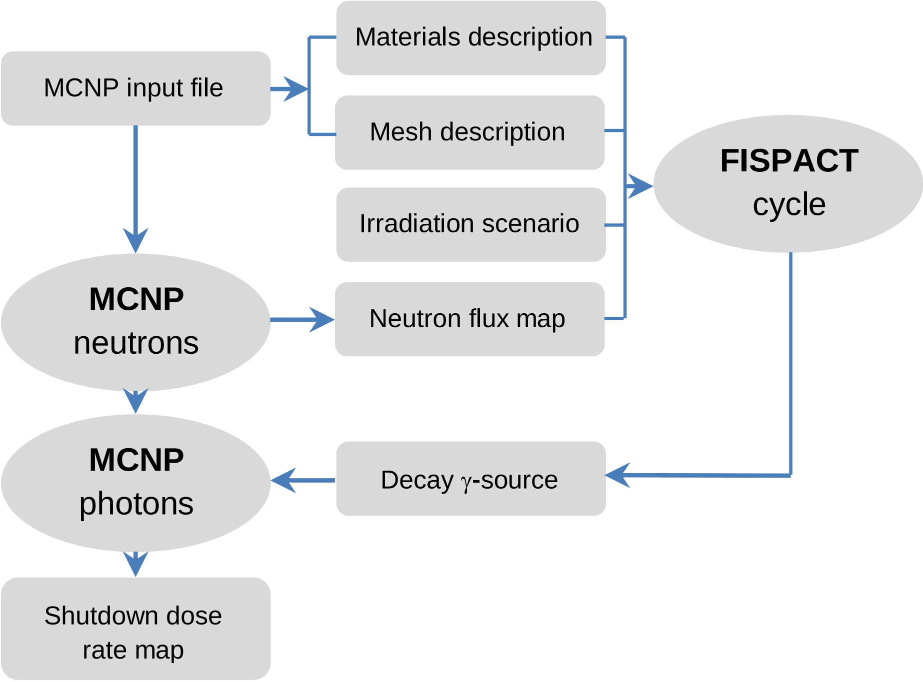
Computational Tools – Coupled transport & activation

Activation and shut-down dose rate distributions

- Coupled systems to calculate nuclide inventories, γ decay sources and resulting radiation fields <u>on high resolution mesh grids</u>
- **R2Smesh**, developed by KIT: MCNP/McDeLicious coupled with FISPACT inventory code (CCFE) $\Rightarrow$ ***used for TTC analyses***
- **R2SUNED**, developed by UNED: MCNP/MCUNED coupled with ACAB (UNED) inventory codes $\Rightarrow$ ***used for AF analyses***

Decay γ source distribution in DONES TTC





<u>Major calculation steps</u>

I. **Neutron transport calculation** using **MCNP** for neutron flux spectra

II. **Activation calculatio**n using **FISPACT/ACAB** for decay photon source distribution

III. **Decay photon transport calculation** using **MCNP** for decay photon fluxes and dose rates

Computational Tools - Nuclear Data

Neutron and deuteron cross-section data for transport simulations and activation calculations

- Neutron cross-sections: Fusion Evaluated Nuclear Data Library (FENDL), version 3.1d ⇒ reference for IFMIF-DONES neutronics.
  - Provided by IAEA, tailored to the needs of ITER and IFMIF
  - Includes neutron activation data library based on obsolete EAF-2010
  - ⇒ *Advanced activation data library, based on TENDL-2017, underway in EUROfusion/PPPT programme*

IAEA
International Atomic Energy Agency

- Deuteron cross-sections: TENDL (“TALYS based Evaluated Nuclear Data Library” data library ⇒ reference for DONES AF nuclear analyses
  - Developed previously by NRG, now PSI + cooperation partners
  - TENDL-2015 in use with MCUNED/ACAB, update to TENDL-2017 underway
  - ⇒ *Improvement of deuteron cross-sections in EUROfusion/PPPT programme*

EUROfusion

- Displacement damage cross-sections: Dedicated evaluations based on advanced and NRT damage models, prepared by KIT
  - Eurofer and SS-316 steels: Available through IAEA/NDS
  - Elements Li to U: Available as JEFF-3.3 dpa cross-section sub-library

NEA
Nuclear Energy Agency

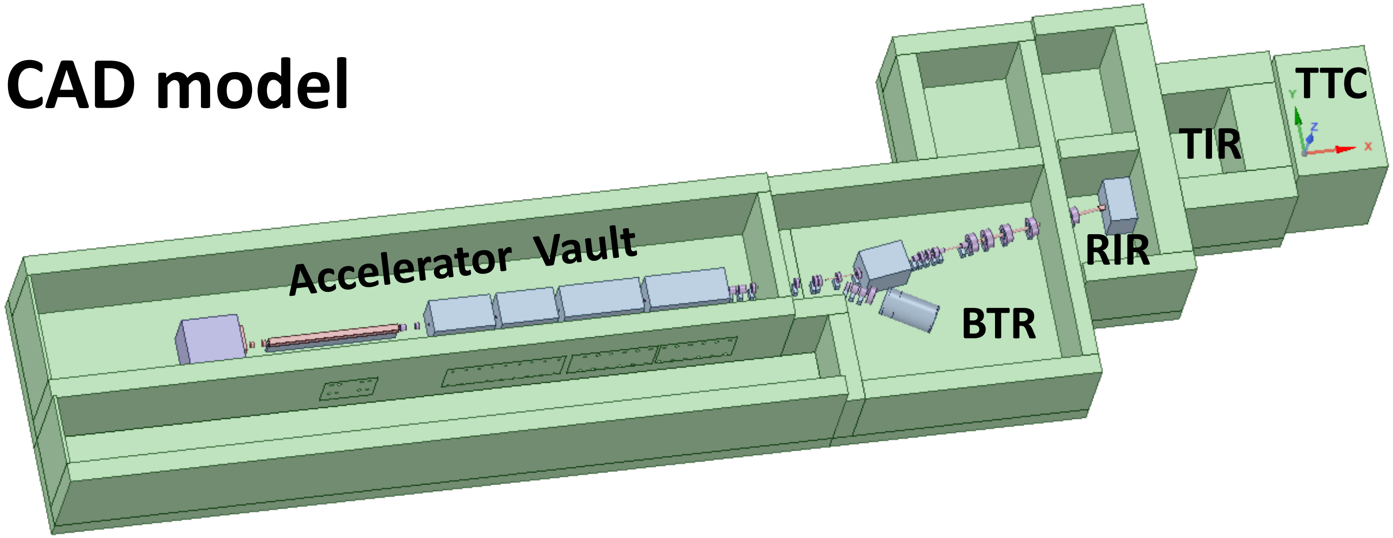
- Introduction
- Computational Approaches, Tools & Data
- **Nuclear Analyses**
- Conclusions & Outlook

Methodology for AF & TTC nuclear analyses

- **Generation of MC simulation model**
  - Basis: IFMIF-DONES engineering **CAD model**
  - Processing with **SpaceClaim** (simplifications, corrections, removal of spline functions, etc.)
  - Conversion into MC model using **McCad**
- **Monte Carlo (MC) transport simulations**
  - **TTC: McDeLicious/MCN**P ⇒ neutron/photon flux spectra, nuclear responses, radiation fields “beam-on” around TTC & surrounding
  - **AF: MCUNED/MCNP** ⇒ deuteron, neutron/photon flux spectra, nuclear responses, radiation fields “beam-on” around AF components
- **Coupled transport-inventory calculations**
  - **TTC: R2Smesh** ⇒ Activity inventories, radiation fields “beam-off” (SDR) in TTC & surrounding rooms
  - **AF: R2SUNED/MCNP** ⇒ Activity inventories, radiation fields “beam-off” due to d and n induced activation reactions

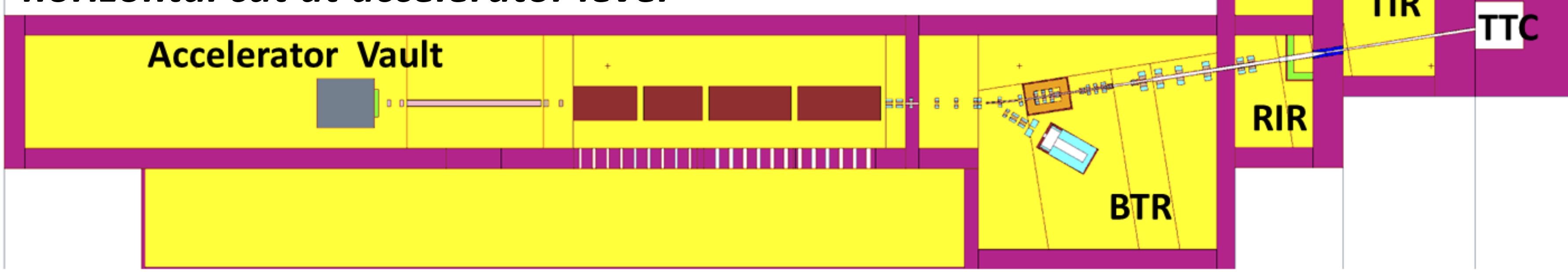
AF nuclear analyses

CAD model

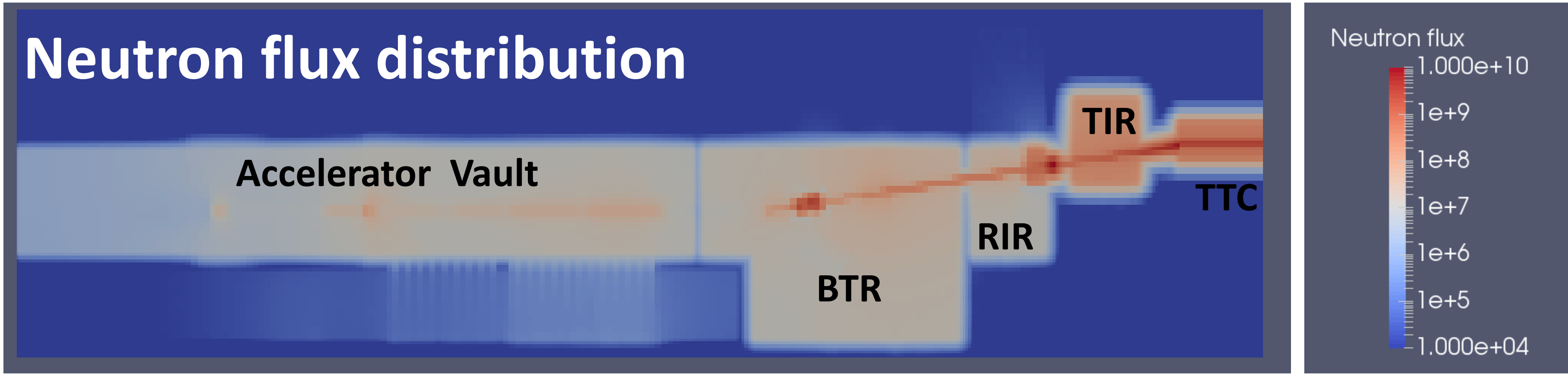


MC simulation model

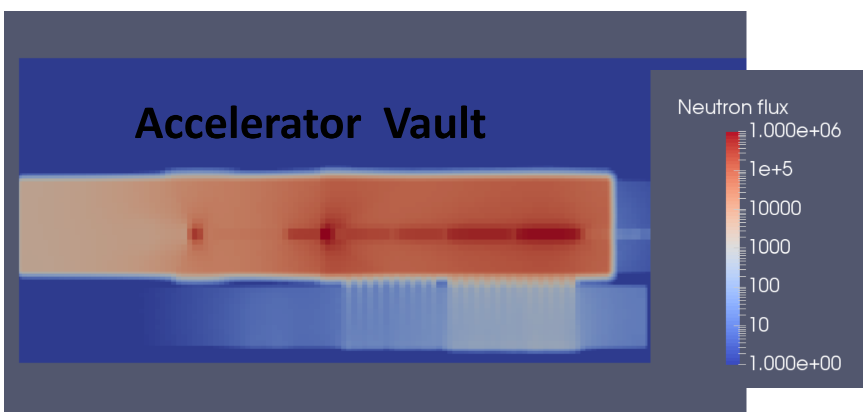
horizontal cut at accelerator level

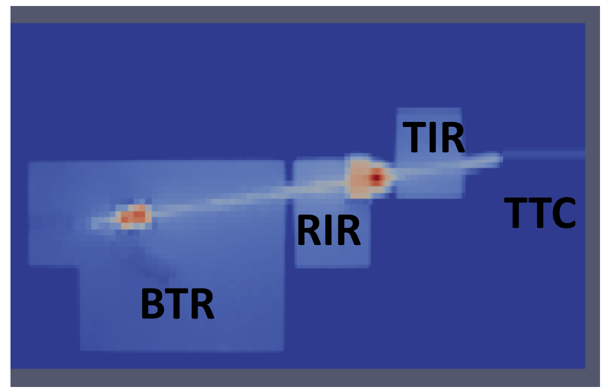


AF nuclear analyses

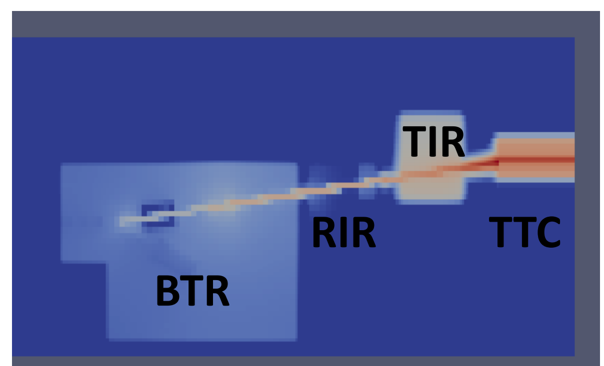


Neutrons from (d,xn) reactions in accelerator vault (*)





Neutrons from (d,xn) reactions in HEBT (scraper & collimator)

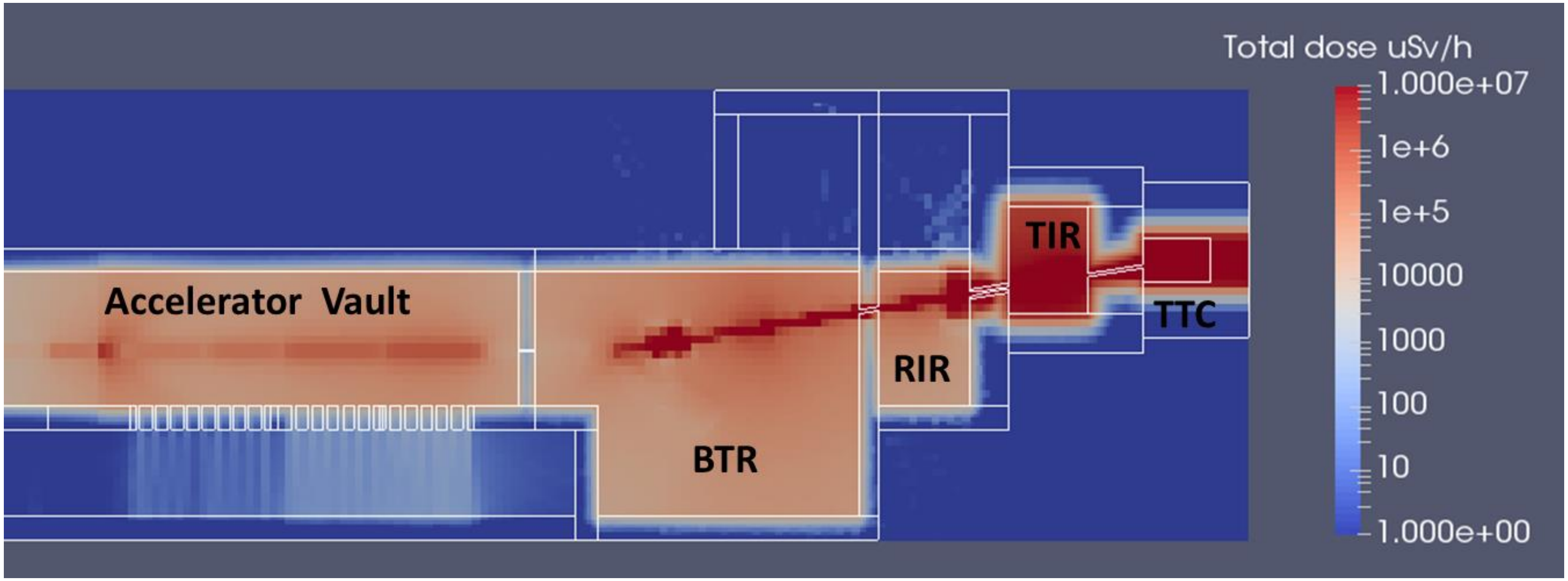


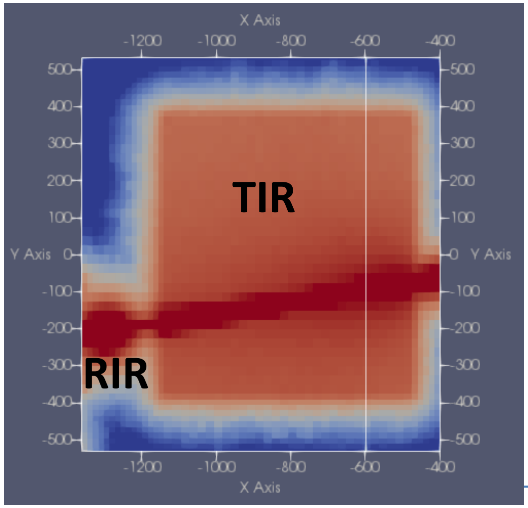
Neutrons streaming from target

(*) *Different scale !*

AF nuclear analyses

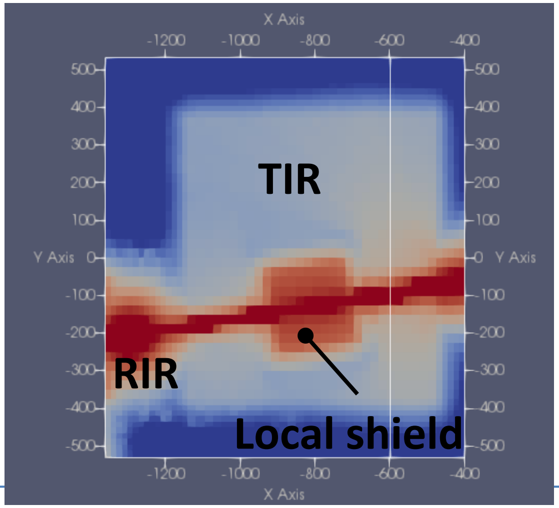
Biological dose rate distribution during beam operation





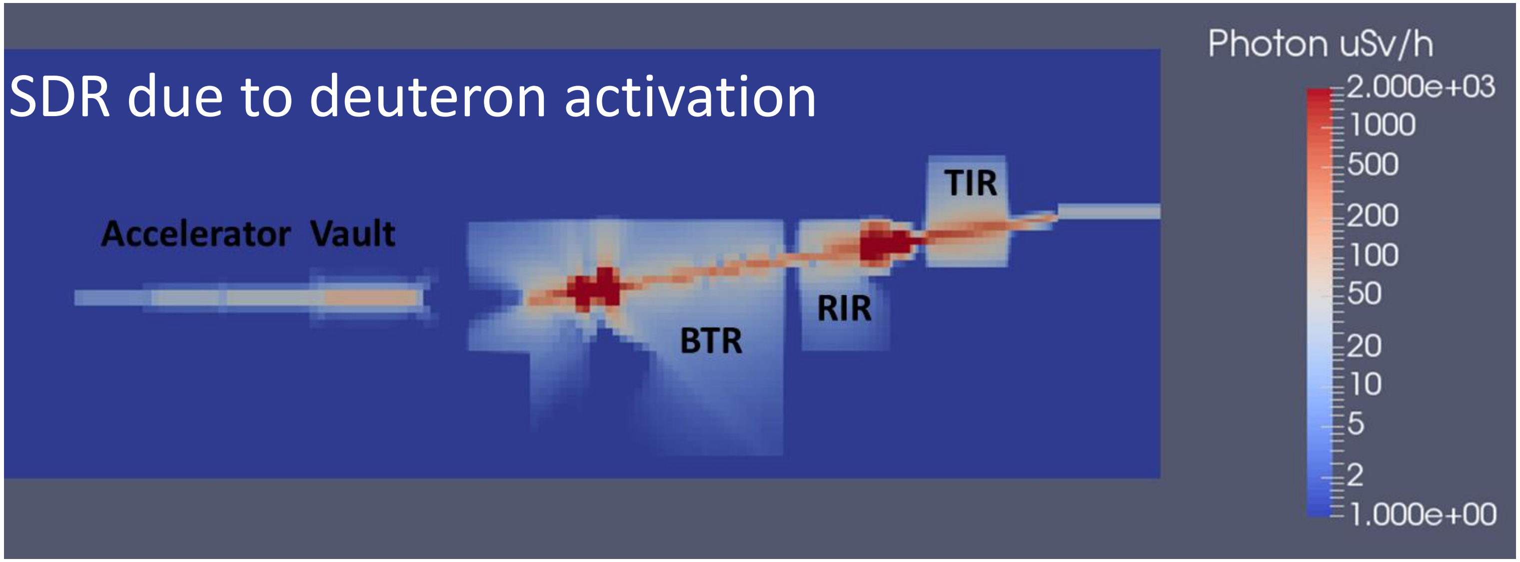
TIR shielding

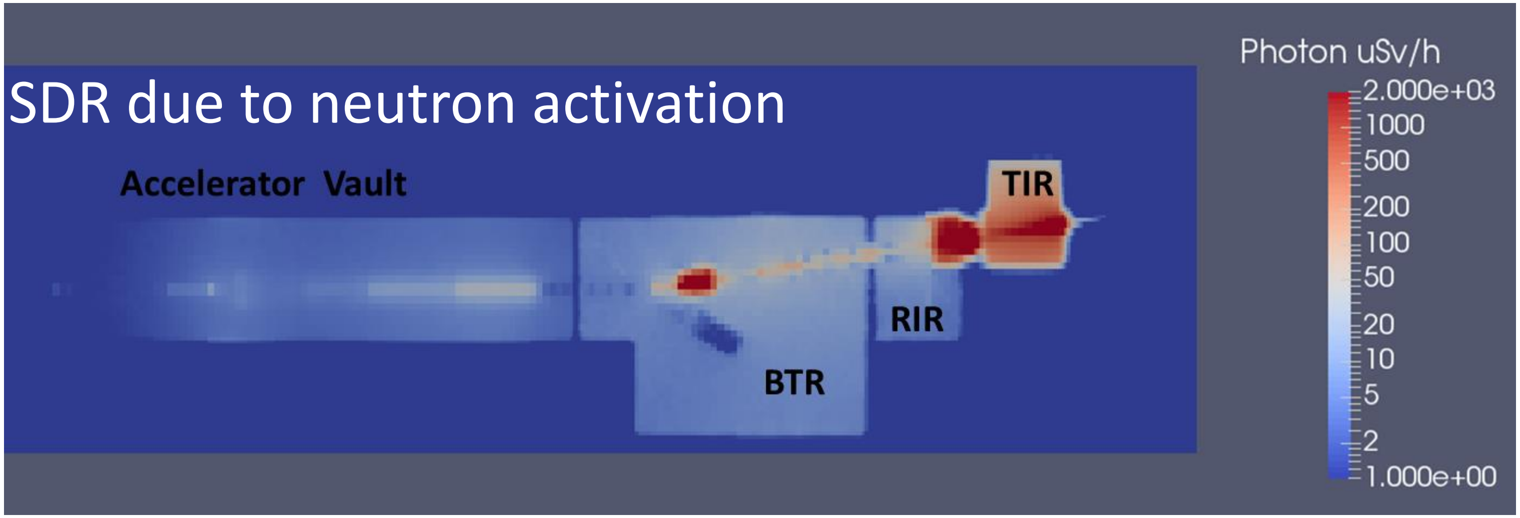
Local shield around beam guide



AF nuclear analyses

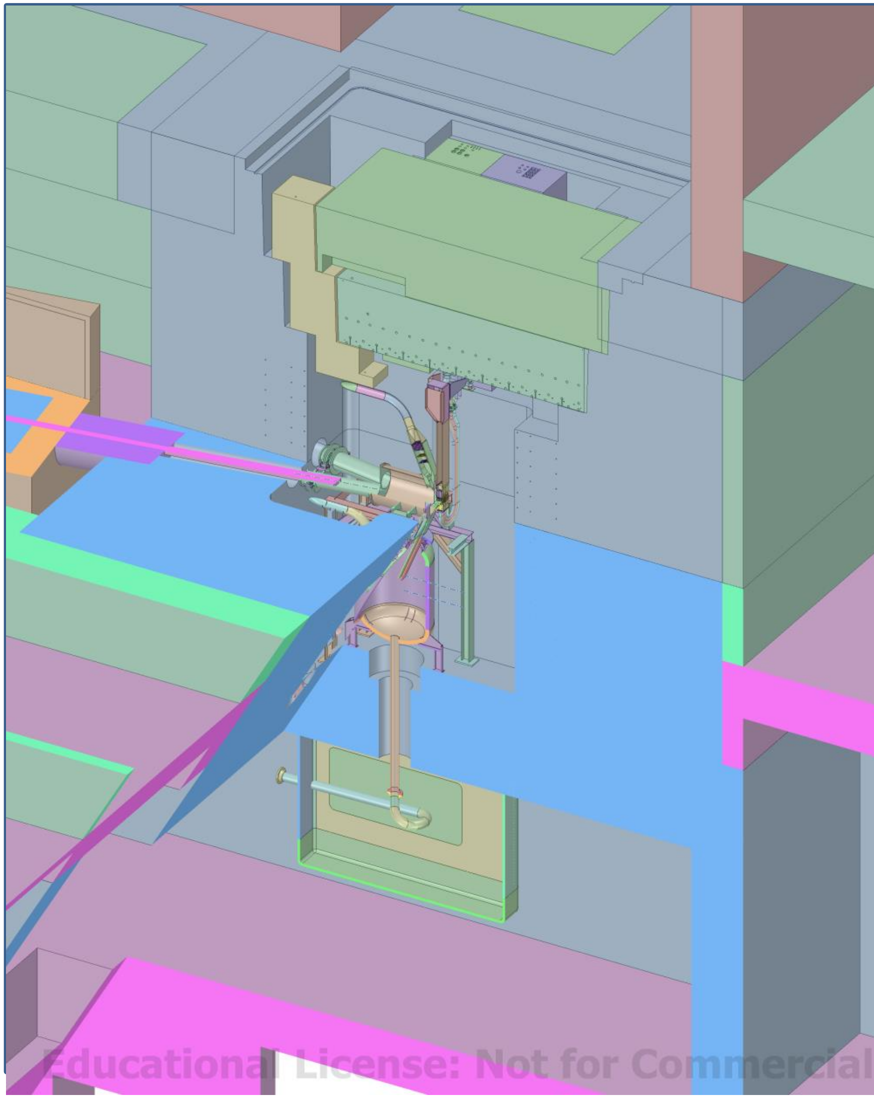
Biological dose rate distributions 1 day after shut-down (SDR)





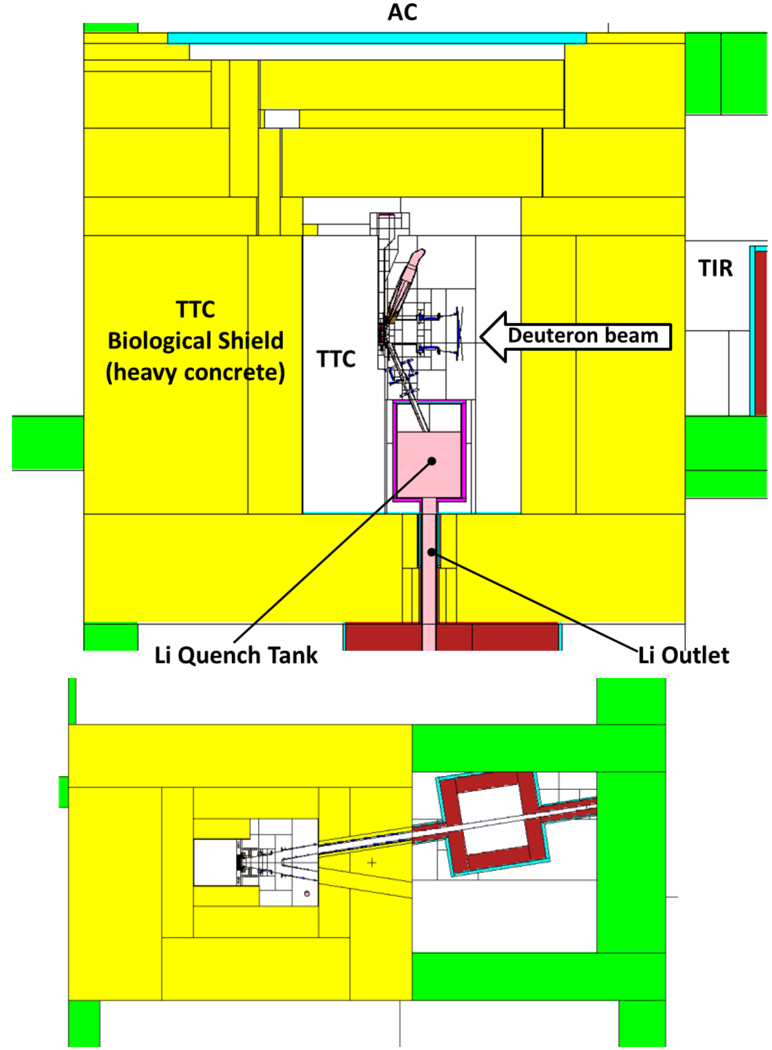
TTC nuclear analyses

CAD model



MC simulation model

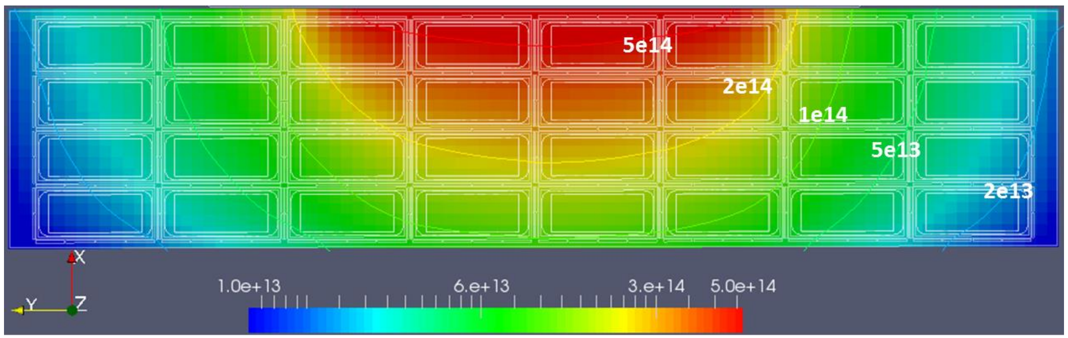
- vertical cut at target center -



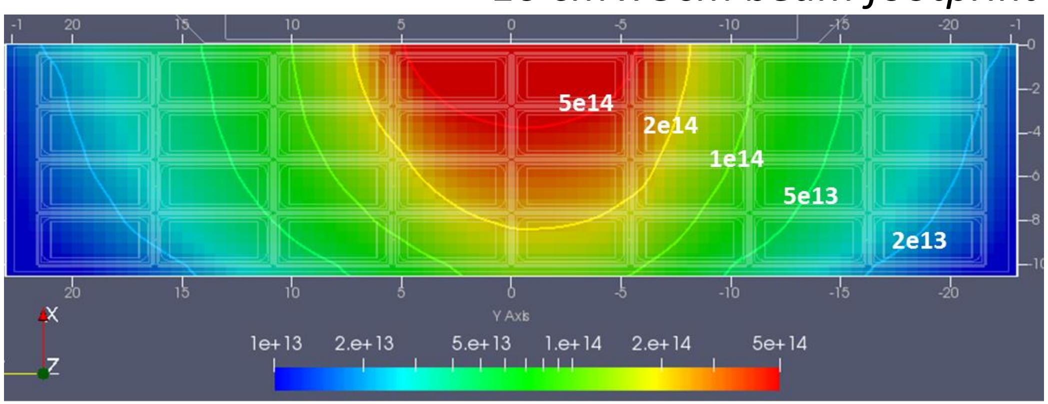
HFTM nuclear analyses

Neutron flux distribution in HFTM

20 cm x 5cm beam footprint

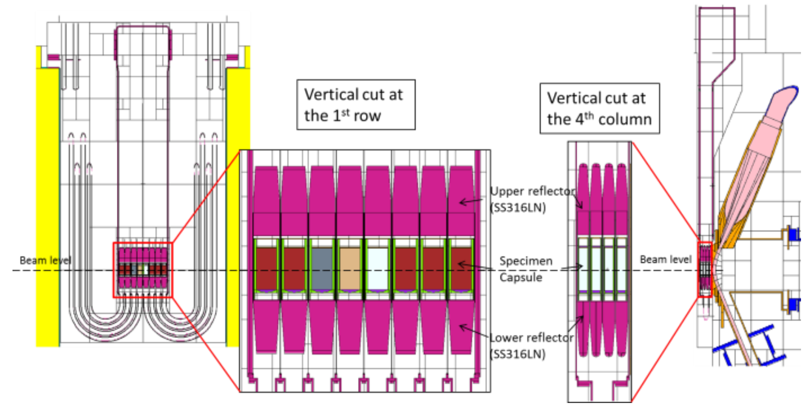


10 cm x 5cm beam footprint

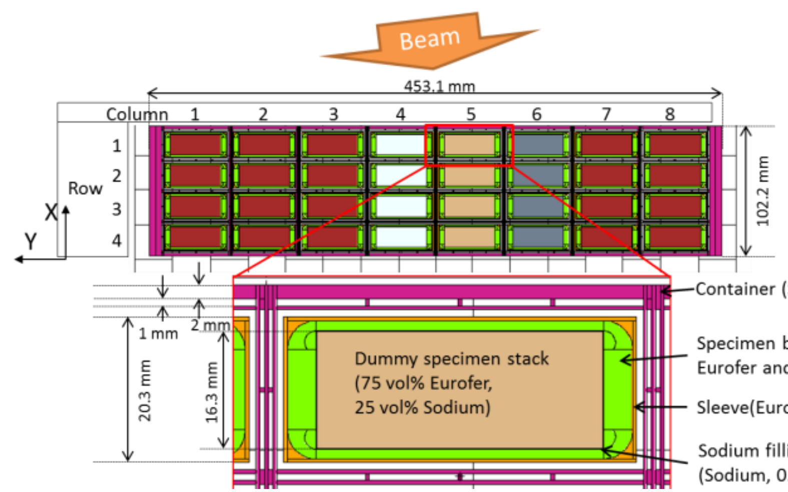


HFTM in TTC simulation model

Vertical cut at target centre

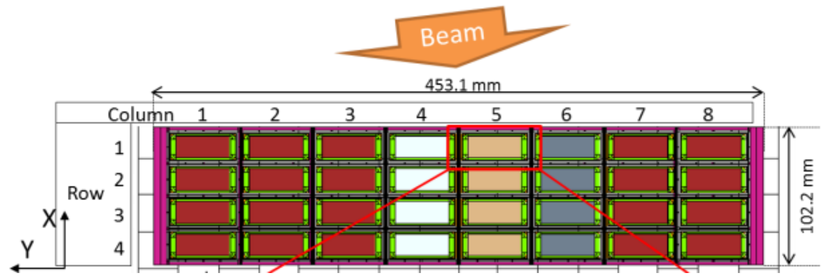


Horizontal cut at beam level



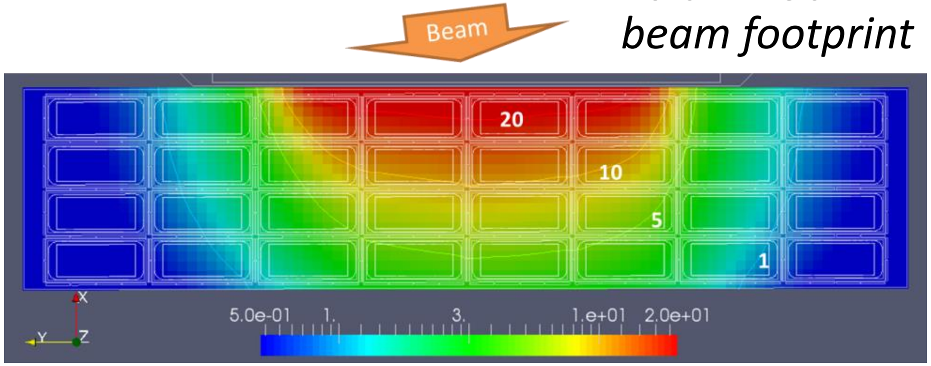
HFTM nuclear analyses

Displacement damage(*) distributions

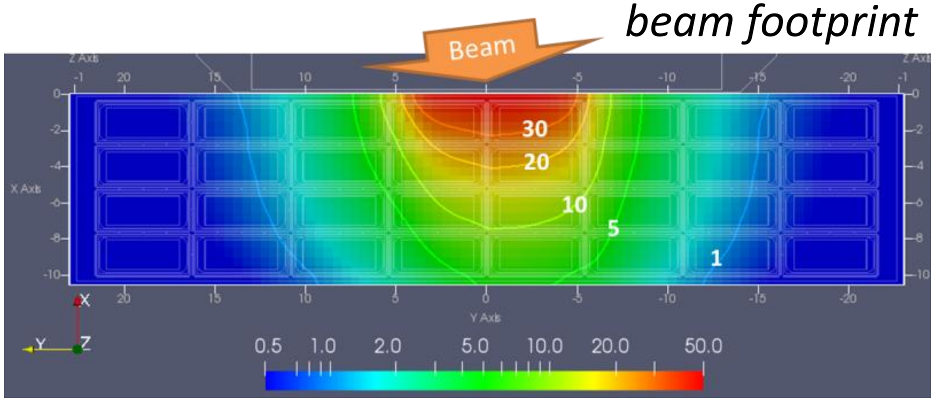


Horizontal cuts at beam level

20 cm x 5cm beam footprint

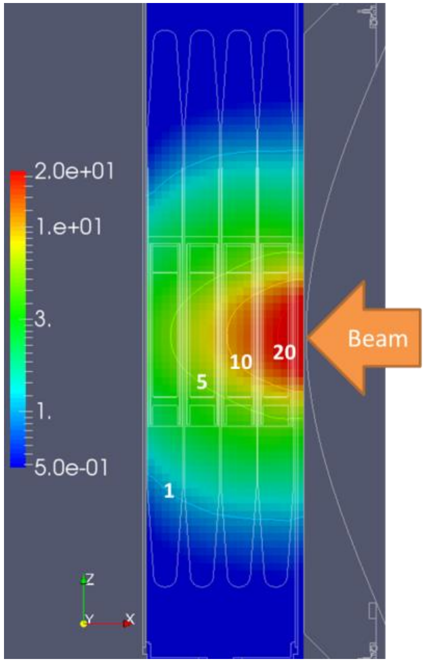


10 cm x 5cm beam footprint

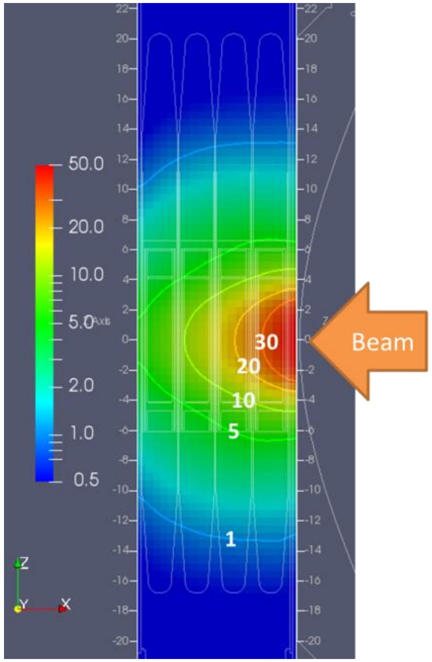


Vertical cuts at target centre

20 cm x 5cm beam footprint



10 cm x 5cm beam footprint

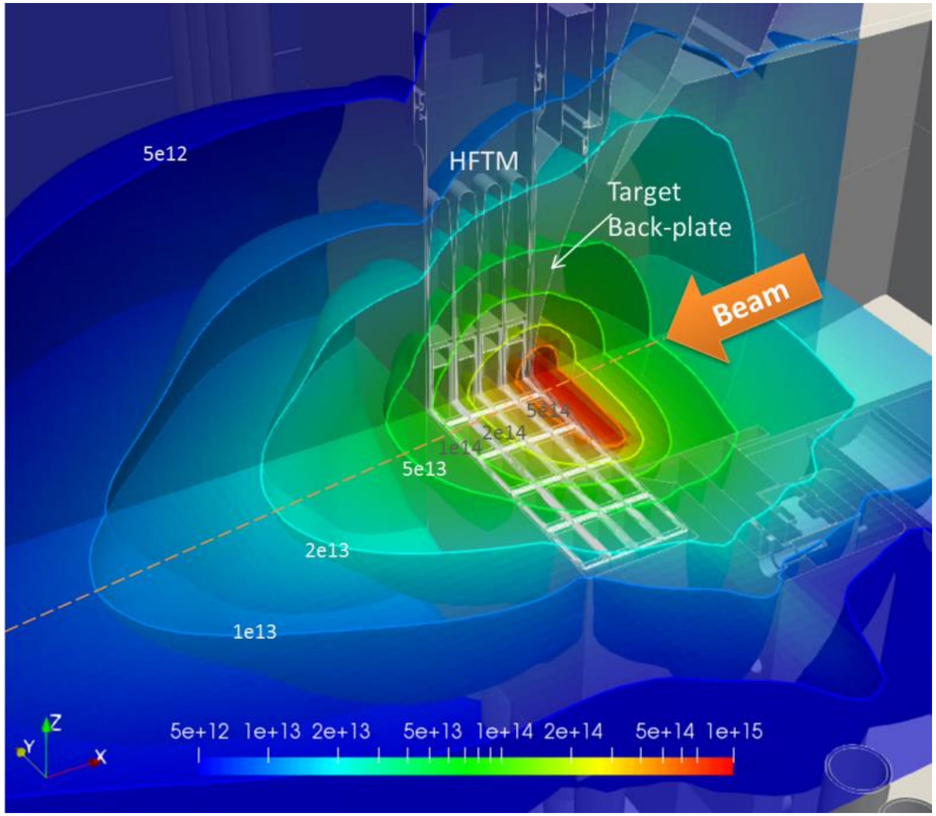


(*)NRT displacements per atom (dpa) to Fe in steel specimens per full power year (fpy)

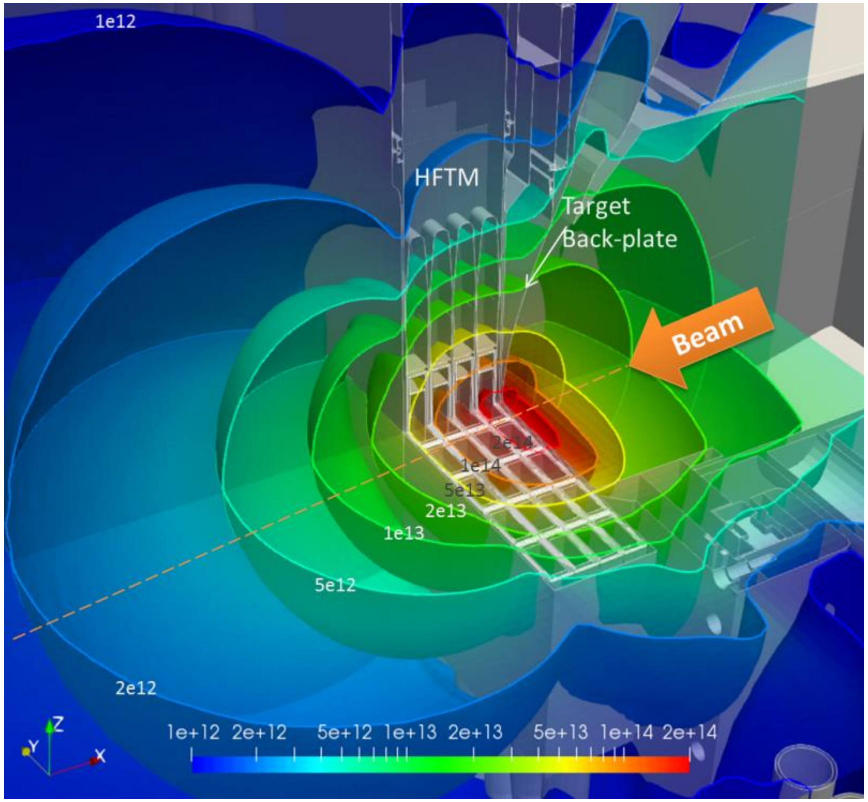
TTC nuclear analyses

Neutron and photon flux distributions in TTC around HFTM

Neutron flux [cm^{-2}s^{-1}]



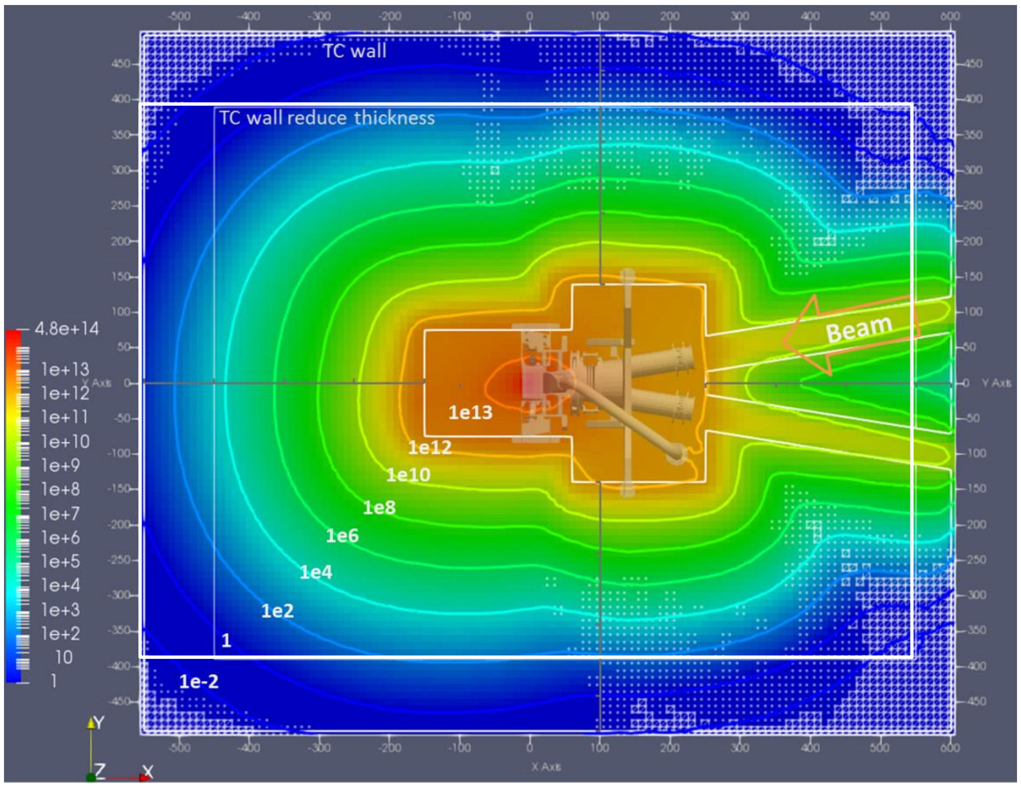
Photon flux [cm^{-2}s^{-1}]



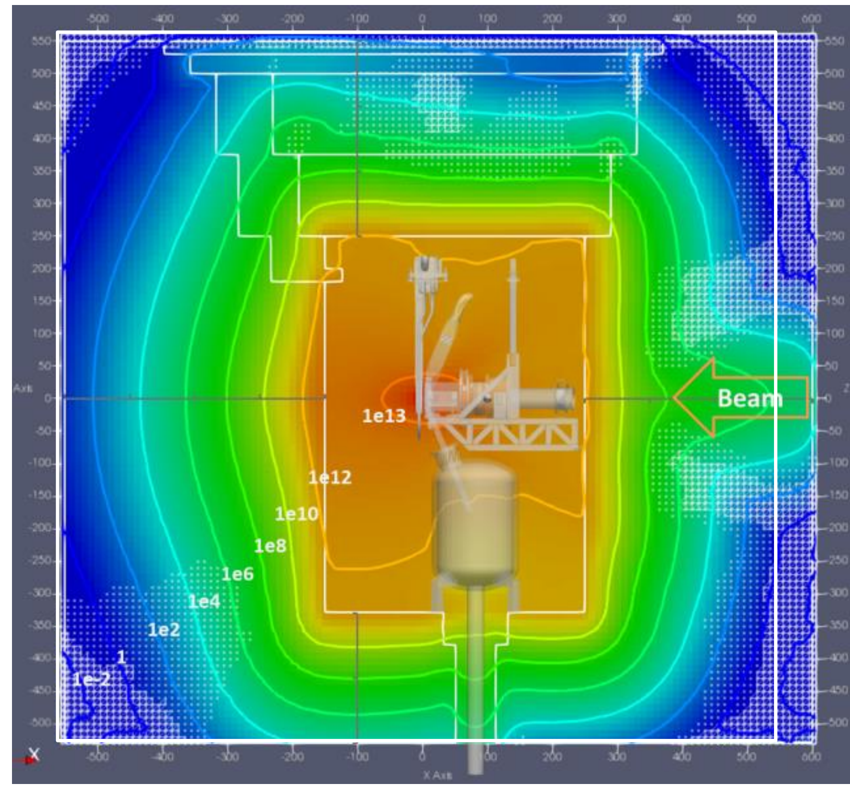
TTC nuclear analyses

Neutron flux distribution in TTC and across bio-shield

Vertical cut at target centre



Horizontal cut at beam level

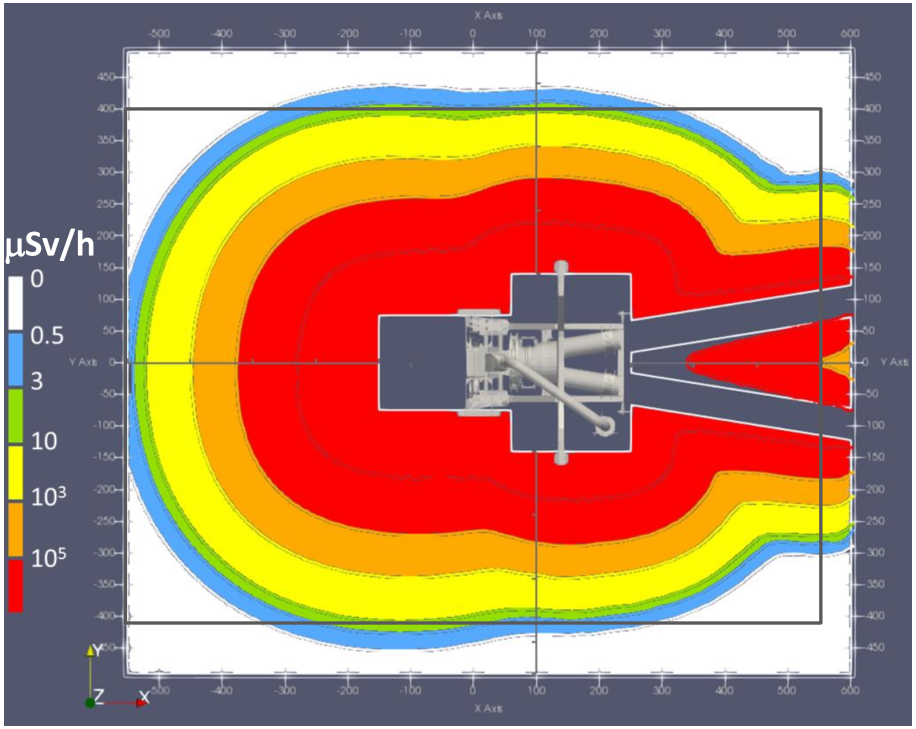


⇒ *Reduction of flux level in TC walls (heavy concrete, up to 400 cm thick) by up to 10^{12}-10^{13}*

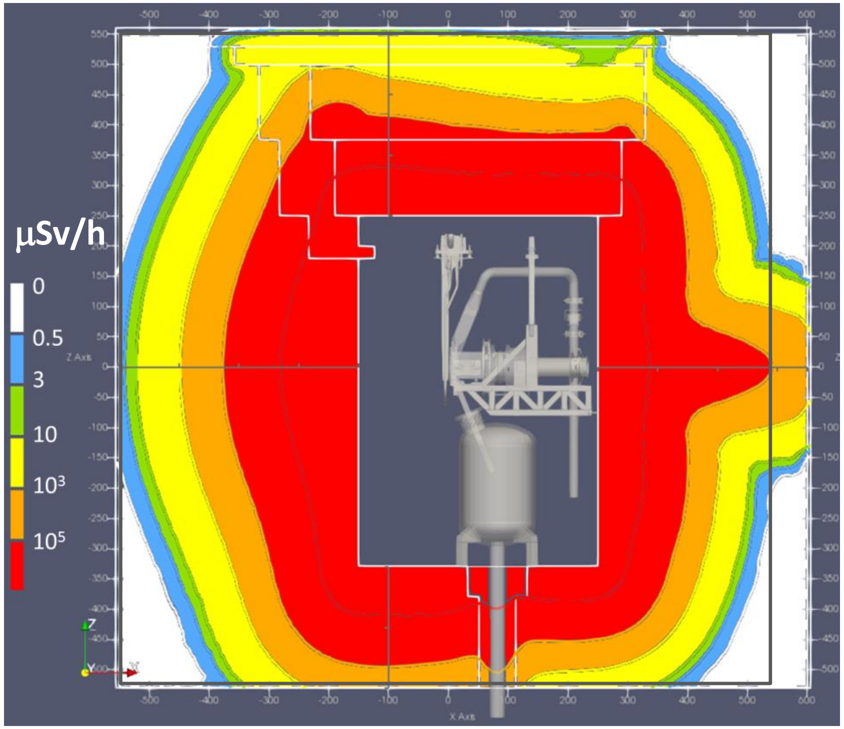
TTC nuclear analyses

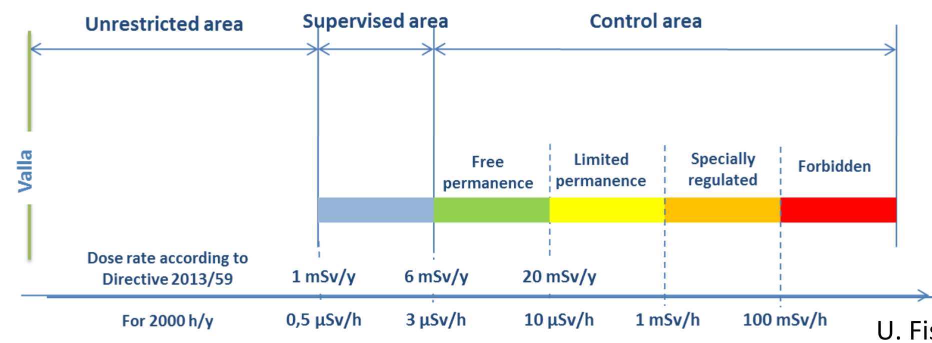
Biological dose rate distribution in TTC and bioshield at "beam-on"

Vertical cut at target centre



Horizontal cut at beam level





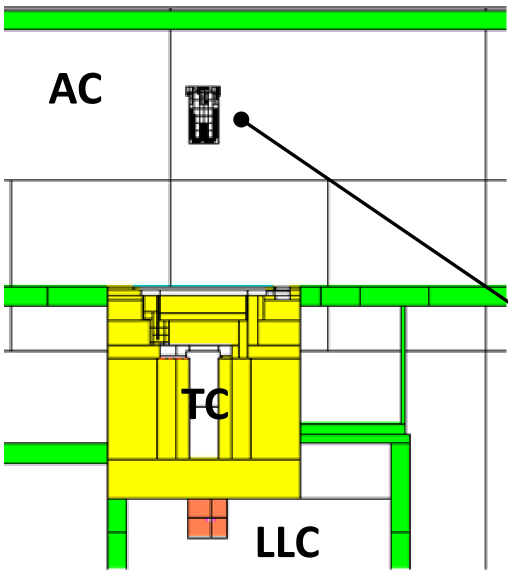
⇒ ***TTC concrete walls sufficient to keep radiation dose level in adjacent rooms in green zone (< 10 μSv/h)***

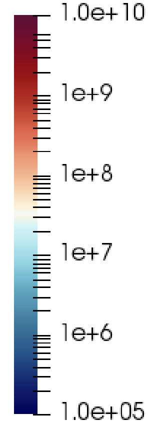
TTC nuclear analyses

Shut-down dose rate distribution in AC with activated HFTM

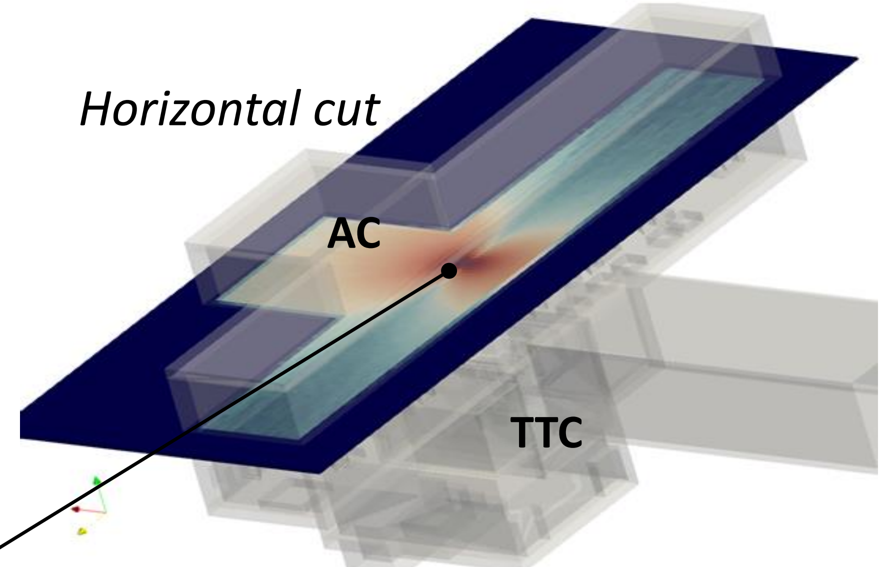
5 hours after irradiation in TTC

MC model (vertical cut)



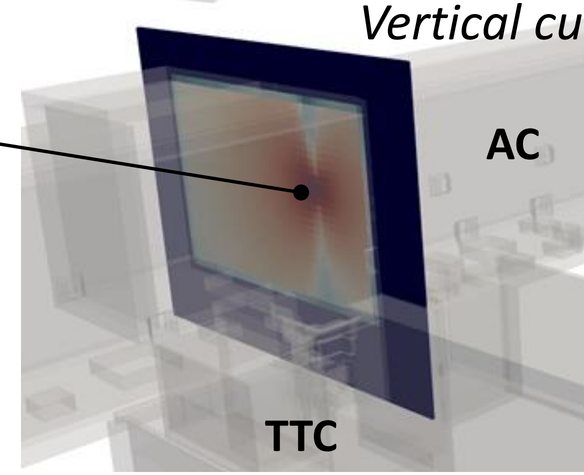


Horizontal cut



Activated HFTM in AC

Vertical cut



- *Dose rate level in AC up to ~10^4 µSv/h*
  - *⇒ Remote maintenance required*
  - *⇒ Shielding requirements to be analyzed*
- *Neighbouring rooms sufficiently shielded by AC walls (1 m concrete)*

Conclusions – IFMIF-DONES neutronics

- Dedicated tools developed
  - *MCUNED for accelerator related nuclear analyses*
  - *McDeLicious for d-Li neutron source & related TTC analyses*

  ⇒ *Continuously up-dated, extended and improved*
- Other tools adapted to specific needs
  - *McCad for generation of simulation models*
  - *R2S schemes for activation and shut-down dose rate calculations*
  - *Variance reduction schemes, based on ADVANTG approach*
- Nuclear data
  - *Provided in co-operation with IAEA & NEA*

  ⇒ *Current development within EUROfusion/PPPT programme*
- Nuclear analyses
  - *Reliable data can be provided for the design, optimisation , and evaluation of IFMIF-DONES.*

  ⇒ *Nuclear performance, shielding, activation, radiation protection, ….*