KIT fusion neutronics and IFMIF-DONES neutronics activities

Yuefeng Qiu, Dieter Leichtle

On behalf of

KIT-INR fusion neutronics group

EUROfusion WPENS neutronics teams

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Introduction

Introduction – KIT/INR

- KIT - Karlsruhe Institute of Technology(卡尔斯鲁厄理工学院)
  - Founded in 2009 as merger of University of Karlsruhe + Karlsruhe Research Centre (FZK)
  - “Research University in the Helmholtz Association” of German large-scale research centers.
- INR - Institute for Neutron Physics and Reactor Technology
  - **Energy research** in the areas of fusion and fission technology, solar thermal energy, thermal storage, thermoelectric conversion as well as safety analyses of nuclear facilities from accelerators to power plants.
  - Numerical-theoretical analyses of facilities and components
  - Decades of R&D in the fusion projects.

Univerisität Karlsruhe (TH)

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Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

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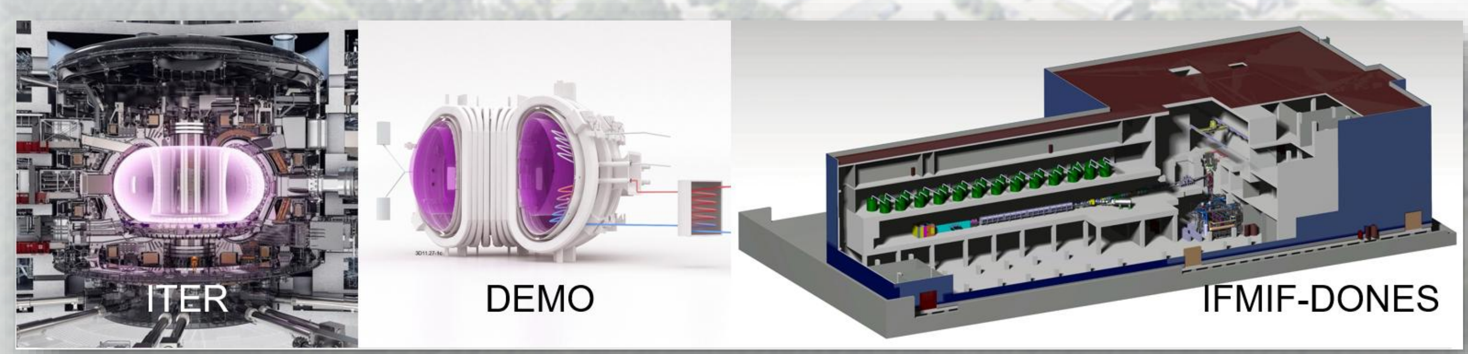
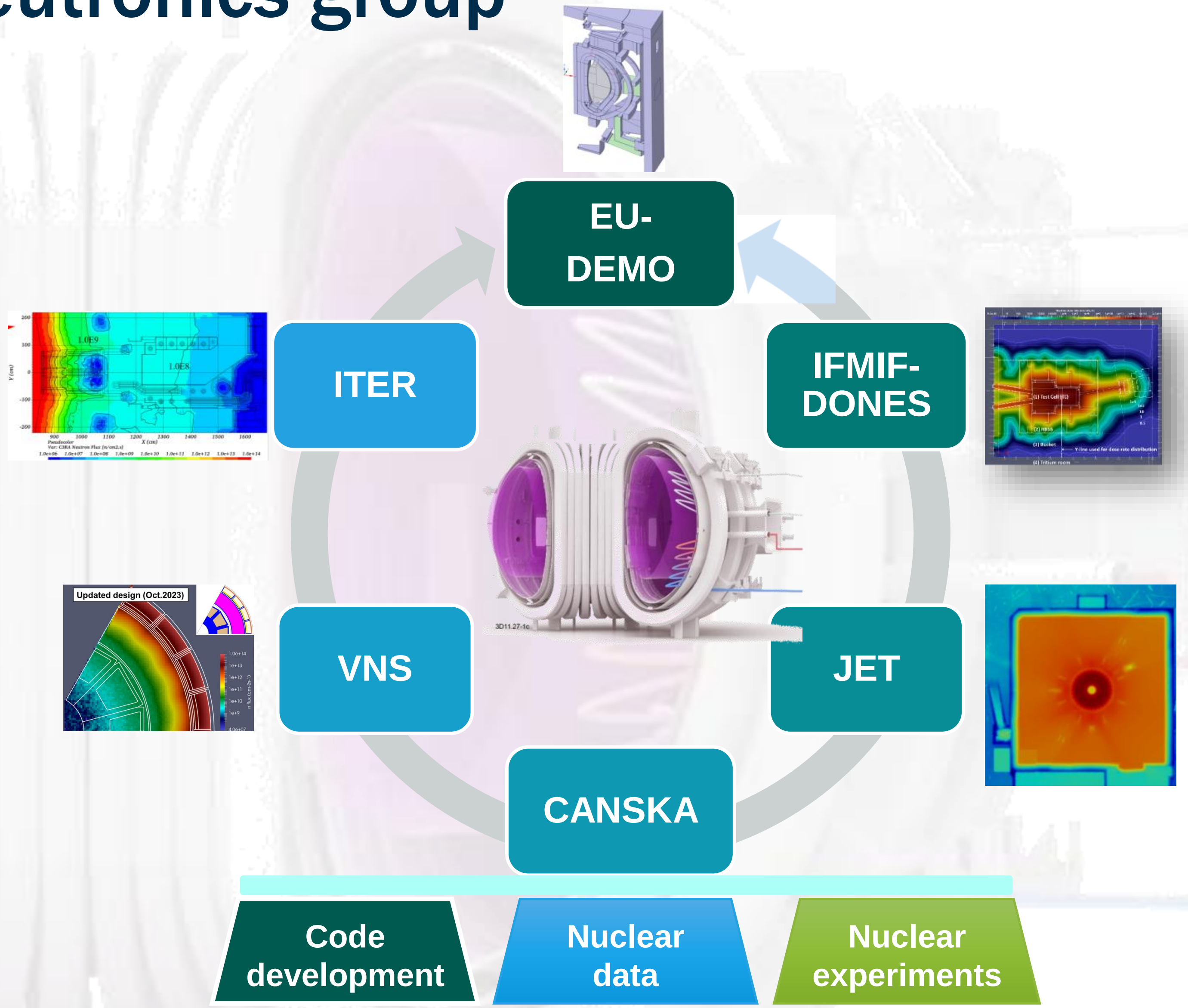
KIT
Karlsruher Institut für Technologie



Introduction – KIT fusion neutronics group

NK Group – Neutronics and nuclear data (中子学和核数据库组，简称KIT聚变中子学组)

- One of the earliest fusion neutronics groups worldwide
- Current member:10
- 30+ years of long-standing role in fusion neutronics: EU-DEMO, ITER, IFMIF-DONES, JET
- Focusing on the development of fusion **neutronics tools and methodologies, nuclear analyses, nuclear data development, and neutronics experiments**



Introduction – KIT fusion neutronics group

Group leader – Dr. Dieter Leichtle

- Neutronics coordinator at EUROfusion Fusion Technology Department
- Coordinator of the EUROfusion nuclear data and experiment program
- Chair of Fusion Working Group of JEFF

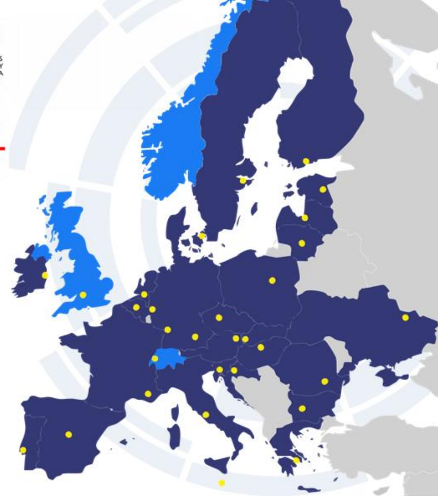
Deputy leader – Dr. Yuefeng Qiu

- KIT permanent senior researcher
- 20 years of professional experience in fusion neutronics
- Coordinator of IFMIF-DONES neutronics activity under EUROfusion
- Neutronics Contact person of EU-JA Broader Approach II

KIT fusion neutronics

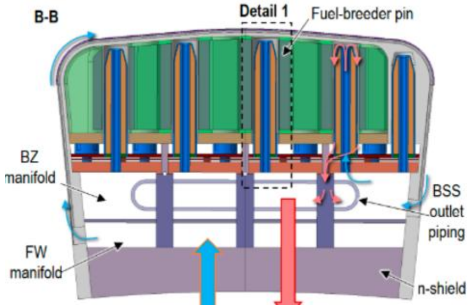
EU-DEMO power plant

- European Consortium for the Development of Fusion Energy - **EUROfusion**
  - Net electric power 300 – 500 MWe
  - Fusion power ≈ 1.8 – 2.0 GWth
  - Major/Minor radius ≈ 9 m/ 3 m
- Blanket concepts
  - Helium-Cooled Pebble Bed
  - Water-Cooled Lithium-Lead
  - Water-Cooled Lead Ceramic Breeder (new)



HCPB

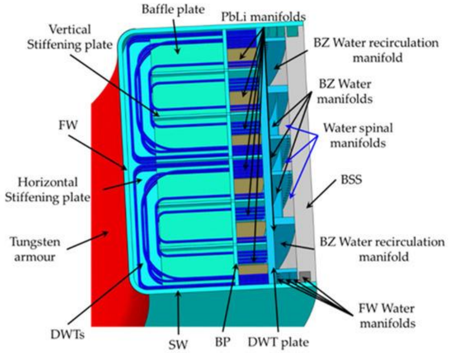
Coolant: He, ~8 MPa
Breeder: Li_4SiO_4 / Li_2TiO_3 pebbles
Multiplier: Be / $Be_{12}Ti$
Mature T-extraction; KIT-led



G. Zhou, et.al.

WCLL

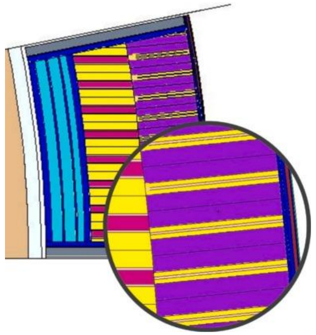
Coolant: H_2O, PWR ~15.5 MPa
Breeder: PbLi eutectic
Multiplier: Pb (in PbLi)
Proven fission-derived cooling



P. Arena, et.al.

WLCB

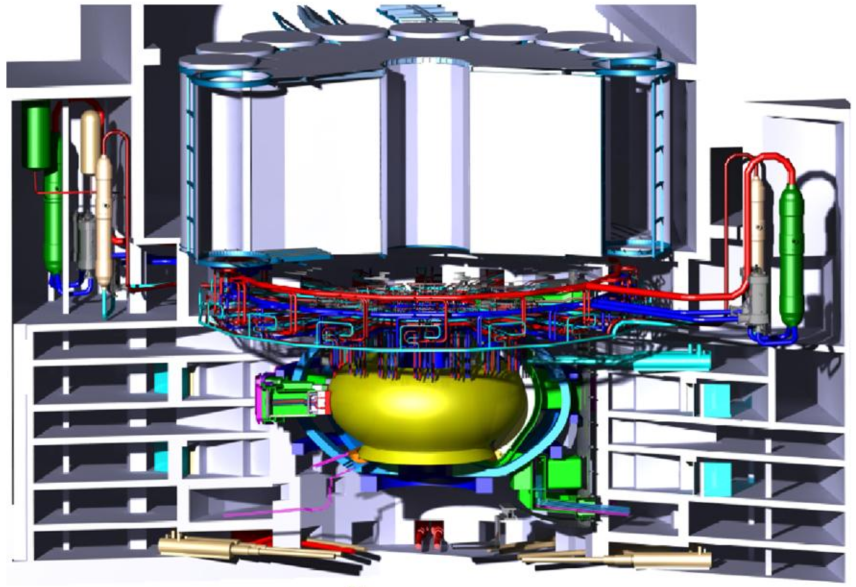
Coolant: H_2O, PWR-like
Breeder: Ceramic pebbles (ACB)
Multiplier: Pb
Hybrid, proposed ~2020 to combine both



I. Palermo, et.al.

DEMO

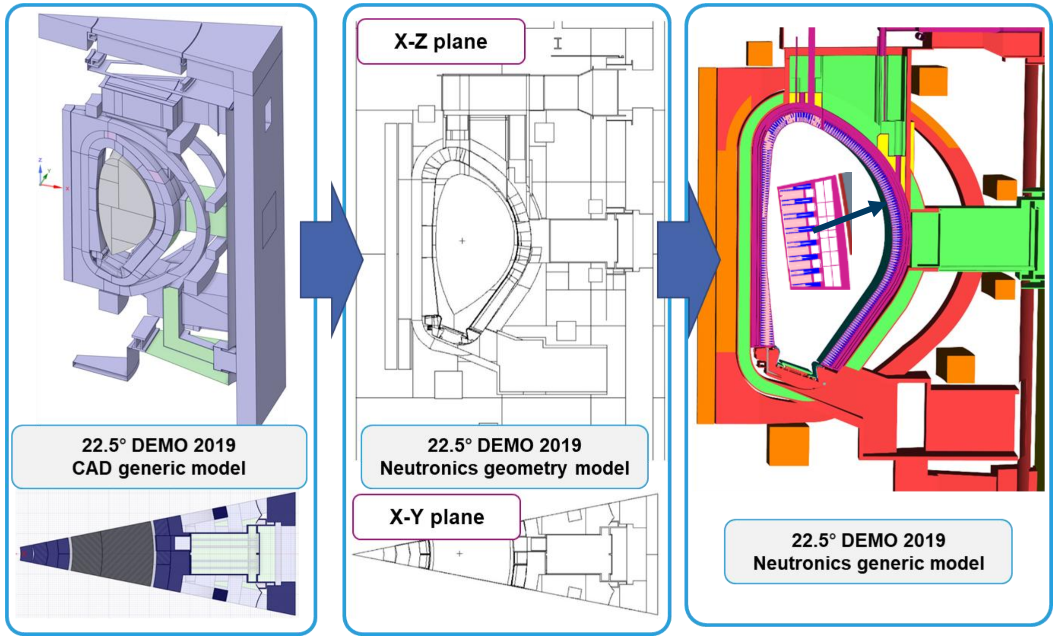
European Demonstration Fusion Energy Power Plant



EUROfusion Source: euro-fusion.org

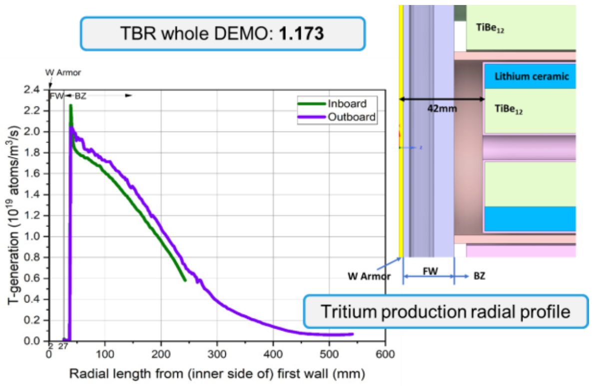
EU-DEMO blanket analysis

- Update and maintenance of the generic neutronics model.
- Nuclear analysis cycle of HCPB design: modeling, nuclear responses, optimizations.

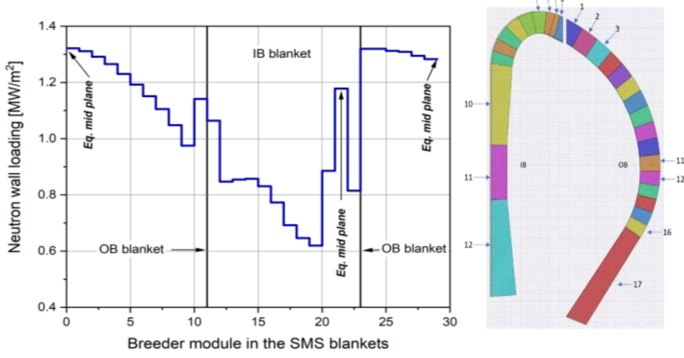


Neutronic modelling

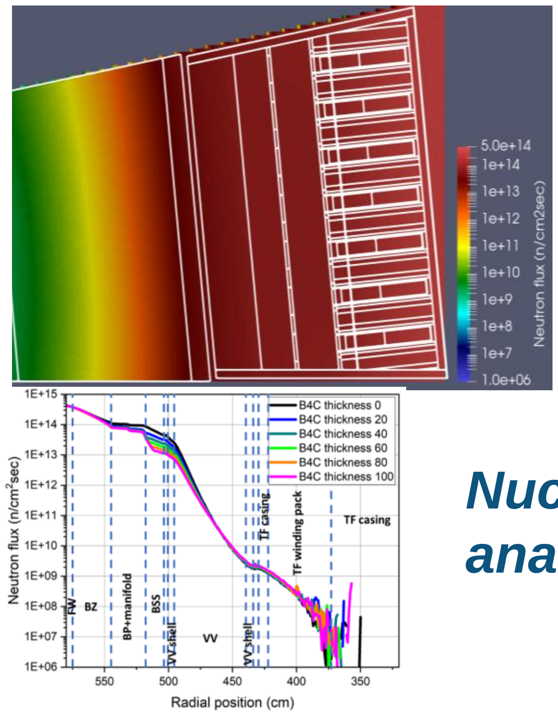
Tritium breeding ratio



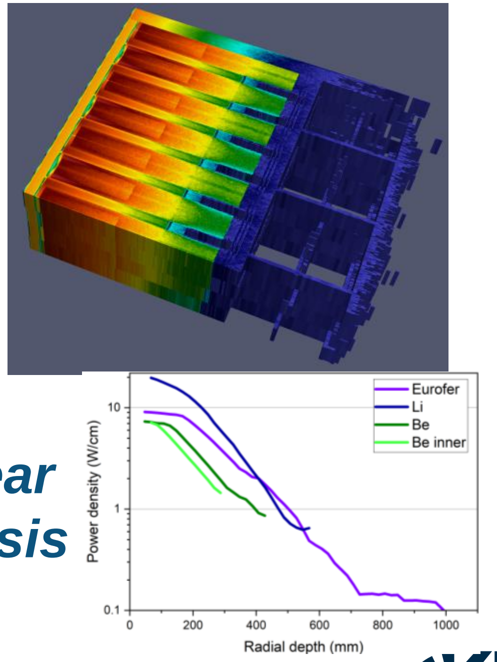
Neutron wall loading



Shielding



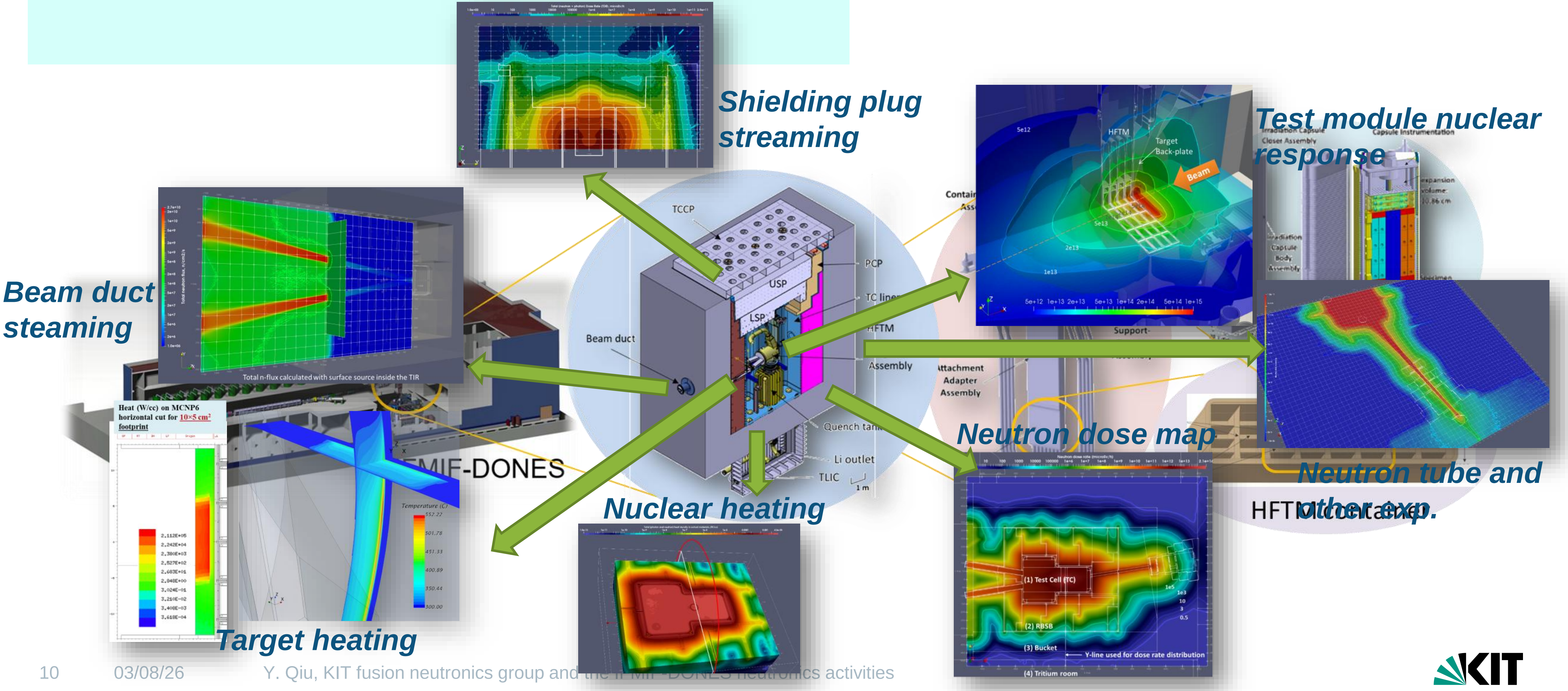
Nuclear heating



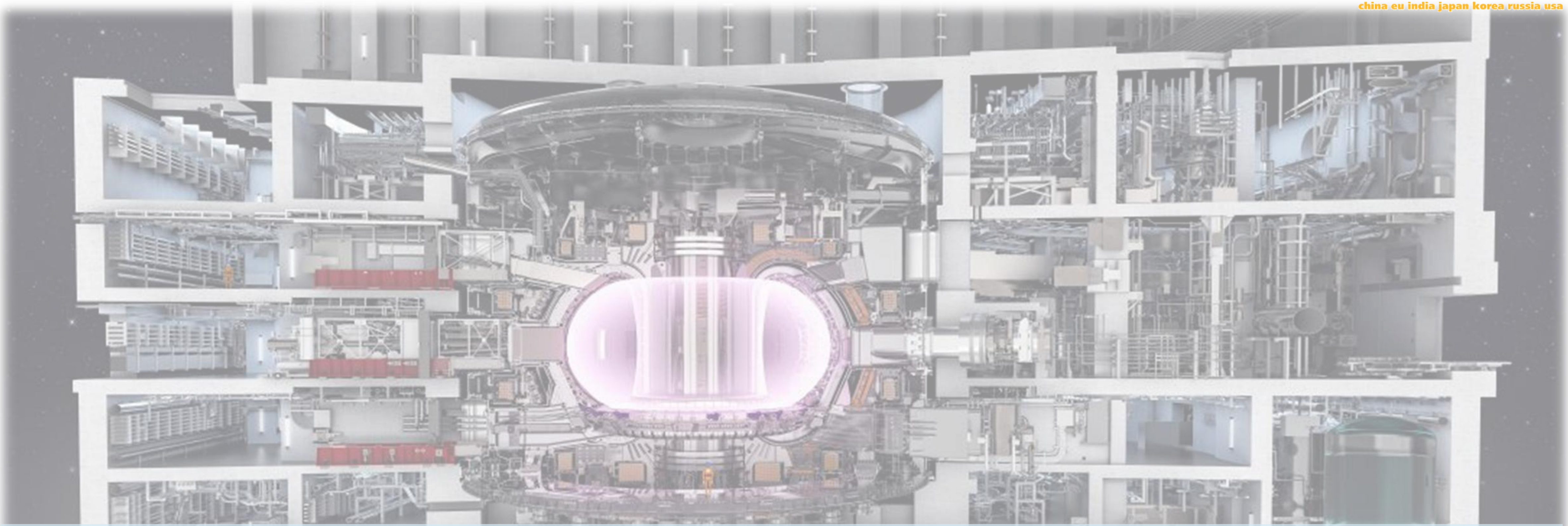
Nuclear analysis

IFMIF-DONES nuclear analysis

Test system nuclear analyses since IFMIF-DONES project starts (2015).



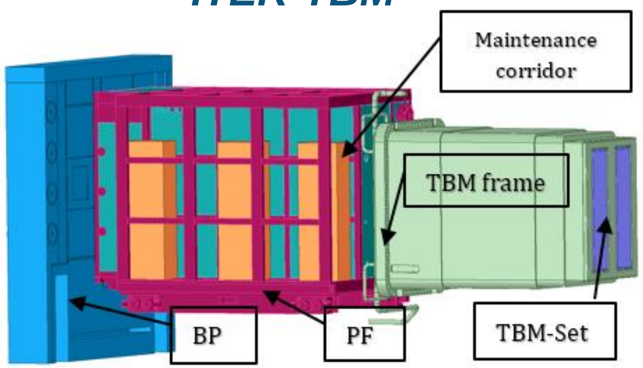
ITER



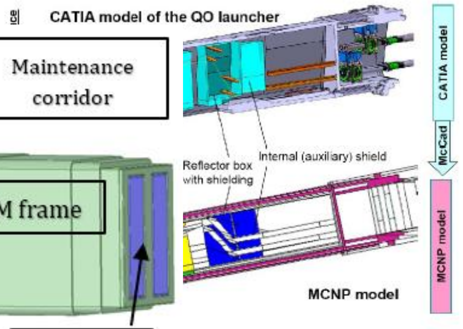
- **Organization**: China, EU/Euratom (+UK, Switzerland), India, Japan, South Korea, Russia, US.
- **Goal**: Demonstrate net fusion energy gain ($Q \geq 10$).
- **Machine**: Tokamak with $R_0 \approx 6.2$ m, $a \approx 2.0$ m, $I_p = 15$ MA, $B_t = 5.3$ T, plasma volume ≈ 840 m^3.
- **First wall**: Switched from beryllium to tungsten in the 2024 rebaseline.
- **New schedule (Baseline 2024)**: Cryostat closure 2033 → Start of Research Operation 2035 → full current/field 2036 → D-T operation 2039 → Q≥10 in 2044.

ITER Nuclear analyses

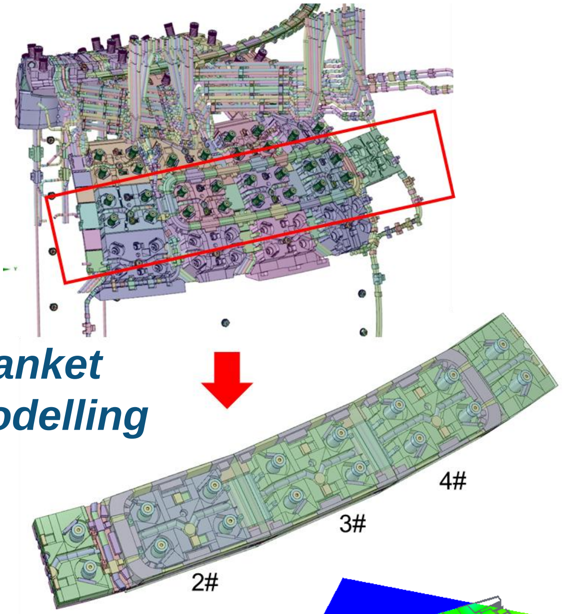
- KIT Involvement in ITER neutronics
  - Baseline neutron model creation.
  - Blanket modeling and analysis
  - IVVS system analysis
  - TBM and port plugs
  - ECRH upper launcher
  - ITER FW
  - NBI



ITER TBM

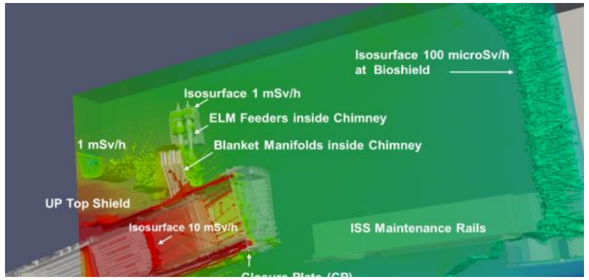


TBM Port Plug and Pipe Forrest

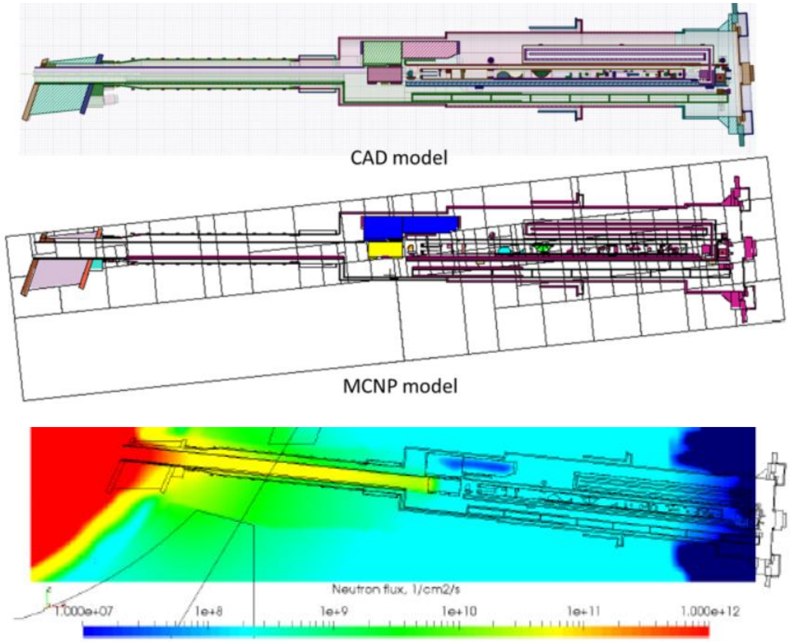


Blanket modelling

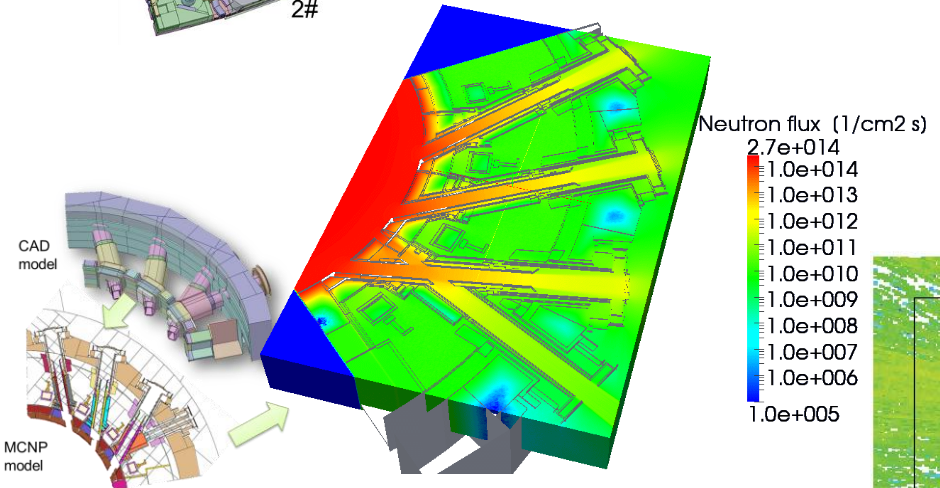
ECRH Upper Launcher



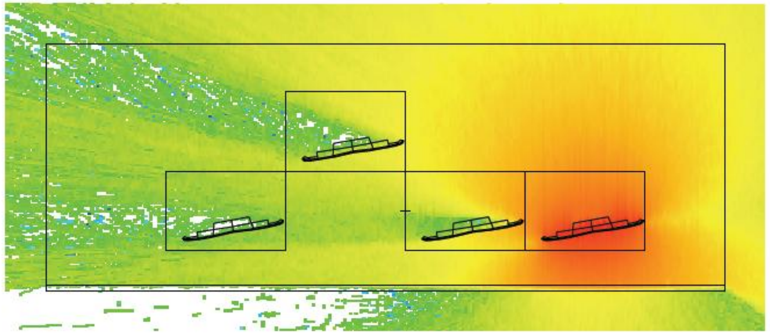
SDR map, 12 days after shut-down



IVVS system

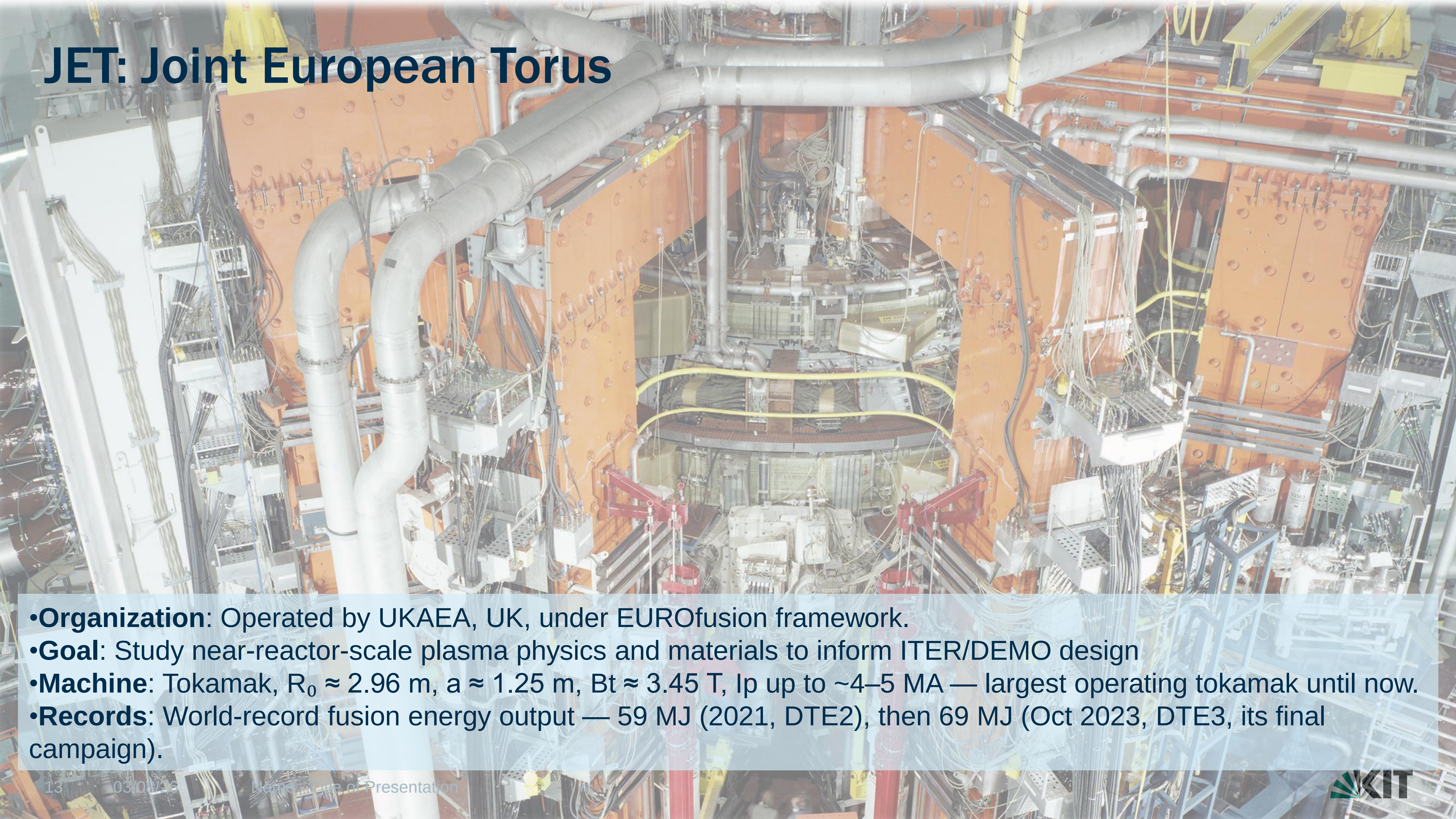


Neutral beam injector system



ITER FW dose rate

JET: Joint European Torus

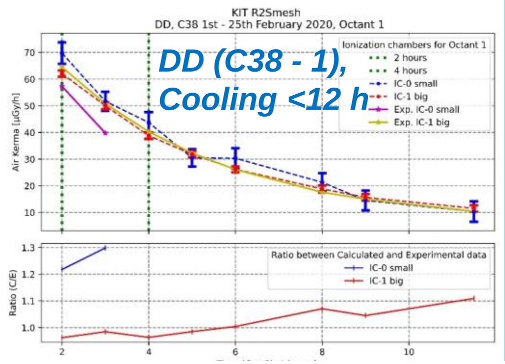


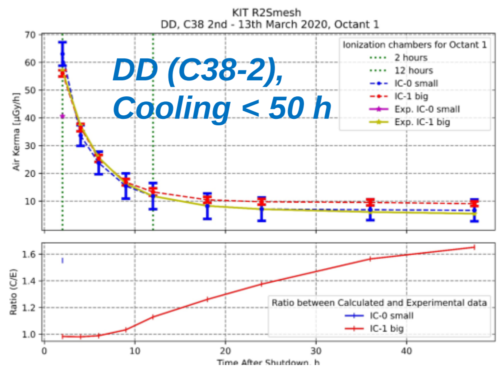
- **Organization**: Operated by UKAEA, UK, under EUROfusion framework.
- **Goal**: Study near-reactor-scale plasma physics and materials to inform ITER/DEMO design
- **Machine**: Tokamak, $R_0 \approx 2.96$ m, $a \approx 1.25$ m, $B_t \approx 3.45$ T, I_p up to ~4–5 MA — largest operating tokamak until now.
- **Records**: World-record fusion energy output — 59 MJ (2021, DTE2), then 69 MJ (Oct 2023, DTE3, its final campaign).

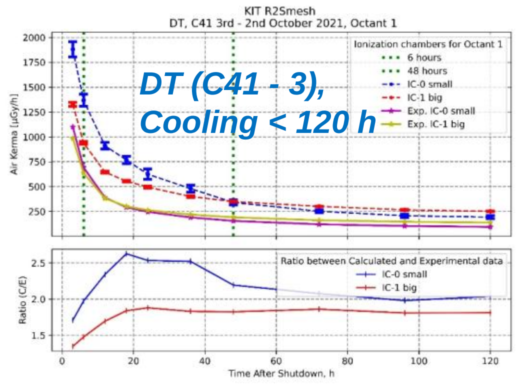
JET experiments and code validations

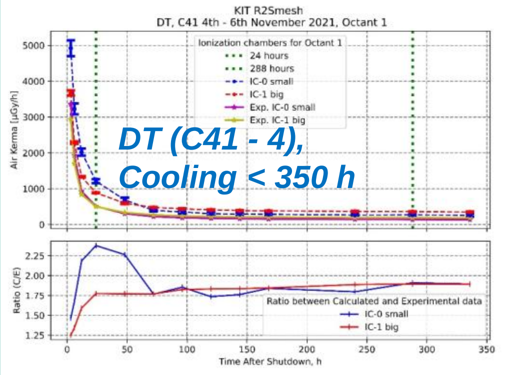
- Validation of KIT SDR tool **R2Smesh**
- Good agreement for DD campaign within 10-h cooling (C/E <1.1),
- Deviation extended along with cooling time (C/E 1.7~2.0) .

JET SDR experiment

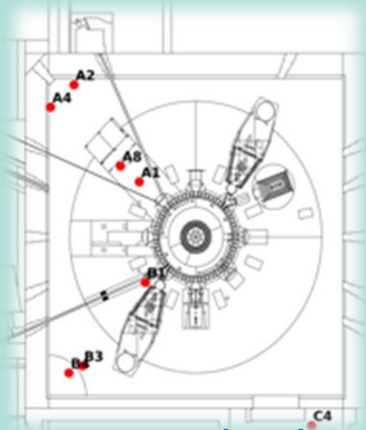






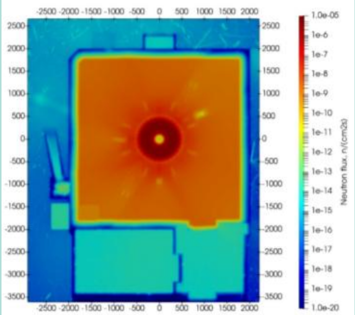


- Validation of KIT Variance Reduction Tool OTF-GVR
- Good agreement with experiment (mostly <10%)
- Better performance than ADVANTG on C/E and FOM



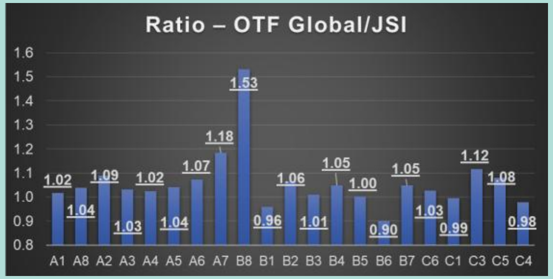
Detector location

JET STRE experiment

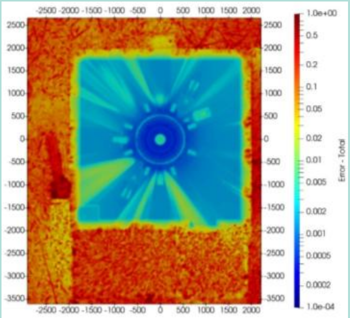


n flux

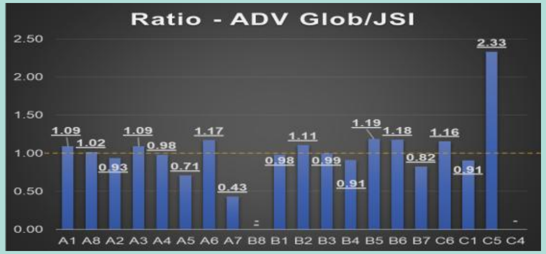
OTF-GVR



ADVANTG



Rel.err.

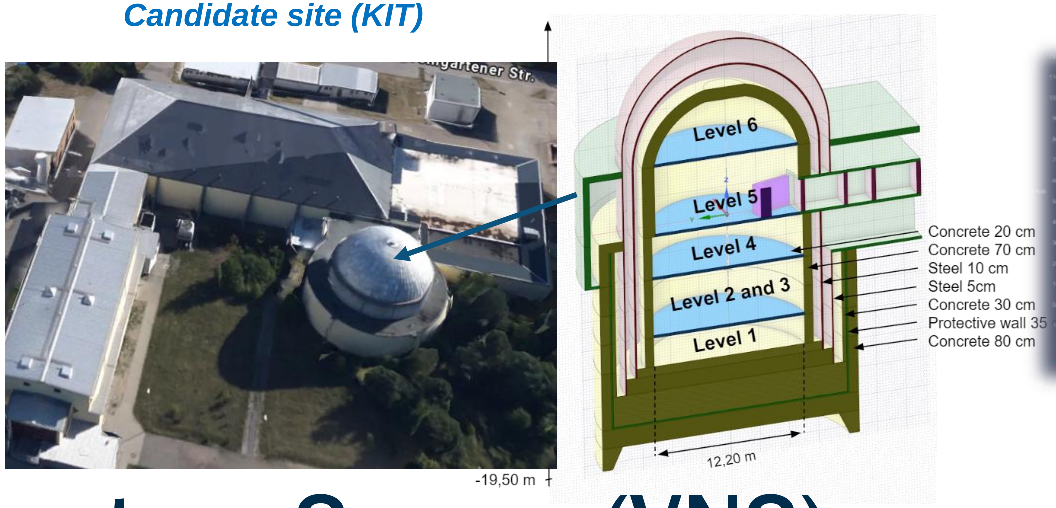


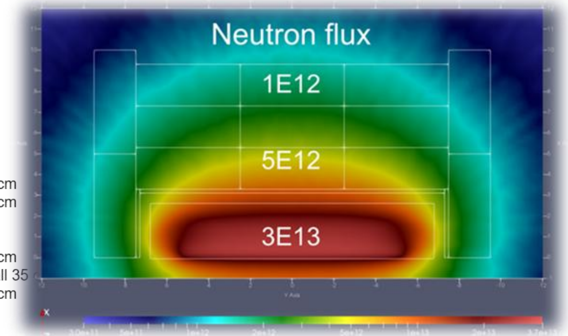
KIT CANSKA conceptual design

CANSKA (Compact Accelerator Neutron Source Karlsruhe)

- Aim for testing and qualifying functional materials for fusion reactors
- **Proton/deuteron: 30 MeV, 10 mA.**
- **Neutron flux 10^{12}-10^{13} n/cm^2/s**
- DPA(NRT): 0.1-0.5 dpa/fpy
- Using Li or GaIn Liquid target

Candidate site (KIT)





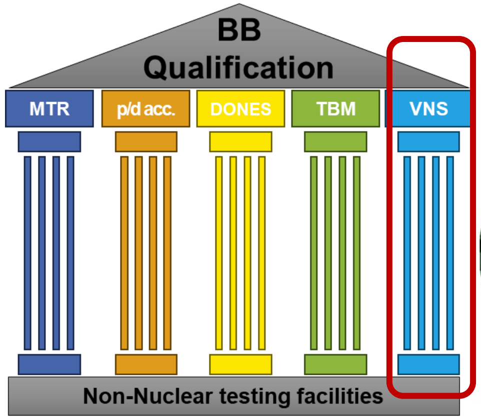
European Volumetric Neutron Source (VNS)

Volumetric Neutron Source (VNS)

- For breeder blanket qualification
- R_0 2.55 m, P_{fus} ~30 MW, NWL peak ~0.5 MW/m^2
- Peak lifetime neutron fluence: 30-50 dpa

Challenging for the shielding design.

- Requirements at TFC: insulator dose < 50 MGy/10fpy, nuclear heat < 450 W/m^3



Breeder blanket qualification

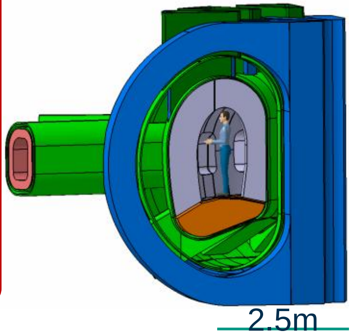
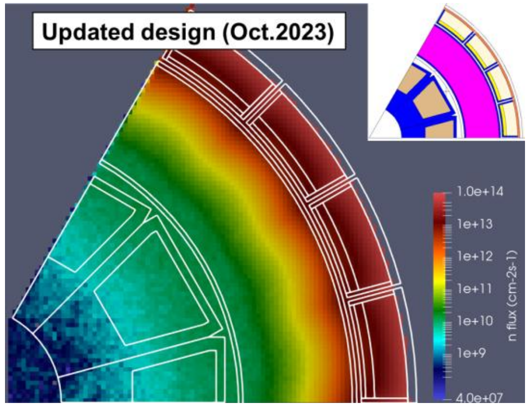


Illustration of VNS



KIT fusion neutronics tool development.

Geometry
- McCad
- SpaceClaim plugins
- MCNP mesh

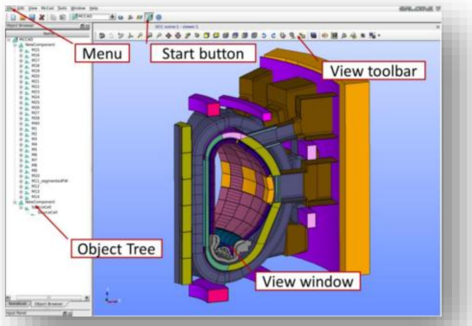
Transport
- McDeLicious
- OpenMC
- MCNP
- Geant4
- D1S-UNED

Variance reduction
- OTF-GVR
- ADVANTG

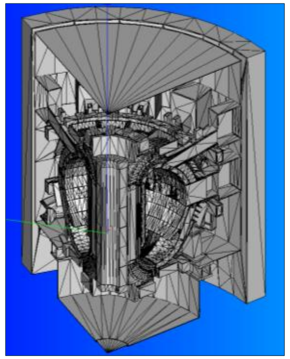
Shutdown dose
- R2Smesh
- H2S
- CAD2CGDS
- CommonR2S

Multiphysics
- McMeshTran

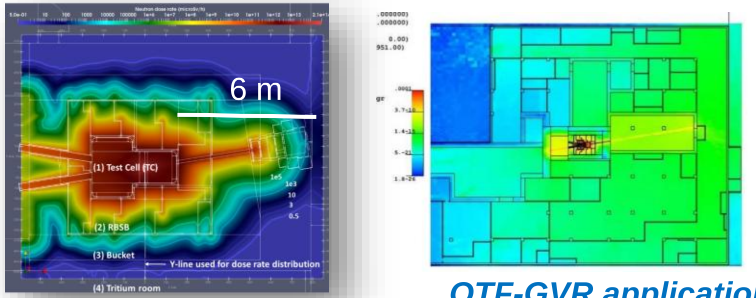
(purple: KIT developments)



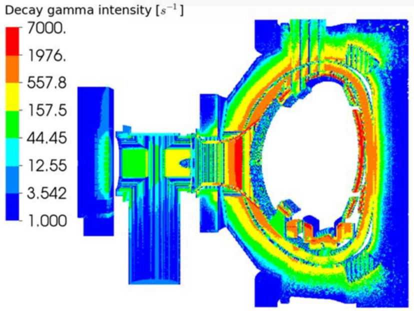
McCad-SALOME



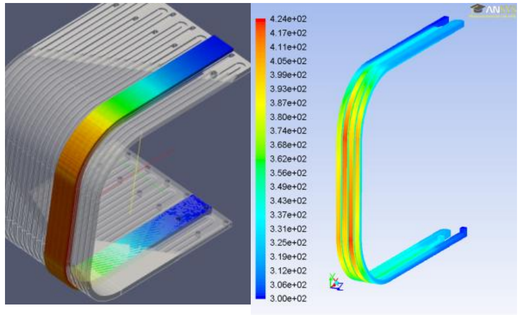
TT Mesh



OTF-GVR application in IFMIF-DONES



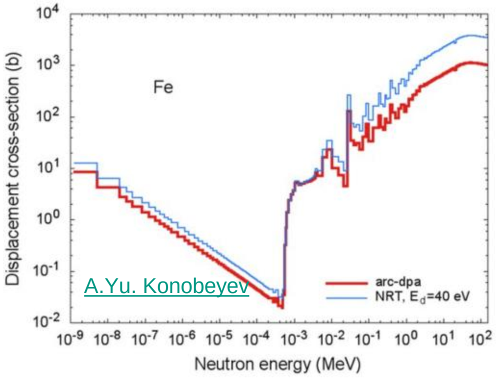
H2S JET decay gammas



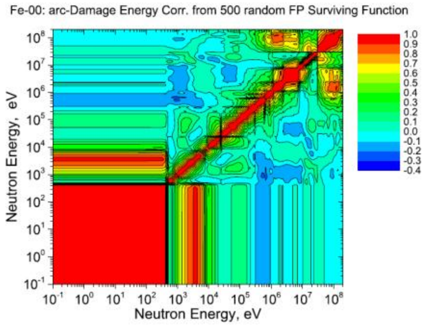
Multiphysics coupling

Nuclear data and experiments

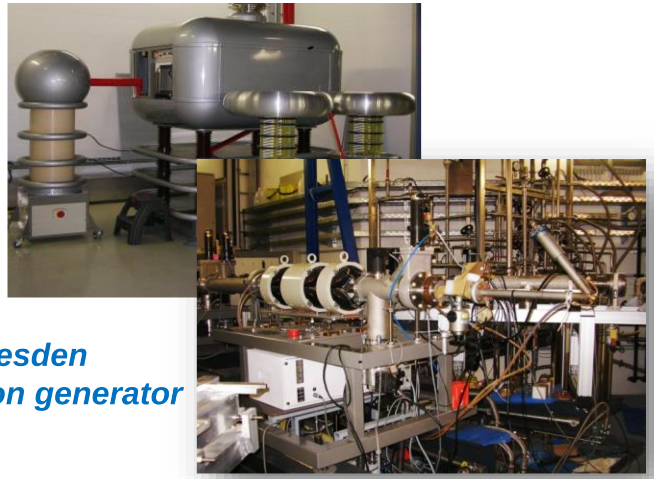
- Development of displacement cross-section and charged particle activation data.
- Operating the TUD neutron generator, contributing to mockup experiments and the development of detectors.



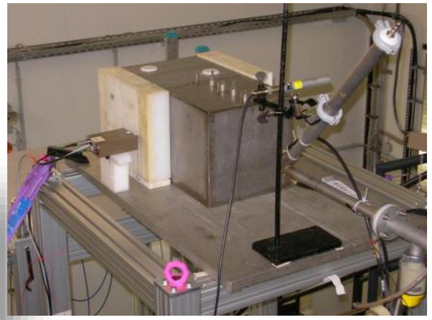
Fe Displacement cross section



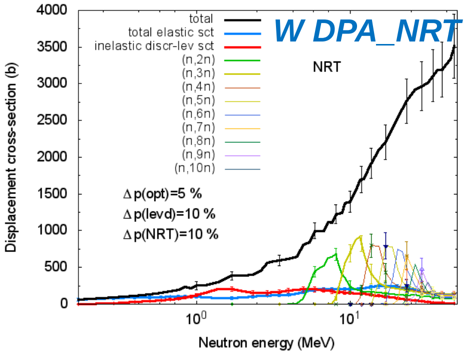
Fe DPA covariance matrix



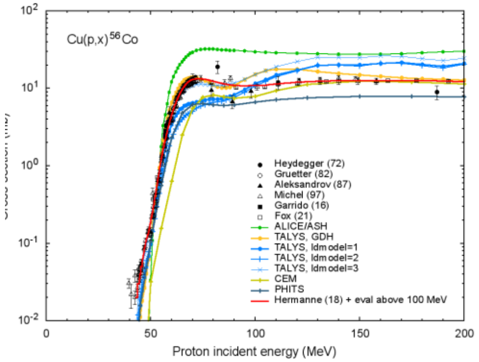
TU-Dresden neutron generator



HCLL mockup exp.

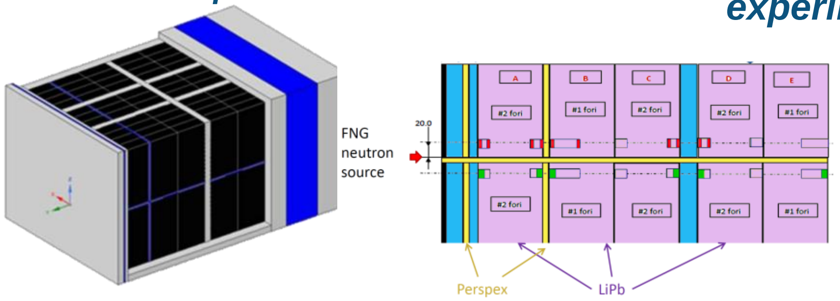


W Displacement cross section

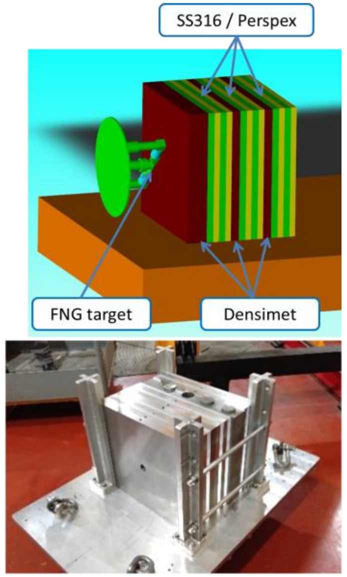


Proton Activation Data File PADF

Water Cooled Lithium Lead (WCLL) blanket mockup



Tungsten mockup experiment

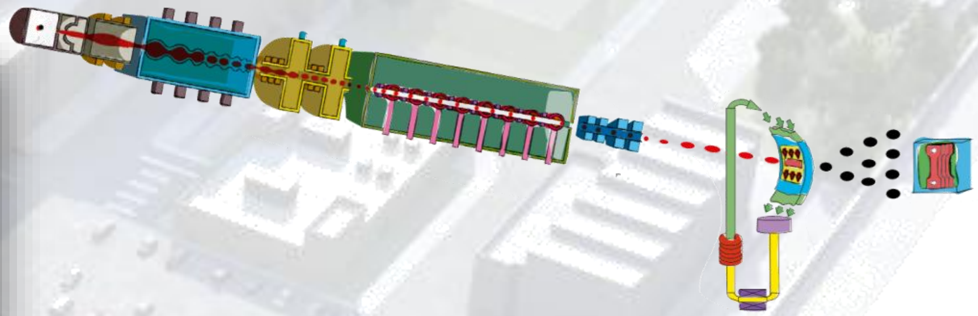


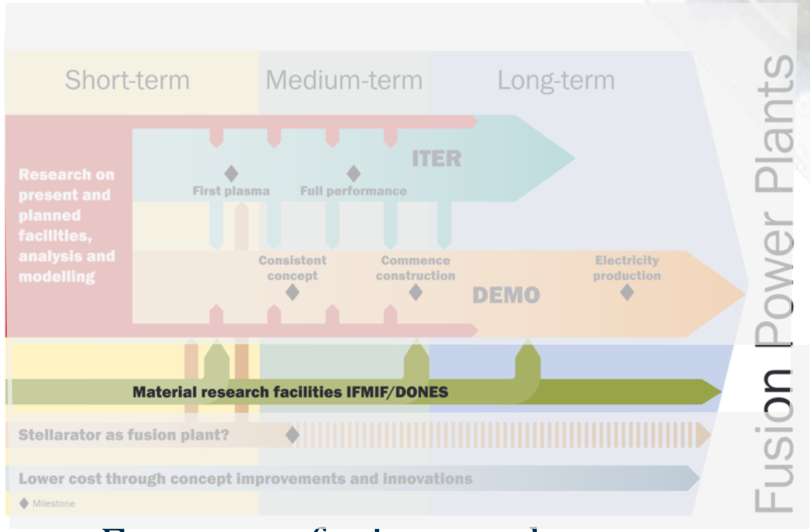
IFMIF-DONES neutronics activities

Introduction of IFMIF-DONES facility

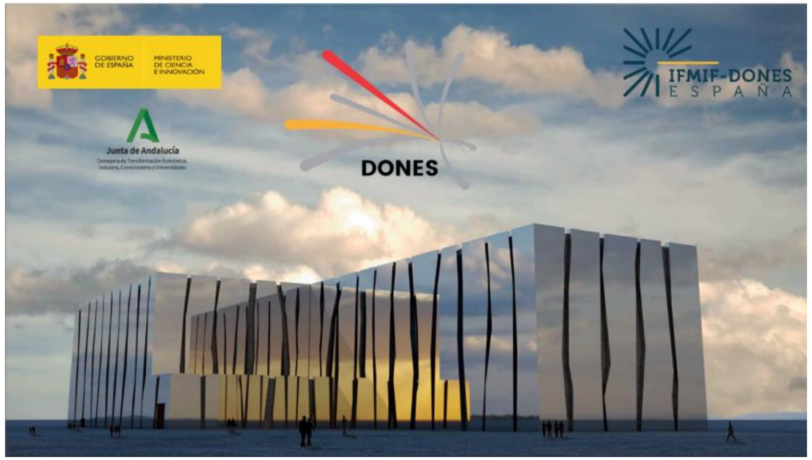
- IFMIF-DONES: International Fusion Material Irradiation Facility - DEmo Oriented Neutron Source
- Provide irradiation data for the construction of DEMO
  - Deuteron accelerator 125 mA, 40 MeV, **5 MW power**
  - Neutrons from Li(d,xn): **flux 10^{15} n/cm^2/s, DPA max. 20-30 dpa/fpy**
  - Under construction in Granada, Spain.
- EUROfusion Work Package Early Neutron Source (WPENS)
  - Contributions from 16+ beneficiaries.
  - One of the important facilities of the European fusion roadmap

Source: ifmif-dones.es





European fusion roadmap

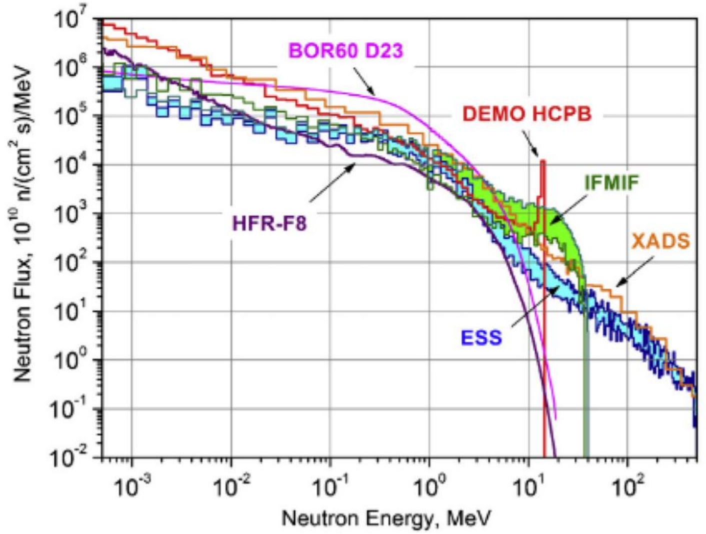


Source: ifmif-dones.es

Why IFMIF-DONES

- Prividing fusion relevant neutron irradiation conditions
  - The d-Li (40 MeV) neutron spectrum is not fully aligned with the fusion mono-energetic spectra.
  - Primary knock-on Atom (PKA) spectra are much more relevant to the fusion first wall compared with fission/spallation sources
  - The key metrics: He(appm)-DPA ratio is in good agreement
    - Fission source : too low; spallation source: too high.

Neutron spectra



Stork, D.et.al. doi.org/10.1088/1741-4326/aa60af

PKA energy spectra

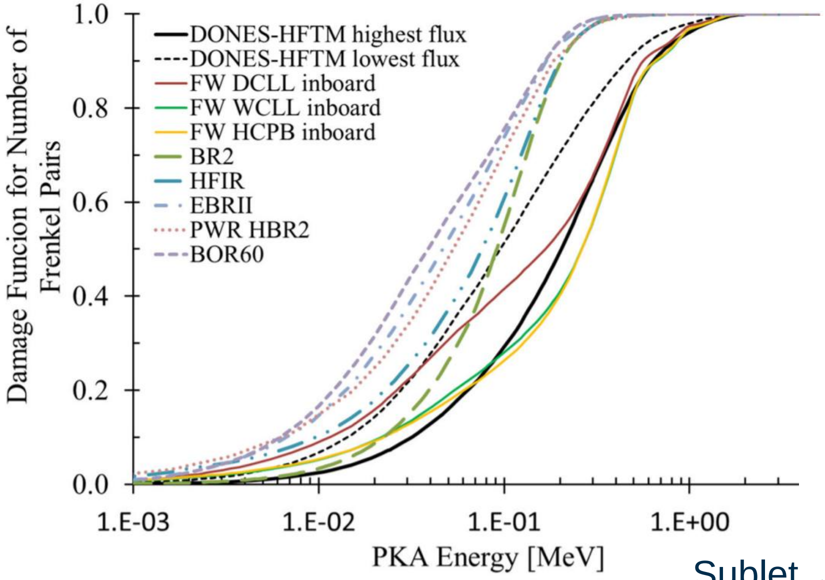


Fig. 43. Damage function for the different neutron sources assessed.

He(appm)/DPA ratio

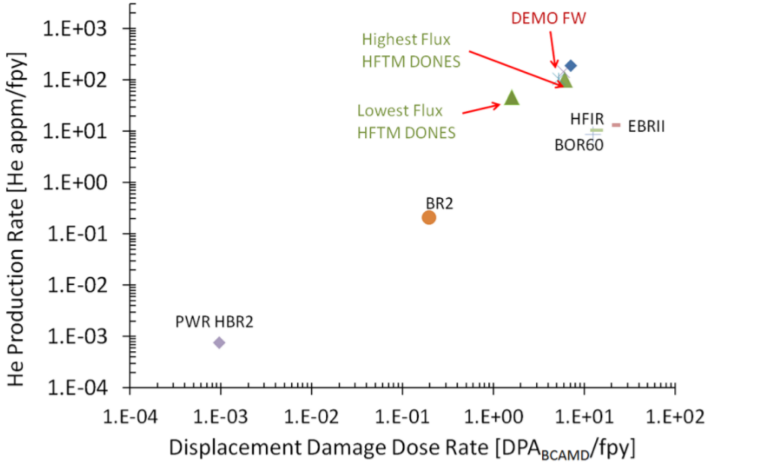
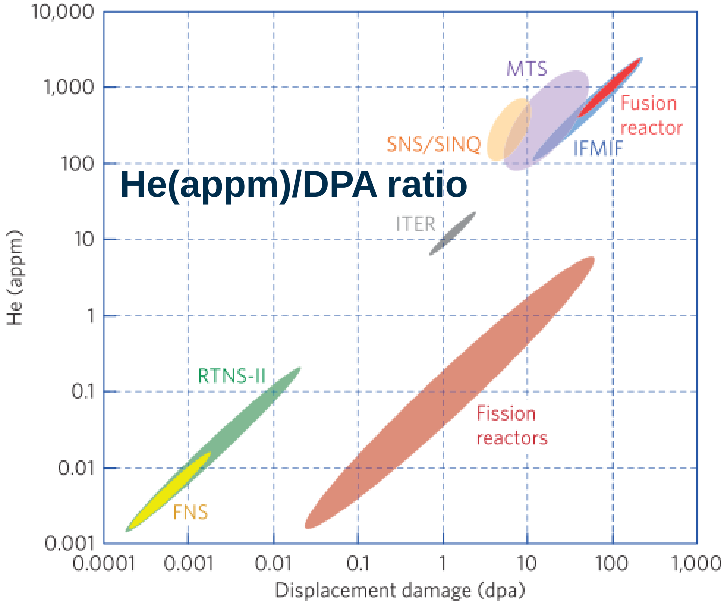


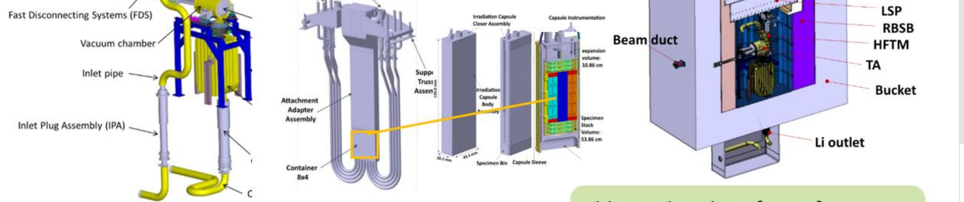
Fig. 44. He production rate [He appm/fpy] *versus* displacement damage rate [DPA_{BCAMD}/fpy].

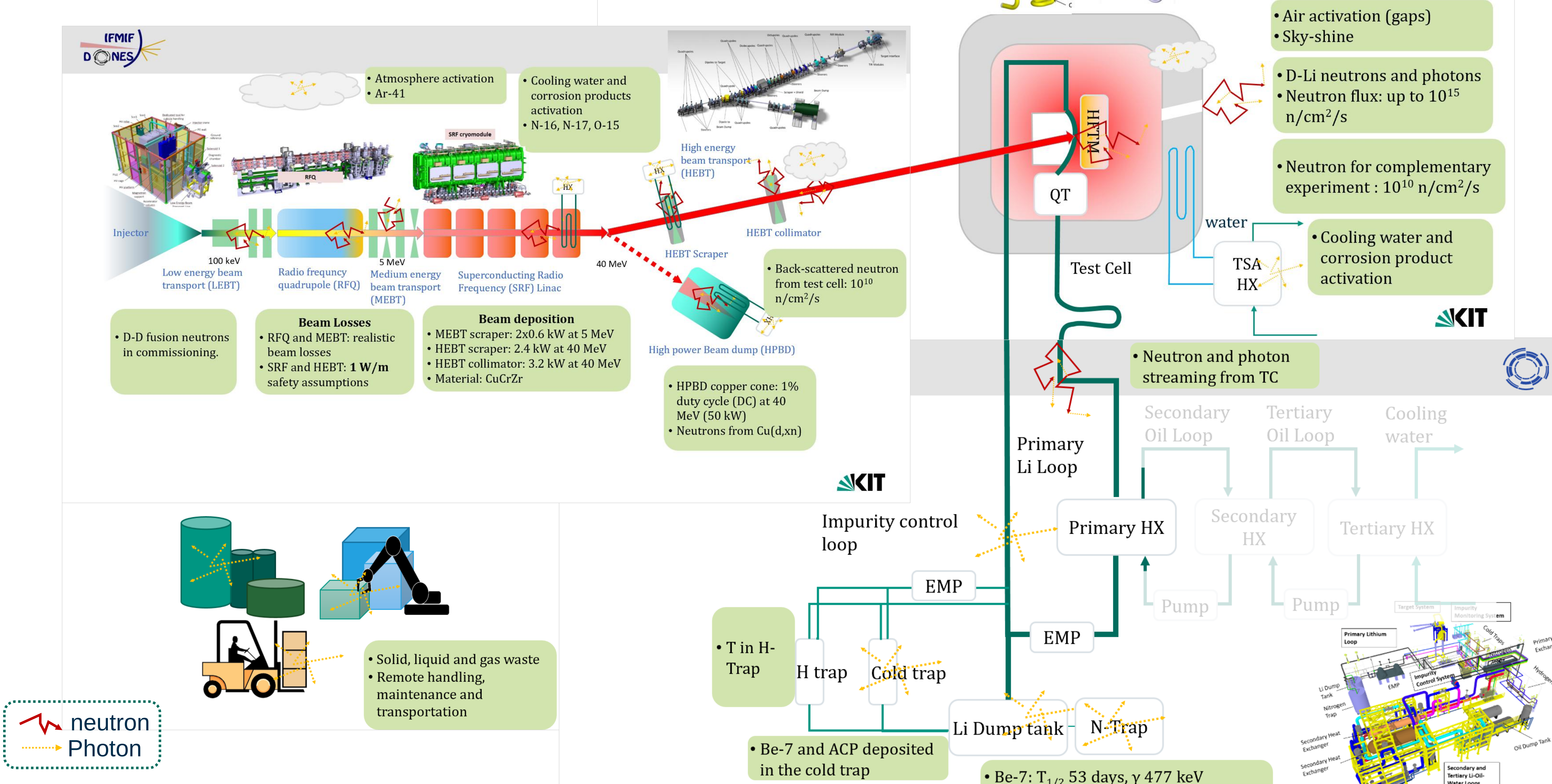
Sublet, J.-C.et.al. doi.org/10.1140/epjp/i2019-12758-y

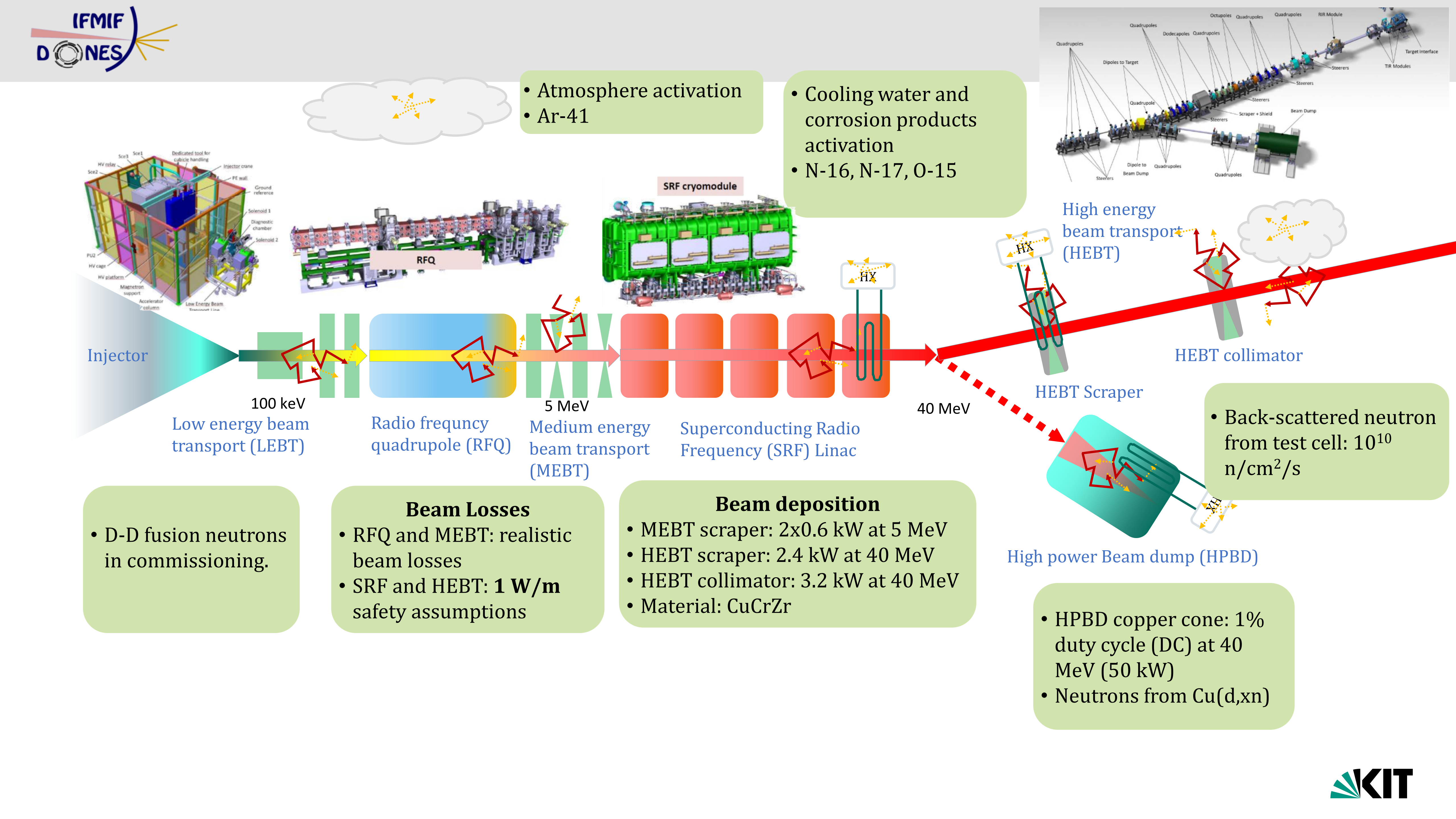


J. Knaster,et.al , doi.org/10.1038/NPHYS3735

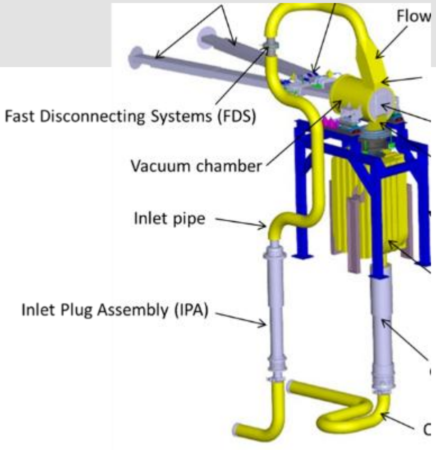
DONES systems and source terms

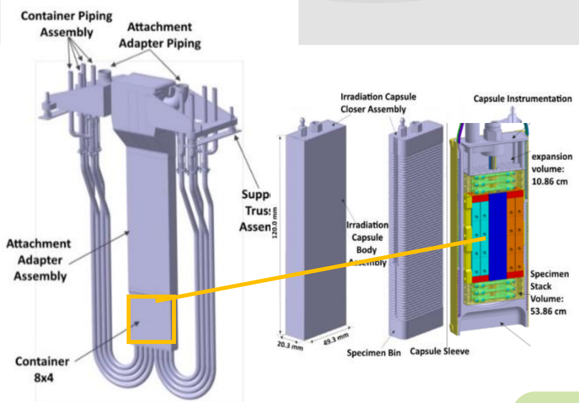


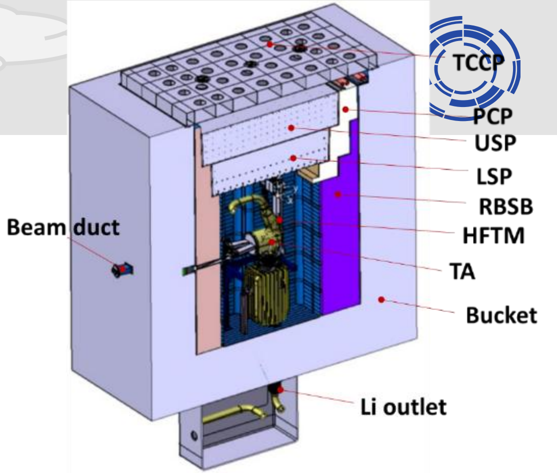


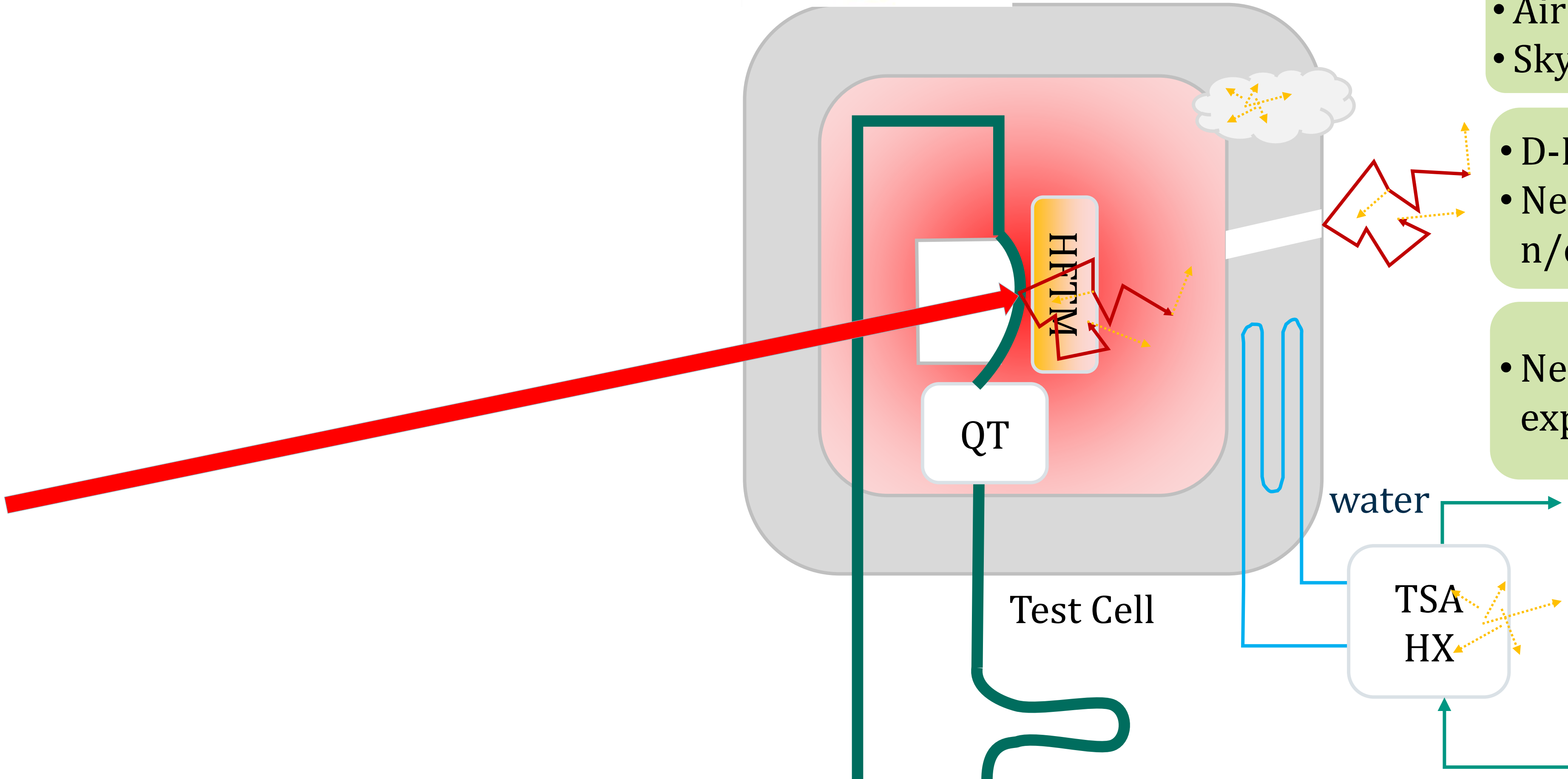


IFMIF DONES
Atmosphere activation
Ar-41
Cooling water and corrosion products activation
N-16, N-17, O-15
SRF cryomodule
RFQ
HX
High energy beam transport (HEBT)
Injector
100 keV
Low energy beam transport (LEBT)
Radio frequncy quadrupole (RFQ)
5 MeV
Medium energy beam transport (MEBT)
Superconducting Radio Frequency (SRF) Linac
40 MeV
HEBT Scraper
HEBT collimator
Back-scattered neutron from test cell: 10^{10} n/cm^2/s
High power Beam dump (HPBD)
D-D fusion neutrons in commissioning.
Beam Losses
RFQ and MEBT: realistic beam losses
SRF and HEBT: **1 W/m** safety assumptions
Beam deposition
MEBT scraper: 2x0.6 kW at 5 MeV
HEBT scraper: 2.4 kW at 40 MeV
HEBT collimator: 3.2 kW at 40 MeV
Material: CuCrZr
HPBD copper cone: 1% duty cycle (DC) at 40 MeV (50 kW)
Neutrons from Cu(d,xn)
KIT









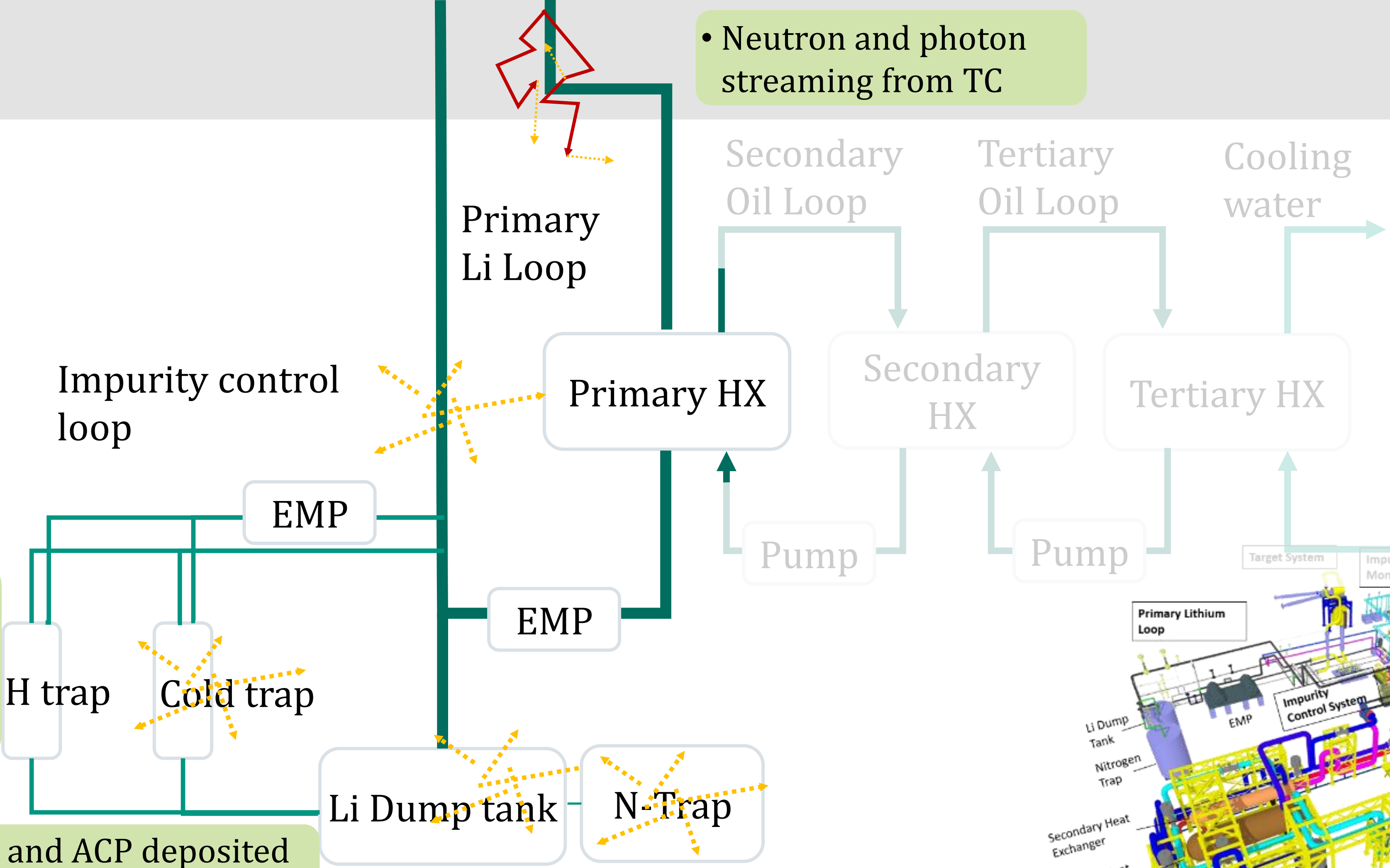
- Air activation (gaps)
- Sky-shine

- D-Li neutrons and photons
- Neutron flux: up to 10^{15} $n/cm^2/s$

- Neutron for complementary experiment : 10^{10} $n/cm^2/s$

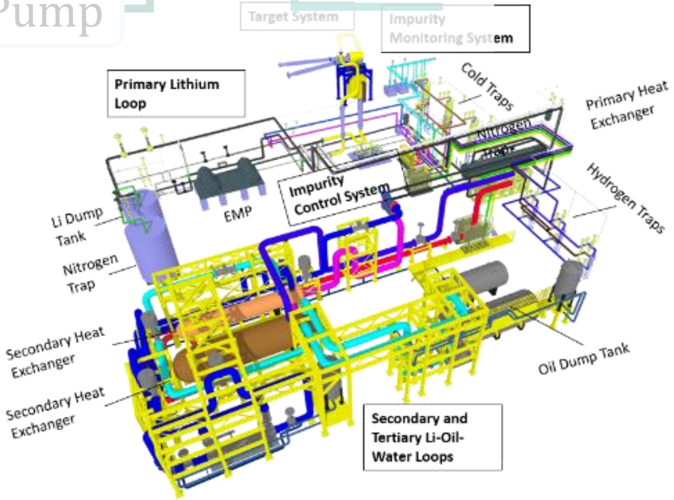
- Cooling water and corrosion product activation

- Neutron and photon streaming from TC

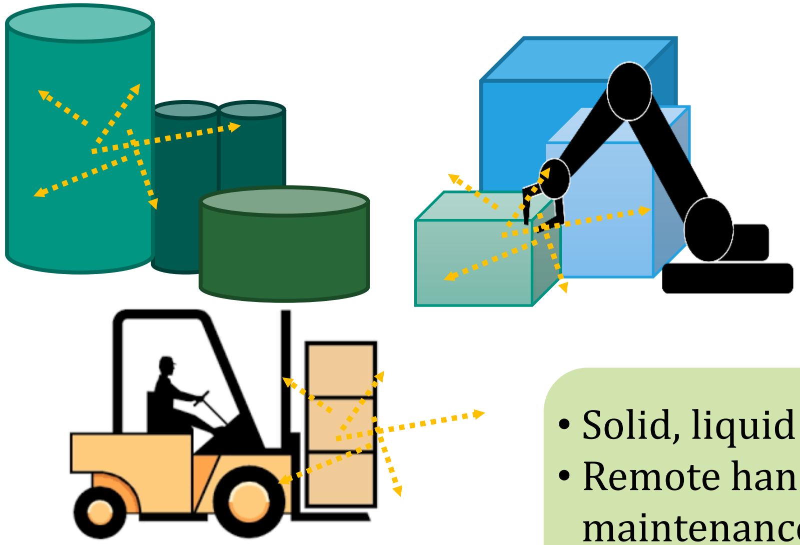


- T in H-Trap

- Be-7 and ACP deposited in the cold trap



- Be-7: $T_{1/2}$ 53 days, γ 477 keV
- Activated corrosion products (ACP)
- Dissolved in Li



- Solid, liquid and gas waste
- Remote handling, maintenance and transportation

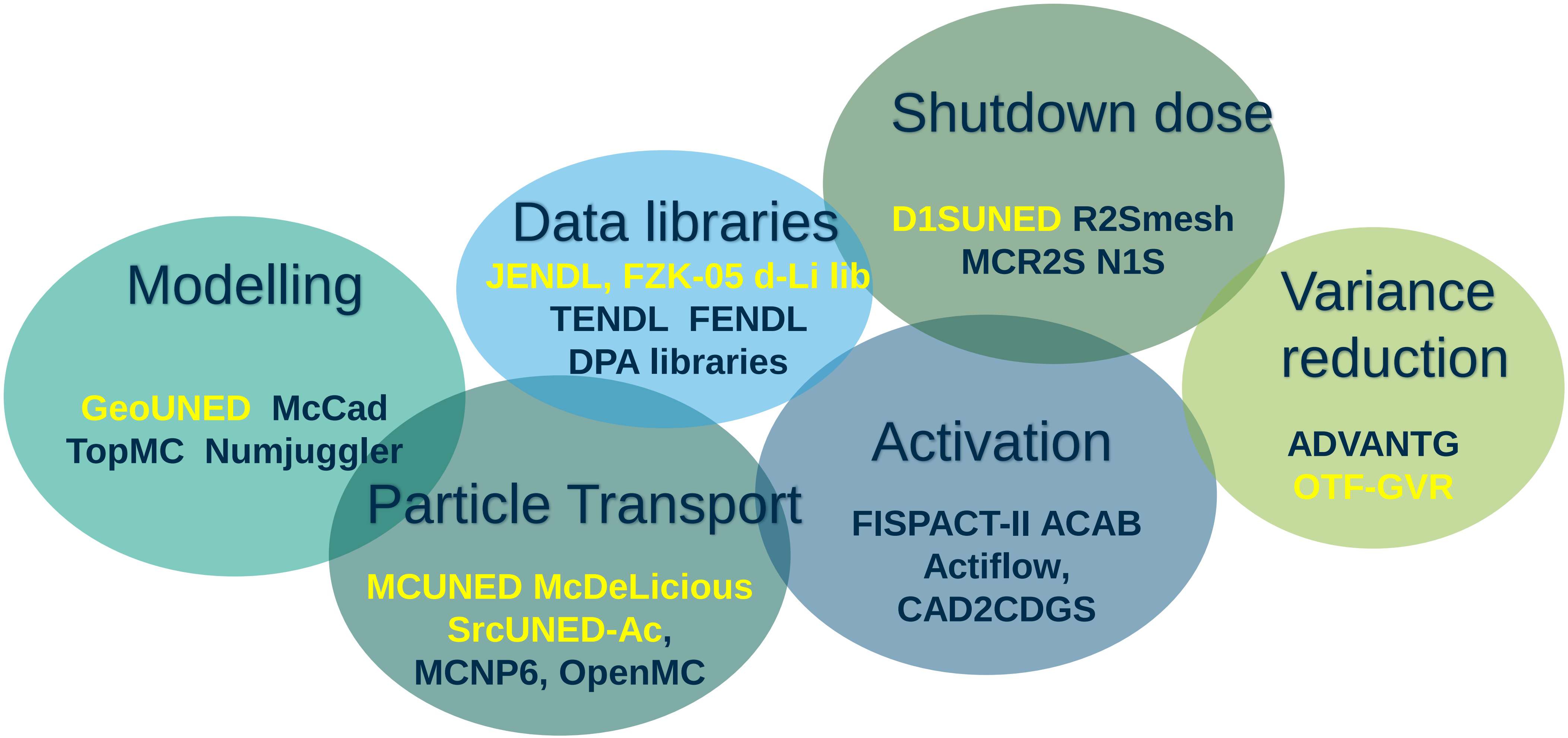
Challenges in IFMIF-DONES neutronics

- One-of-a-kind facility.
- Multiple radiation source contributions.
- High energy tails beyond the fusion neutron regime.
- Shielding of large source area, thick shielding with penetrations.

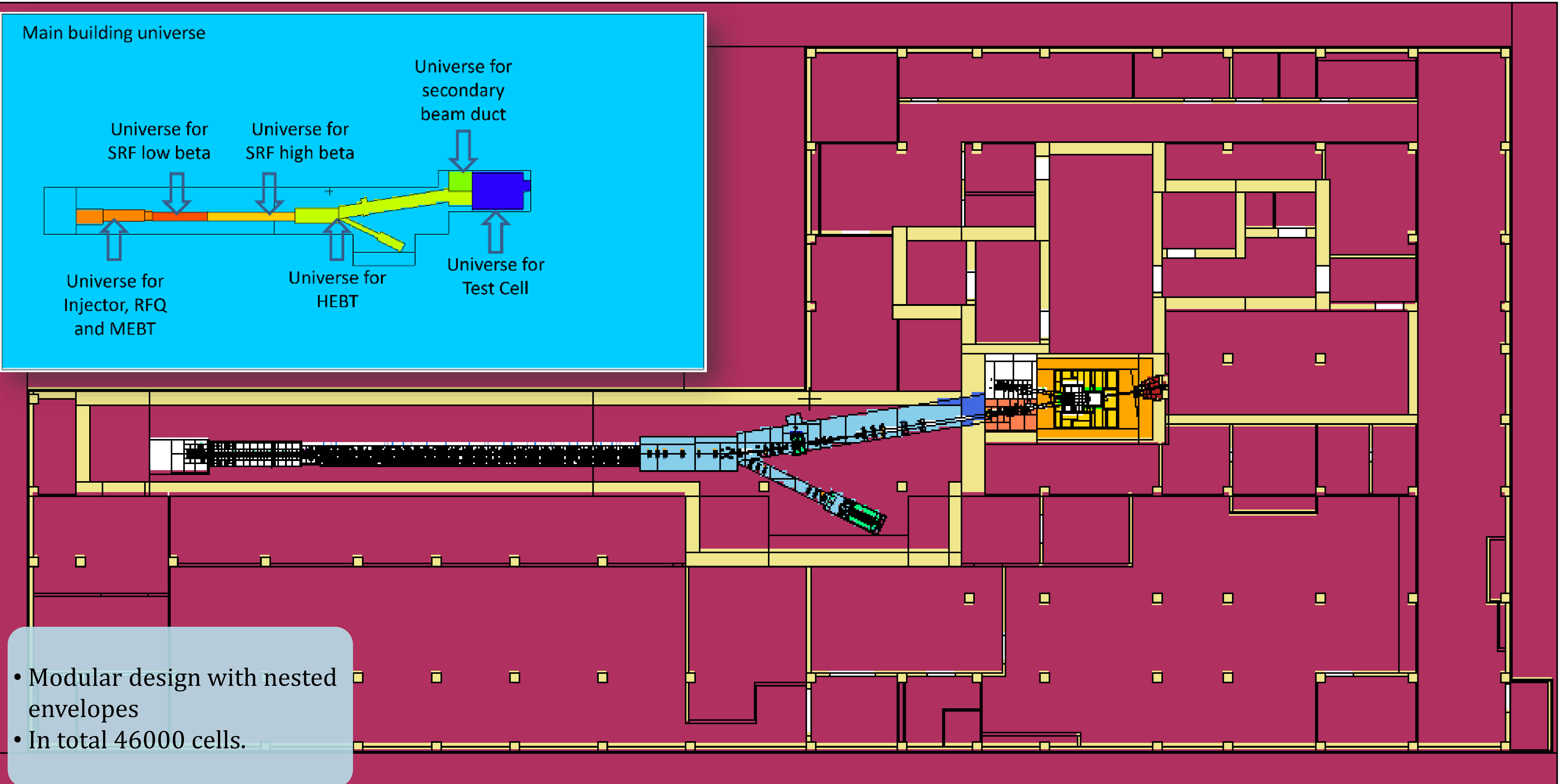
Simulation tools and models

Simulation tools and data libraries

- Selected from the fusion neutronic toolbox
- Validated and extended for charged particle, neutrons beyond fusion (> 14 MeV), and specific applications.

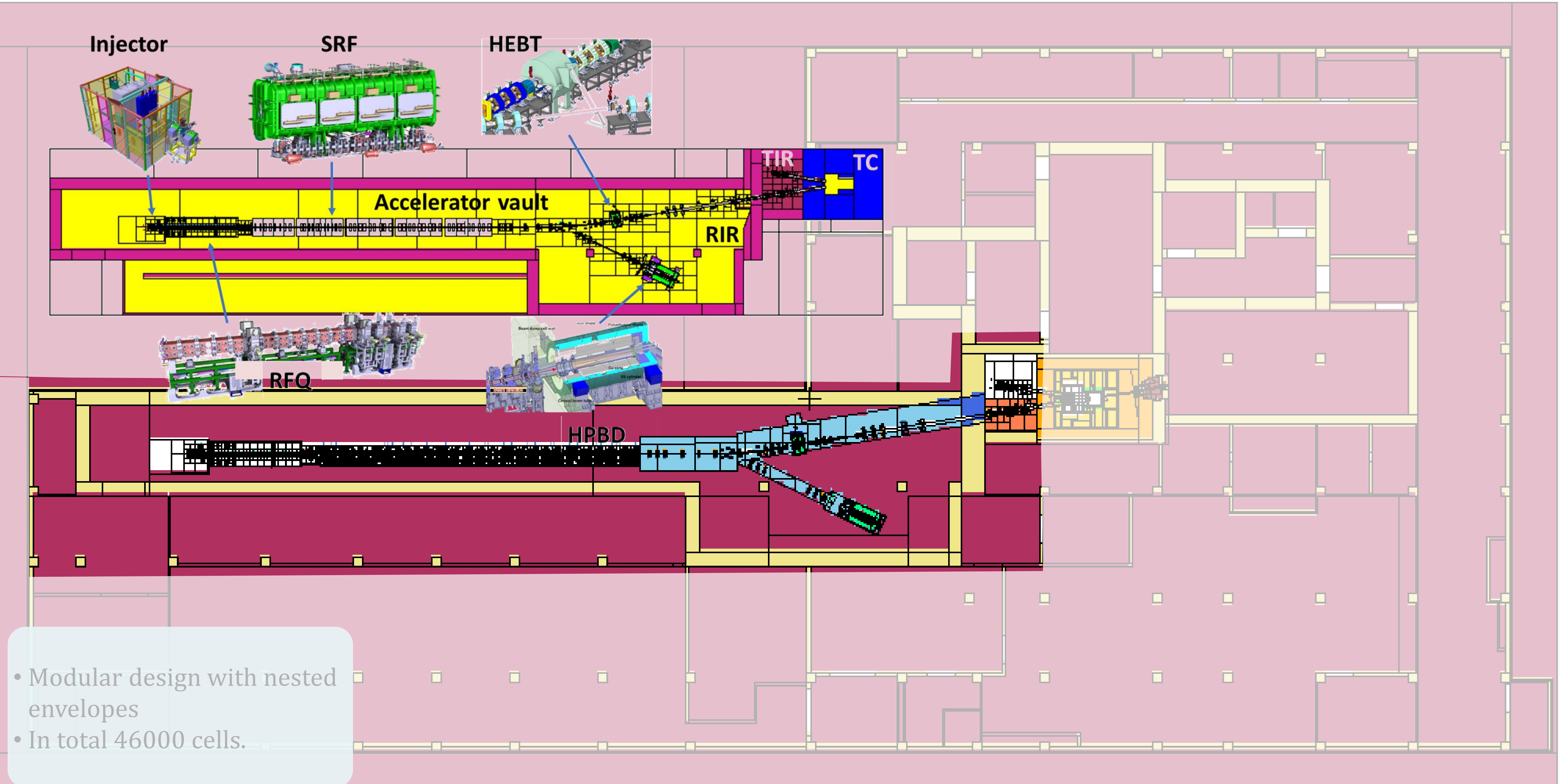


Neutronic models



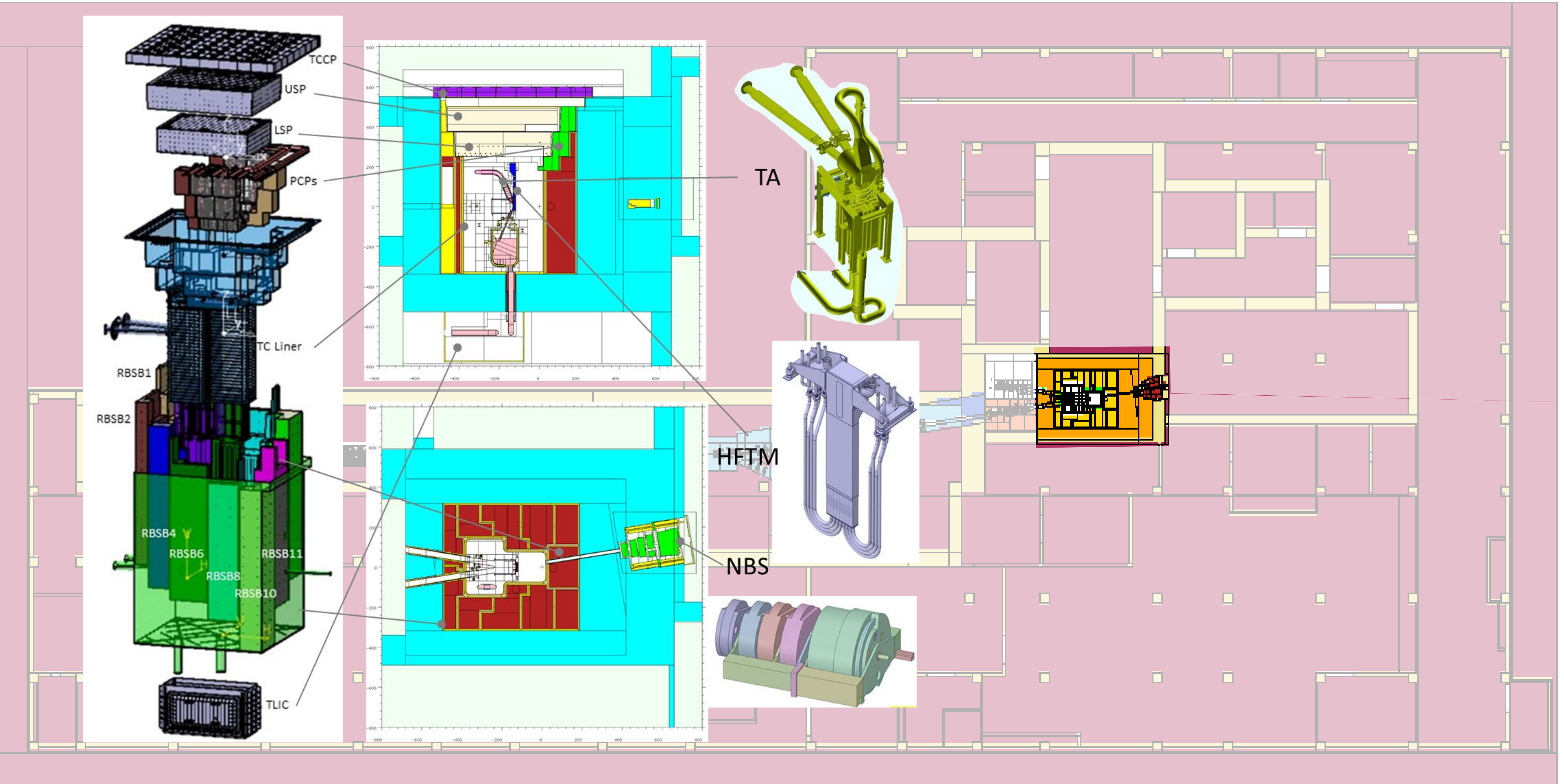
- Modular design with nested envelopes
- In total 46000 cells.

Neutronic models



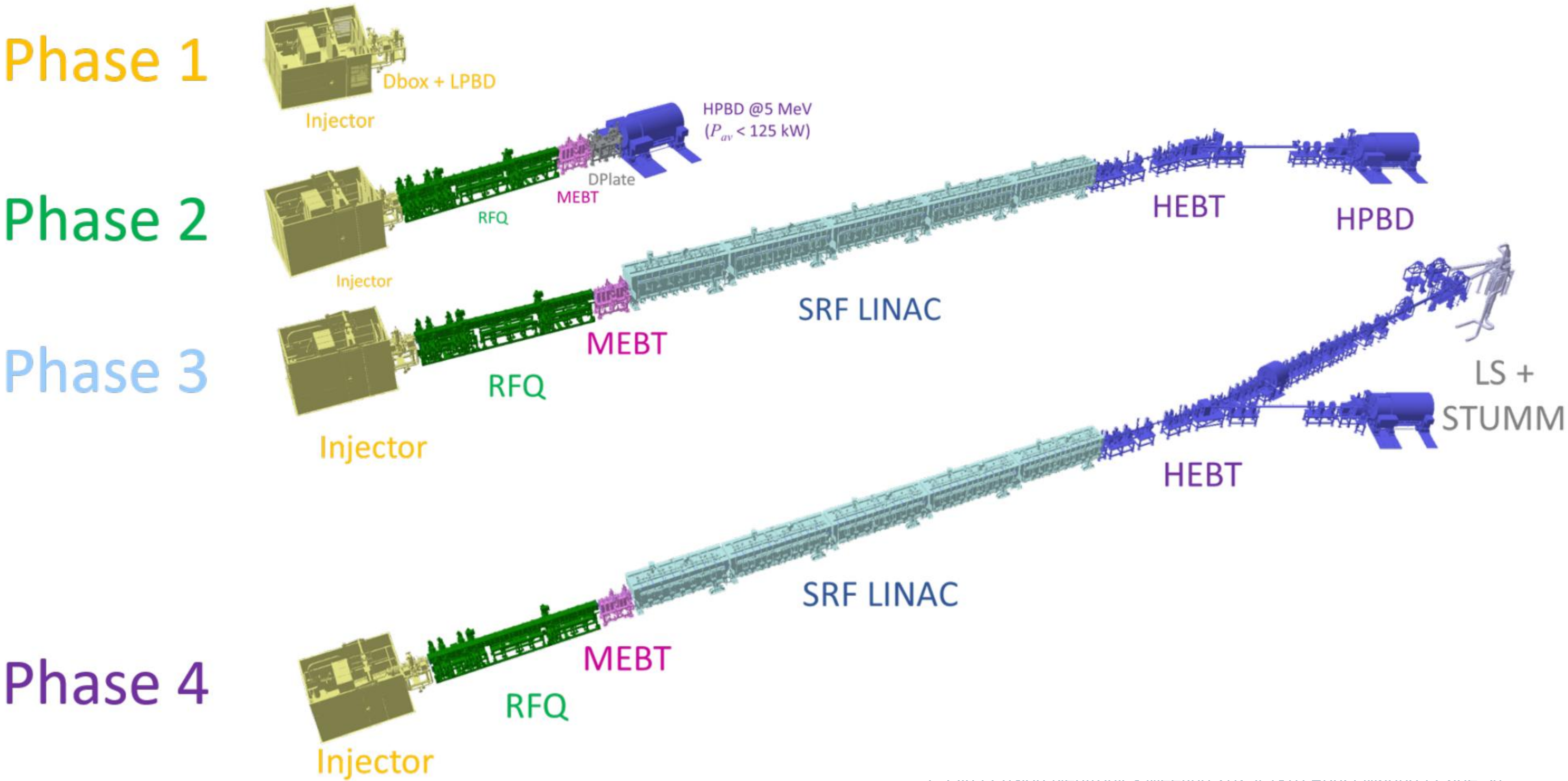
- Modular design with nested envelopes
- In total 46000 cells.

Neutronic models



Commissioning studies

Commissioning studies



Commissioning studies

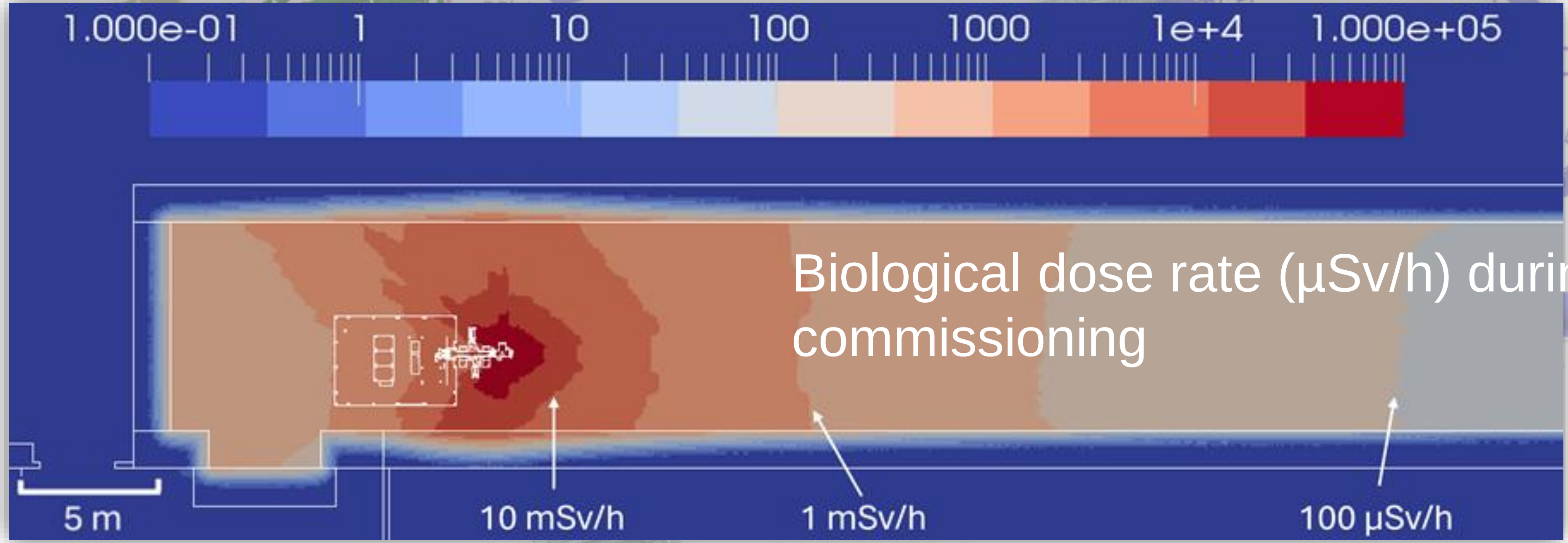
Continuous wave 140 mA at 100 keV

Phase 1

HPBD @5 MeV (P_{av} < 125 kW)

Phase 2

Phase 3



LS + STUMM

SRF LINAC

Phase 4

- Deuteron implanted in beam dump
- D-D neutron yield 3.6E9 n/s
- Important results for the first licensing phase.

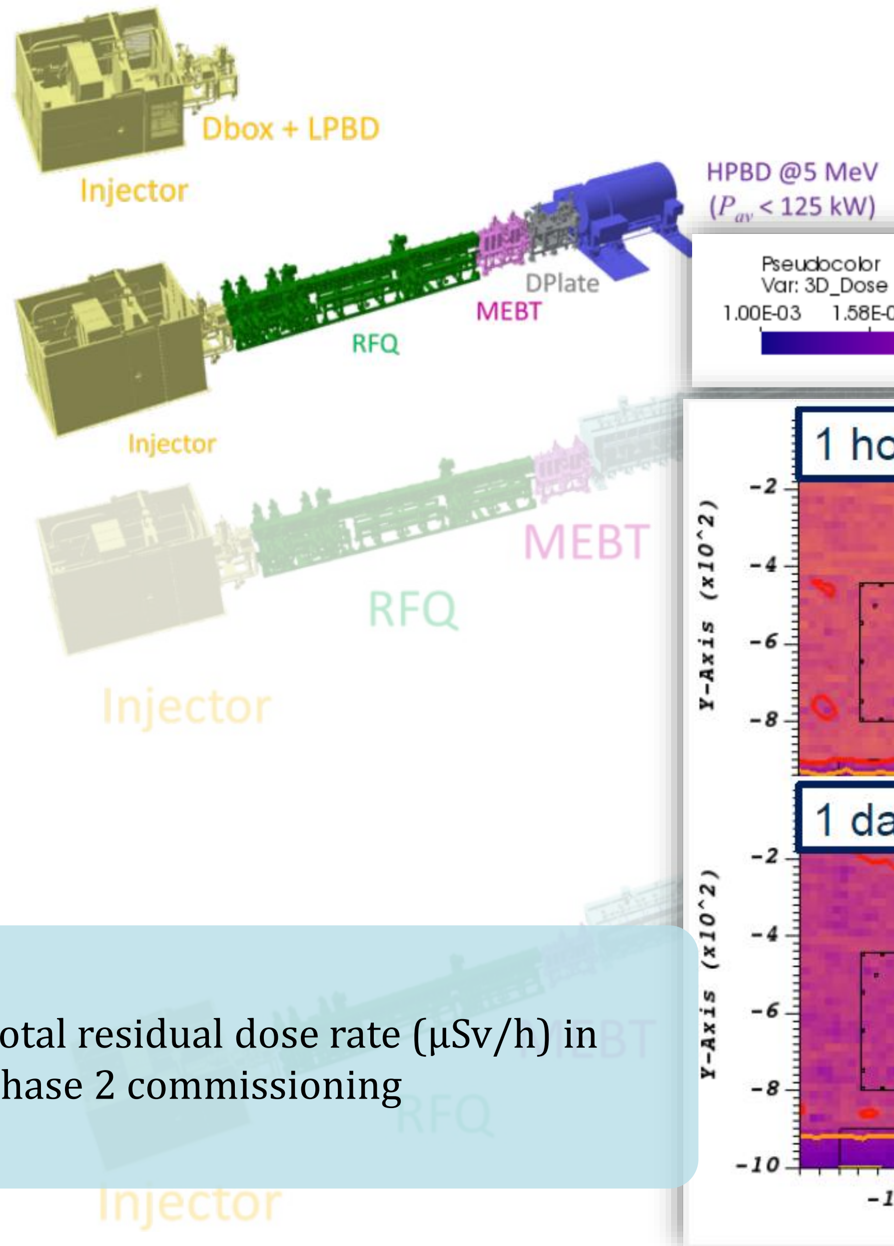
Commissioning studies

Phase 1

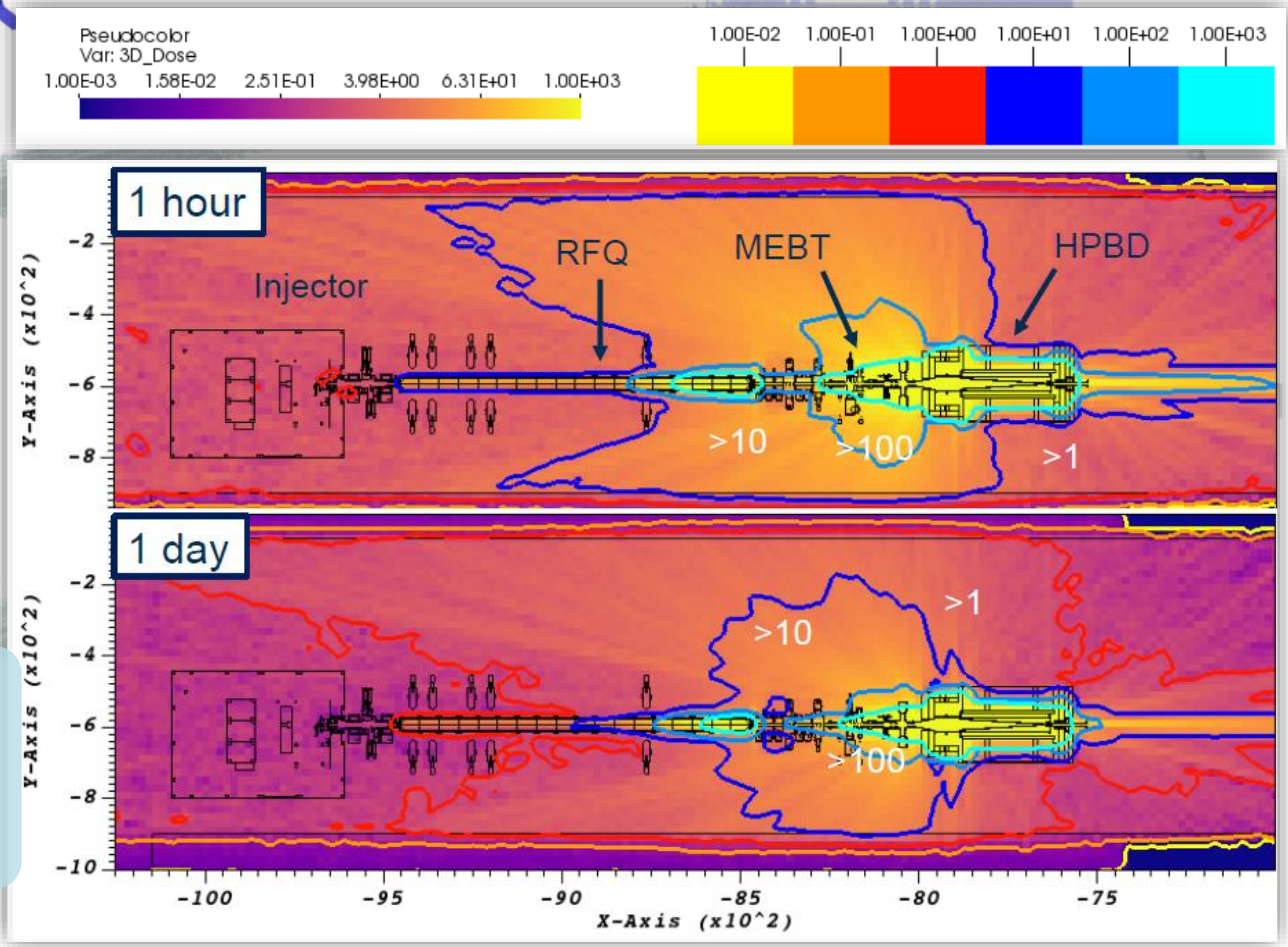
Phase 2

Phase 3

Phase 4



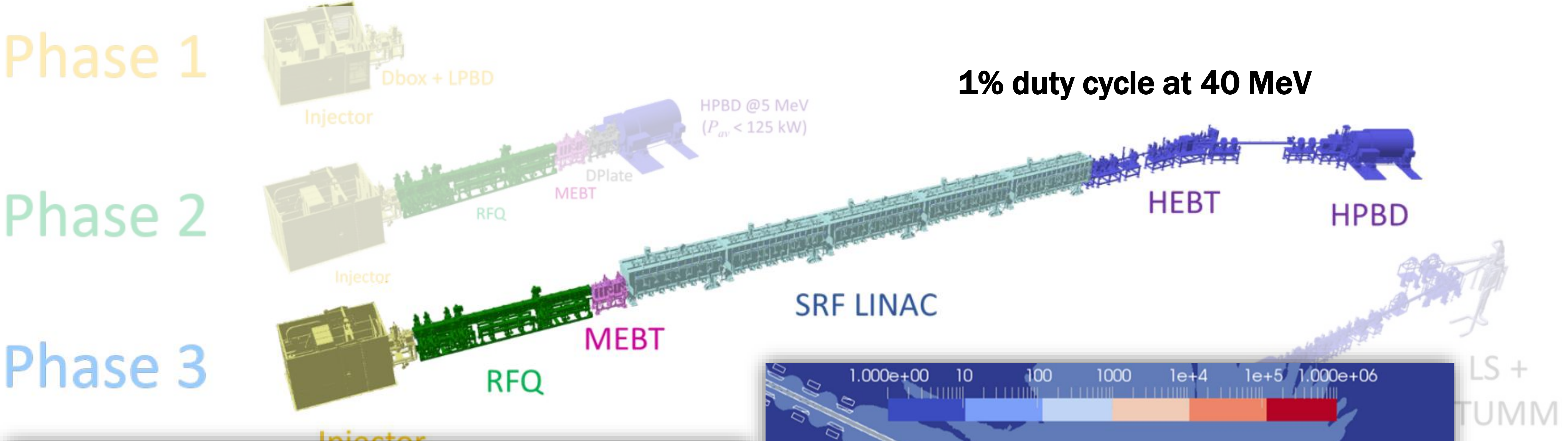
20% duty cycle at 5 MeV

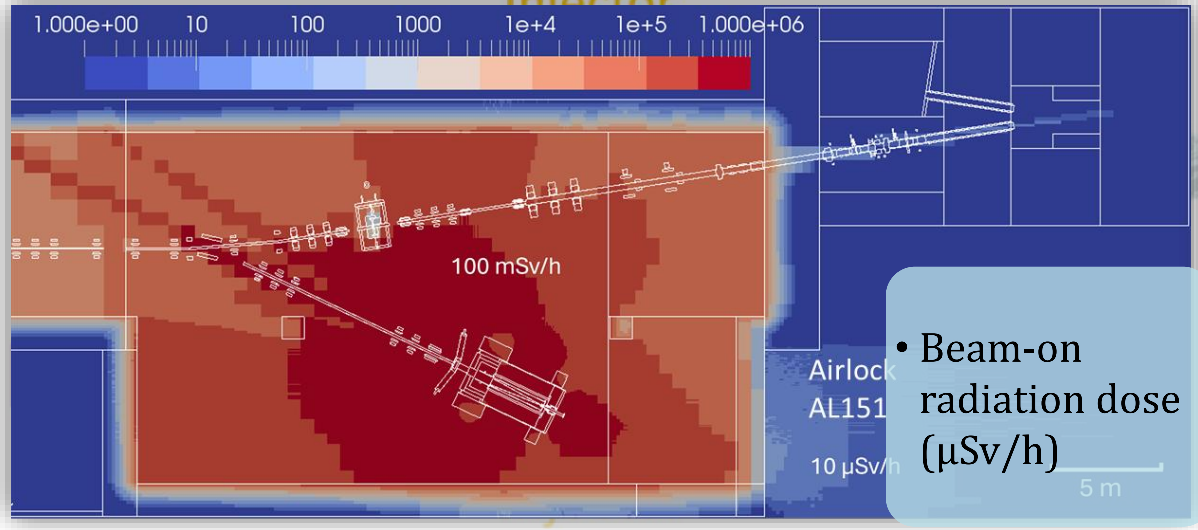


- Total residual dose rate (µSv/h) in Phase 2 commissioning

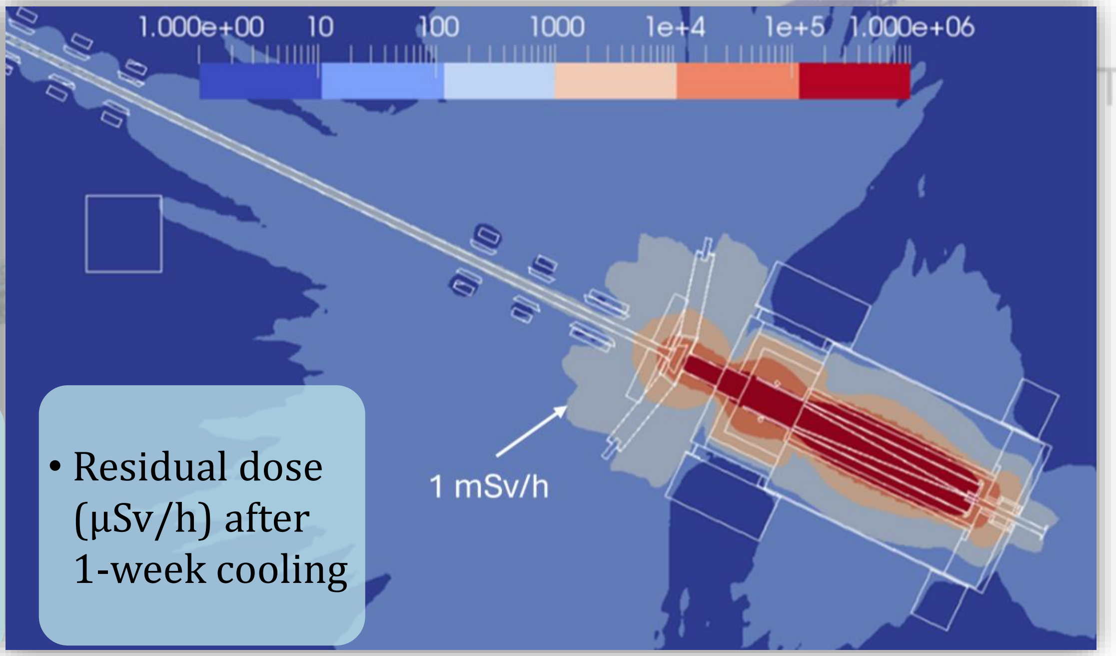
Commissioning studies

1% duty cycle at 40 MeV



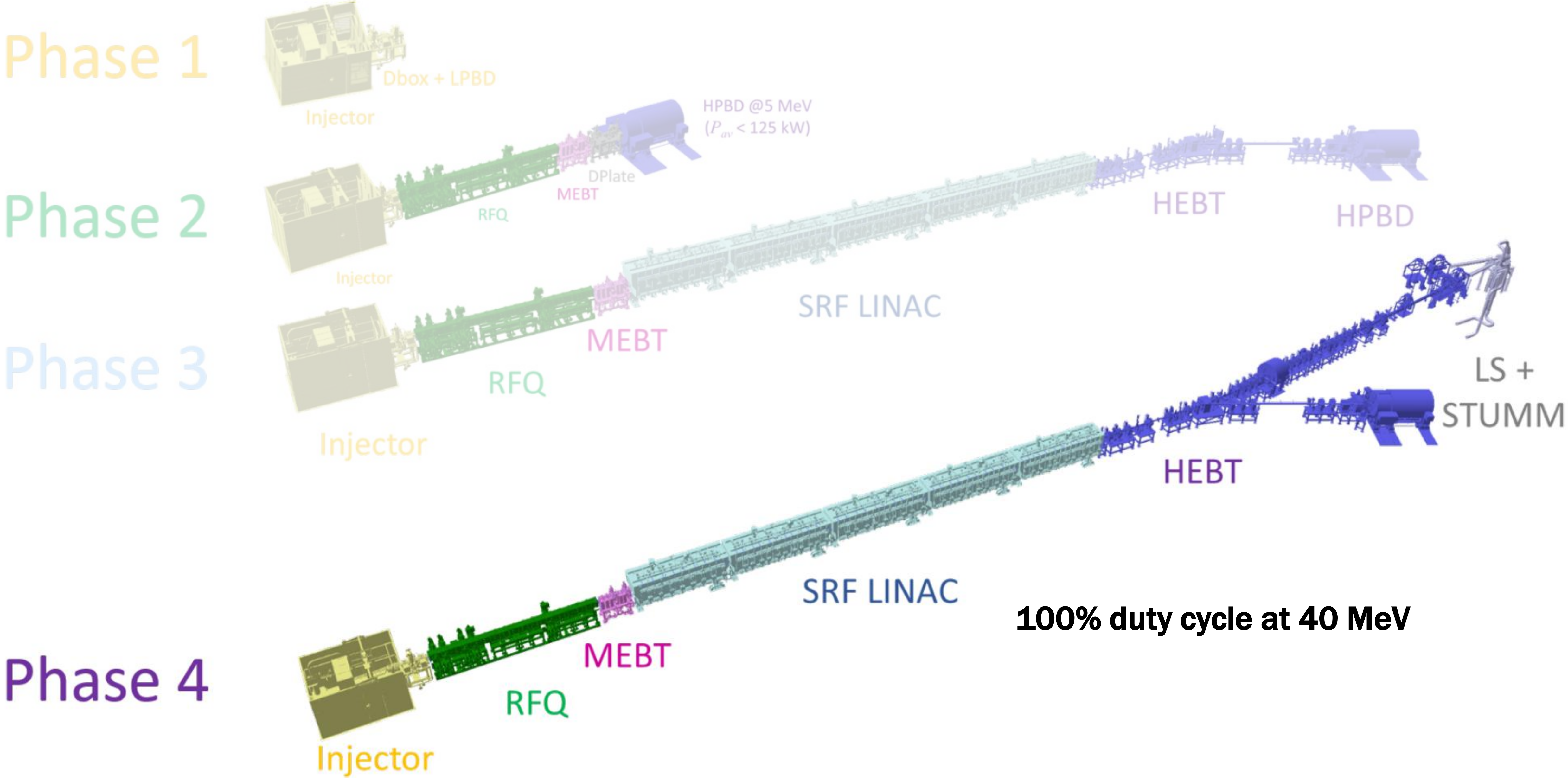


- Beam-on radiation dose (μSv/h)



- Residual dose (μSv/h) after 1-week cooling

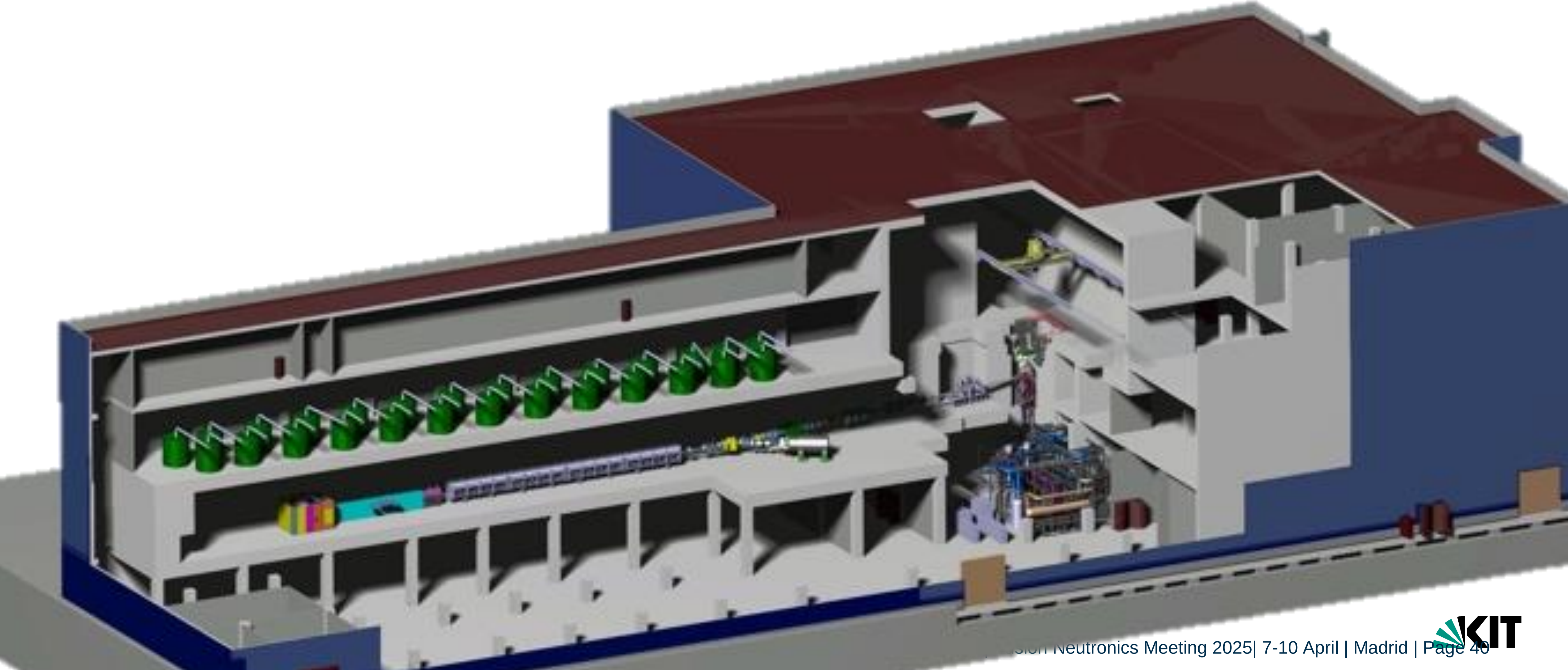
Commissioning studies



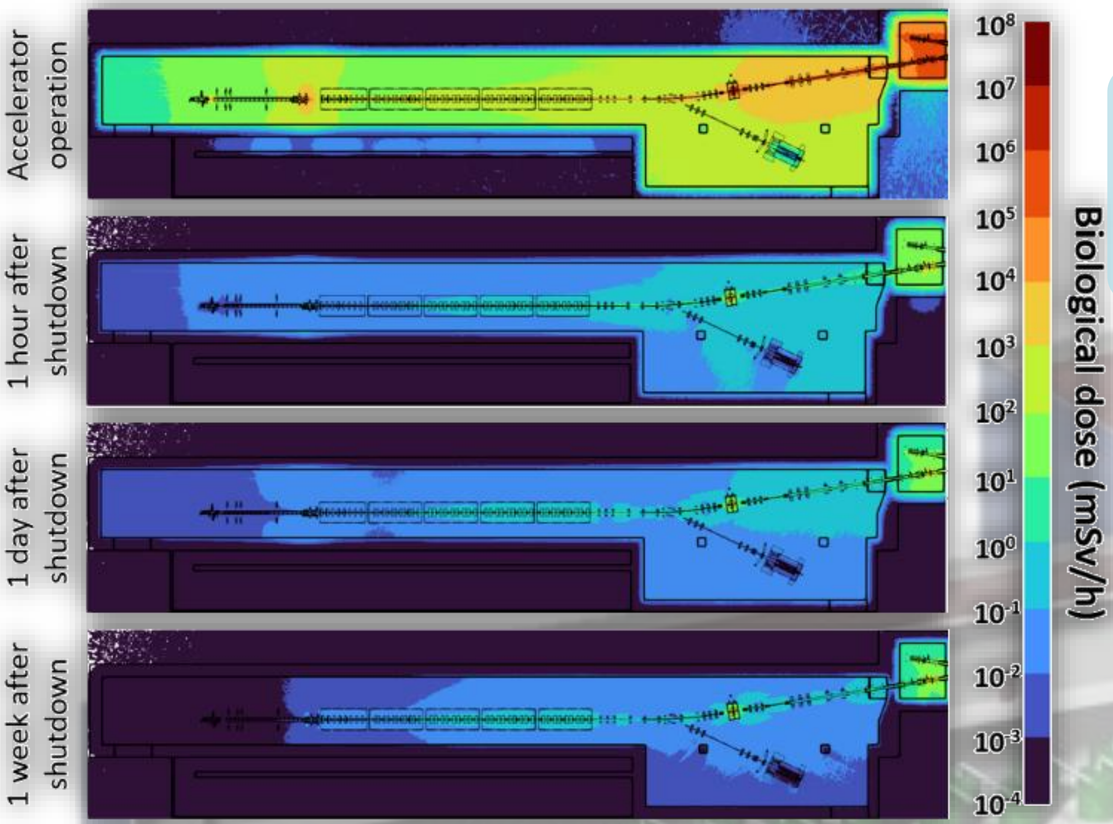
100% duty cycle at 40 MeV

Beam-on and beam-off dose maps

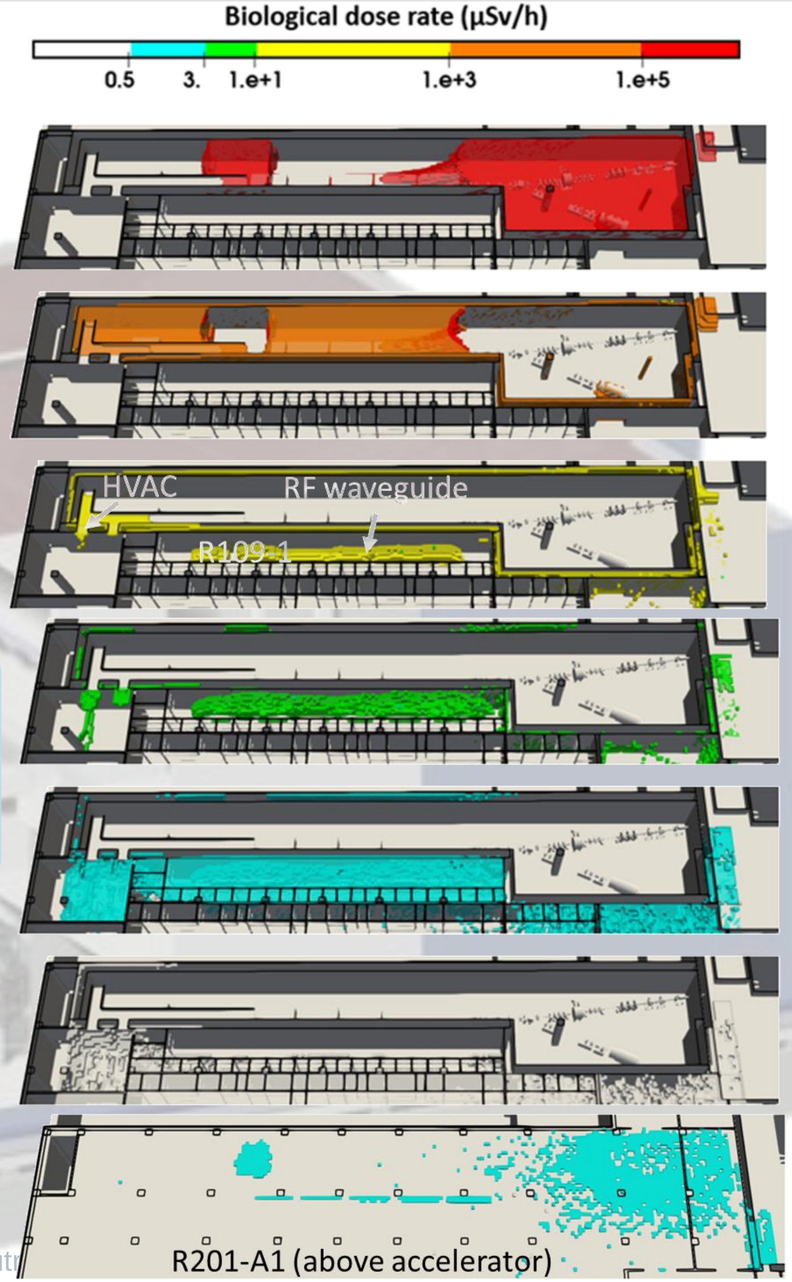
Beam-on and beam-off operational doses



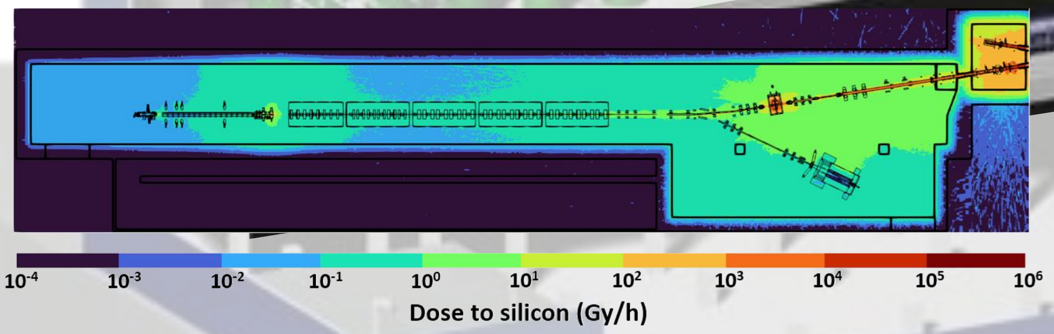
Beam-on and beam-off operational doses



- Beam-on and beam-off biological dose (μSv/h)

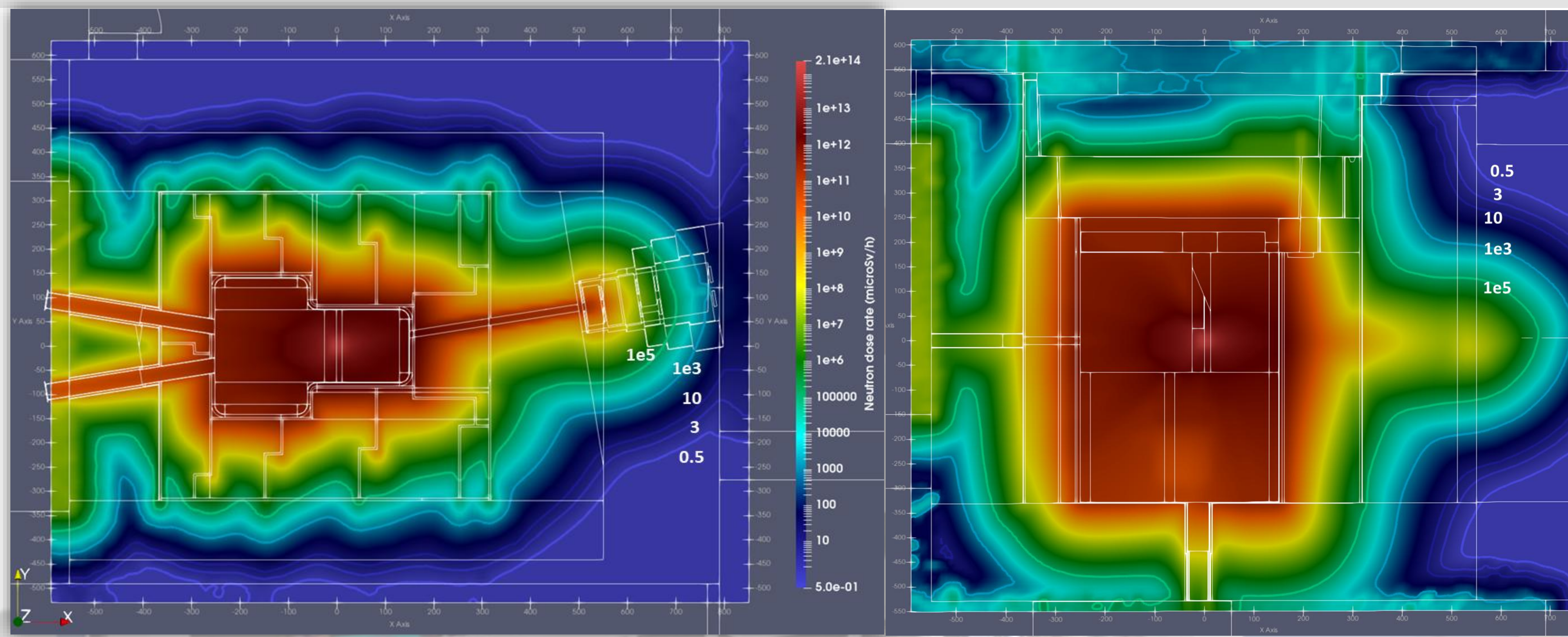


- Dose to the neighboring cells through penetrations



- Beam-on silicon absorbed dose (Gy/h)

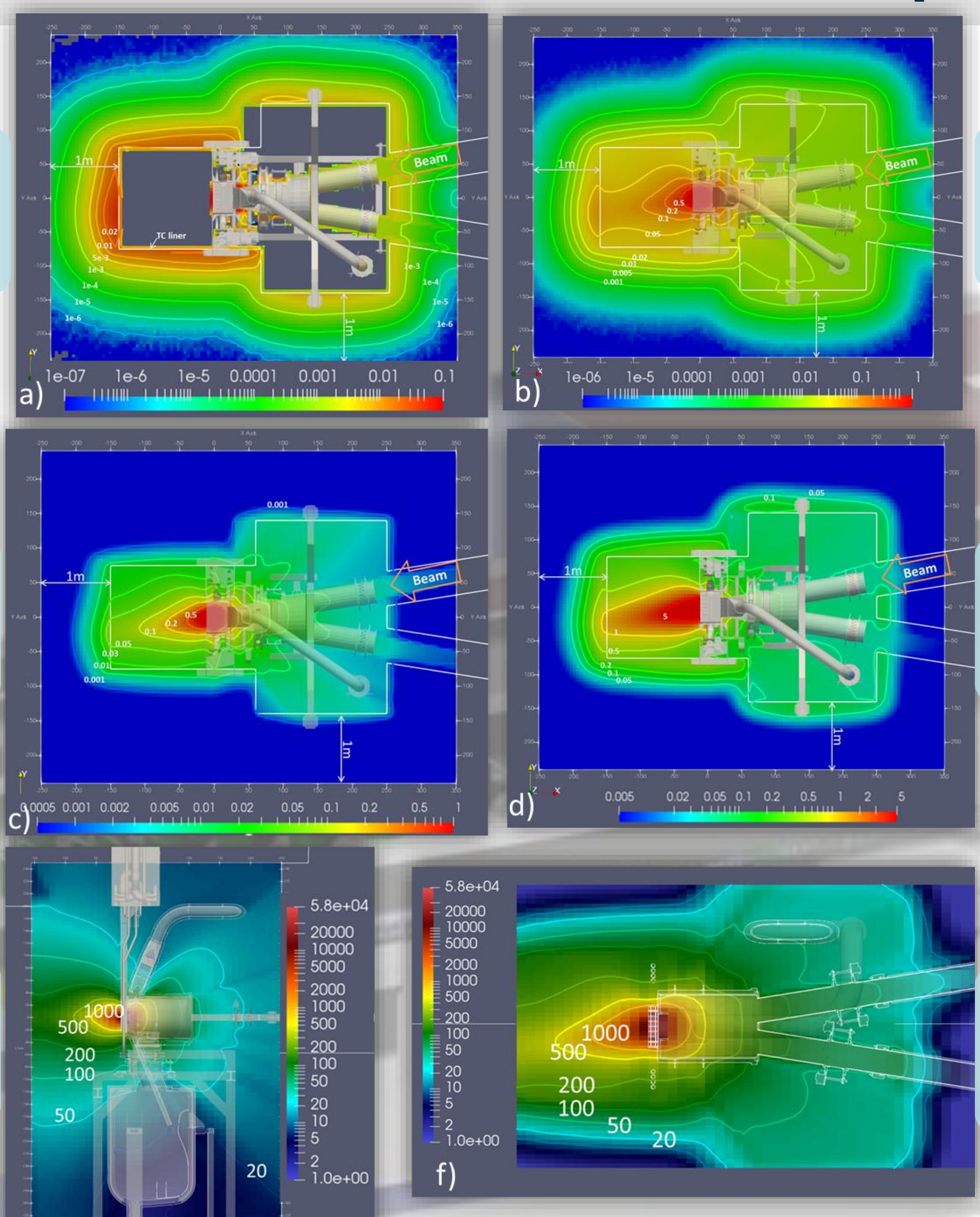
Beam-on and beam-off operational doses



- Beam-on neutron biological doses (μSv/h)
- Photon doses are expected to be <10%

Beam-on and beam-off operational doses

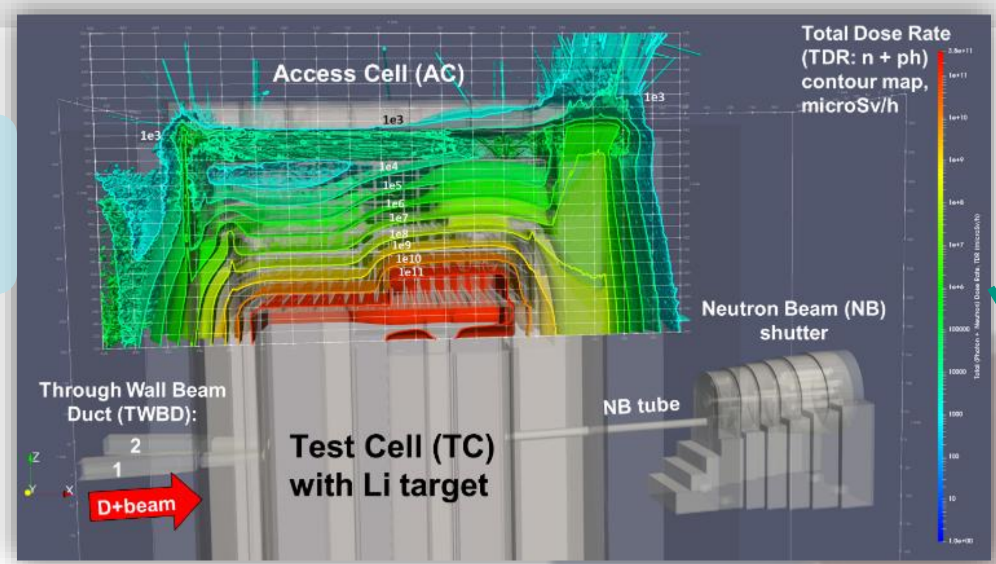
- Nuclear heating (W/cm^3)
- Damage dose rate in Fe (dpa/fpy)
- Si-dose (Mgy/fpy)



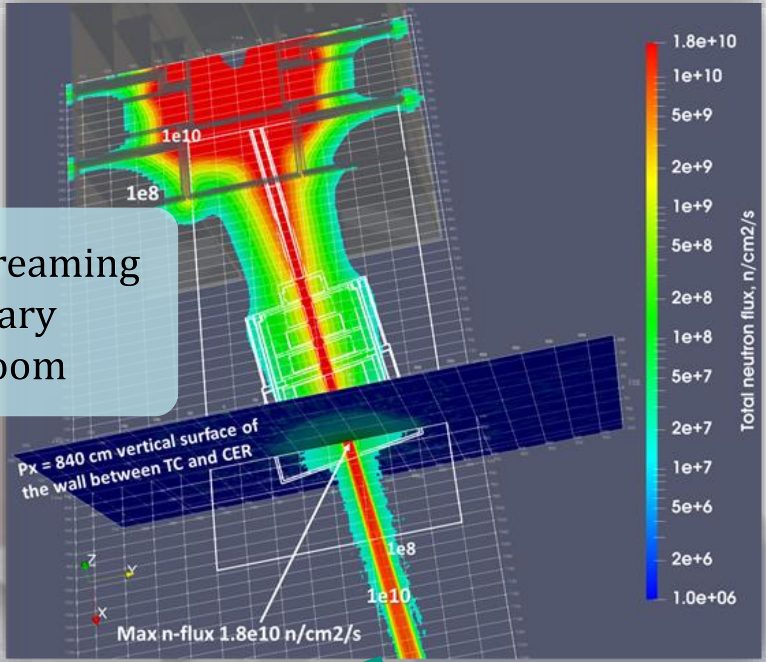
- Nuclear heating in SS316L (W/cm^3)
- Helium production in SS316L(appm/fpy)
- Si-dose (Mgy/fpy)

Beam-on and beam-off operational doses

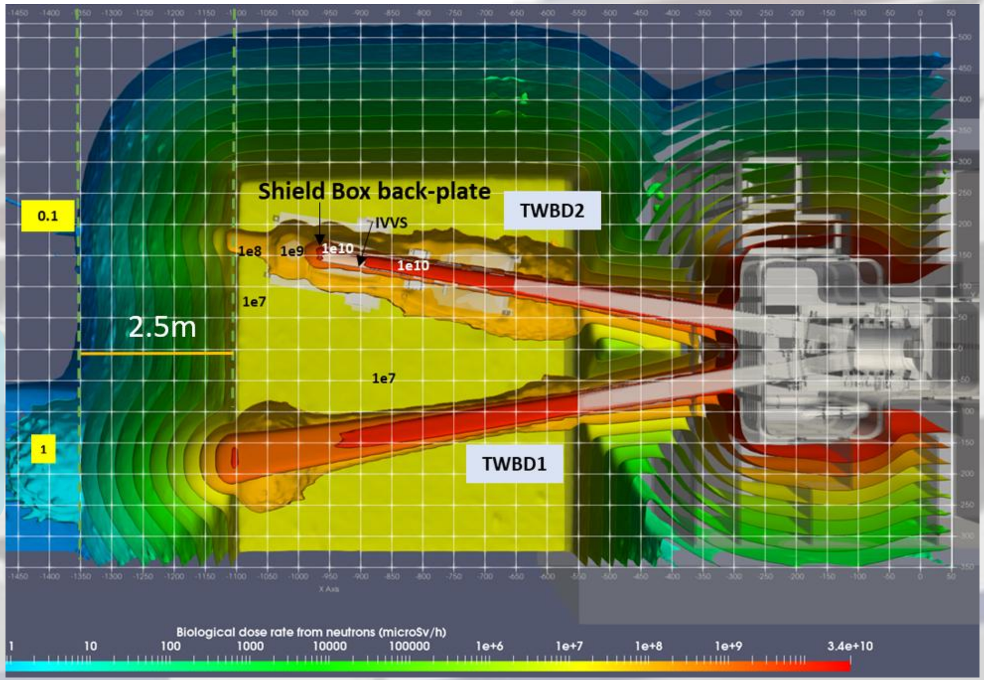
- Neutron dose rate (μSv/h) streaming from the test cell

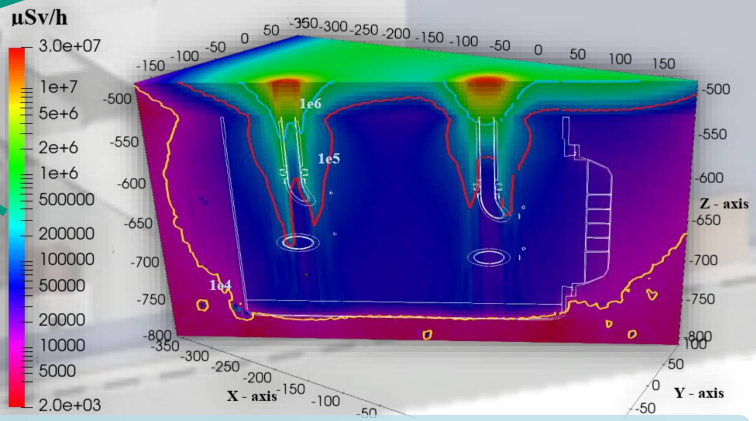


- Neutron flux streaming to Complementary experimental room



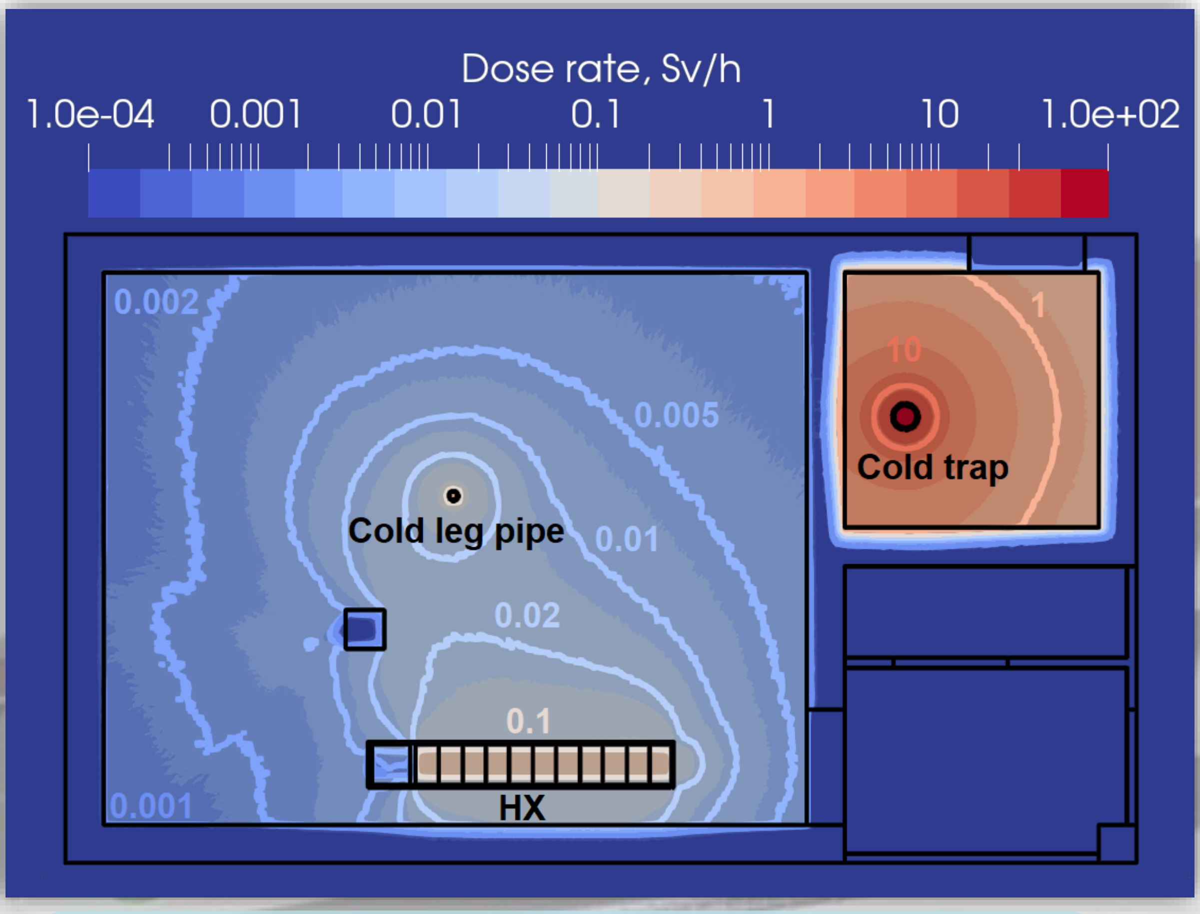
- Neutron dose streaming to the Target Interface Room (TIR)





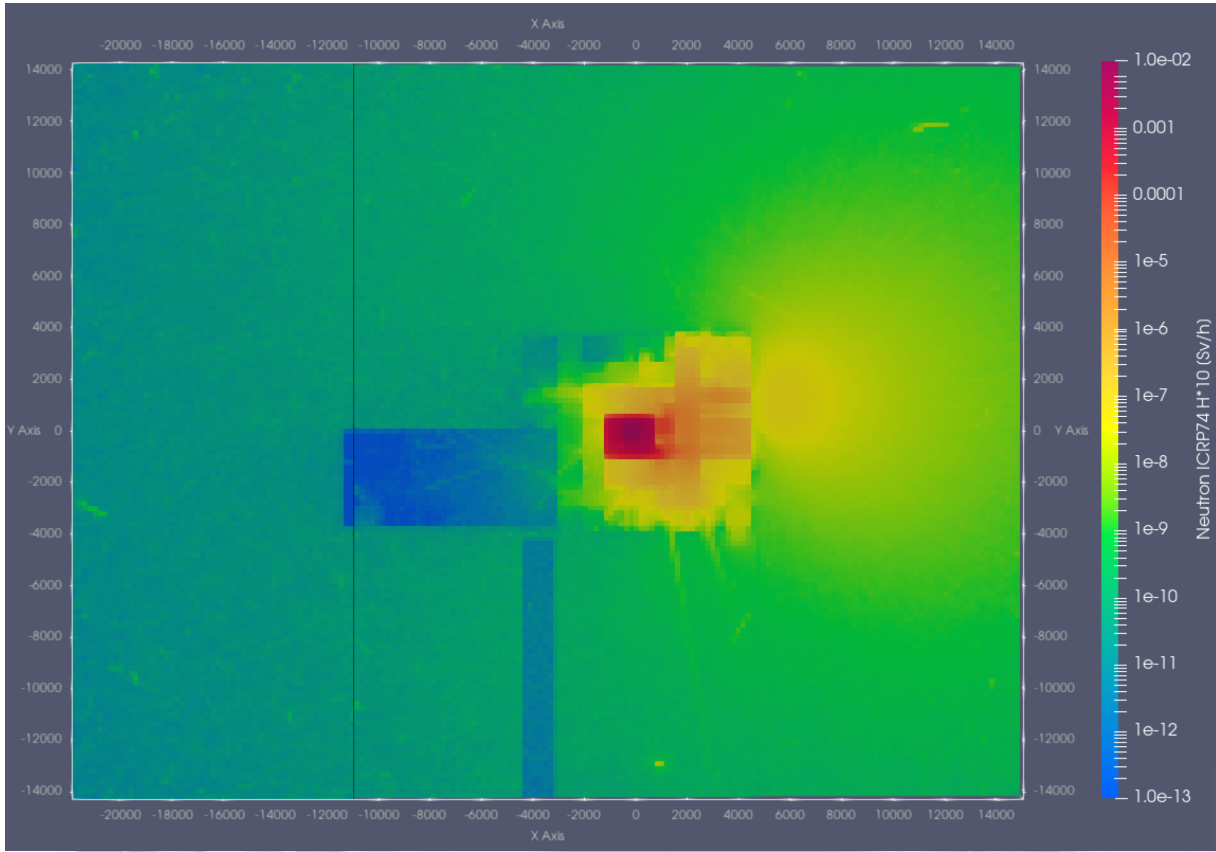
- Total dose rate (μSv/h) to the Lithium loop cell

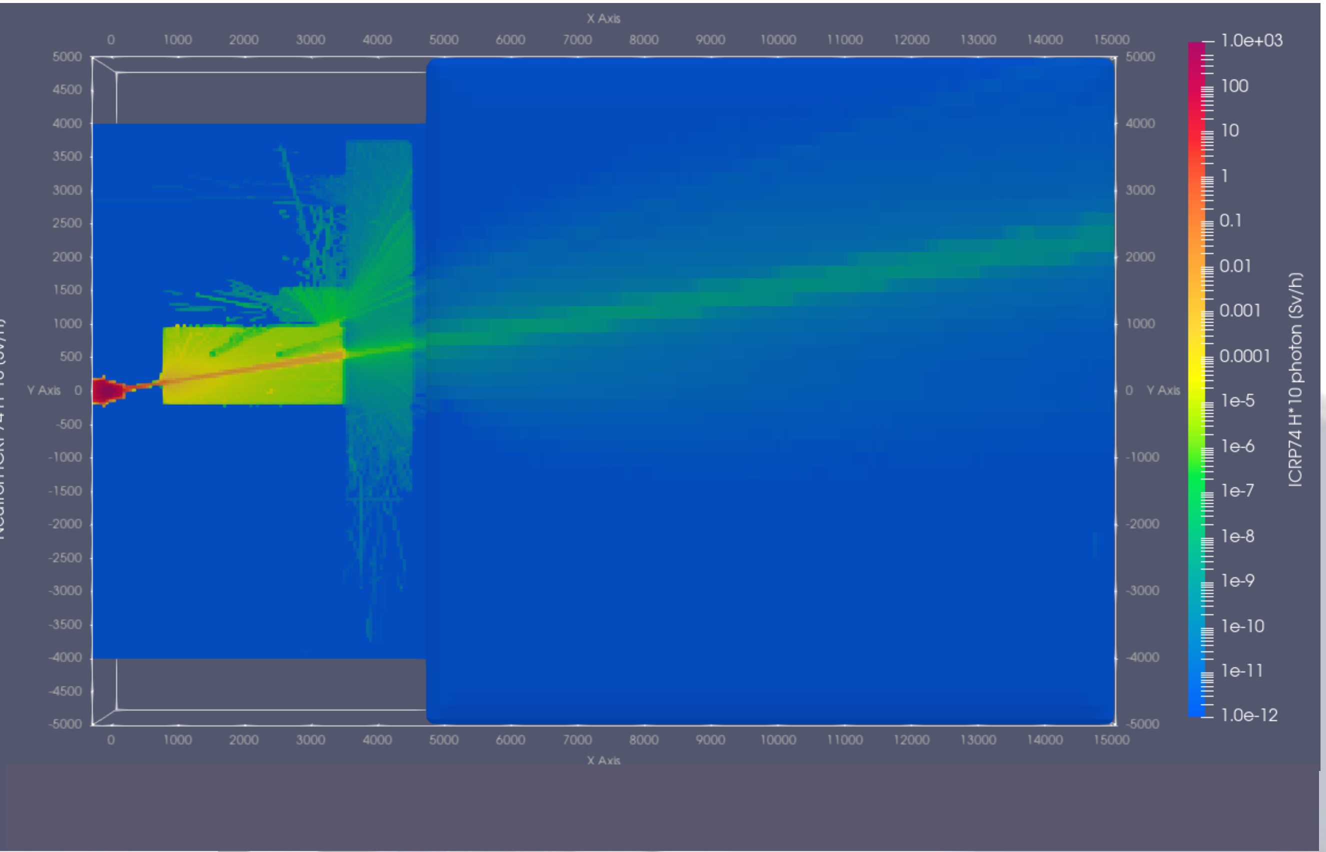
Beam-on and beam-off operational doses



- Beam-on dose rate (Sv/h) in the Lithium loop cell
- Be- production: Li-6 (d, n) 15%, and Li-7 (d,2n) 83%
- Be-7 dominant in the cold trap area
- Activated corrosion products (ACP) contribution to the Lithium loop cell

Beam-on and beam-off operational doses



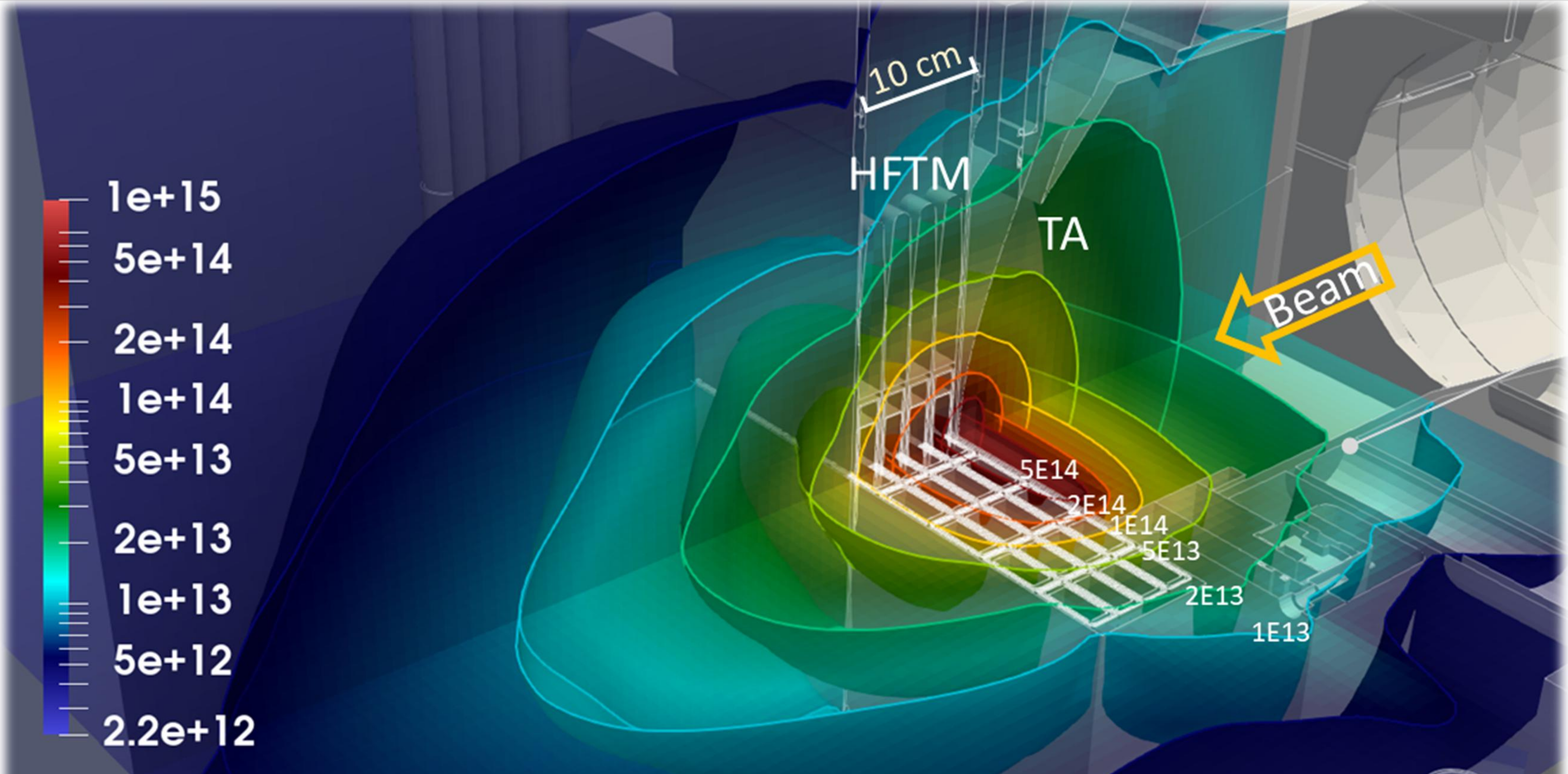


- Neutron dose rate (Sv/h) at ground level
- Dose slightly higher than the allowable limit of 1 mSv/y due to shielding deficiency in CER (problem is resolved)

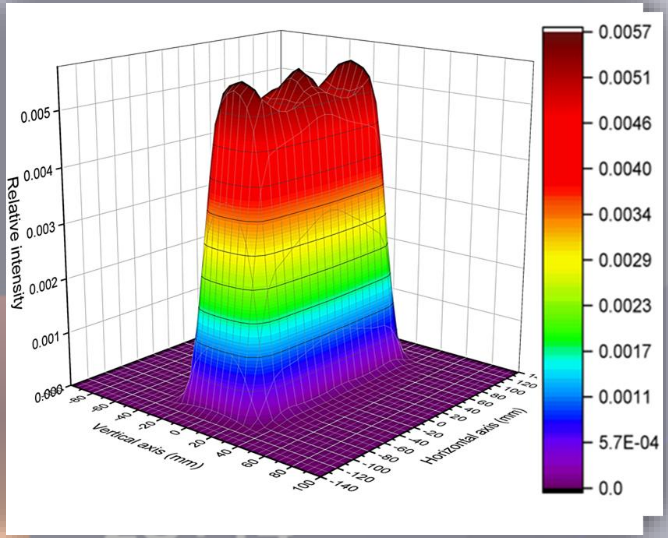
- Photon dose rate (Sv/h) at beam level

DONES material irradiation

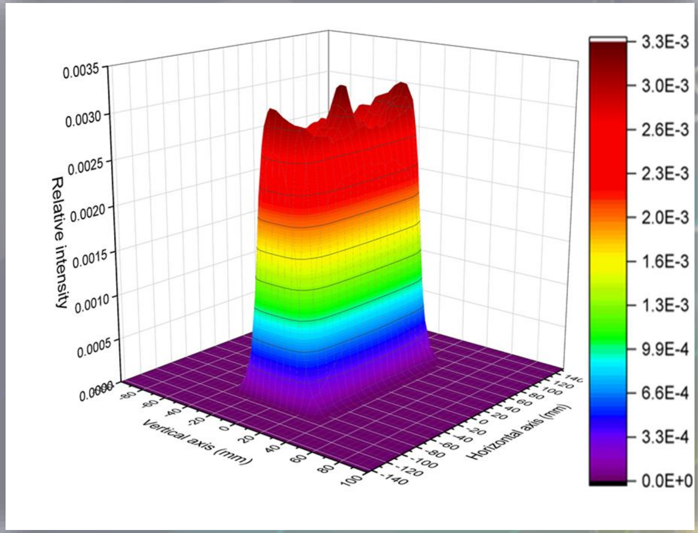
Neutron flux map



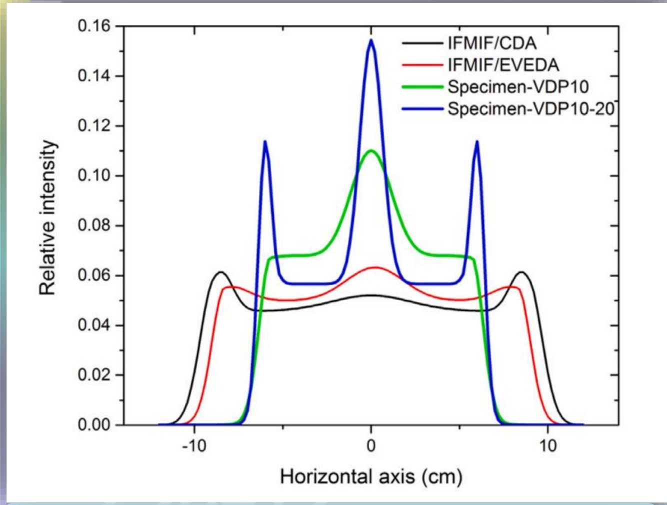
Beam profile assessments



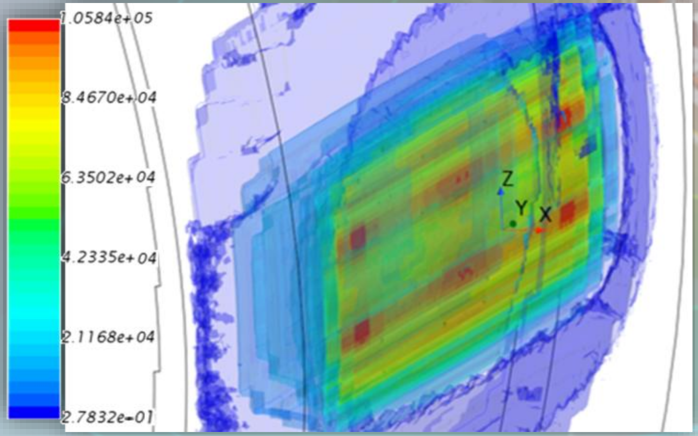
• Beam footprint at IFMIF/EVEDA phase



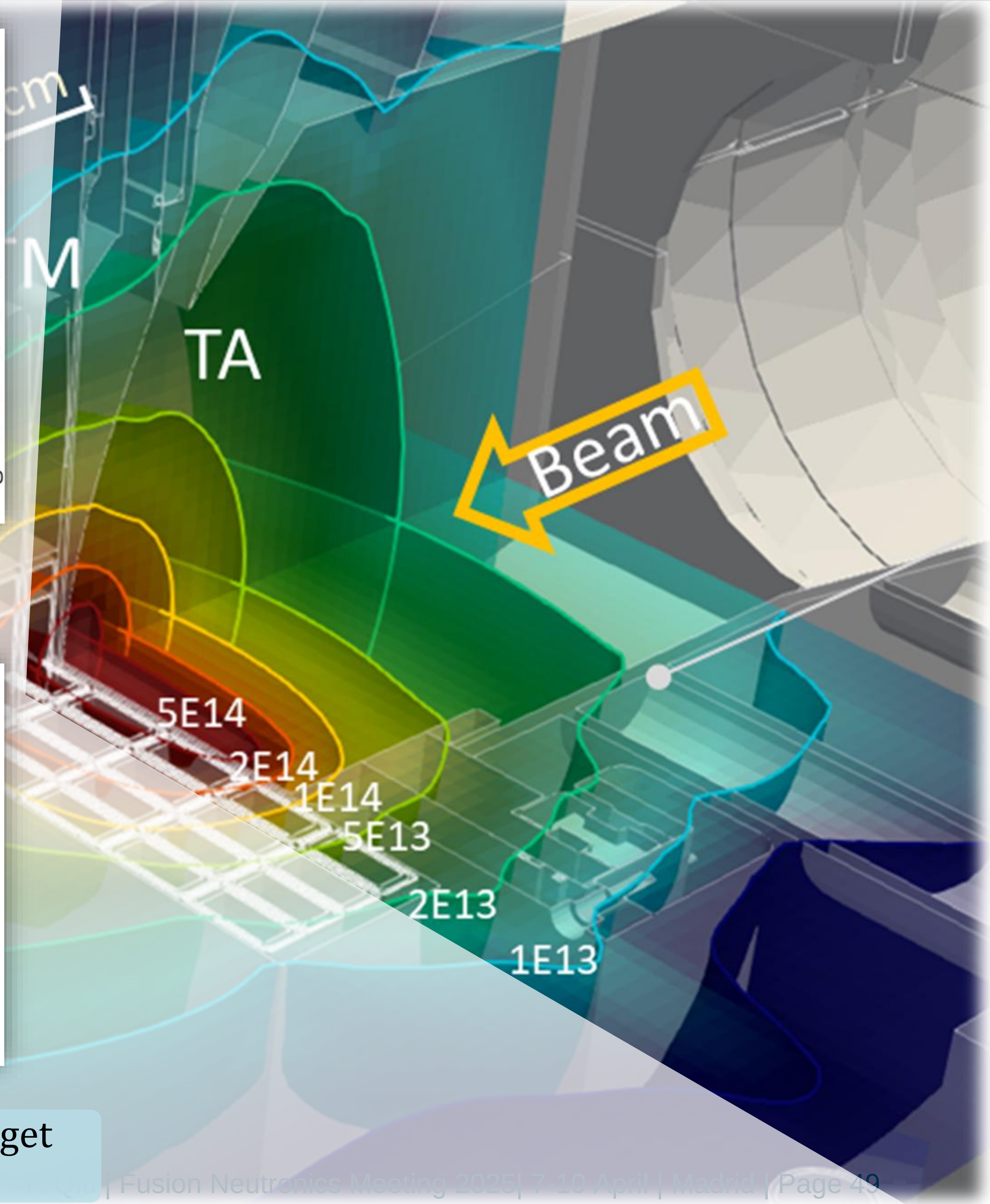
• New reference beam footprint for IFMIF-DONES



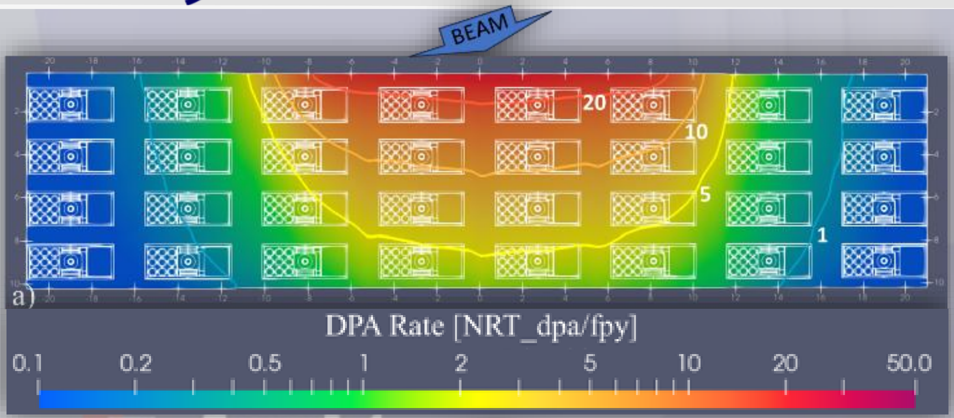
• Beam profile optimization using a genetic algorithm



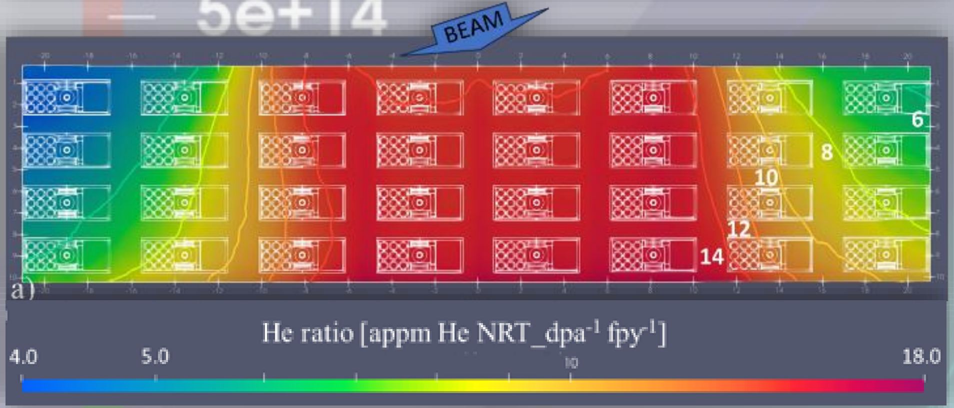
• Beam heat deposition in the Li target (W/cm^3)



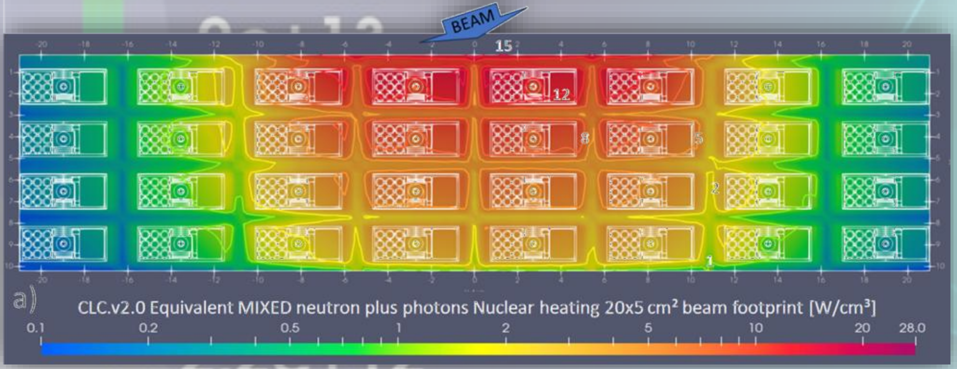
Material irradiation capabilities



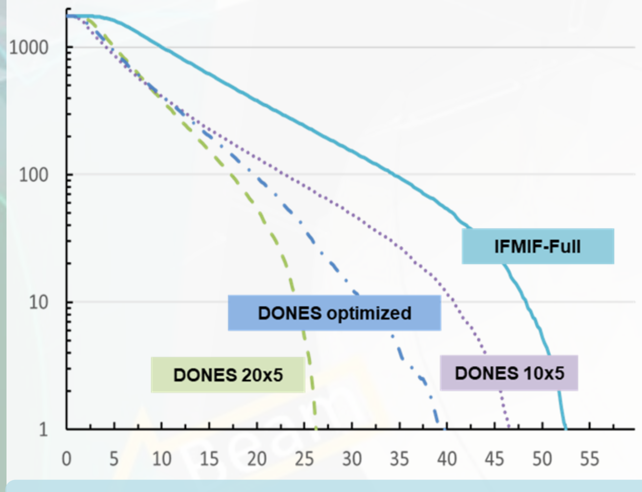
- DPA rate in NRT model (dpa/fpy)
- 5-20 dpa/fpy



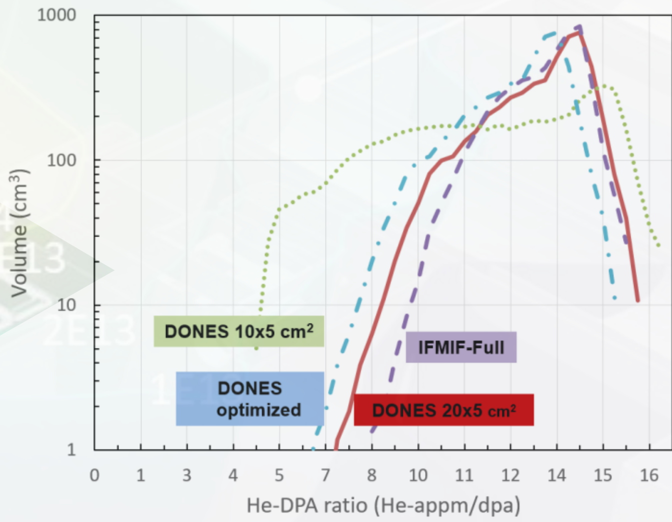
- He-DPA ratio (He-appm/dpa)
- 12-14 He-appm/dpa



- Total nuclear heating (W/cm^3)
- Peak heating 15 W/cm^3



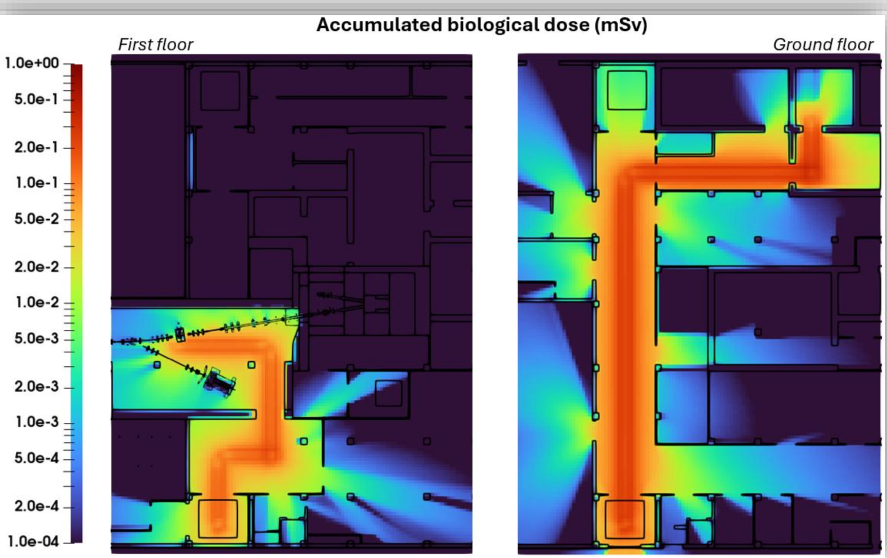
- Available volume (cm^3) v.s. DPA



- He-DPA ratio (He-appm/dpa) distribution

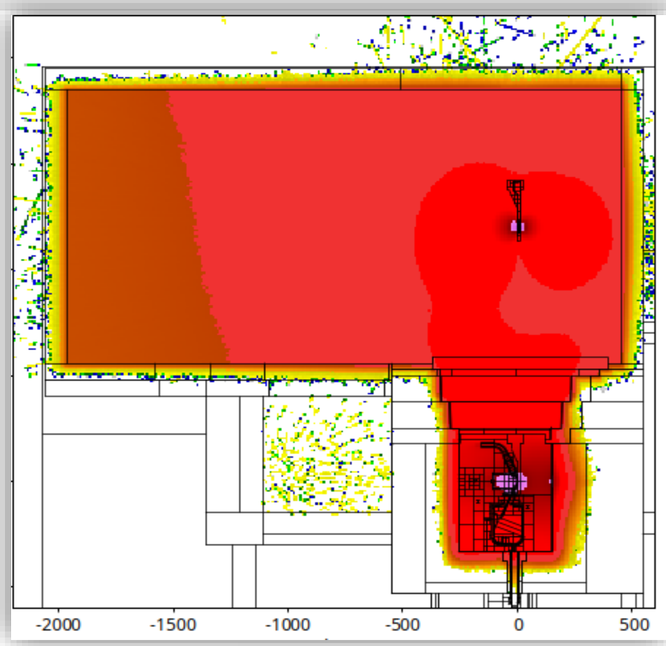
Components, liquid and atmosphere activations

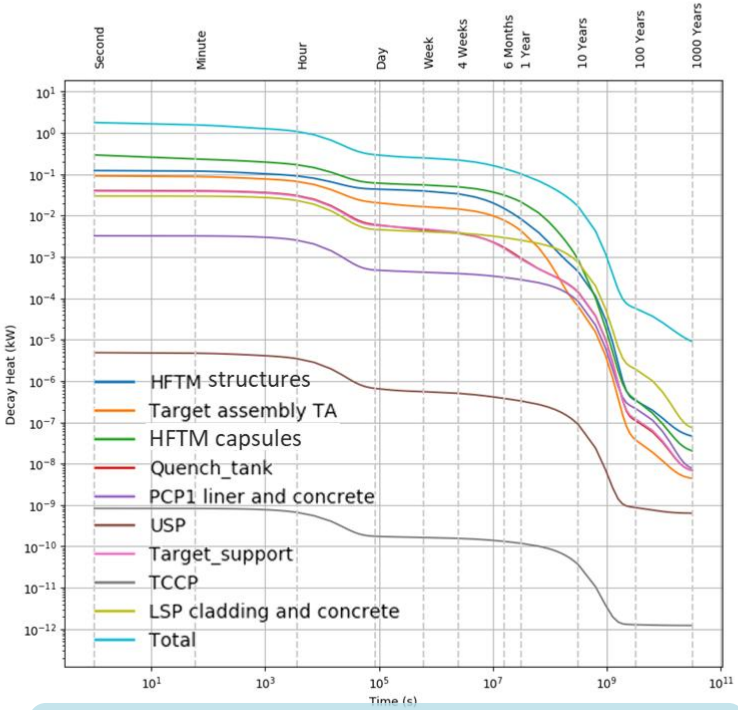
Activation inventories and waste handling



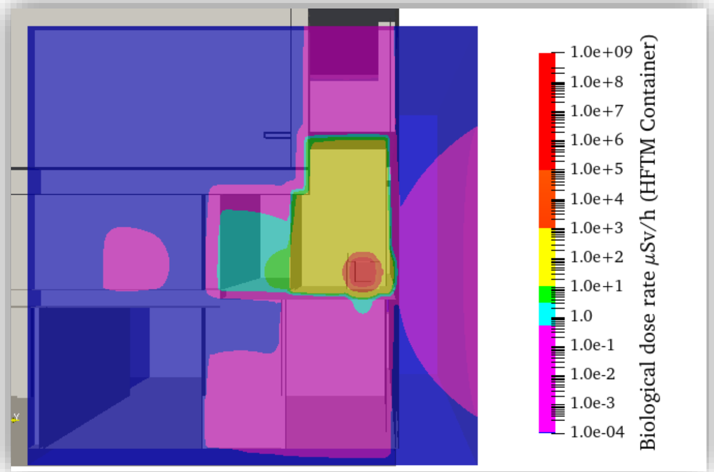
- Accumulated biological doses (mSv) along the transport path

- Dose rate (μSv/h) during transporting HFTM

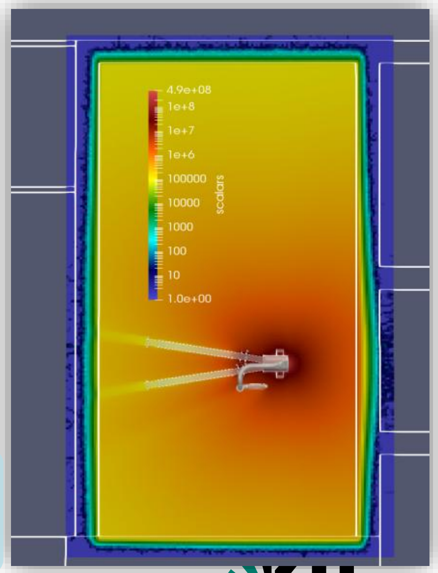




- Database of activation inventories
- Database of decay gamma sources



- Dose rate (μSv/h) of HFTM in waste container

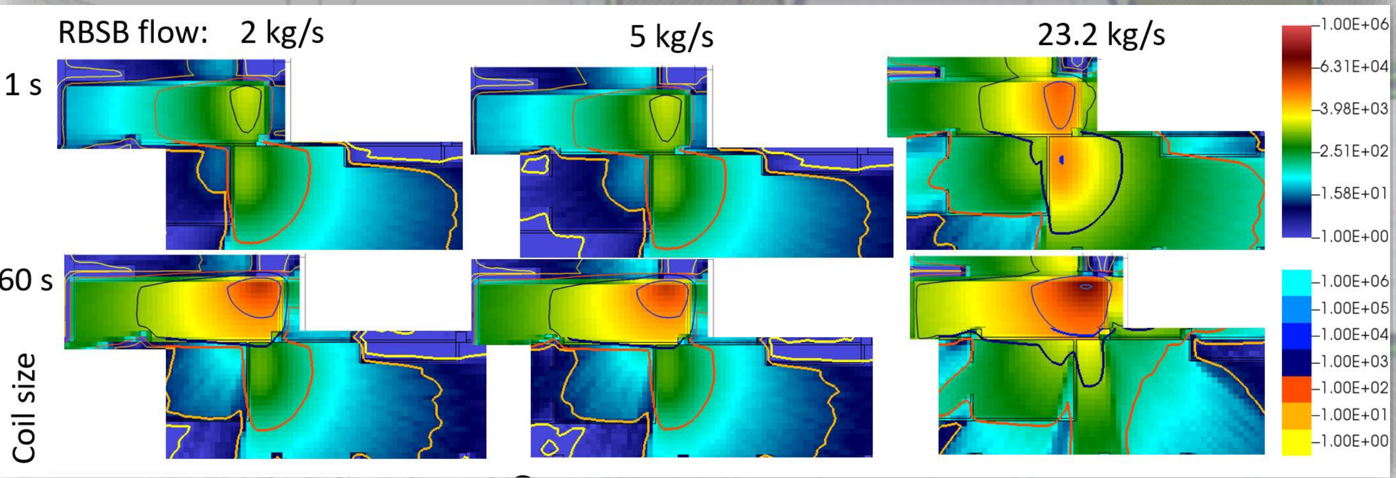


- Dose rate (μSv/h) during handling of Target Assembly

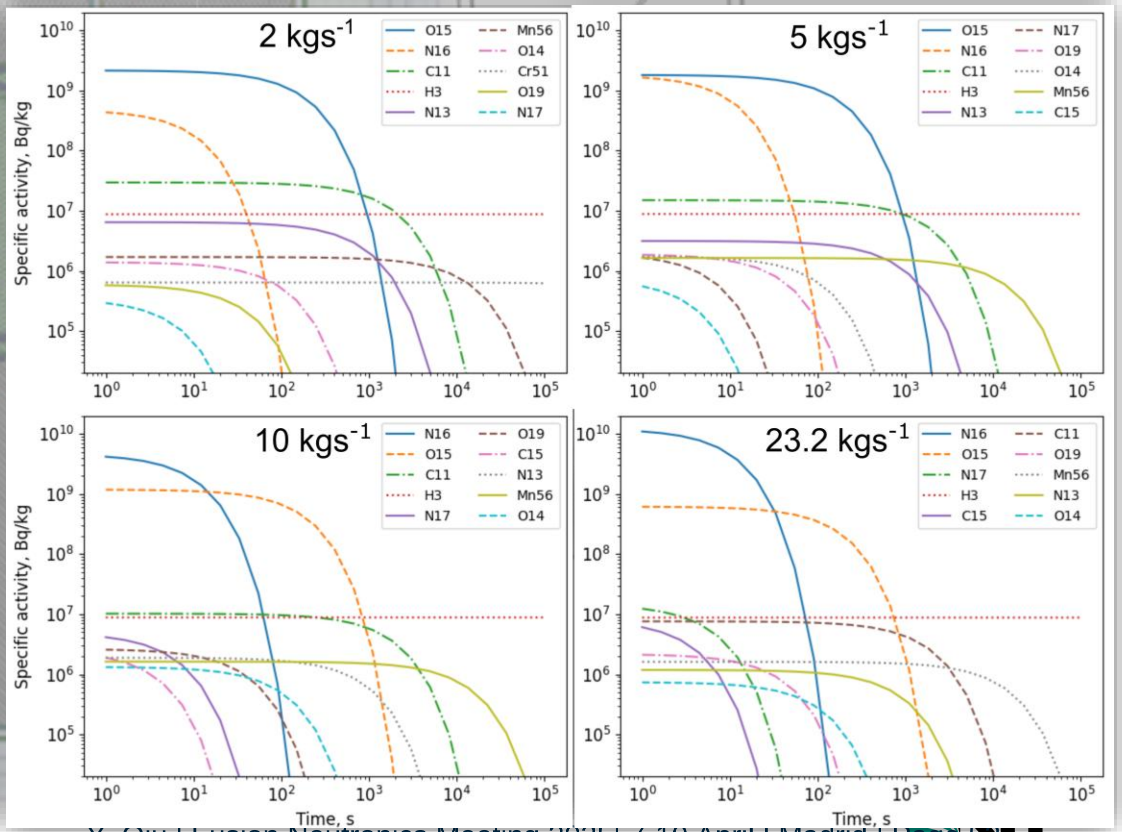
Test Cell Water Cooling System

Reaction	Radionuclide	Half-life, s
$^{16}O(n,p)$	^{16}N	7.1
$^{16}O(n,2n)$	^{15}O	122
$^{17}O(n,p)$	^{17}N	4.2
$^{18}O(n,\gamma)$	^{19}O	27

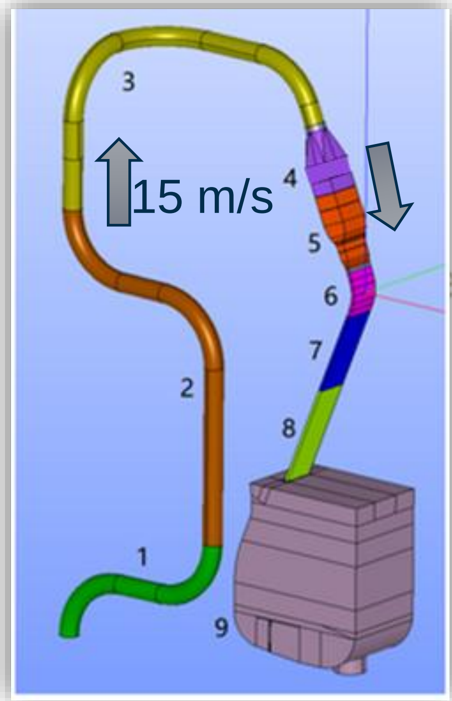
- Scoping analysis on the flow rate and decay time
- Higher flow rate increases the doses!



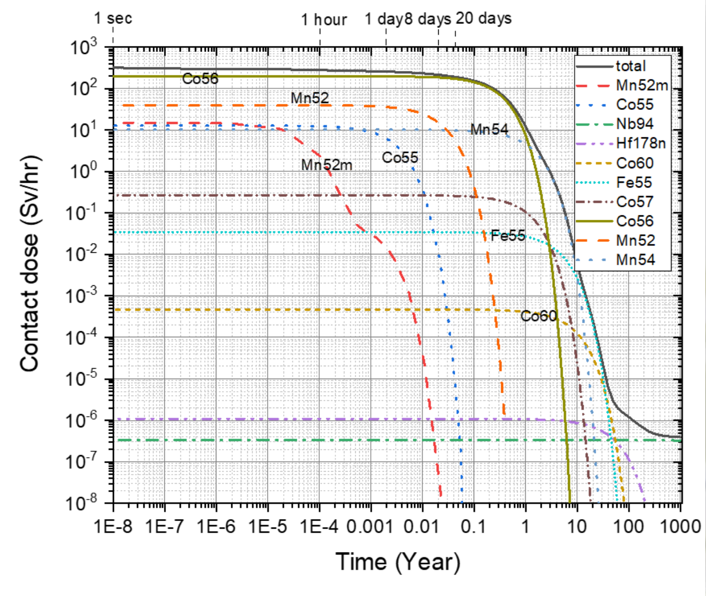
- Activity (Bq) in different flow rate



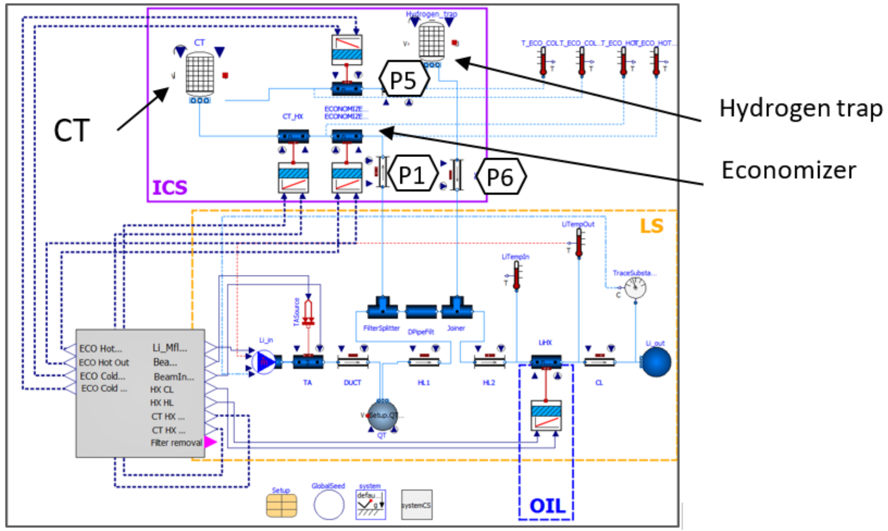
Li activation analysis



- Simulation of activation rate in Li segments



- Dominant isotopes for contact dose for Eurofer activated by deuteron

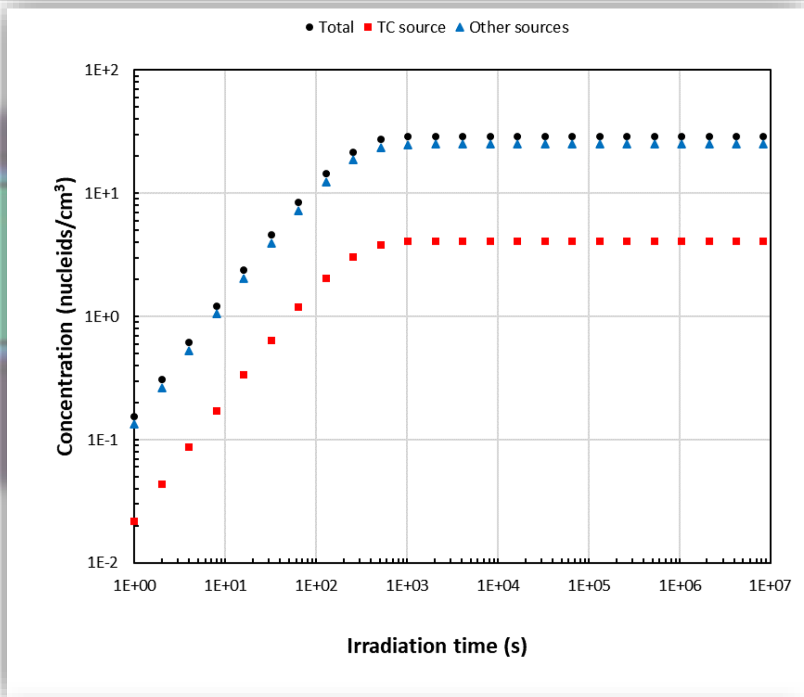


- Mass transfer model for Modelica code
- Simulation of Be-7 and ACP dissolution and deposition in the Li loop

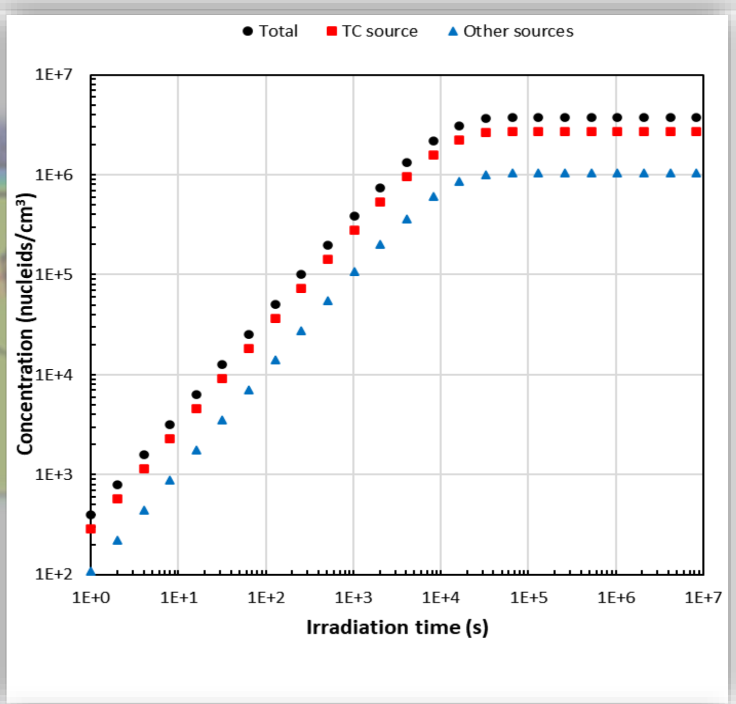
- Activated corrosion products and distributions

Element	Sum. Wall [mg]	Li avg. mg/kg	LiHX [mg]	CL [mg]	CL_TC [mg]
Fe-55	4.01E-01	8.66E-05	1.66E-01	1.77E-01	5.77E-02
Mn-51	0.00E+00	2.80E-11	0.00E+00	0.00E+00	0.00E+00
Mn-52	0.00E+00	2.05E-07	0.00E+00	0.00E+00	0.00E+00
Mn-52m	0.00E+00	2.43E-10	0.00E+00	0.00E+00	0.00E+00
Mn-54	0.00E+00	3.30E-05	0.00E+00	0.00E+00	0.00E+00
Mn5-6	0.00E+00	9.61E-09	0.00E+00	0.00E+00	0.00E+00
Cr-51	3.19E-03	6.88E-09	2.38E-04	9.54E-04	2.00E-03
Ni-57	0.00E+00	8.47E-08	0.00E+00	0.00E+00	0.00E+00
Co-55	0.00E+00	2.58E-08	0.00E+00	0.00E+00	0.00E+00
Co-56	0.00E+00	2.23E-05	0.00E+00	0.00E+00	0.00E+00
Co-57	0.00E+00	7.13E-05	0.00E+00	0.00E+00	0.00E+00
Co-58	0.00E+00	2.08E-05	0.00E+00	0.00E+00	0.00E+00
Co-58m	0.00E+00	8.20E-08	0.00E+00	0.00E+00	0.00E+00
Co-60	0.00E+00	3.39E-06	0.00E+00	0.00E+00	0.00E+00
Co-60m	0.00E+00	8.33E-11	0.00E+00	0.00E+00	0.00E+00
W-181	3.76E-06	1.61E-12	5.22E-08	0.00E+00	3.86E-07
V-52	0.00E+00	4.59E-12	0.00E+00	0.00E+00	0.00E+00
A-l28	0.00E+00	2.71E-11	0.00E+00	0.00E+00	0.00E+00

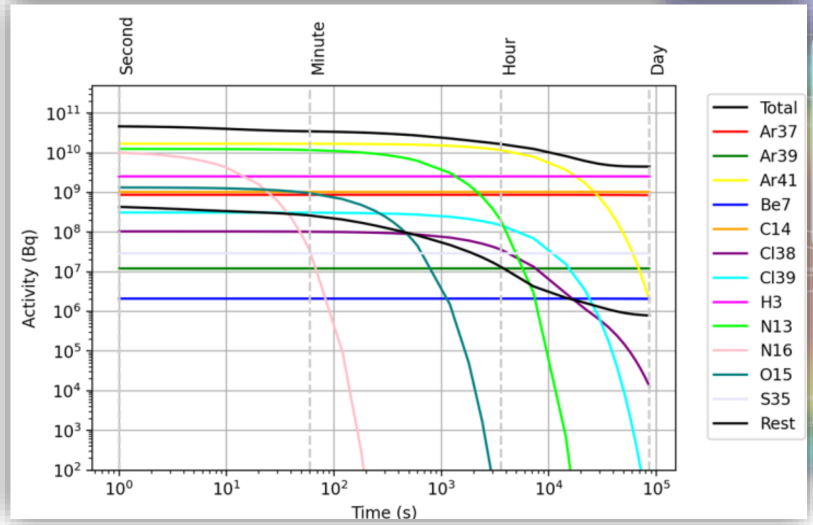
Atmopheric activation



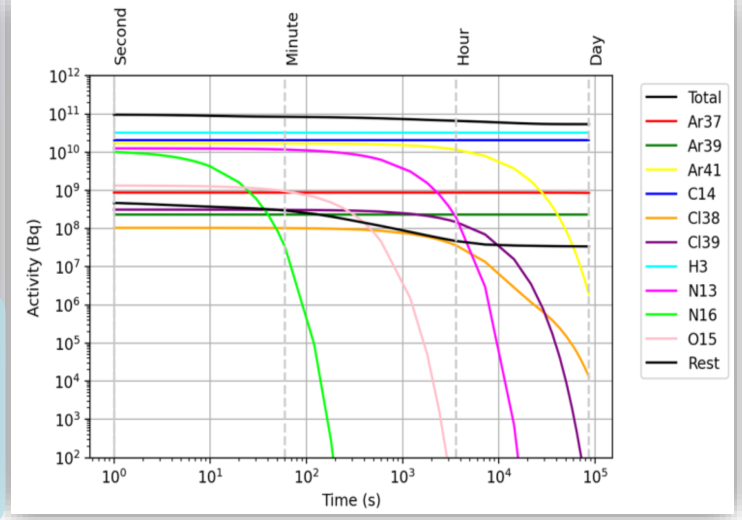
- ^{41}Ar Production AS rooms



- ^{41}Ar Production TIR room



- Air activation in the TC gaps (1 year)



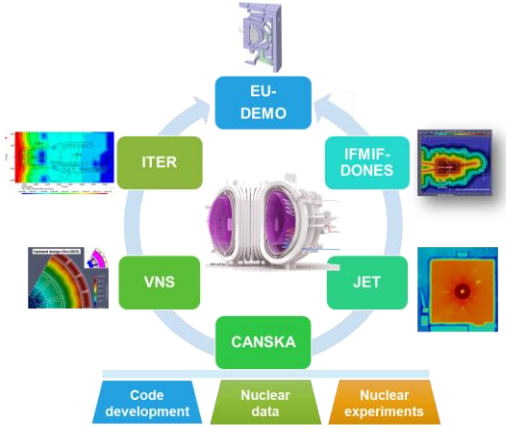
- Air activation in the TC gaps (20 year)

Summary

Summary

- **KIT fusion neutronics group**
  - KIT fusion neutronics group plays active roles in the European fusion neutronics activities, with a focus on DEMO/VNS and DONES projects.
  - We are actively developing simulation tools and nuclear data, and perform validation and mock-up experiments.

- **IFMIF-DONES fusion neutronics achievements**
  - Achievements of neutronics WPENS: ~**160 Subtasks and 440 ppm** contributed from 20 scientists across 10 research units during the last 5 years.
  - These activities include design analyses and optimization, radiation dose maps, shielding, activation and inventory, models, tools and data developments, and experimental benchmarks and validations.
  - Recently published article: special issue of the **Nuclear Fusion journal**.



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