Nuclear data used for IFMIF-DONES and current issues

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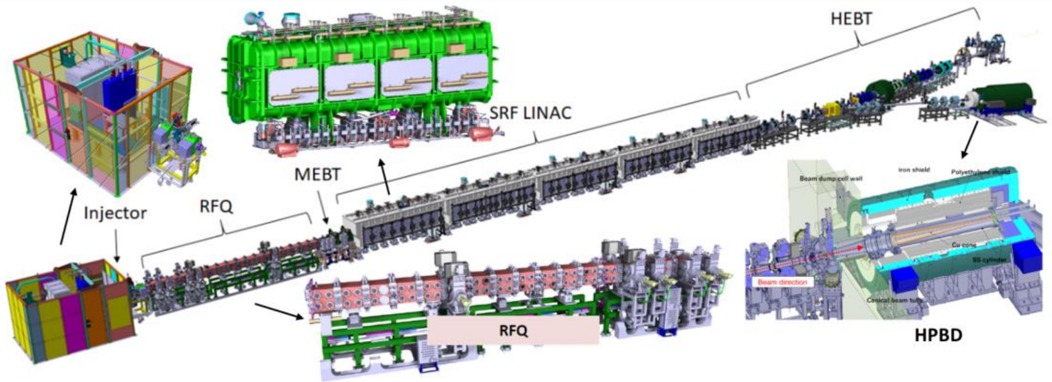
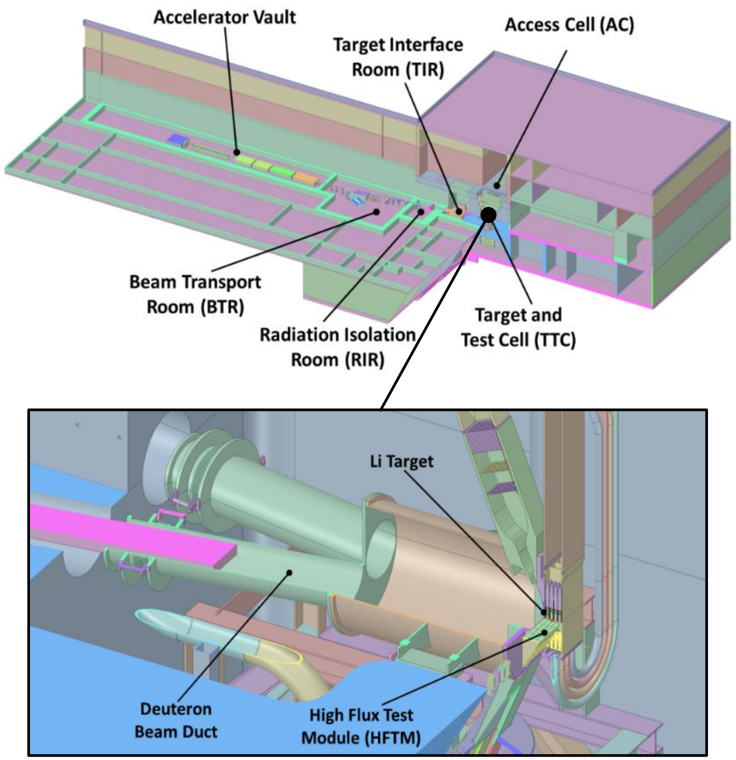
Outline

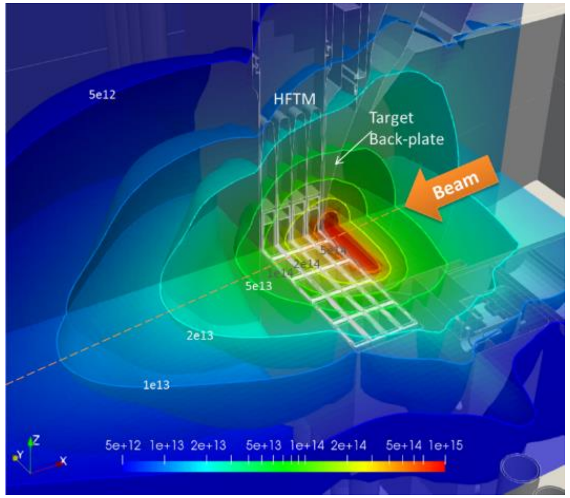
- Introduction of IFMIF-DONES and reference nuclear data
- Deuteron data
- Neutron data
- Summary and discussions

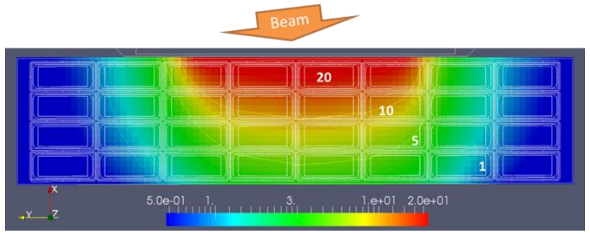
Introduction of IFMIF-DONES

- **IFMIF-DONES:** International Fusion Material Irradiation Facility – Demo- Neutron Source
  - **Deuteron-lithium** neutron source. Linear accelerator with **125 mA** and deuteron beam of **40 MeV**.
  - Neutron produced from d-Li stripping reactions, peak flux **10^{15} n/cm^2/s** and energy up to **55 MeV**.
  - Damage dose rate **5-20 dpa/fpy** in HFTM, with irradiation parameters similar to fusion environments.







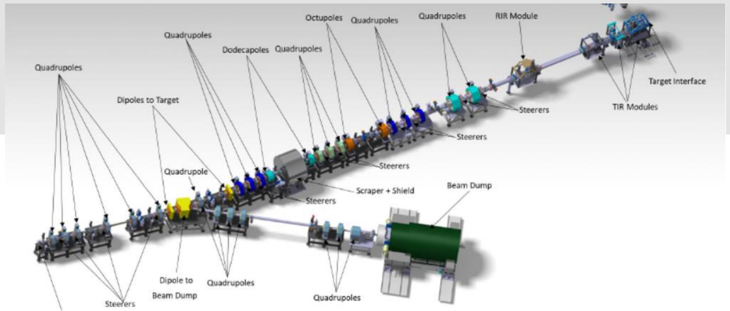


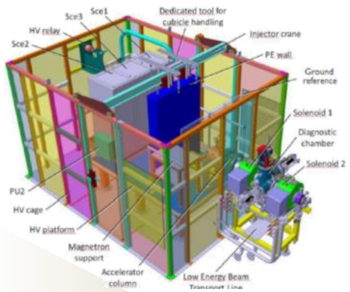
Displacement damage on Iron (dpa/fpy)

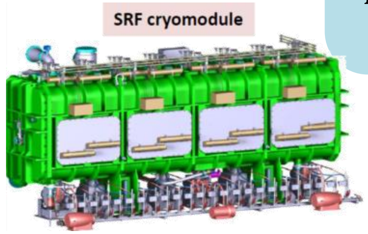
IFMIF DONES

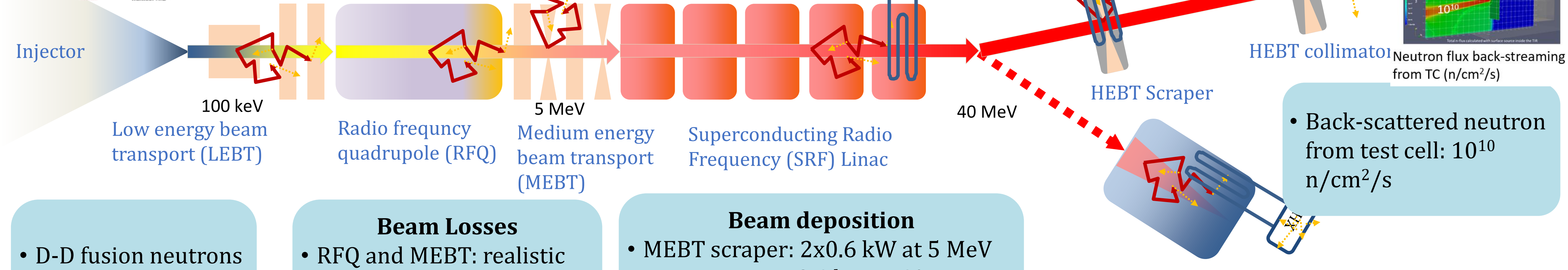
- Atmosphere activation
- Ar-41

- Cooling water and corrosion products activation
- N-16, N-17, O-15









- Back-scattered neutron from test cell: 10^{10} n/cm^2/s

- D-D fusion neutrons in commissioning.

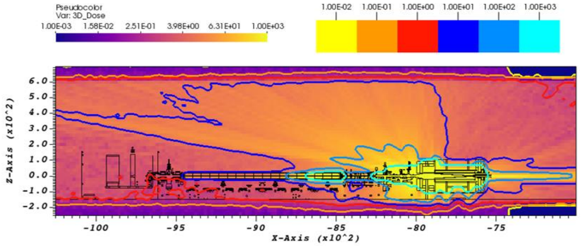
Beam Losses

- RFQ and MEBT: realistic beam losses
- SRF and HEBT: **1 W/m** safety assumptions

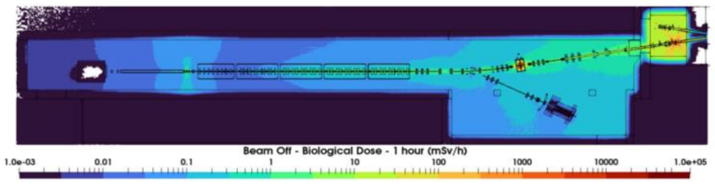
Beam deposition

- 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

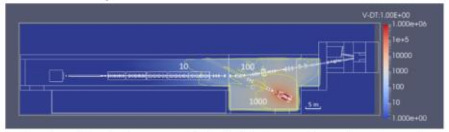
- HPBD copper cone: 1% duty cycle (DC) at 40 MeV (50 kW)
- Neutrons from Cu(d,xn)



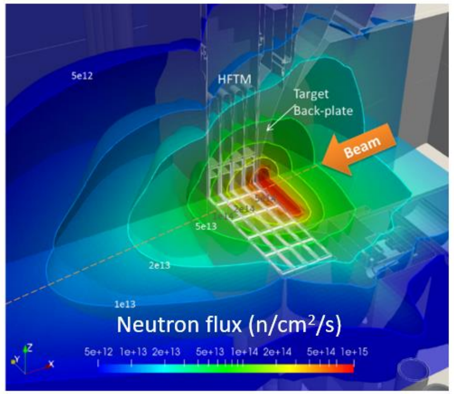
Total residual dose rate (µSv/h) in **Phase 2** (1-hour cooling)

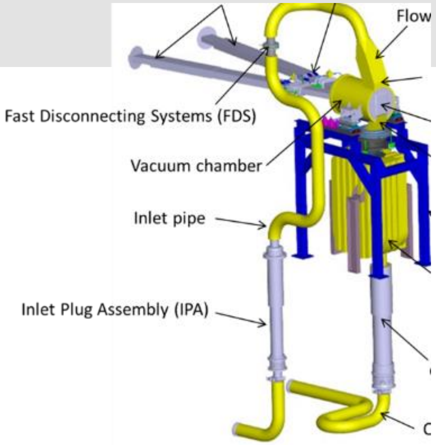


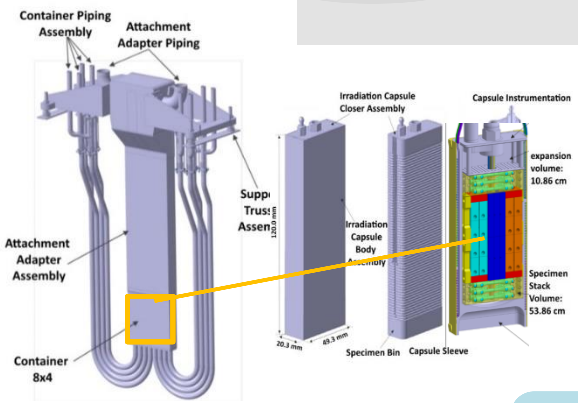
Biological dose (mSv/h) at 1-hour of cooling time in the AS room

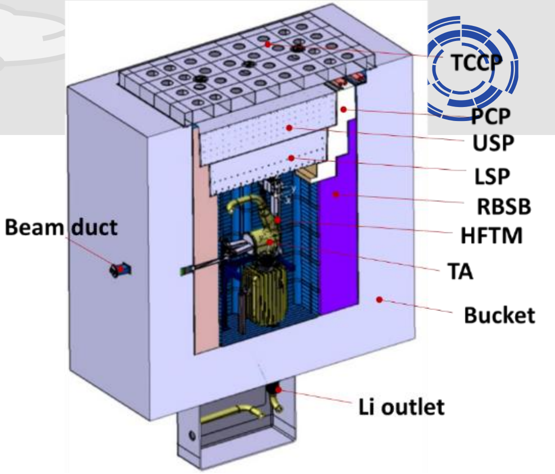


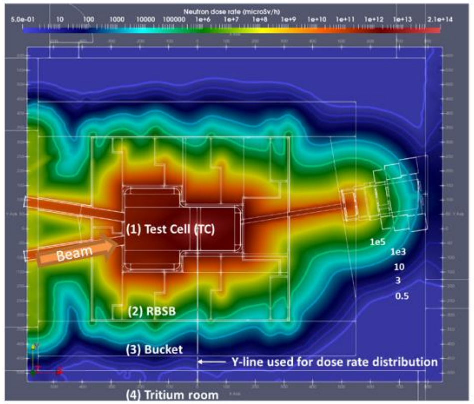
Total residual dose rate (µSv/h) 1 hour after shutdown in Phase 3 commissioning

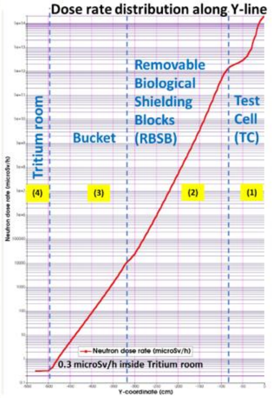








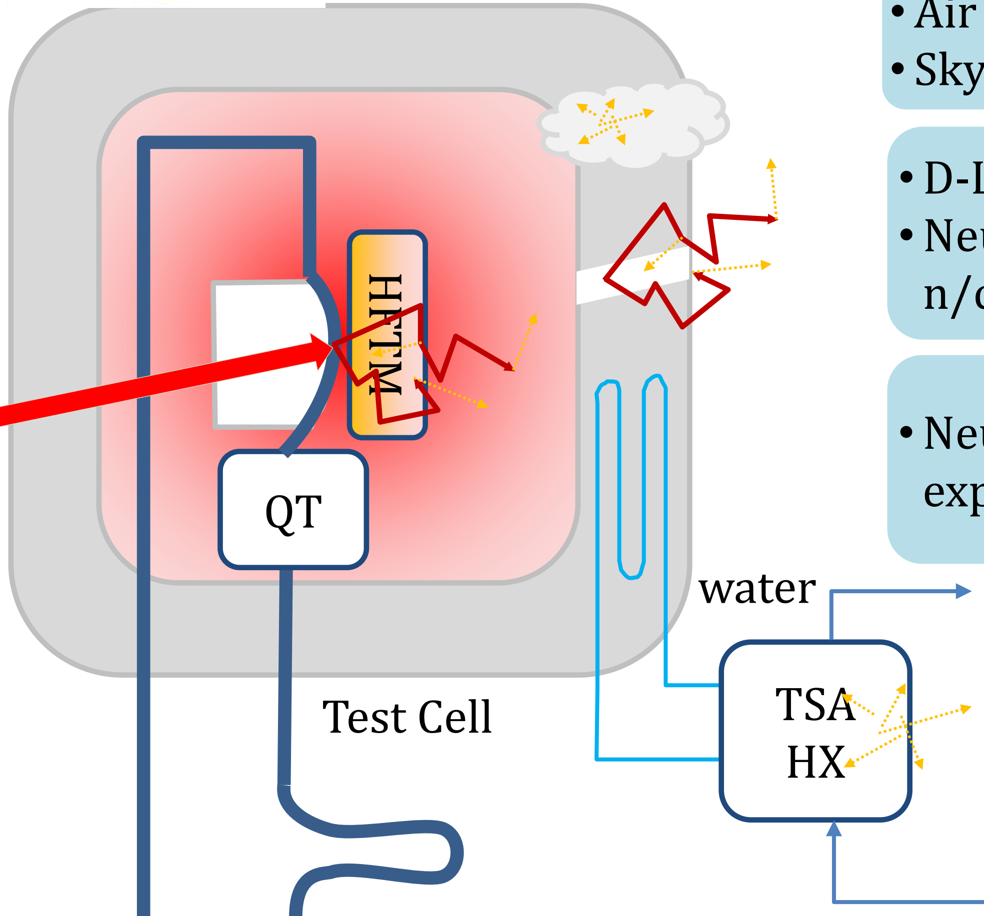




- Air activation (gaps)
- Sky-shine

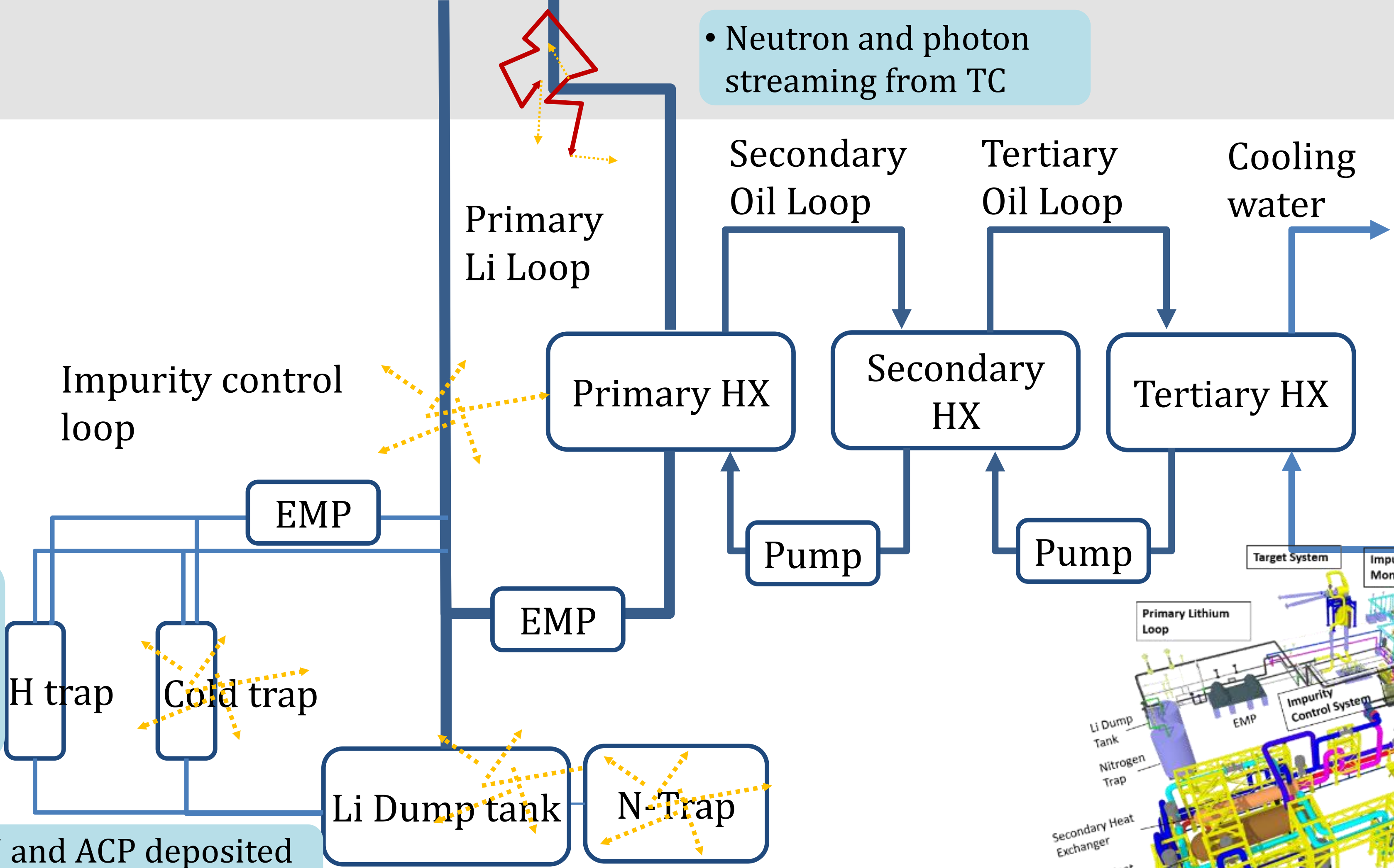
- D-Li neutrons and photons
- Neutron flux: up to 10^{15} n/cm^2/s

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



- Cooling water and corrosion product activation

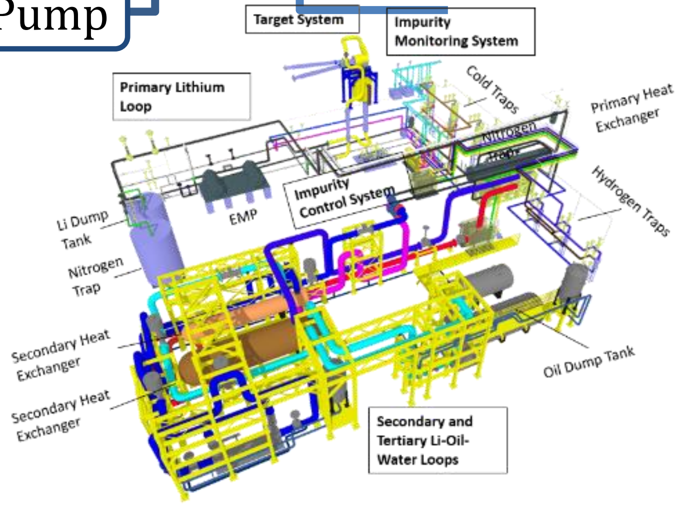
- Neutron and photon streaming from TC

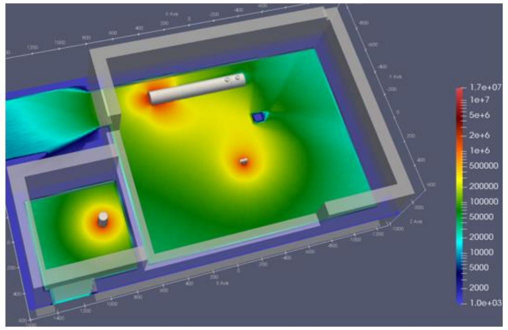


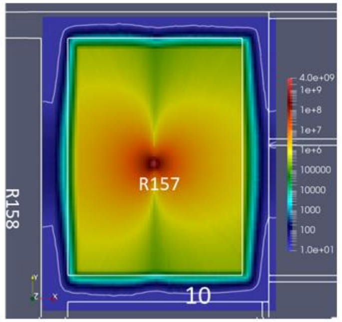
- H-3 in H-Trap

- Be-7 and ACP deposited in the cold trap

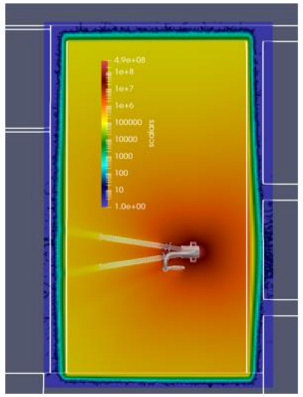
- Be-7:T1/2 53 days, γ 477 keV
- Activated corrosion products (ACP)
- dissolved in Li



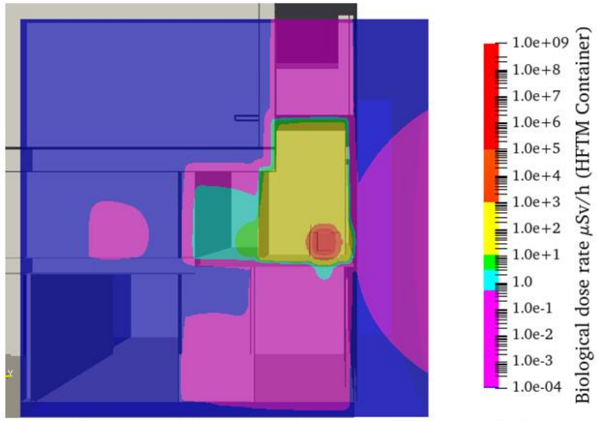




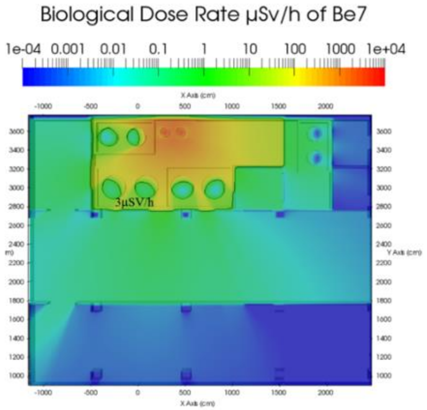
HFTM dose rate [μSv/h] in RW treatment cell at 1-day after shutdown



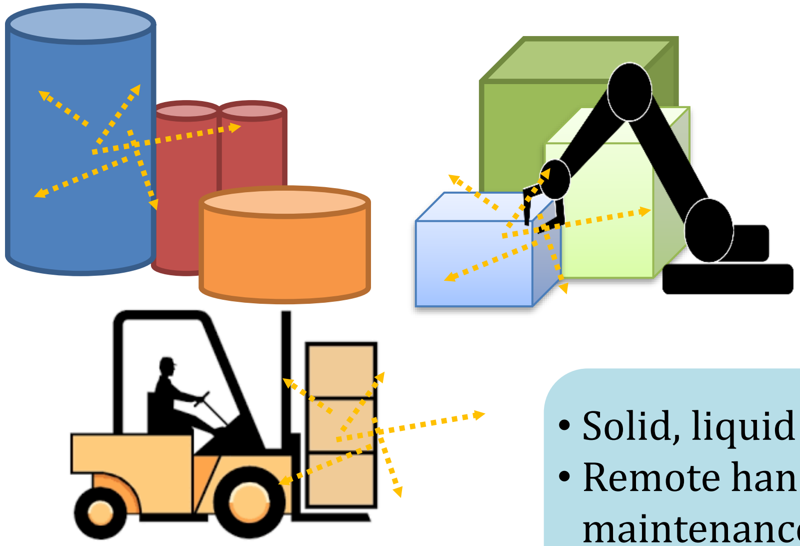
TA dose rate [μSv/h] in irradiating RW storage cell at 1-day cooing



beam dump stopper in waste container located in solid waste storage cell.



Radiation dose liquid waste storage cells



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

Reference nuclear data

- Deuteron cross section data
  - **Li**: ***FZK-2005*** data for transport (McDeLicious code) and activation
  - **Cu**: ***JENDL-5*** data for transport, ***TENDL-2021/EAF2010*** for activation.
  - Other isotopes: ***TENDL-2021*** for transport and activation
  - Current **FENDL-3.2** : from TENDL-2011, except Li, Be and C.
- Neutron cross section
  - Transport: ***FENDL-3.1d***. Updating to ***FENDL-3.2*** is ongoing
  - Activation: ***TENDL-2017*** (released with FISPACT-II)
  - Displacement cross section: Special lib for Eurofer and SS316L[1]

AS systems	Beam facing materials
Injector/LEBT	SS304L, Copper
RFQ	Copper
MEBT	SS316L, Copper
SRF	NbTi,
HPBD	Copper,
HEBT	CuCrZr, SS316L, Alumiumum
Target	Li, EUROFER

Test systems	Materials
Target Assembly	Li, EUROFER, SS316L
HFTM	EUROFER, SS316LN, Na
Liner	SS316L
RBSB, PCP, LSP, USP	Heavy concrete, SS316L, water
Bucket	Ordinary concrete
Building	Ordinary concrete

[1] A. Y. Konobeyev, et.al., “Evaluation of advanced displacement crosssections for the major EUROFER constituents based on an atomistic modelling approach,” Kerntechnik, vol. 80, no. 1, pp. 7–12, Mar. 2015.

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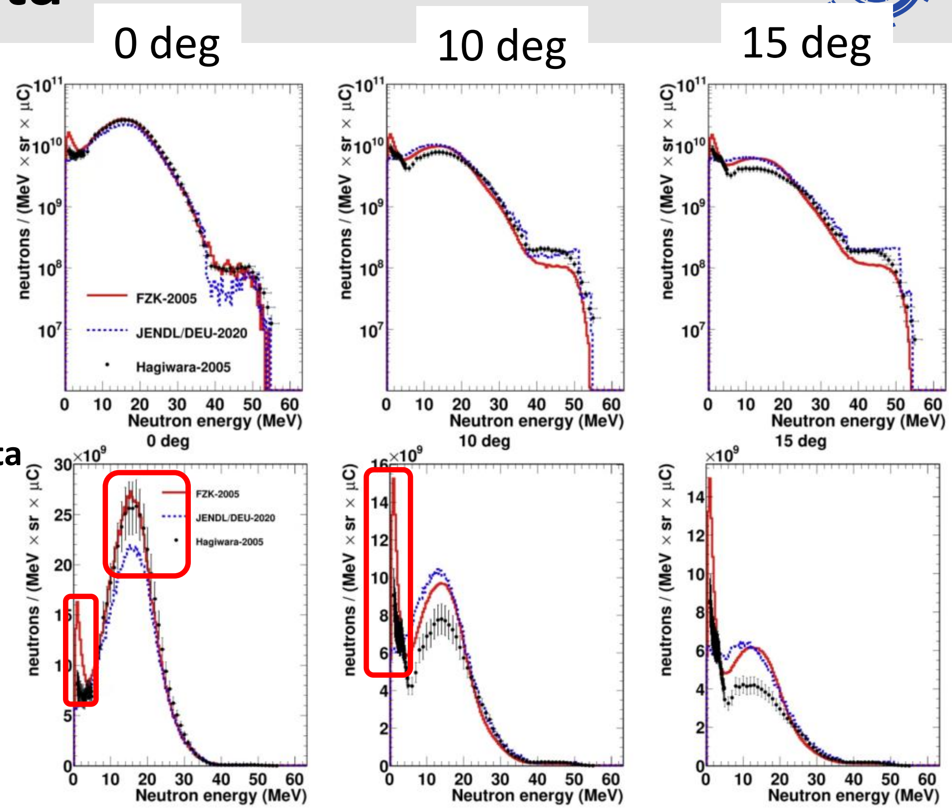
d-Li transport data

- **d-Li** transport data and current issues
  - Current two evaluations: **FZK-2005** and **JENDL-DEU/2020**.
  - Comparisons by E. Mendoza [1] show some discrepancies in the **forward angles**, and neutron yield for lower energy (~**1 MeV**).
  - Results for the neutron flux and other nuclear responses results in the High Flux Test Module result in a **large discrepancy** (>20%).
- Actions ongoing
  - **Additional experimental** data for confirming the neutron yield at forward angle, where the high energy are mostly emitted.
  - After data improvements in **FZK-2005** or **JENDL-DEU/2020** (JENDL-5), we need to decide the reference data

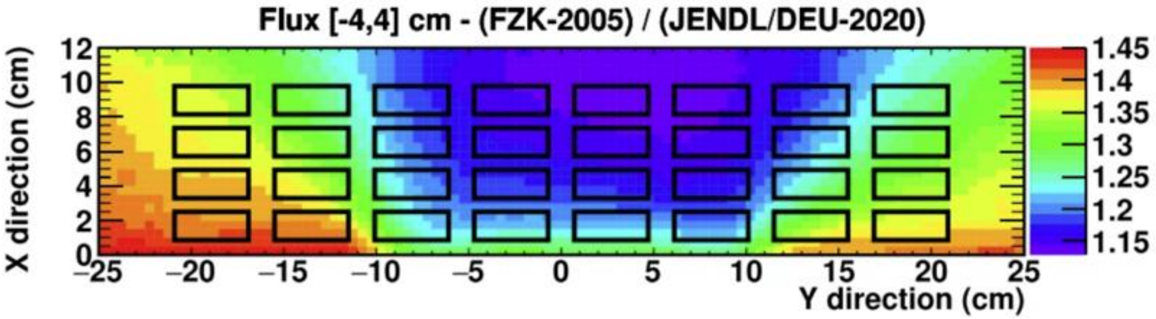
Log. scale

Deuteron Lithium data

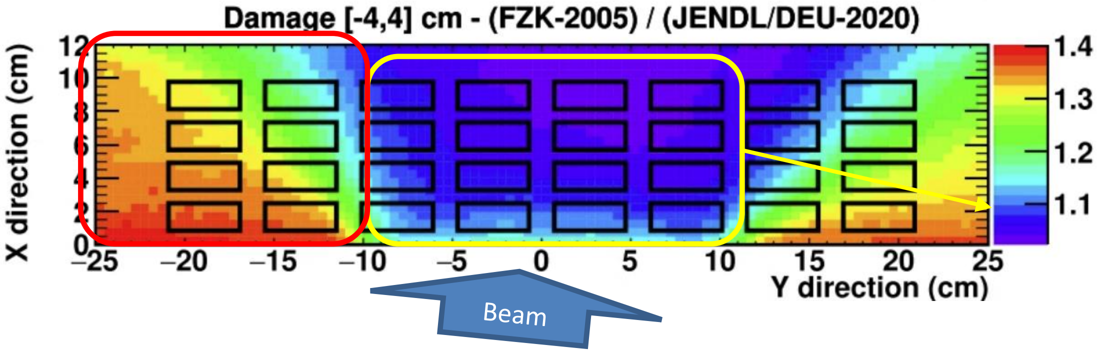
Lin. scale



Total n-flux



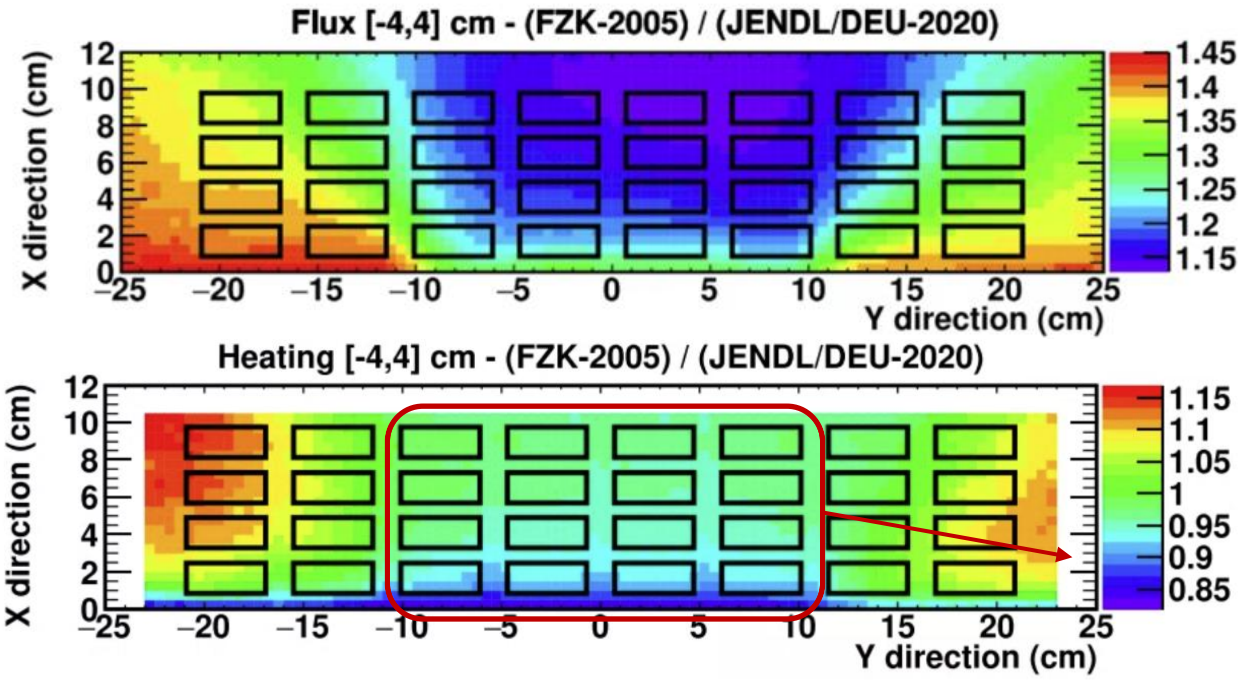
Damage dose rate

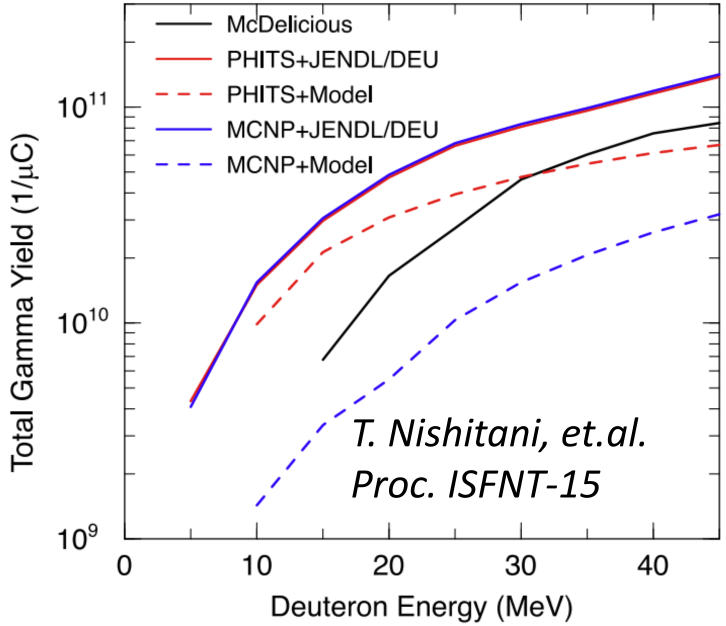


[1]Mendoza, et.al. (2022). Nuclear data libraries for IFMIF-DONES neutronic calculations. Nuclear Fusion, 62(10), 106026

d-Li transport data

- **d-Li gamma production** data and issues.
  - JENDL/DEU-2020 predict lower neutron flux, but higher gamma flux (impact on heating up to 15%).
  - Total gamma yield of JENDL/DEU-2020 predict 2x larger than FZK-2005 (McDeLicious).
  - Currently no experimental data to support the evaluation.
- Action needed: experimental data for the d-Li gamma yield





Total primary gamma yield from the thick Li target, without neutron-induced gammas

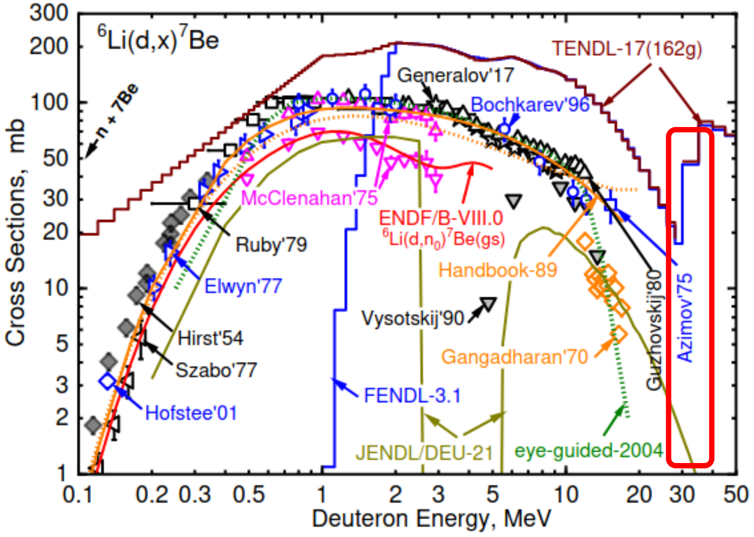
d-Li activation data

d-Li induced ^{7}Be and ^{3}H productions [1] and current issues

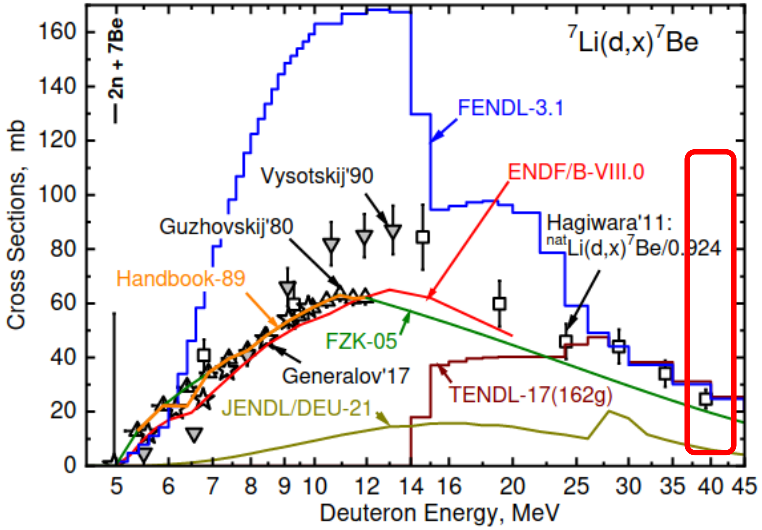
- **^{7}Be** (57 days, 477 keV, **9.7 10^{15} Bq/fpy**), **^{3}H** (**1.4 10^{15} Bq/fpy**) mostly produced by D-Li activation.
- **^{7}Be** production: ^{7}Li(d,x) ^{7}Be **no measurements at Ed ≥ 12 MeV**, ^{6}Li (d,n) ^{7}Be production is **missing in FZK-2005**
- **^{3}H** production: FZK-2005 and TENDL-17 data deviate by a **factor of 3** at 40 MeV. No reliable ^{6,7}Li(d,x) ^{3}H experimental data for E_d above 5 - 7 MeV

Action needed

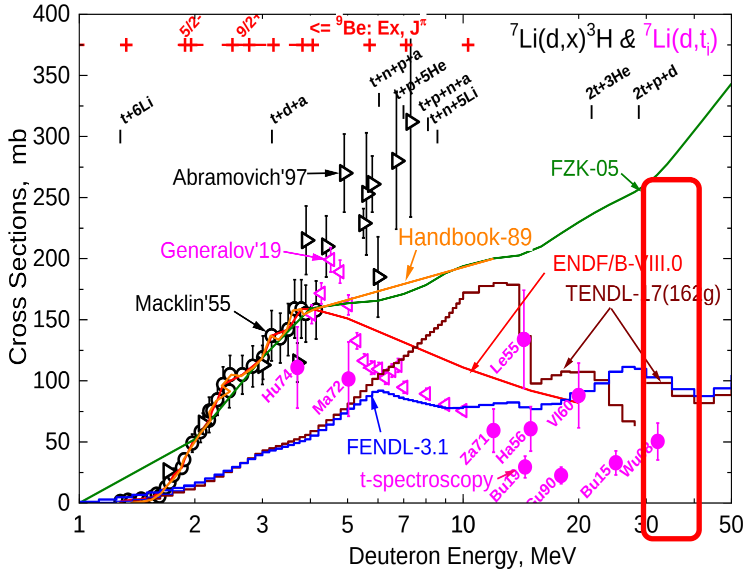
- The correct estimation of the ^{7}Be and ^{3}H inventory has a direct impact on the for safety and licensing.
- More **experimental data** is needed with 40 MeV deuteron, then follow by re-evaluation of the available data.



^{6}Li (d,n) ^{7}Be data



^{7}Li (d,n) ^{7}Be data



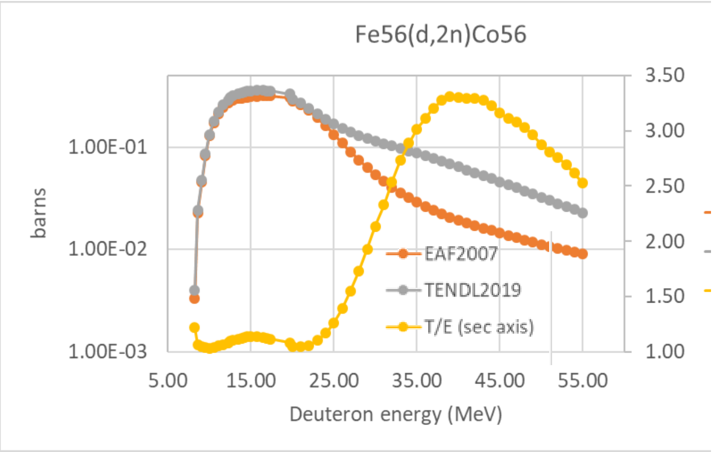
^{7}Li (d,n) ^{3}H data

[1] S. P. Simakov, et.al., “Status and benchmarking of the deuteron induced Tritium and Beryllium-7 production cross sections in Lithium,” KIT report, 2020.

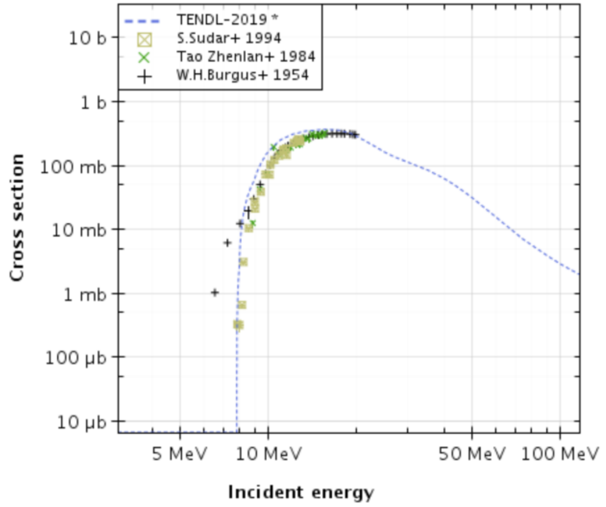
D-Fe activation data

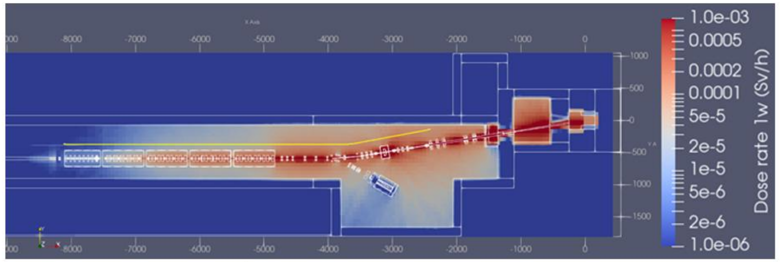
- Deuteron libraries of **Iron** and current issues
  - Cross sections for the important materials **Cu, Fe** have deviations of a **factor 2~3** for TENDL-2015 and EAF-2007. Similar issue spotted for Nb, and Al.
  - **New nuclear models** have been updated by M. Avrigeanu et.al. [1] in the new version of the TALYS code. However, TENDL-2021 hasn't implemented these important update.
- Ongoing Actions
  - Urge the next **TENDL-2023** will include the **updated physics model by M. Avrigeanu**.
  - Collaboration with QST/JAEA on the inclusion of **dueteron activation data for JENDL-5**.

***d-Fe** activation cross section (F. Ogando)*



Fe56 (d,2n) or Co56 production

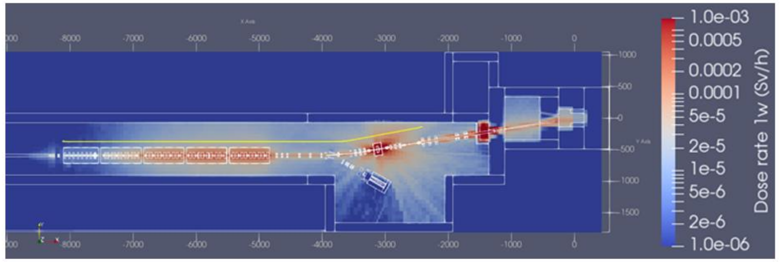




Dose rate [μSv/h] calculated using **Steel** (1-week)

Dominant nuclei for deuteron-activated contact doses

Aluminum	Stainless steel
• Na-24 (T=12h): 1 day 86%, 1w: 0.3% • Co-56 (T=77d): 1d: 2%, 1w: CD 16% • Na-22 (T=2.6y)1d: CD 8.6%, 1w: 67%	• Co56 (CD 66-75%, T=77d) • **From Fe56(d,2n)** • Mn52 (CD 17-9%, T=5.6d) • Mn54 (CD 7%, T=312d)

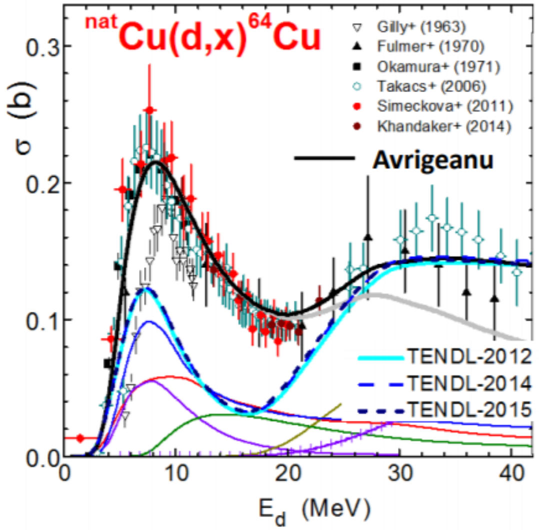


Dose rate [μSv/h] calculated using **Aluminum** (1-week)

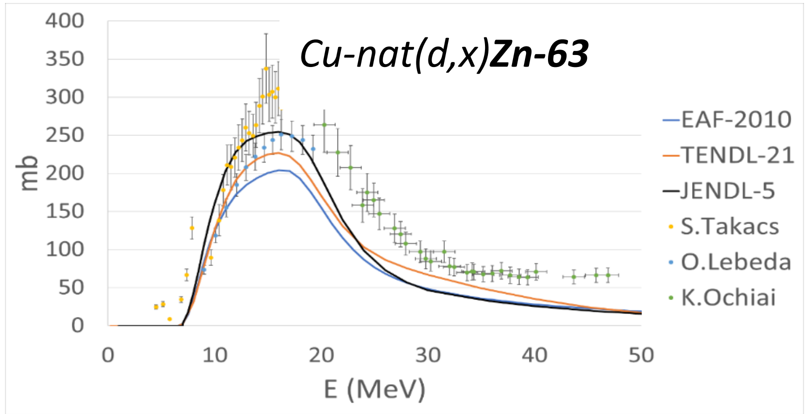
[1] Avrigeanu, M.et.al.(2022). **Advanced breakup-nucleon enhancement of deuteron-induced reaction cross sections**. *European Physical Journal A*, *58*(1), 1–13.

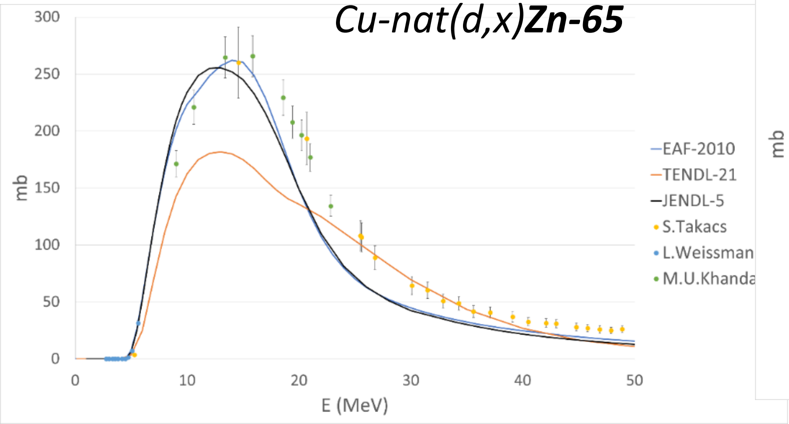
D-Cu activation data

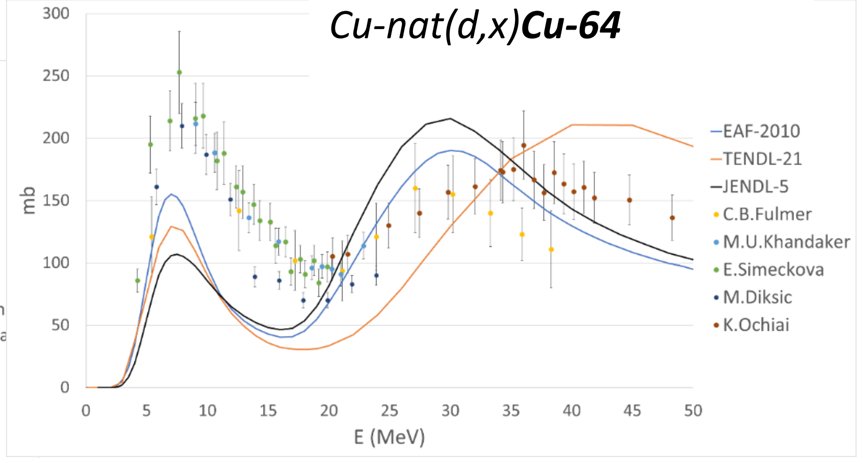
- Deuteron libraries of **copper** and current issues
  - Cross sections for the important materials **Cu, Fe** have deviations of a **factor 2~3** for TENDL-2015 and EAF-2007. Similar issue spotted for Nb, and Al.
  - **New nuclear models** have been updated by M. Avrigeanu et.al. [1] in the new version of the TALYS code. However, TENDL-2021 hasn't implemented these important update.
- Ongoing Actions
  - Urge the next **TENDL-2023** will include the **updated physics model by M. Avrigeanu**.
  - Collaboration with QST/JAEA on the inclusion of **dueteron activation data for JENDL-5** (possibly under EU-JA bilateral agreement)



***d-Cu** cross section comparisons (U. Fischer | ND-2019)*







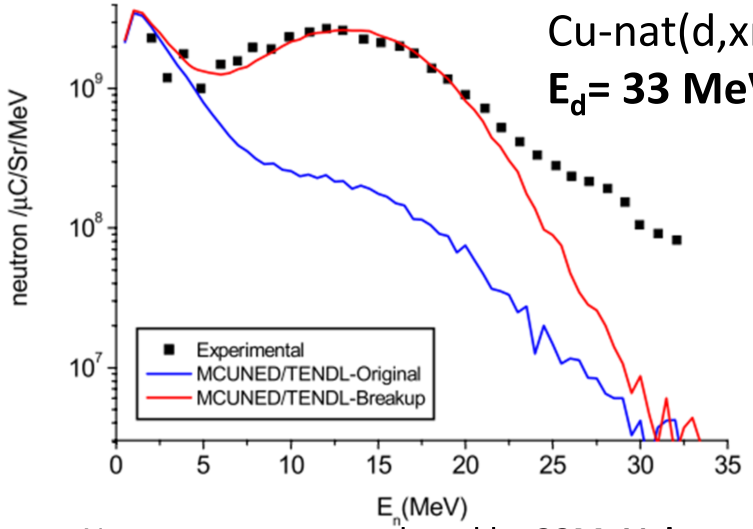
***d-Cu** cross section comparisons on Cu-64, Zn-65, Zn-63 production (V. Lopez| 2023)*

[1] Avrigeanu, M.et.al.(2022). **Advanced breakup-nucleon enhancement of deuteron-induced reaction cross sections**. *European Physical Journal A*, *58*(1), 1–13.

D-Cu transport data

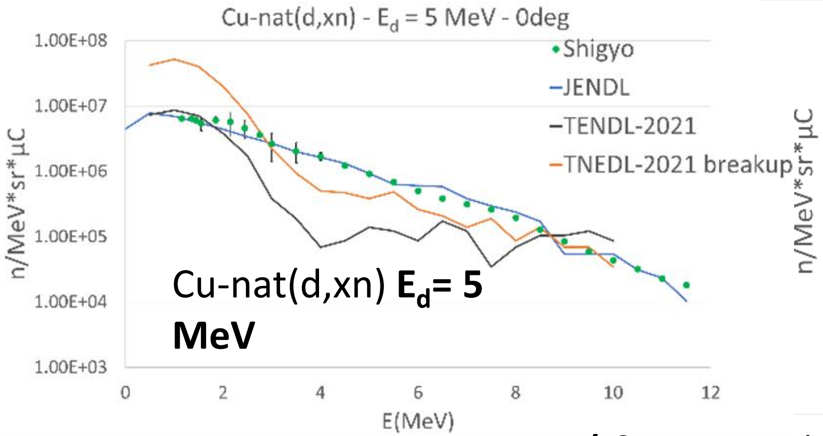
- Current Issues with the deuteron **copper neutron production**
  - P. Sauvan [1] has implemented in MCUNED an important update on the implementation of the **Kalbach neutron angular distribution** from the deuteron break-up reaction. However, only **special versions of TENDL** libraries have the necessary parameters needed for MCUNED code.
  - **JENDL-5** produced better agreement with experimental data, since tabular angular distribution is used (results in large data size).
- Action ongoing
  - Seek for strong support from **TENDL-2023** to implement the Kalbach (possibly in the official release?)
  - Proposing **JENDL** deuteron data to implement the Kalbach neutron emission.

Cu-nat(d,xn)
E_d= 33 MeV

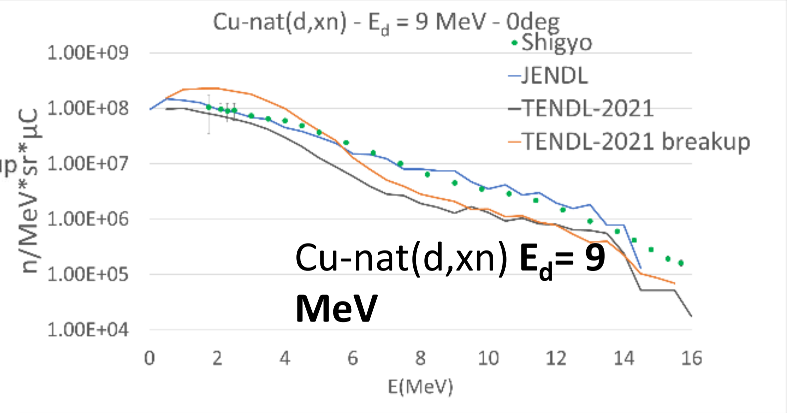


Neutron spectra produced by **33MeV deuteron** on thick (3mm) Copper target (P. Sauvan et.al.)

[1] P. Sauvan, etl.al "Implementation of a new energy-angular distribution of particles emitted by deuteron induced nuclear reaction in transport simulations," in EPJ Web of Conferences, 2017.

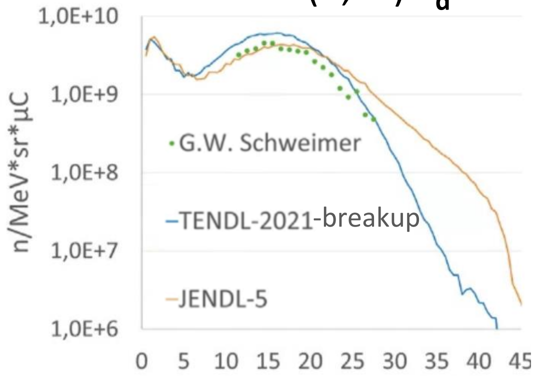


Cu-nat(d,xn) **E_d= 5 MeV**



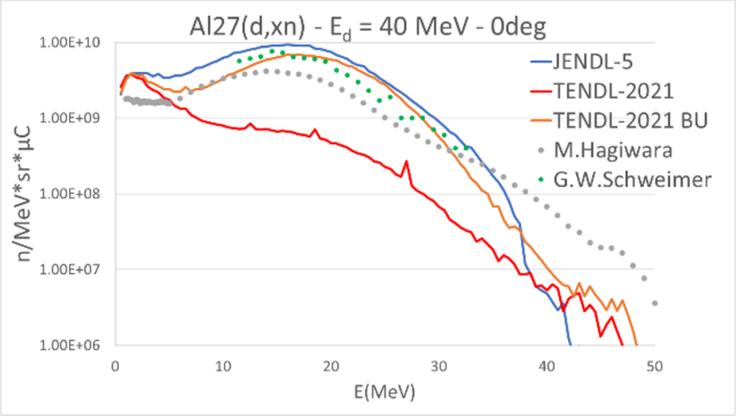
Cu-nat(d,xn) **E_d= 9 MeV**

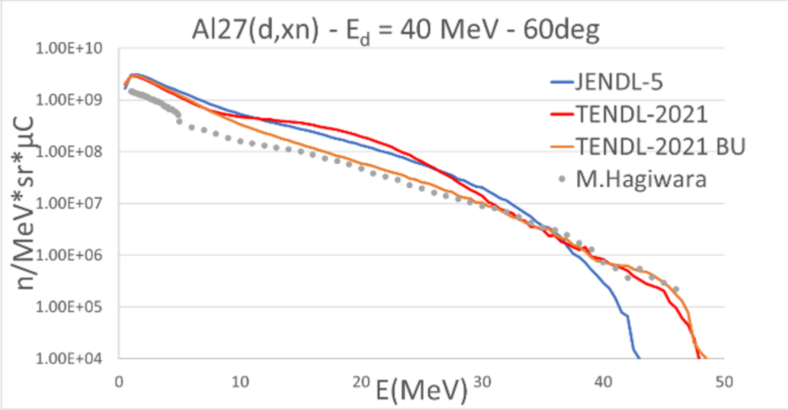
Cu-nat(d,xn) **E_d= 40 MeV**

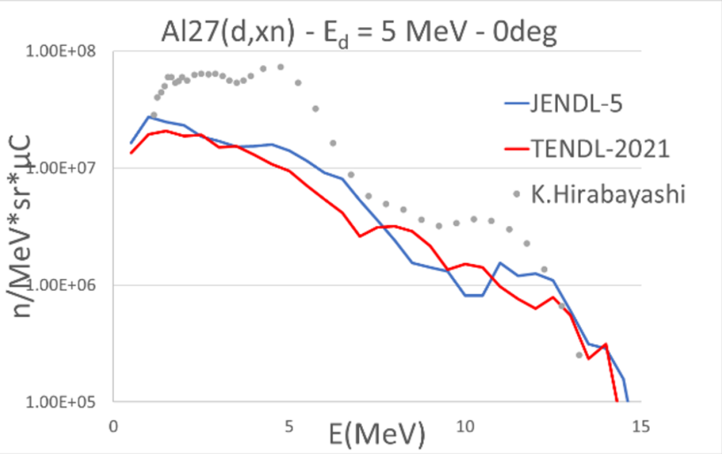


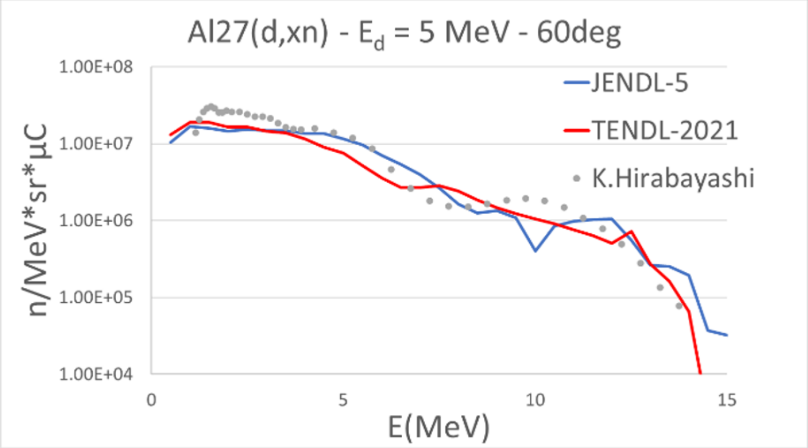
***d-Cu** neutron yield at **0 deg** (V. Lopez| 2023)*

D-Al transport data







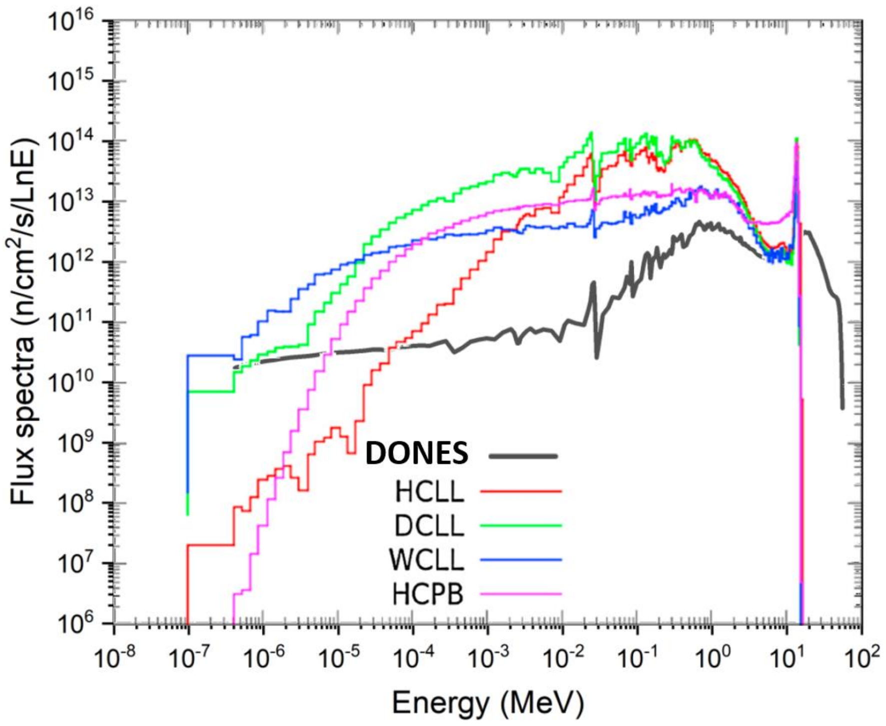


Outline

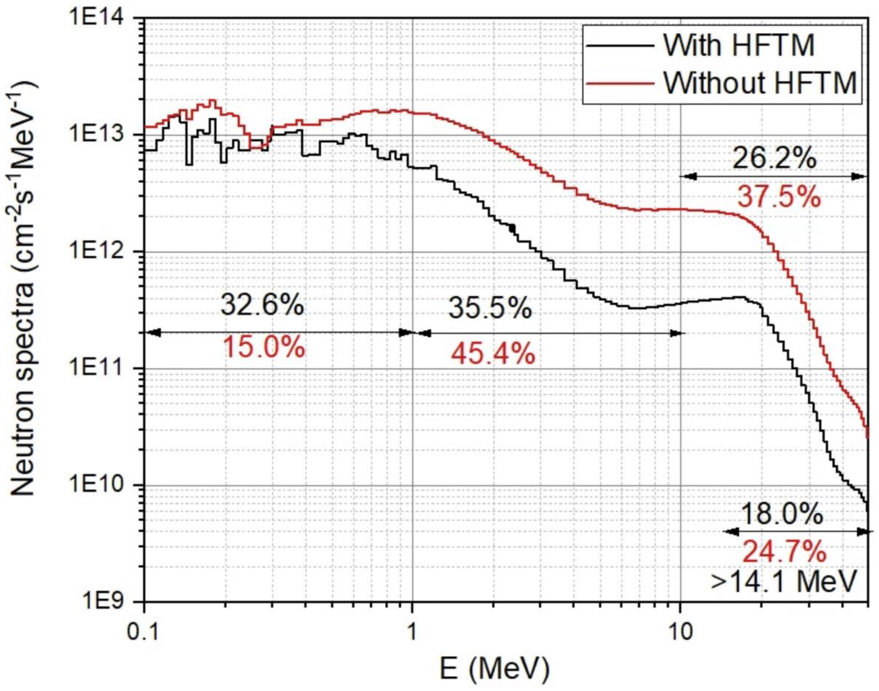
- Introduction of IFMIF-DONES and reference nuclear data
- Deuteron data
- Neutron data
- Summary and discussions

DONES Neutron spectra

- Neutron spectra at the target and HFTM
  - Broad peak at 14-15 MeV.
  - Most of "uncollided" neutron are fast neutron, with ~25% higher than 14.1 MeV.



Neutron spectra comparison with DEMO FW

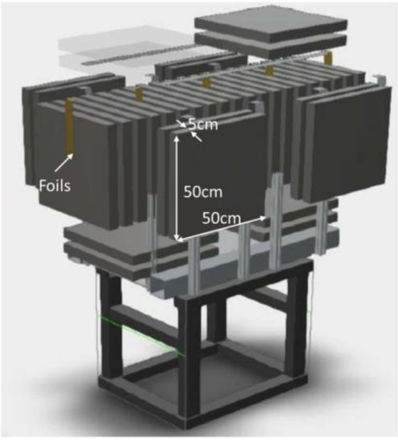


Neutron spectra with/without HFTM

Neutron cross section

- Towards the adoption of FENDL-3.2
  - Current FENDL-3.1d is the references
  - Computational benchmark for the isotopes using e.g. JADE is still ongoing (contribution from JSI)
  - Needs of experimental benchmarking for high neutron energy (except TIARA, in which several issues of Fe and O at 20 MeV was observed).
  - Additional benchmarks, e.g. IFMIF-DONES concrete shielding experiments, are to be added into the list.
- Neutron Activation data
  - Currently TENDL-2017 is adopted instead of FENDL-3.0/A.
  - Benchmarks for

    E_n> 14 MeV



FENDL: A library for fusion research and applications

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VERIFICATION AND VALIDATION

A. Computational Benchmarks
1. Leakage Sphere
2. ITER 1-D
3. ITER 3-D
4. FNSF 3-D
5. FNSF 1-D
6. ITER-1D HCPB and WCLL TBM
7. EU DEMO-3D divertor

B. Experimental Benchmarks
1. Oktavian
2. FNS experiments
3. TIARA shielding experiments
4. FNG Cu, WCLL, W-SS-Water shield
5. Research Center Rez 10.7 and 12.7 MeV quasi monoergetic neutron source: Dosimetrical reactions
6. Research Center Rez ^{252}Cf(s.f.) source: Ni Fe, Cu, stainless steel, and Pb leakage spectrum and dosimetrical reactions
7. LLNL Pulsed Sphere
8. JET Activation Foils
9. SINBAD benchmarks

Outline

- Introduction of IFMIF-DONES and reference nuclear data
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Summary and discussion

- As IFMIF-DONES is approaching the final design and construction/commission phase, it relies strongly on high-quality nuclear data.
- D-Li neutron yield has large discrepancies between FZK-2005 and JENDL/DEU-2020, mainly due to the forward angle, low energy peak, and gamma productions.
- D-Li produced (safety-important) Be-7 and H-3 has large discrepancies among the evaluations. Experiment are urgently needed.
- D-Cu transport data show that JENDL-5 is preferable, as well as special version of TENDL with Kalbach neutron angular distribution for MCUNED calculations.
- D activation data is has many issues, which could possibly resolved by TENDL-2023 with M. Avrigeanu updated nuclear model.
- Neutron transport cross section from FENDL-3.2 requires further benchmarking, in particular with neutron energy >20 MeV.

- Taking the benefit of JADE code
  - For high neutron energy data (>20 MeV)
  - For activation data.
  - For deuteron data, e.g. TENDL version, EAF-2010
- FENDL-3 in future
  - Inclusion of EUROFER and SS DPA file
  - Covariance data

Discussion

- Taking the benefit of JADE code
  - For high neutron energy data (>20 MeV)
  - For activation data.
  - For deuteron data, e.g. TENDL version, EAF-2010
- FENDL-3 in future
  - Inclusion of DPA
  - Covariance data

Thank you!

IFMIF DONES GRANADA | THE KEY TO THE FUTURE