EUROfusion

Nuclear data validation and verifications for IFMIF-DONES

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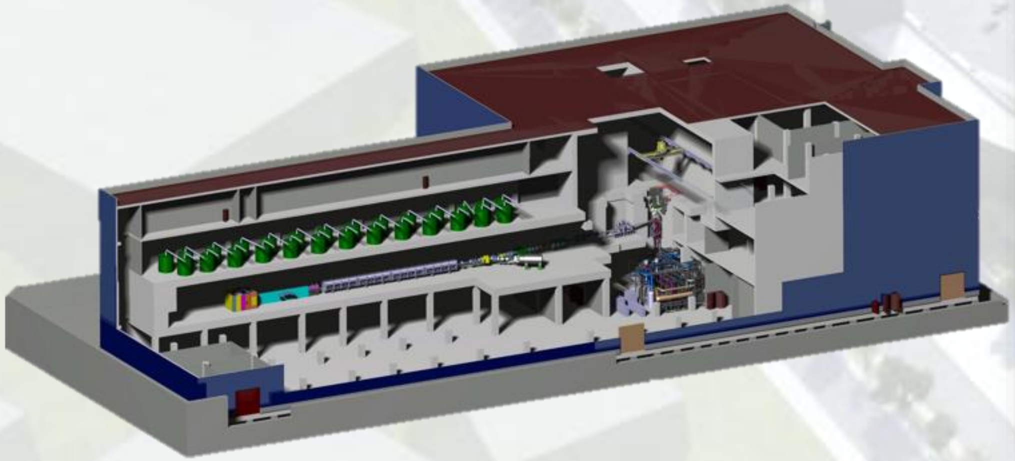
Outline

- Neutron transport cross section
- DPA and gas production uncertainties
- Deuteron cross sections
- Summary and discussion

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), generating fusion-relevant neutrons through Li(d,xn) reactions
- Currently under construction at Granada, Spain
    - Handover phase between EUROfusion and IFMIF-DONES consortium on-going.
    - Estimation of first irradiation in early 30s



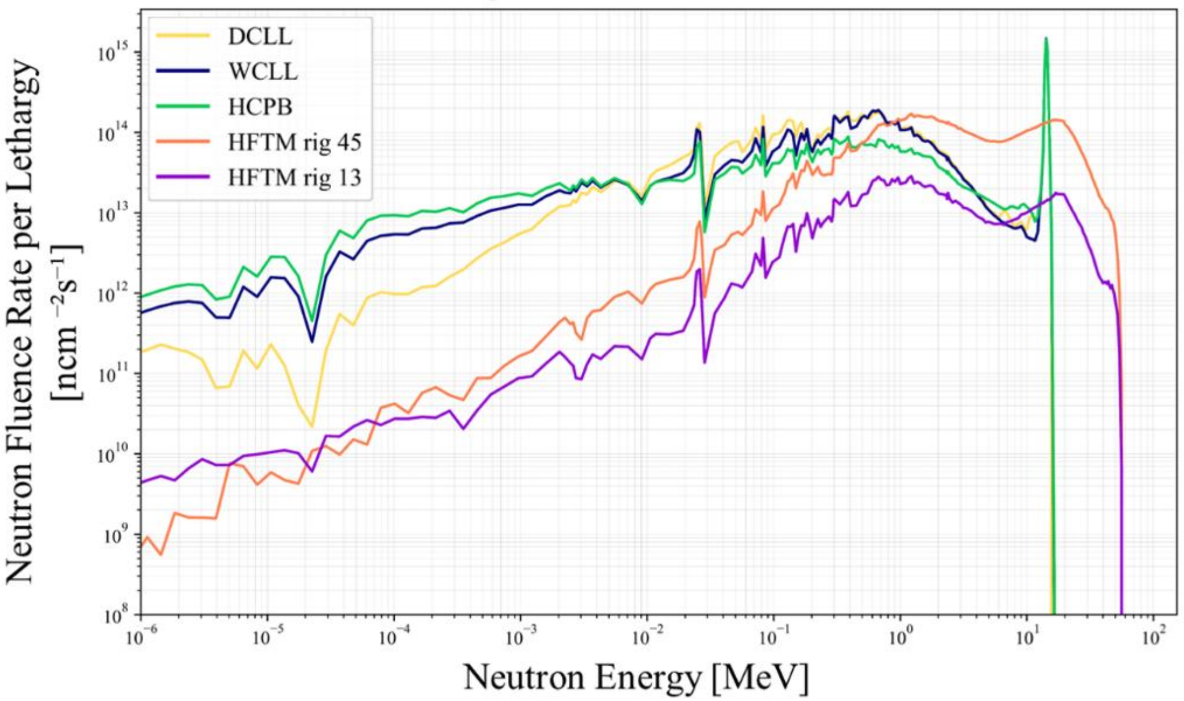
Source: fusionforenergy.europa.eu

Neutron flux spectra in DONES test region

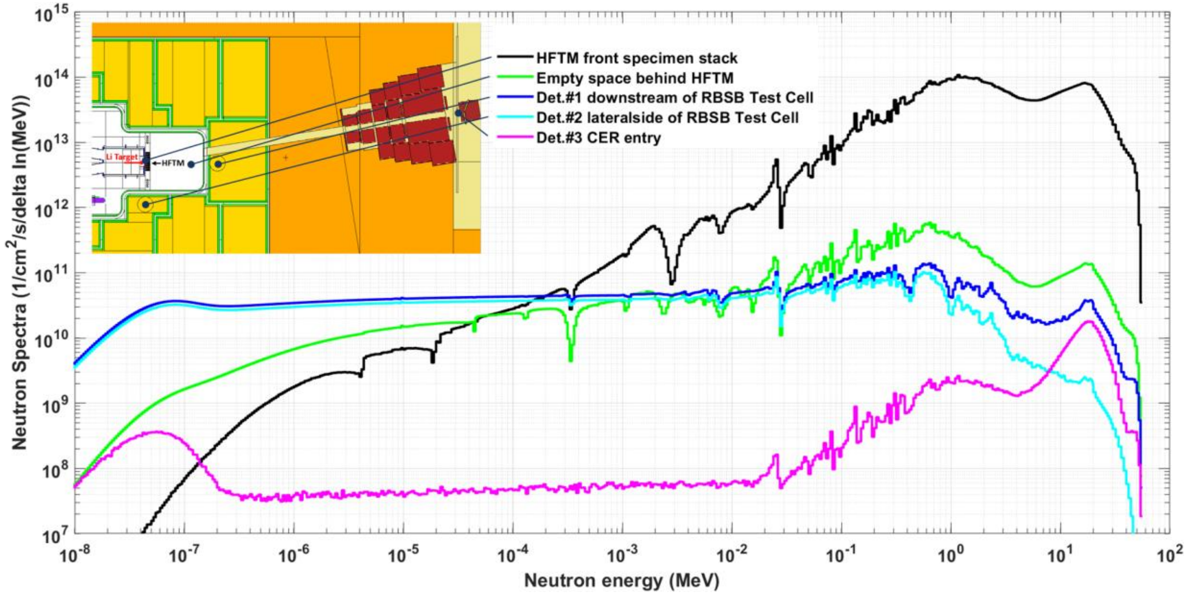
- Neutrons in different energies at DONES target region
  - Large amount of neutrons with energy consistent with fusion 0.1-14 MeV
  - **12%-14%** of neutrons with energy higher than 14 MeV.
- We observe the lack of high-energy validation benchmarks, including simulation and experiments.

Neutron fluxes and energy distributions

Neutron energy[MeV]	Target back-plate	High Flux Test Module
<0.1	2.6%	3.1%
0.1-1	28%	31%
1-14	58%	52%
14-20	**6.0%**	**7.3%**
>20	**6.1%**	**6.6%**
Total flux [n/cm^2/s]	1.35E+15	9.89E+13



Neutron flux spectra comparison with DEMO blanket

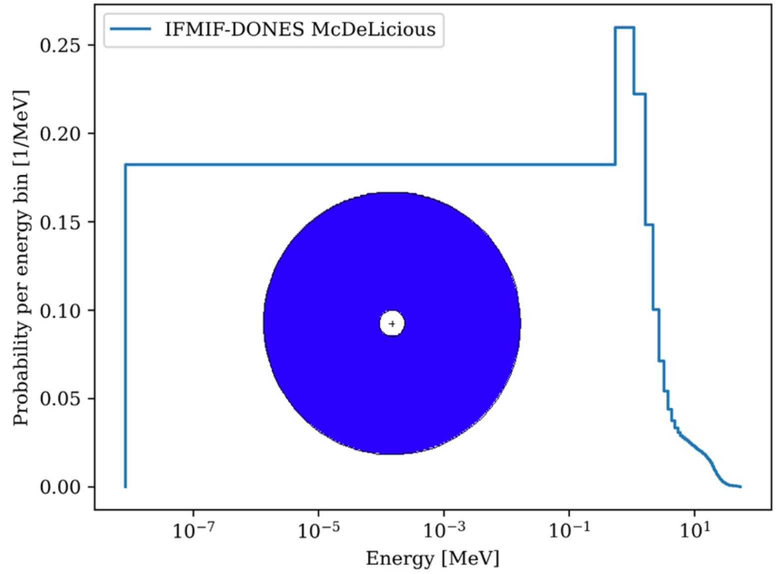


Neutron flux spectra at different location of test cell

High-energy leakage sphere simulation benchmark

*Report: B. Kos, et.al. EUROfusion IDM **2RMEHN***

- **Leakage sphere**: computation benchmark used in JADE. point source with target neutron spectrum calculated using McDeLicious code.
- **Elements**: all 192 nuclides in FENDL3.2b is tested, key elements for DONES (Li, Be, B, O, Si, Ca, Cr, Fe, Ni, Cr, Cu, Zr, W, Pb) are analysed
- **Libraries**: FENDL-3.1d (T1), FENDL-3.2b(T2) and JEFF-3.3 (reference, R).
- **Analysis Tools**: JADE code is mainly used for automatic MCNP input, execution, output and plotting.
- **C/C**: providing deviations between the libraries.



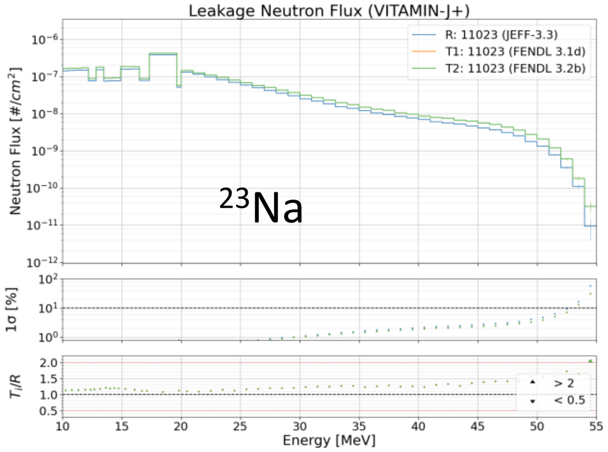
Model and neutron spectrumd

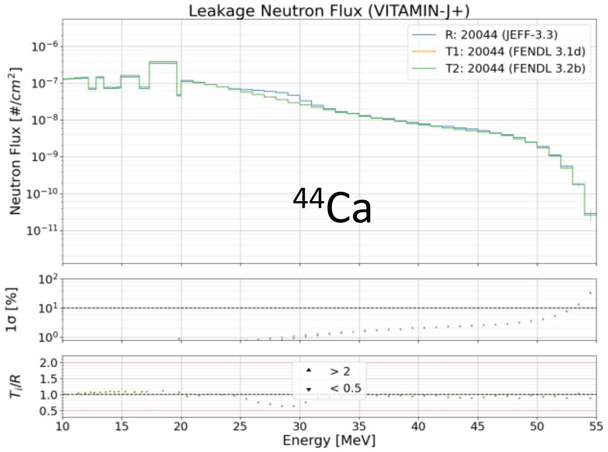
High-energy leakage sphere simulation benchmark

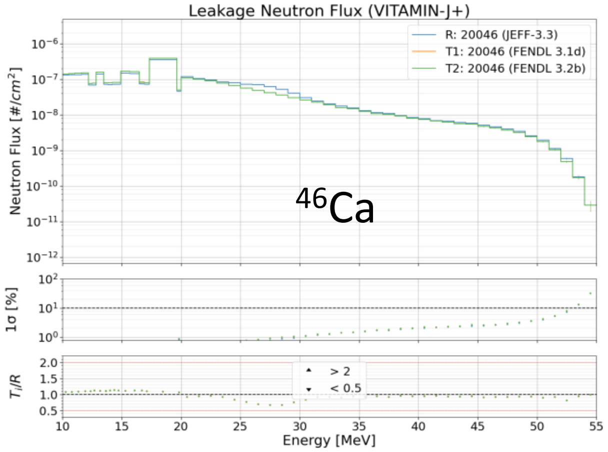
- No Significant Differences (Within Statistical Fluctuations)
  - Isotopes: ^{16}O, ^{17}O, ^{18}O, ^{29}Si, ^{30}Si, ^{40}Ca, ^{42}Ca, ^{43}Ca, ^{58}Fe, ^{61}Ni, ^{64}Ni, ^{90}Zr, ^{91}Zr, ^{92}Zr, ^{94}Zr, ^{96}Zr, ^{204}Pb
- Slight Differences (Factor ≤ 1.5, Specific Energy Ranges)
  - ^{23}Na, ^{44}Ca, ^{46}Ca, ^{50}Cr, ^{52}Cr, ^{53}Cr, ^{54}Cr
- Notable differences Primarily Below 20 MeV
  - ^{63}Cu, ^{65}Cu, ^{182}W
- Notable differences Above 20 MeV
  - ^{186}W, ^{206}Pb, ^{207}Pb, ^{208}Pb
- Significant Differences Above 20 MeV (Factor > 2, Further Investigation Needed)
  - ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{28}Si, ^{58}Ni, ^{60}Ni, ^{183}W, ^{184}W

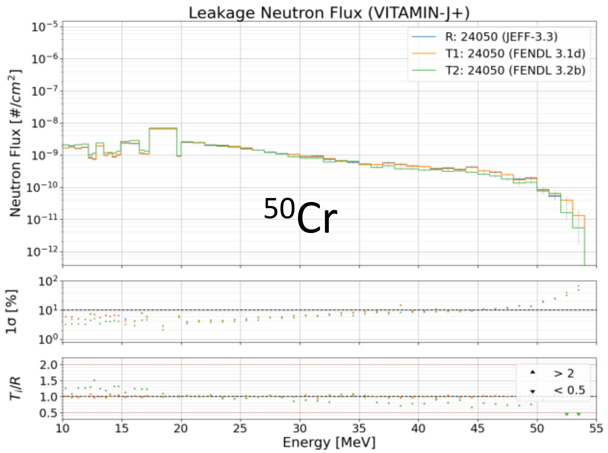
High-energy leakage sphere simulation benchmark

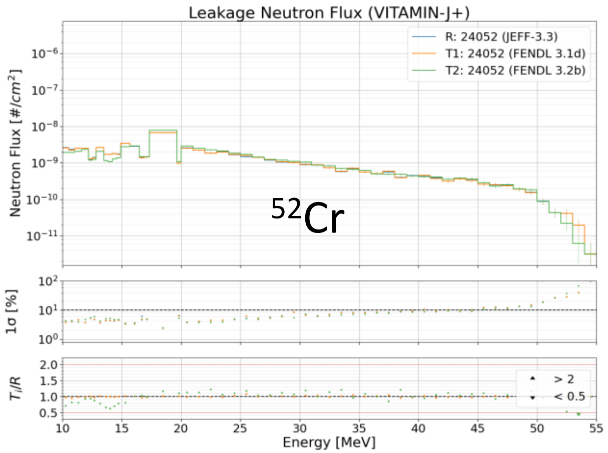
- Slight Differences: ^{7}Li, ^{23}Na, ^{44}Ca, ^{46}Ca, ^{50}Cr, ^{52}Cr, ^{53}Cr, ^{54}Cr

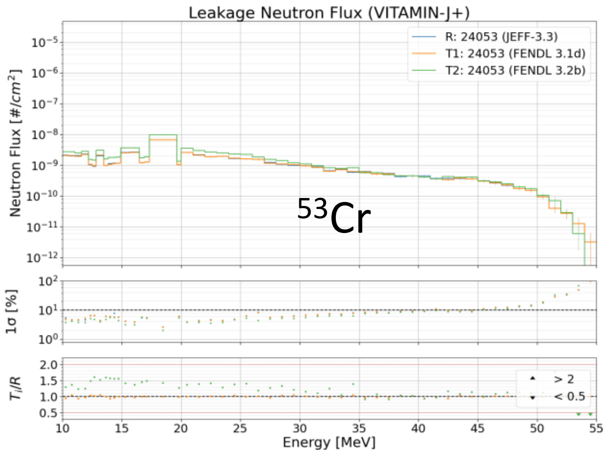


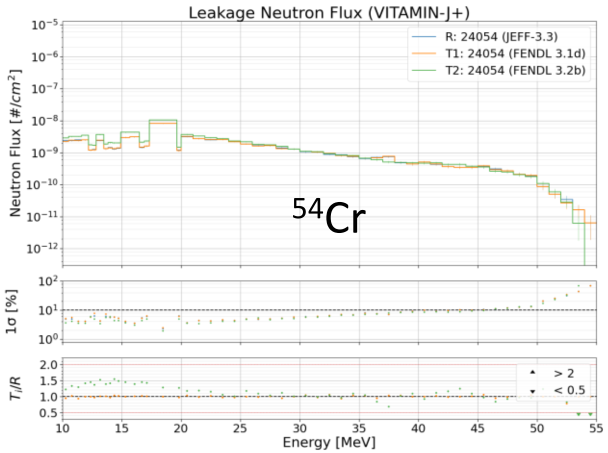






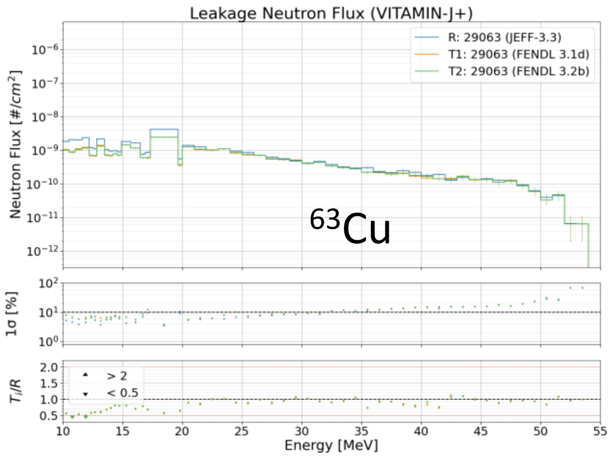


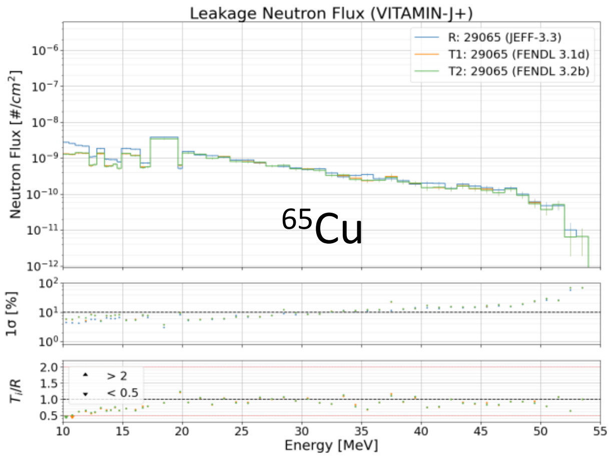


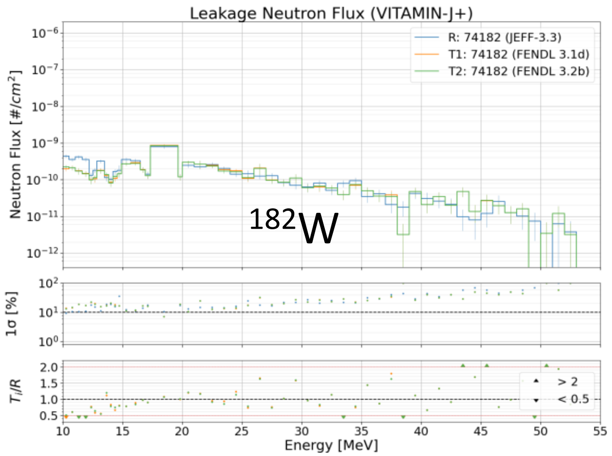


High-energy leakage sphere simulation benchmark

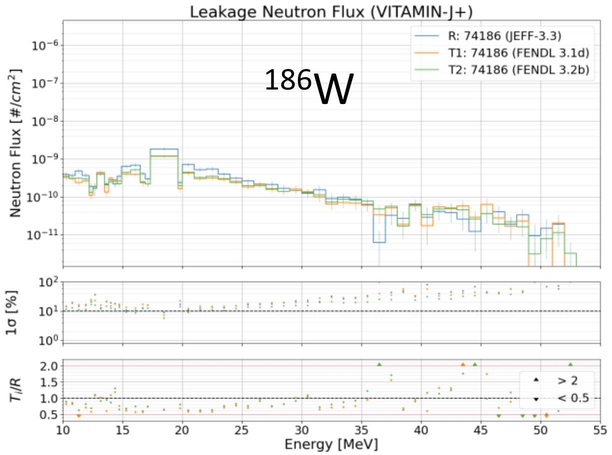
- Differences Primarily Below 20 MeV: ^{63}Cu, ^{65}Cu, ^{182}W

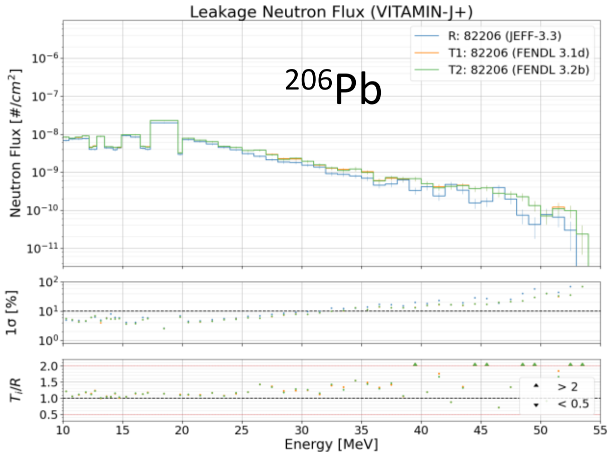


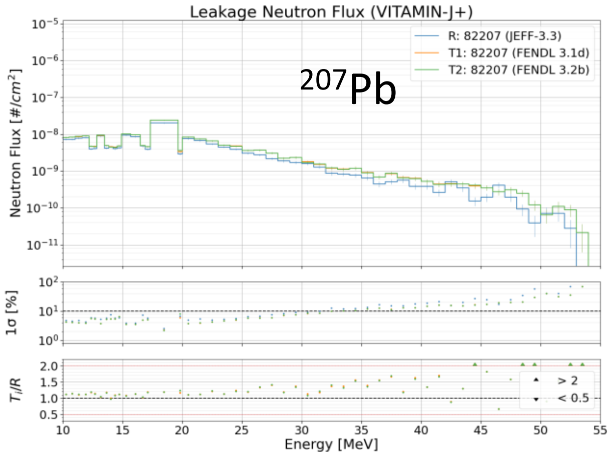


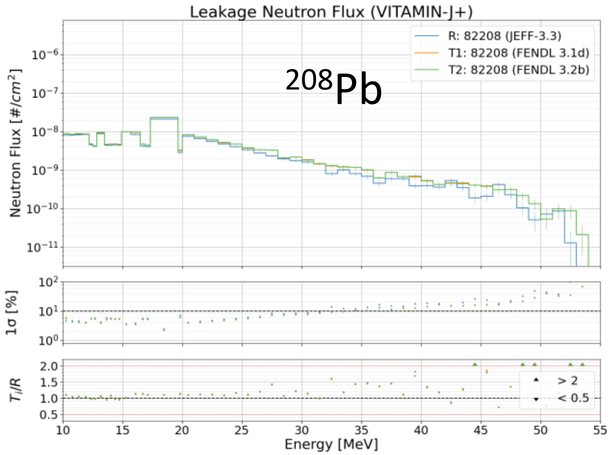


- Differences above 20 MeV: ^{186}W, ^{206}Pb, ^{207}Pb, ^{208}Pb



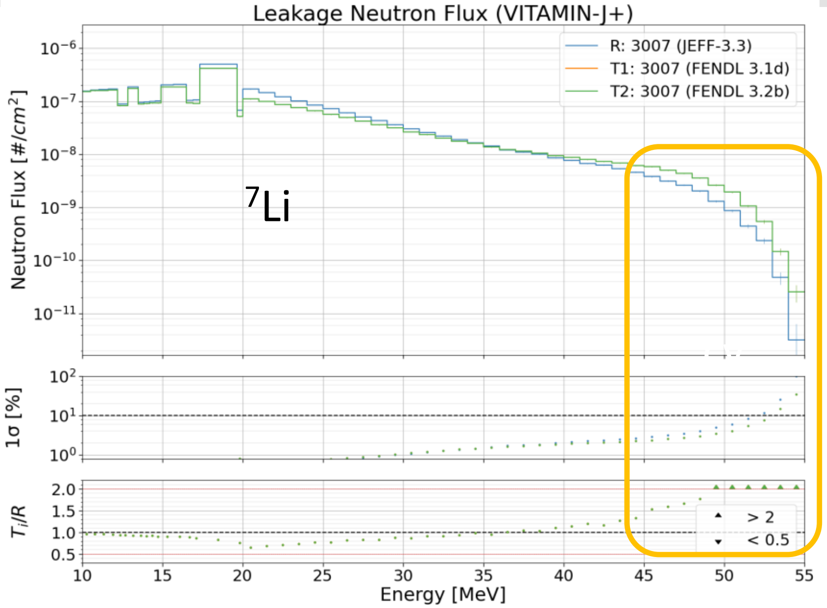


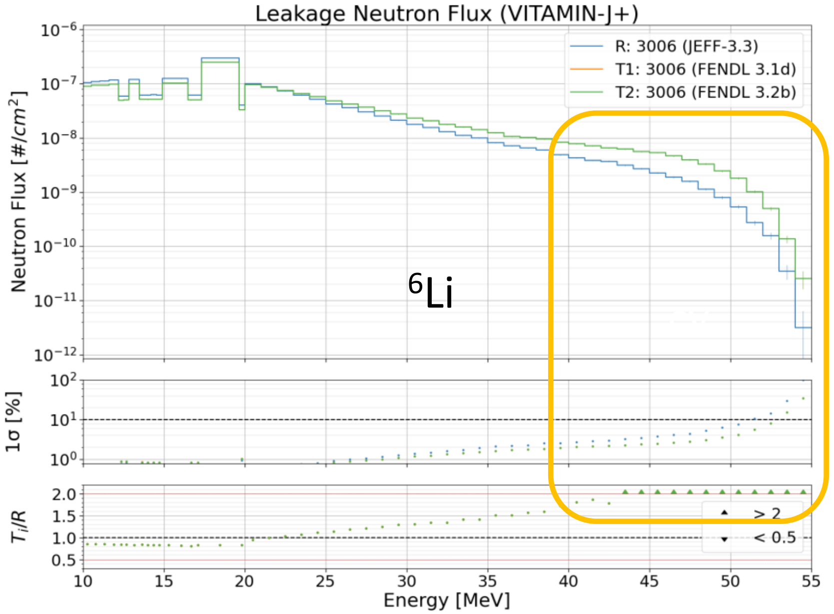


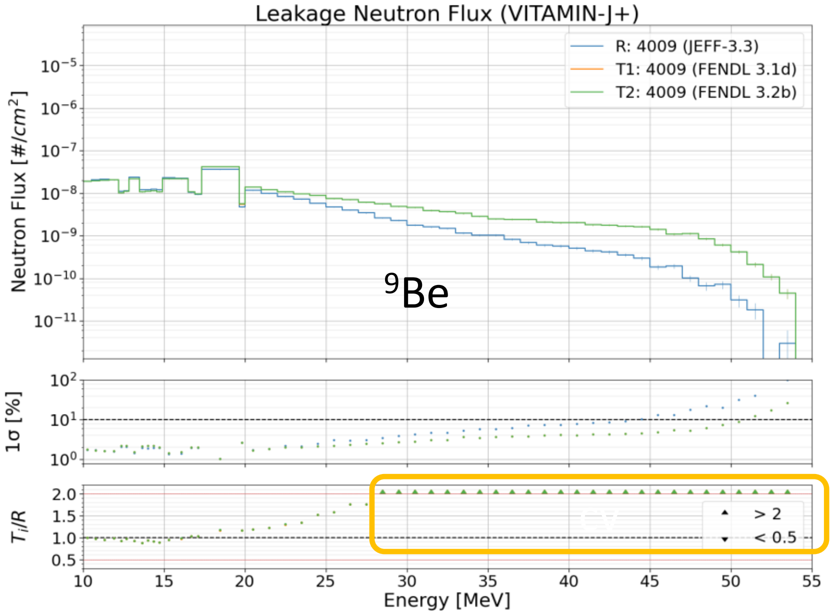


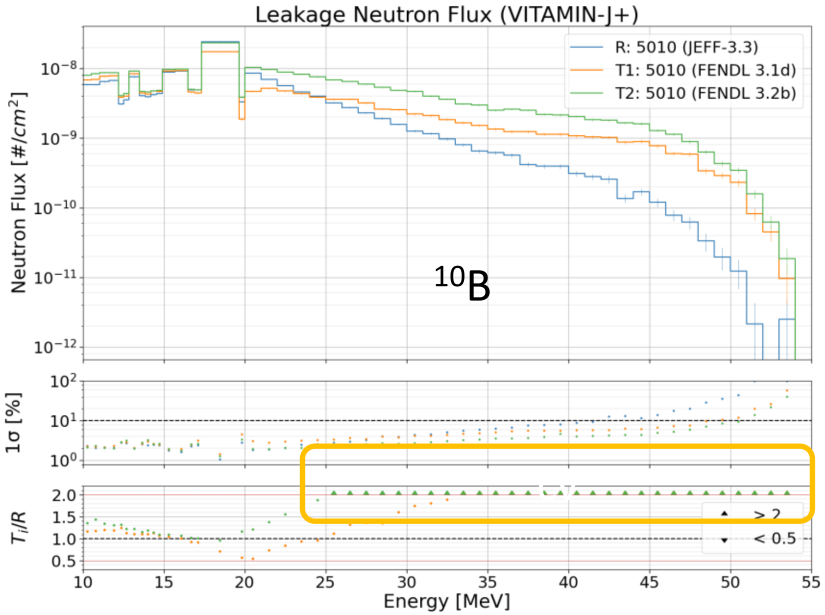
High-energy leakage sphere simulation benchmark

- Significant Differences Above 20 MeV (Factor > 2): ^{6}Li, ^{9}Be, ^{10}B, ^{11}B, ^{28}Si, ^{58}Ni, ^{60}Ni, ^{62}Ni, ^{180}W, ^{183}W, ^{184}W
- The difference of ^{10}B and ^{11}B between FENDL3.1d and FENDL3.2b are also quite significant.









High-energy leakage sphere simulation benchmark

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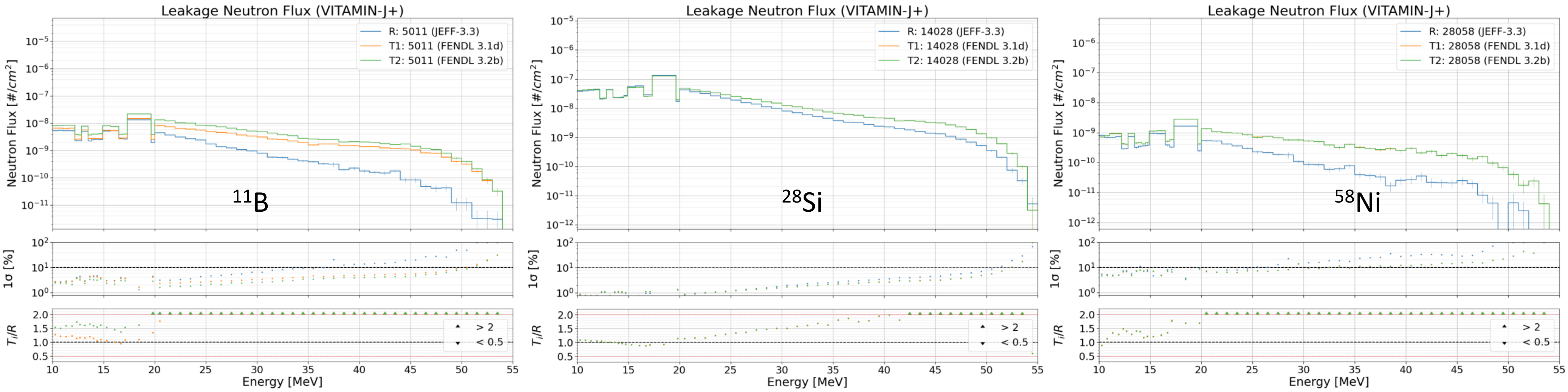

High-energy leakage sphere simulation benchmark

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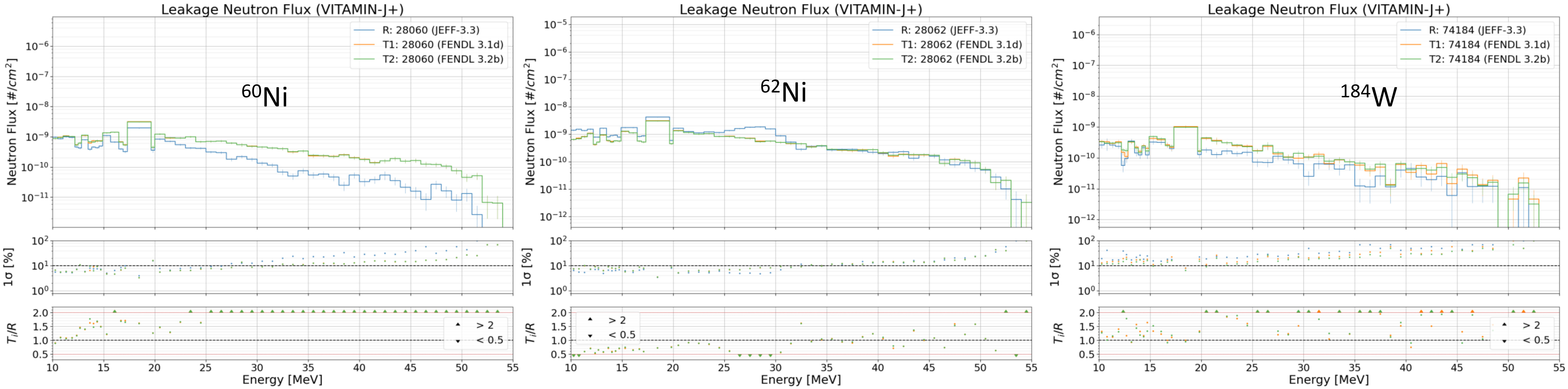
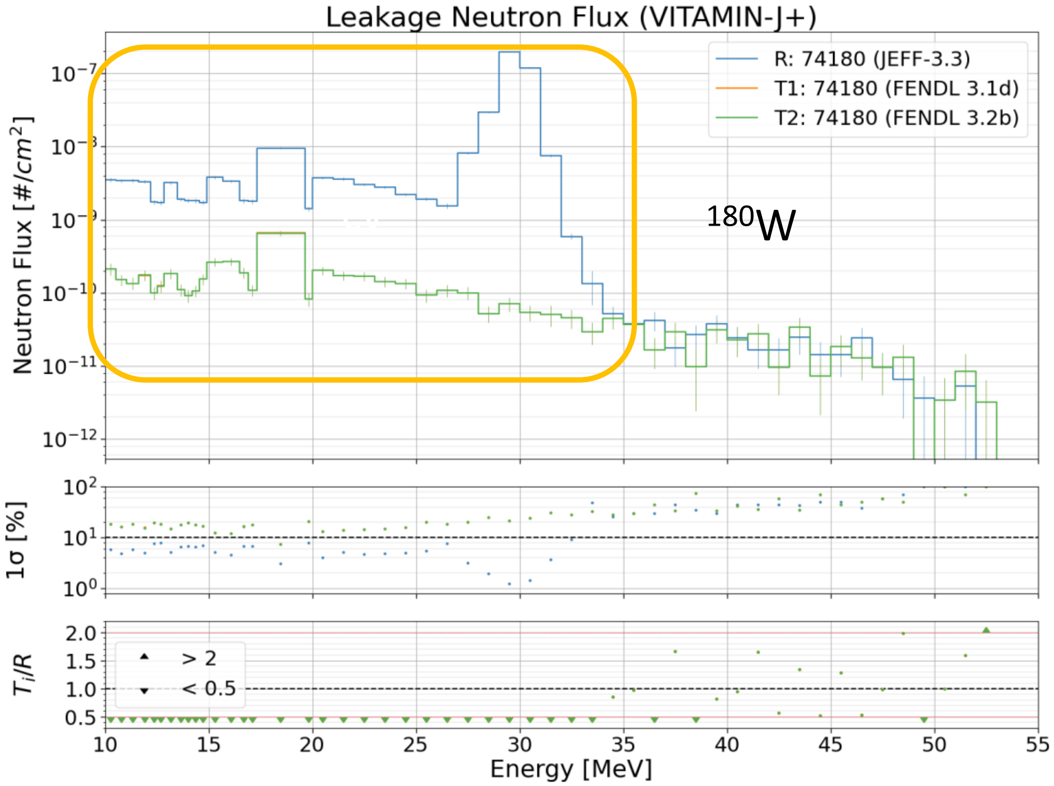
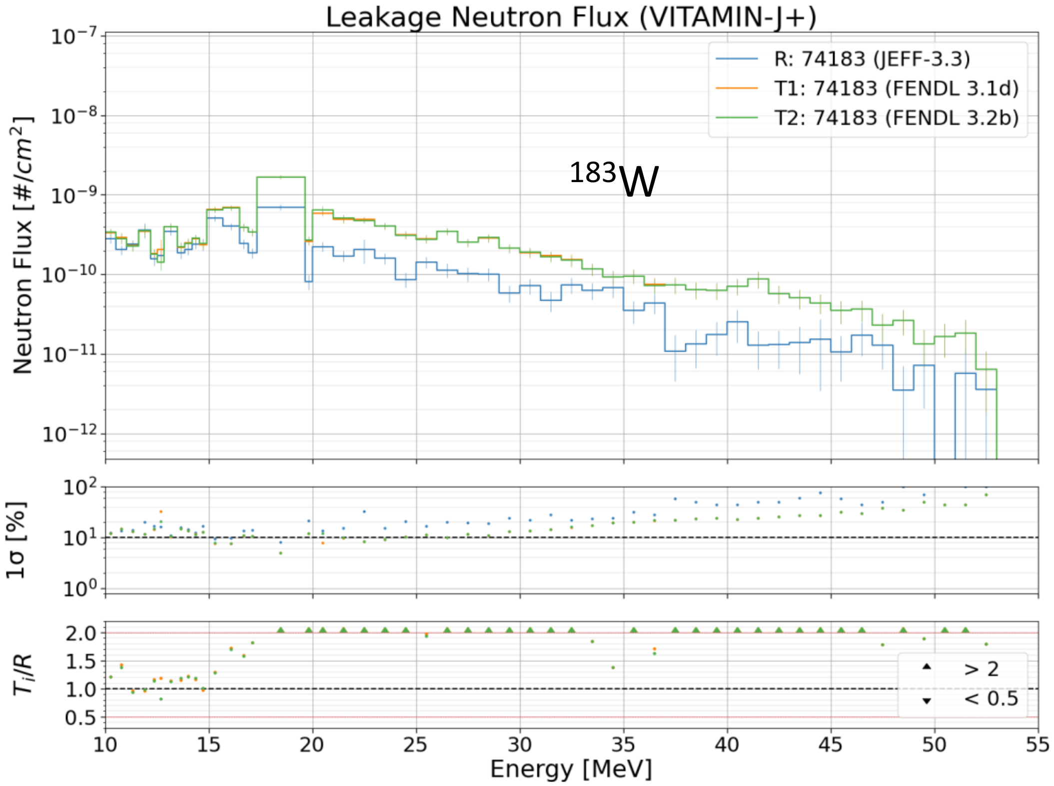


High-energy leakage sphere simulation benchmark

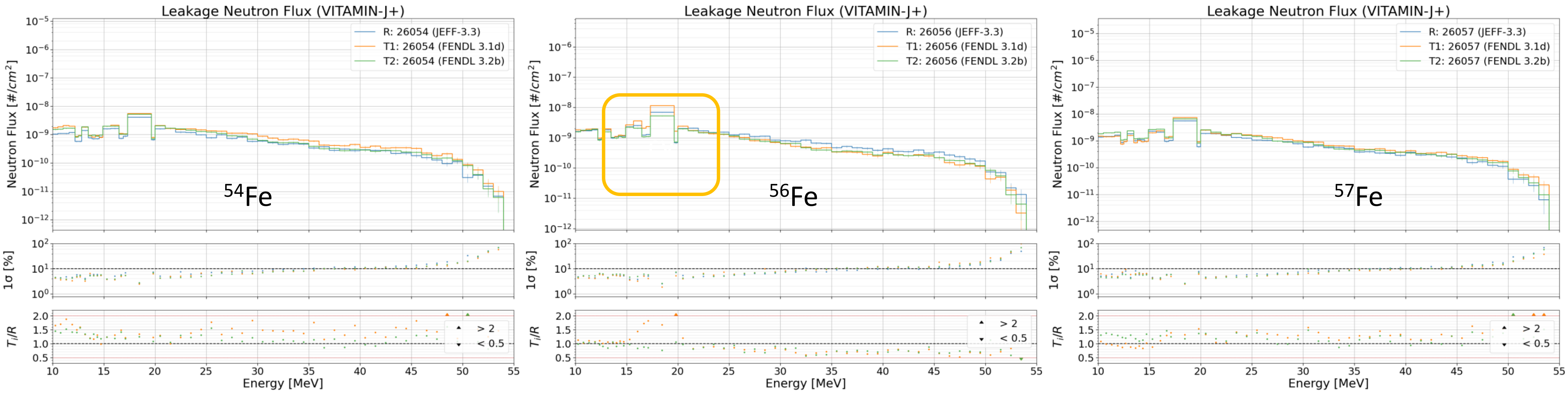
- Significant Differences Above 20 MeV (Factor > 2): ^{6}Li, ^{9}Be, ^{10}B, ^{11}B, ^{28}Si, ^{58}Ni, ^{60}Ni, ^{62}Ni, ^{180}W, ^{183}W, ^{184}W
- In the case of ^{180}W, JEFF-3.3 is about 2-3 order of magnitude higher, and has a peak at 30 MeV which does not visible in FENDL3.1d and FENDL3.2b.





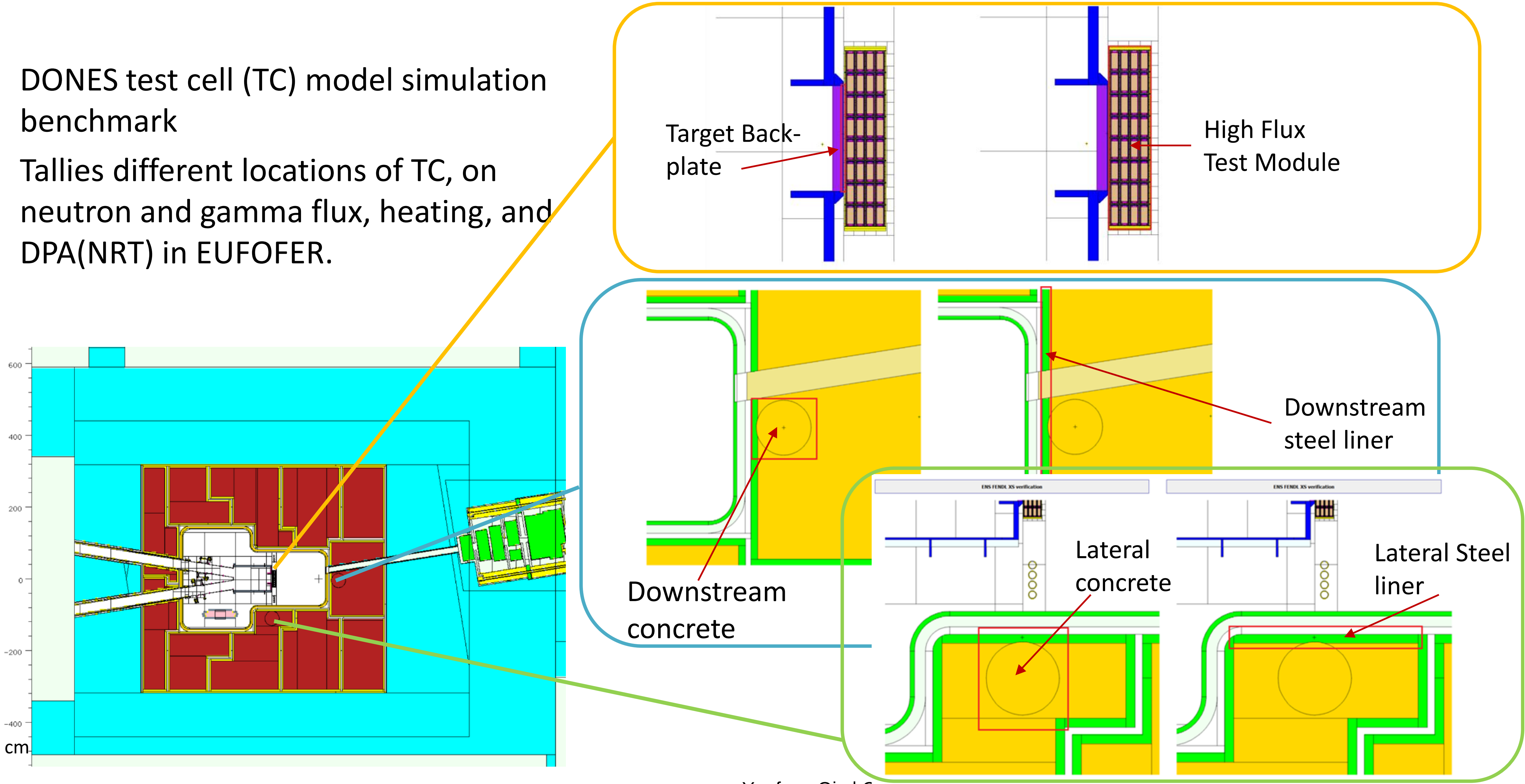
High-energy leakage sphere simulation benchmark

- Fe data are overall in good consistency
  - FENDL-3.1d shows significantly higher results in ^{56}Fe data in the energy range between 15 MeV and 20 MeV



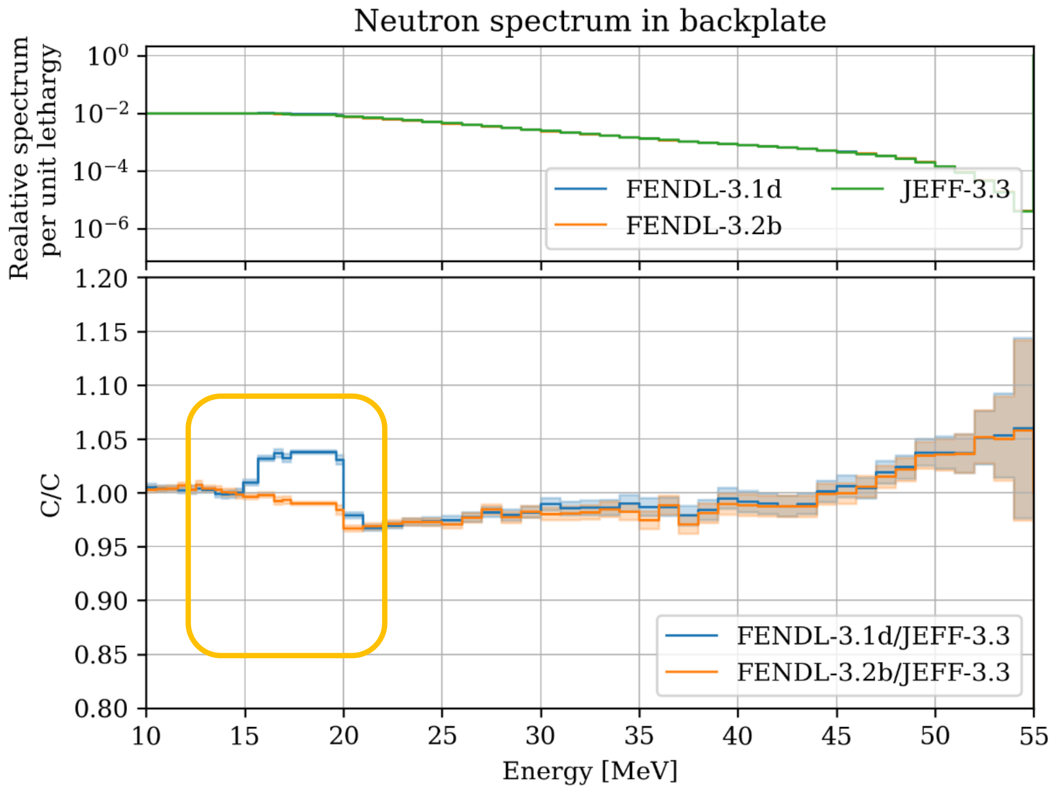
IFMIF-DONES computational benchmark

- DONES test cell (TC) model simulation benchmark
- Tallies different locations of TC, on neutron and gamma flux, heating, and DPA(NRT) in EUFOFER.

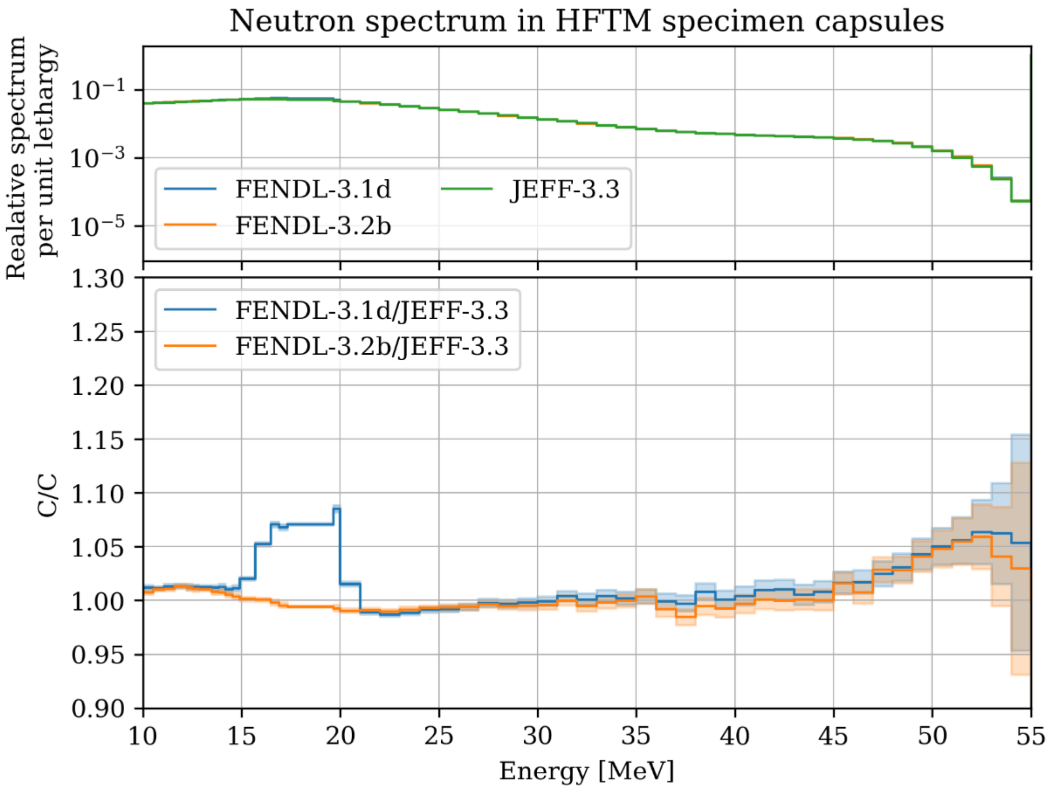


IFMIF-DONES computational benchmark

- Target backplate and HFTM
  - Deviation of around 5 % between 10-55 MeV.s
  - Between 15 MeV and 20 MeV the FENDL-3.1d results differ from the FENDL-3.2b results.
  - Differences in the ^{56}Fe nuclear data could be the cause



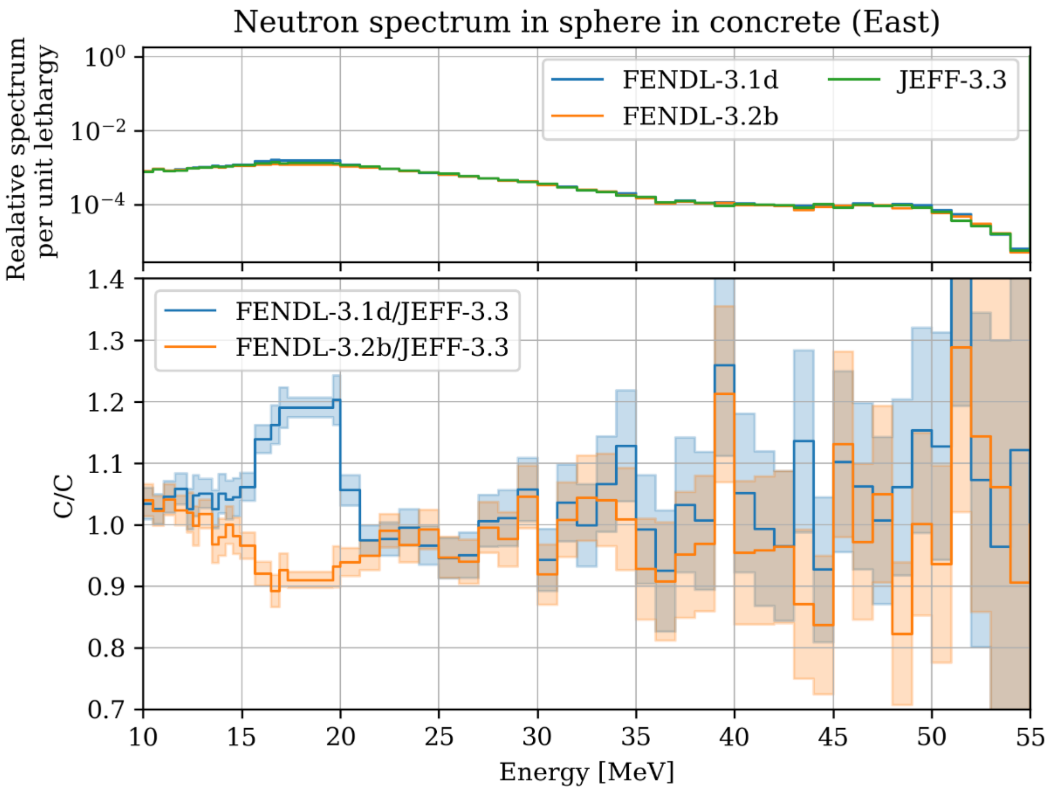
Target backplate



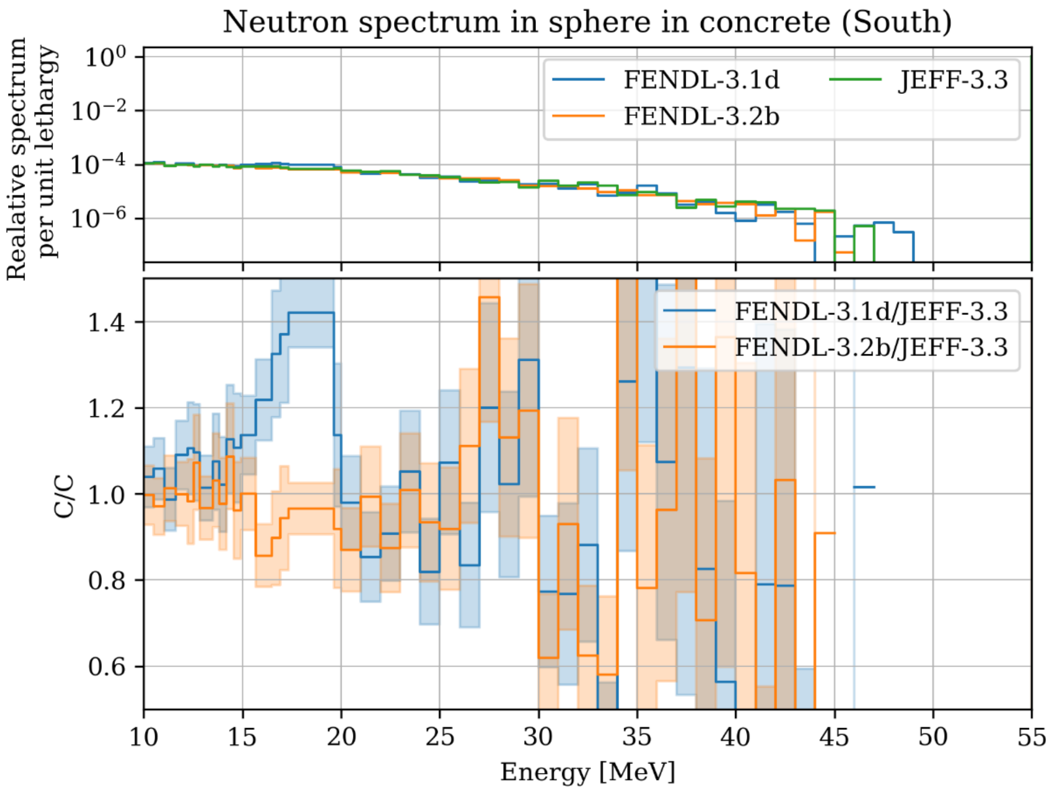
High Flux Test Module

IFMIF-DONES computational benchmark

- Concrete downstream and lateral
  - Statistics are poor, which can count for some deviations.
  - 15- 20 MeV range for the FENDL-3.1d is deviate from JEFF-3.3 for 20%-40%.



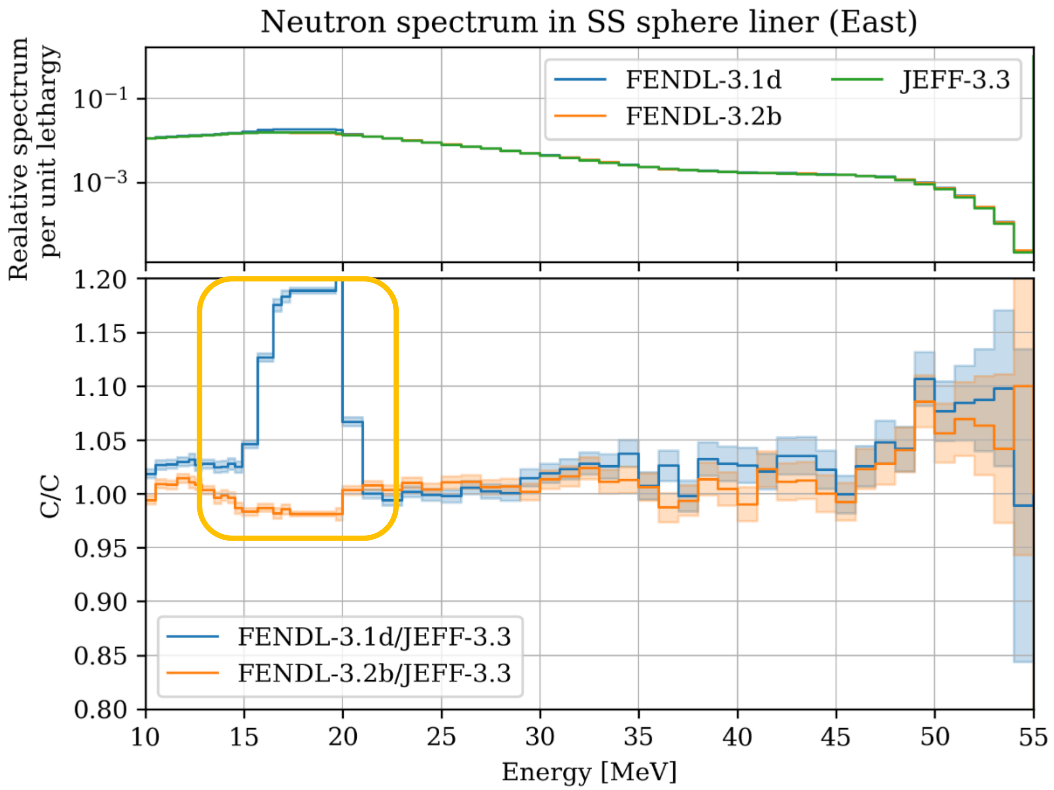
Concrete downstream



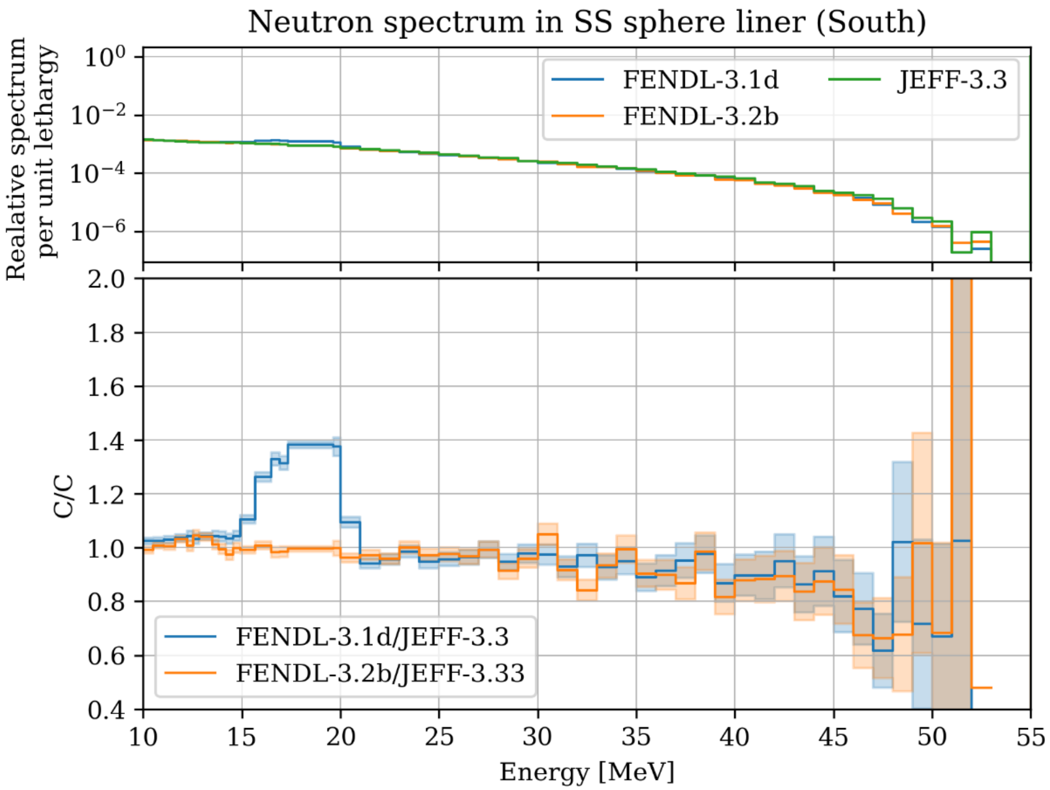
Concrete lateral

IFMIF-DONES computational benchmark

- Steel liner downstream and lateral
  - Similar finding for FENDL3-1d between 15-20 MeV
  - It has visible impact on the shielding calculation
  - We have recommended the DONES guideline to use FENDL3.2b Fe data.



Steel liner downstream



Steel liner lateral

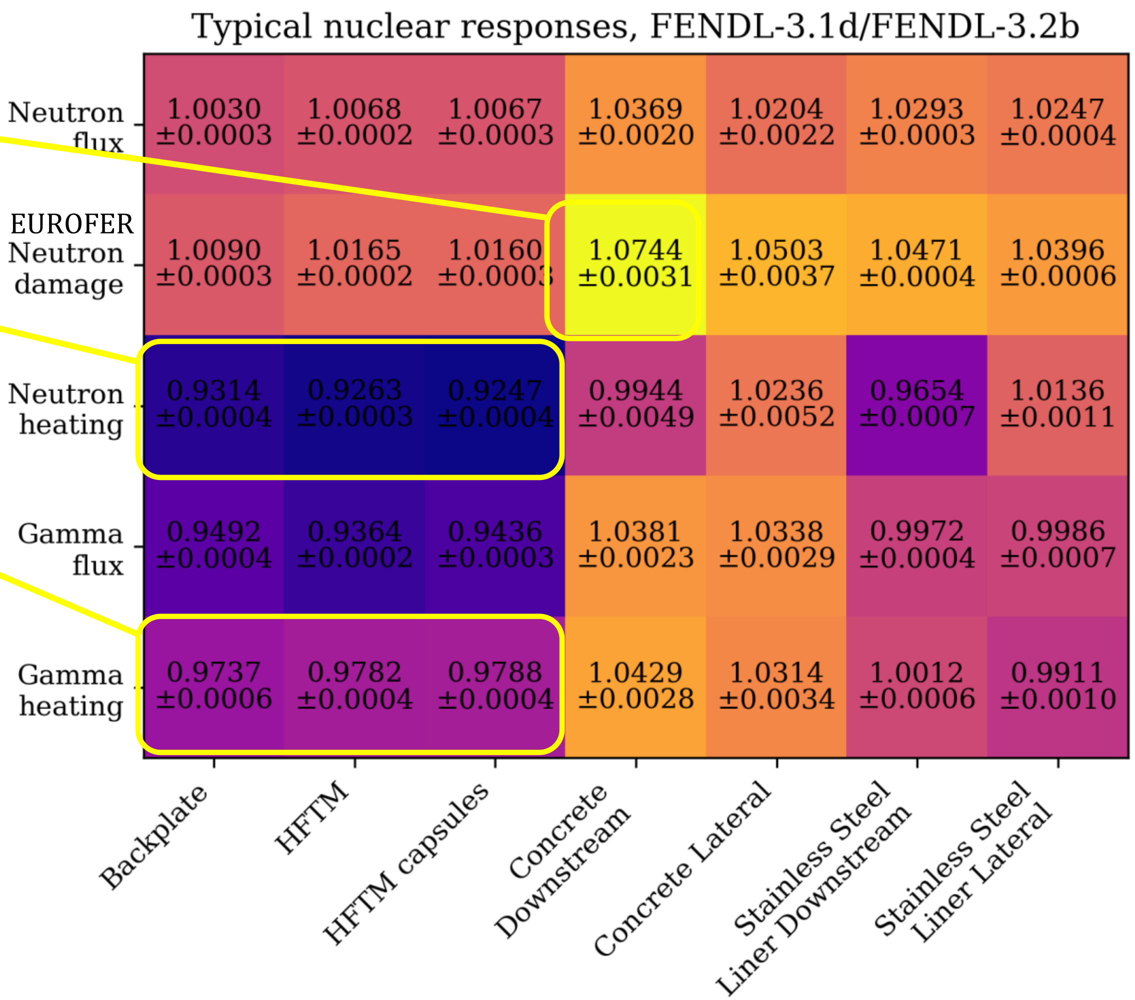
IFMIF-DONES computational benchmark

- Neutron and gamma flux, heating, DPA computed with FENDL3.1d and FENDL3.2b

DPA difference are small in HFTM, but high at concrete downstream (negligible impact).

Neutron heating in FENDL-3.2b increase 7%, which brings uncertainties for the HFTM design.

Together with the gamma heating, the total heating is expect to have ~5% of deviation.



- Additional safety margins need to be considered in HFTM heat removal design.

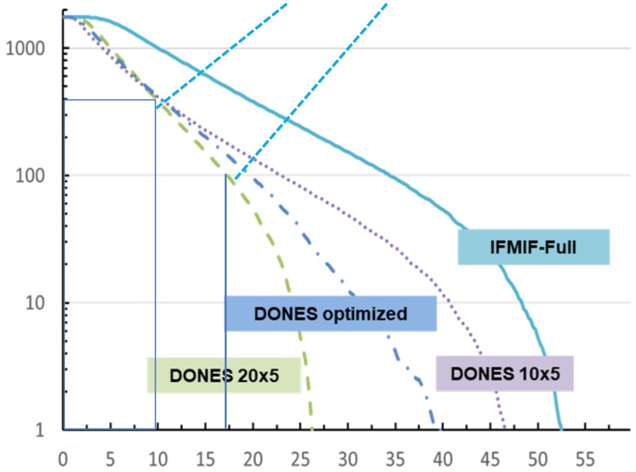
Outline

- Neutron transport cross section
- DPA and gas production uncertainties
- Deuteron cross sections
- Summary and discussion

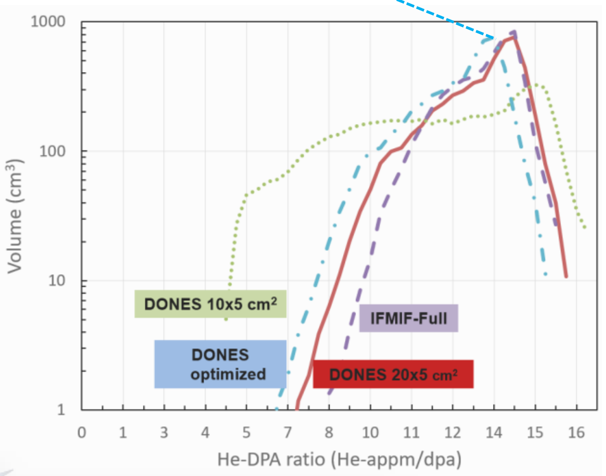
DPA and gas production uncertainties in DONES HFTM

- Damage dose rate (NRT) in the High Flux Test Module (HFTM)
  - Center 5-20 dpa/fpy, and side 1-5 dpa/fpy.
- He production
  - Production rate at the center-front capsules : 120-190 appm/fpy,
  - Synergistic effect of DPA and Helium production:
    - DEMO value: 11-14 He-appm/DPA
    - DONES: ~14-15 He-appm/DPA.

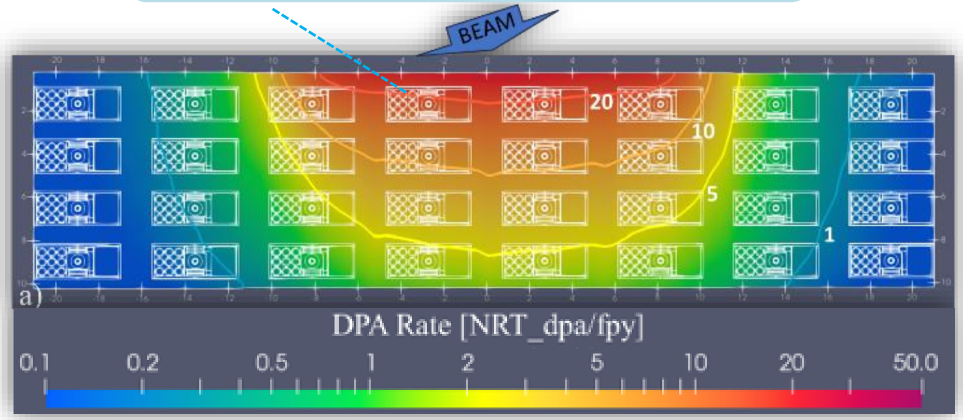
Volume: ~100 ml with >17 dpa/fpy, and ~400 ml with 10 dpa/fpy



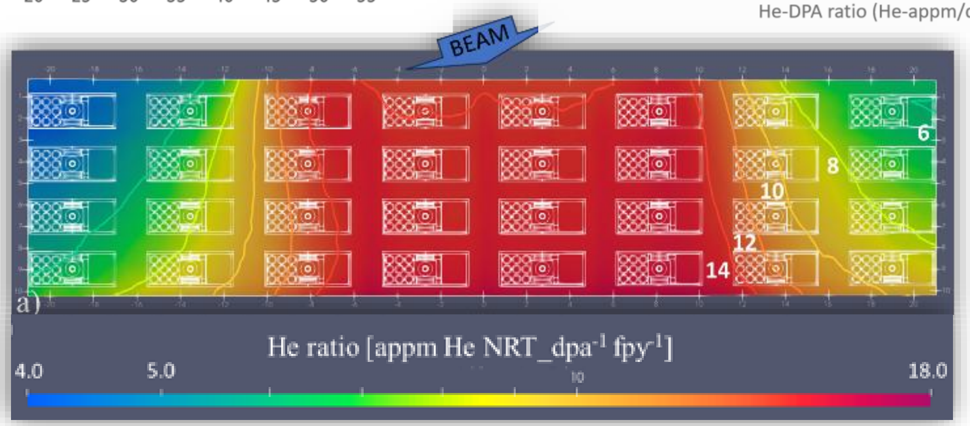
Feature He-DPA ratio:14-15 He-appm/DPA



Center 5-20 dpa/fpy, and side 1-5 dpa/fpy



Damage doses rate in DONES HFTM

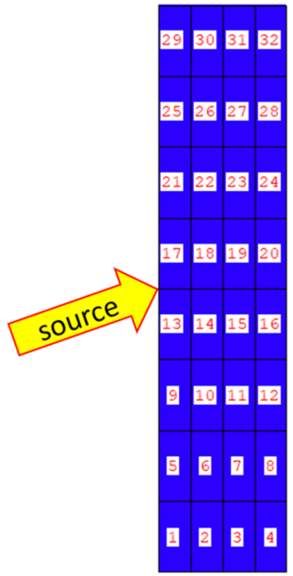


He-DPA ratio in DONES HFTM

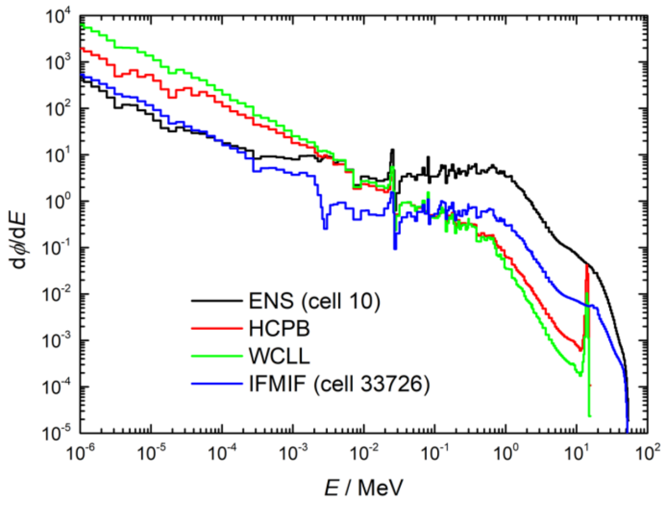
Estimation of DPA uncertainties

*Report: G. Zerovnik, et.al. EUROfusion IDM **2PLVP6***

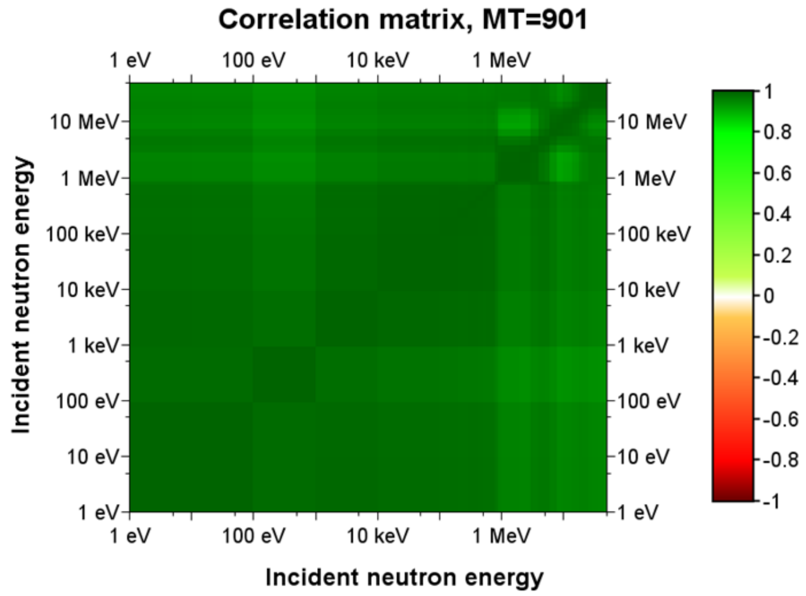
- Objective: Uncertainty on the DPA values calculated in DONES and DEMO
- Libraries: **reference EUROFER DPA library**(MT=900 arc-dpa and MT=901 NRT-dpa) from **KIT (A.Yu. Konobeyev, et.al),** up to 150 MeV, including covariance data.
- Neutron flux: DONES detailed model (IFMIF), DONES simplified model (ENS) and DEMO (upper limiter spectra from HCPB and WCLL concept)
- Simulation tools: MCNP, ADVANTG, NJOY. SANDY for random sampling and RR_UNC for deterministic estimation.



Simplified DONES HFTM model (label: ENS)



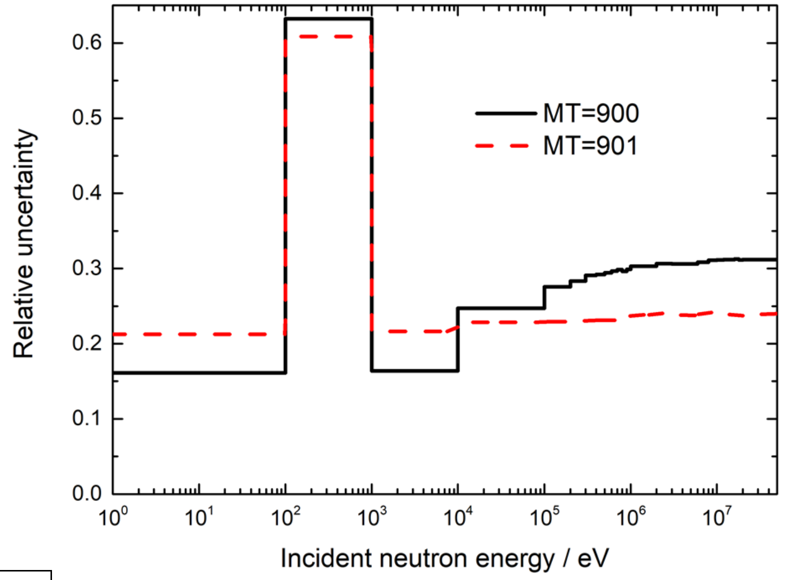
Neutron spectra in DONES and DEMO



EUROFER DPA covariance data

Estimation of DPA uncertainties

- DPA uncertainty along the neutron energy
  - ~23% for dpa-NRT at fast neutron energy.
  - The estimation from SANDY and RR_UNC confirms this value.
  - A good piece of information for understanding the DONES irradiation performance.



EUROFER DPA uncertainty based (base lib JEFF-3.3)

Irradiation facility	Nominal value (unperturbed)	Mean value (SANDY)	Relative standard deviation (SANDY)	Relative standard deviation (RR_UNC)
ENS “cell 10”	729.7 b	727.3(9.1) b	0.217	0.234
ENS “cell 16”	665.8 b	663.4(8.3) b	0.217	0.234
ENS “cell 17”	855.4 b	863(11) b	0.217	0.236
ENS “cell 29”	681.3 b	679.0(8.5) b	0.217	0.234
HCPB	391.7 b	385.9(4.8) b	0.216	0.233
WCLL	185.7 b	196.3(2.5) b	0.221	0.232
IFMIF “cell 33726”	704.4 b	704.0(8.8) b	0.217	0.234

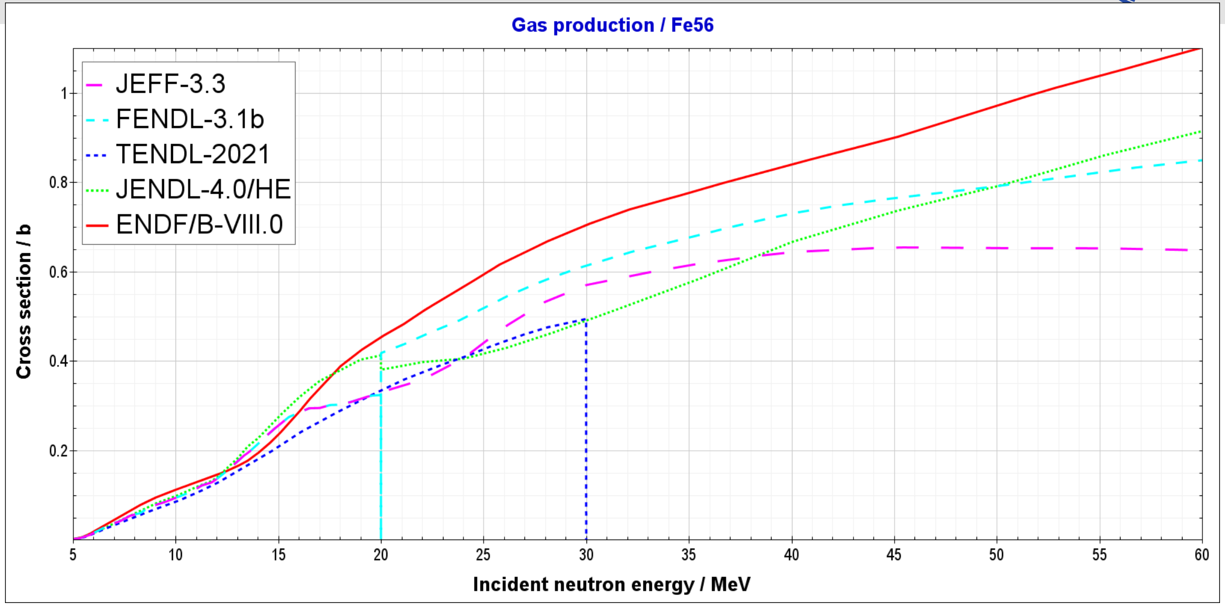
Flux averaged DPA cross section and uncertainties

Overall average uncertainty within 23%

Report: G. Zerovnik, et.al. EUROfusion IDM ***2PLVP6***

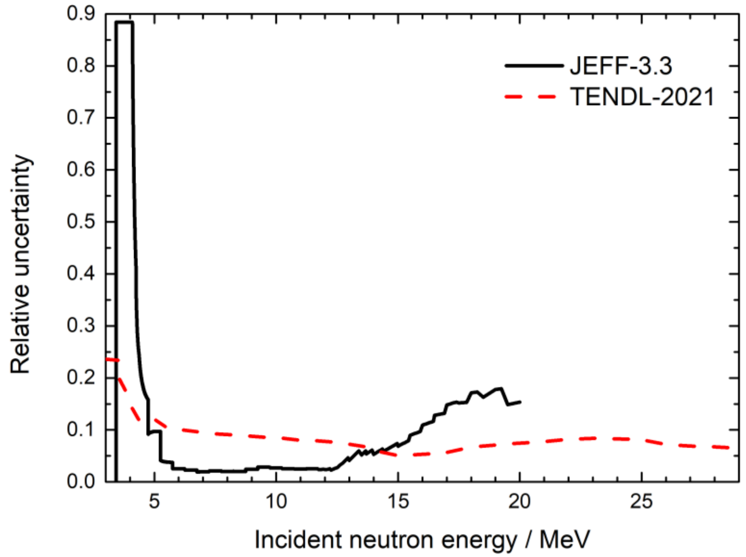
Estimation of Fe-56 gas production uncertainties

- Objective: obtain a clear picture on uncertainties of gas (He+H) productions estimated for DONES and DEMO
- Fe-56 gas production Libraries :
  - JEFF-3.3: **uncertainty data up to 20 MeV**.
  - **FENDL-3.1d**: <20 MeV identical with JEFF3.3, unphysical jump above 20 MeV.
  - TENDL-2021: uncertainty data **up to 30 MeV**.
  - JENDL-4.0/HE: no uncertainty data
  - ENDF/B-VII.0: no uncertainty data
- Uncertainty for Fe-56 :
  - JEFF-3.3: high at threshold energy, 3% from 6-12 MeV, and increases to 20% at 20 MeV.
  - TENDL-2021: overall 10% from 5-30MeV.



Cross sections for gas (MT=203-207) production in ^{56}Fe

Relative uncertainty of the gas production in Fe-56



Estimation of Fe-56 gas production uncertainties

ENDF/B-VIII.0 is the main outliner

- Estimated uncertainty based on the flux-averaged gas production cross section
  - Gas production(MT=203-207) : +- 15% for DONES and +- 10% for DEMO around mean values
  - He productions (MT=206-207): +- **25%-30% for DONES around mean values**, and 15%-20% for DEMO.
- Key takeaway
  - Gas production uncertainty data are mostly missing for cross section above 20 MeV.
  - The calculated values among the libraries give ~15-30% for DONES.
  - New release of FENDL and other libraries needs to be assessed in the next step.

Spec. \ ND library	JEFF-3.3	JENDL-4.0/HE	ENDF/B-VIII.0	FENDL-3.1d	TENDL-2021*
ENS “cell 10”	0.121 b	0.129 b	0.146 b	0.130 b	0.110 b
ENS “cell 16”	0.128 b	0.136 b	0.154 b	0.137 b	0.116 b
ENS “cell 17”	0.123 b	0.131 b	0.148 b	0.131 b	0.112 b
ENS “cell 29”	0.127 b	0.135 b	0.152 b	0.135 b	0.115 b
HCPB	0.167 b	0.178 b	0.154 b	0.167 b	0.141 b
WCLL	0.156 b	0.165	0.144 b	0.156 b	0.132 b
IFMIF “cell 33726”	0.173 b	0.184 b	0.212 b	0.187 b	0.156 b

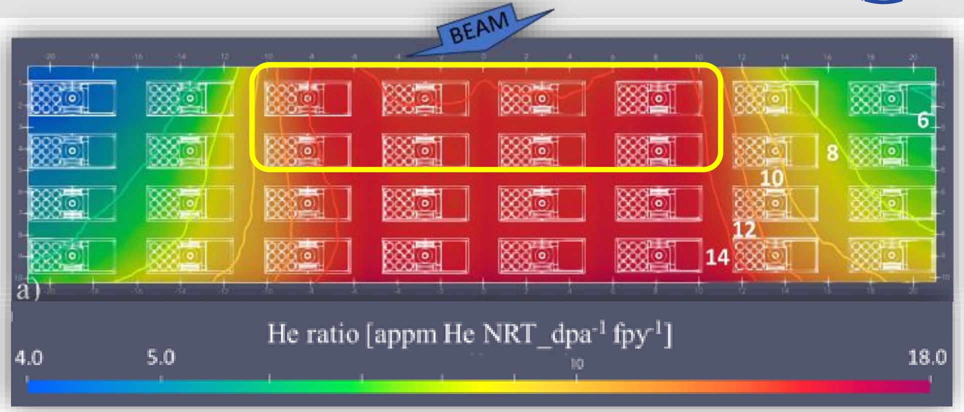
Gas production cross sections average over spectra

Spec. \ ND library	JEFF-3.3	JENDL-4.0/HE	ENDF/B-VIII.0	FENDL-3.1d	TENDL-2021*
ENS “cell 10”	0.0248 b	0.0265 b	0.0330 b	0.0256 b	0.0183 b
ENS “cell 16”	0.0261 b	0.0278 b	0.0345 b	0.0269 b	0.0193 b
ENS “cell 17”	0.0252 b	0.0270 b	0.0335 b	0.0260 b	0.0186 b
ENS “cell 29”	0.0259 b	0.0276 b	0.0343 b	0.0267 b	0.0191 b
HCPB	0.0328 b	0.0331 b	0.0376 b	0.0328 b	0.0248 b
WCLL	0.0307 b	0.0310 b	0.0354 b	0.0307 b	0.0230 b
IFMIF “cell 33726”	0.0346 b	0.0370 b	0.0451 b	0.0364 b	0.0265 b

He production cross sections average over spectra

Estimation of EUROFER gas production

- Comparison between FENDL3.1d and FENDL3.2b
  - Average over the HFTM capsules
  - Helium production: overall estimated deviation **15%**
  - Hydrogen production overall estimated deviation **5%**
- Large impact on the He/DPA feature of DONES
  - Need to further validate the data and calculations



	damage dose (dpa/fpy)	Helium appm/dpa (FENDL3.1d)	Helium appm/dpa (FENDL3.2b)	Ratio-He FENDL3.2b/FENDL3.1d	Hydrogen appm/dpa (FENDL3.1d)	Hydrogen appm/dpa (FENDL3.2b)	Ratio-H FENDL3.2b/FENDL3.1d
Row1-1	9.30	12.44	14.32	1.15	53.64	56.60	1.055
Row1-2	14.90	12.91	14.88	1.15	55.61	58.74	1.056
Row1-3	15.36	12.98	14.95	1.15	55.88	59.01	1.056
Row1-4	11.75	13.28	15.31	1.15	57.09	60.29	1.056
Row2-1	5.61	12.29	14.04	1.14	52.92	55.38	1.046
Row2-2	9.30	13.14	15.04	1.14	56.45	59.14	1.048
Row2-3	9.70	13.24	15.16	1.14	56.88	59.59	1.048
Row2-4	7.50	13.48	15.44	1.15	57.82	60.57	1.048

Outline

- Neutron transport cross section
- DPA and gas production uncertainties
- Deuteron cross sections
- Summary and discussion

Deuteron libraries status and open issue

- Current **deuteron data** used for DONES neutronics
  - Transport: TENDL-2021, JENDL-5
  - Activation: TENDL-2021
  - Li library: FZK-2005 (KIT d-Li evaluation)
- Important elements for accelerators: **Cu, Al, Fe**, **W,** Nb, Mn, Zr, Cr

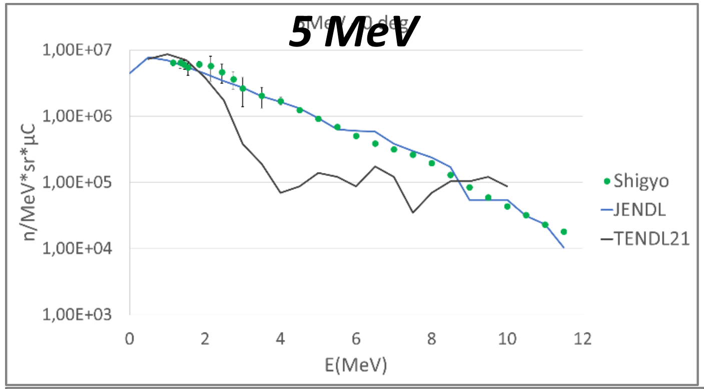
systems	Beam facing materials
Injector/LEBT	SS304L, Copper
RFQ	Copper
MEBT	SS316L, Copper
SRF	NbTi,
HPBD	Copper,
HEBT	CuCrZr, SS316L, Alumiumum
Target	Li, EUROFER

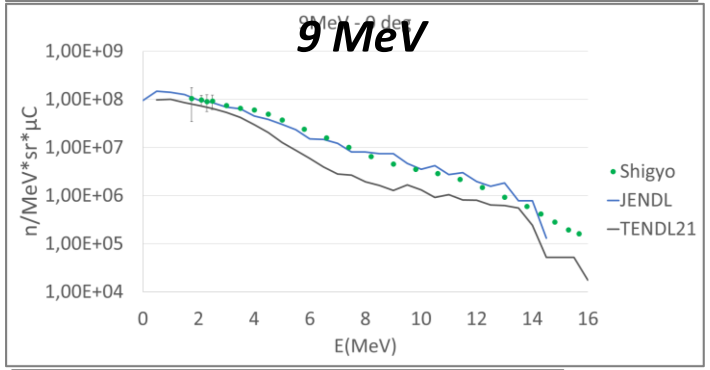
Comparison of two deuteron libraries

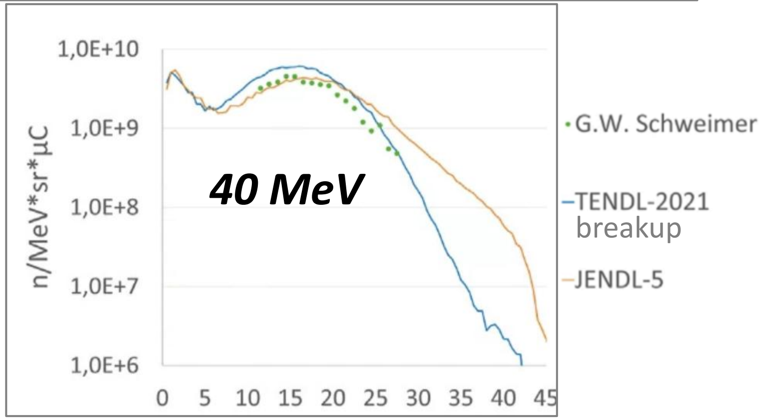
	TENDL-2021 +	JENDL-5
Isotopes	++ Huge list (2850)	- 9 isotopes Li-6,7, Be-9, C-12,13, Al-27, Cu-63,65, and Nb-93
Neutron yield data	-- Overall underestimated.	+ Close to the experiment data
Activation data	+ complete set of activation data - Many of them are away from the experimental data	-- Lack of activation data
d-Li data	- From ENDF/B-VIII.0	+ good evaluation with experiments (Hagiwara.et.al.)

Deuteron neutron yield data

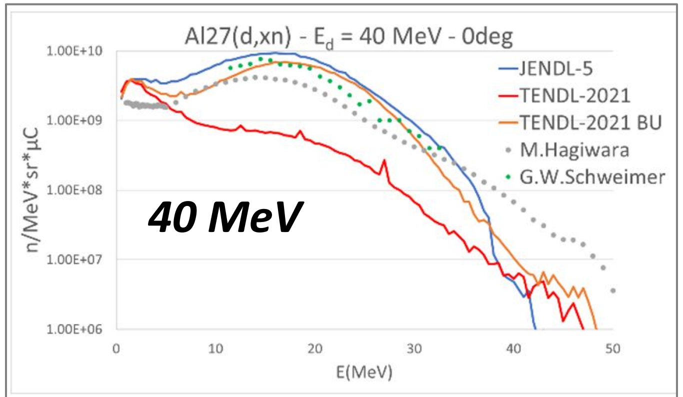
V. Lopez et.al.

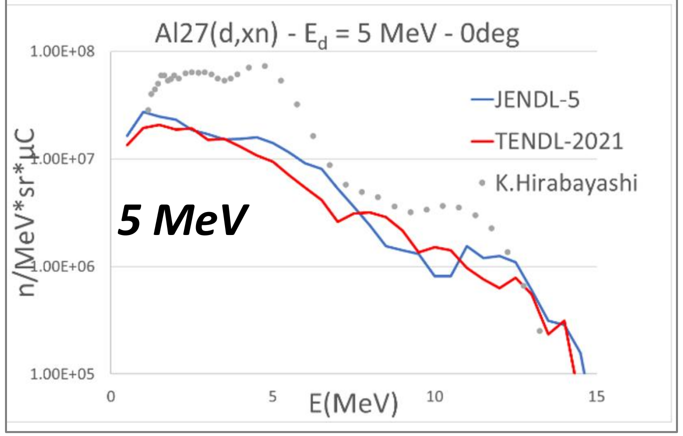




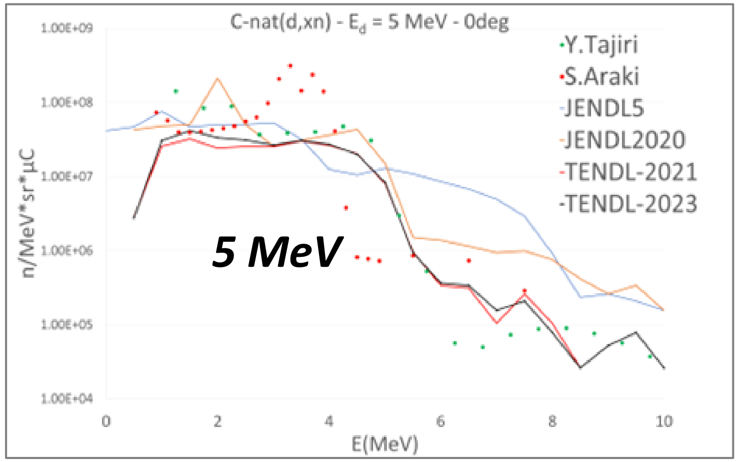


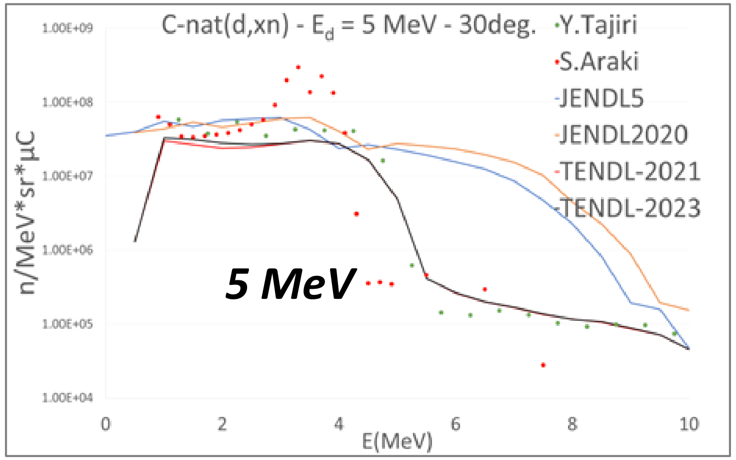
d-natCu neutron yield at 0-deg





d-27Al neutron yield at 0-deg



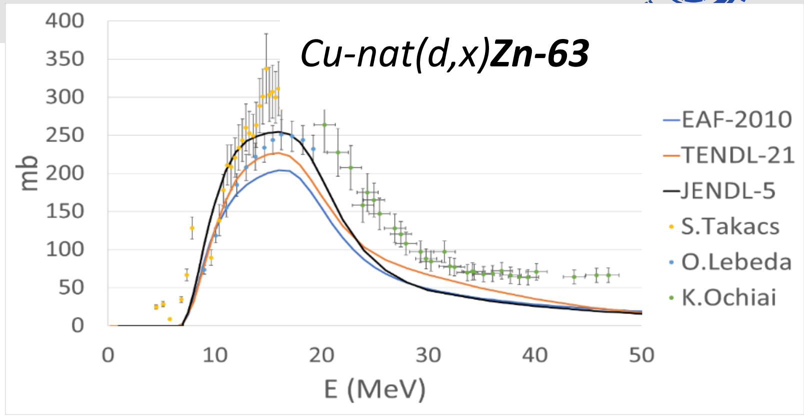


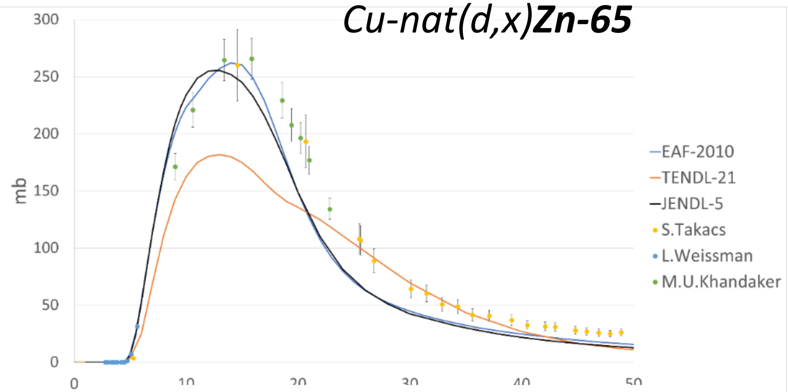
d-natC neutron yield at 0/30-deg

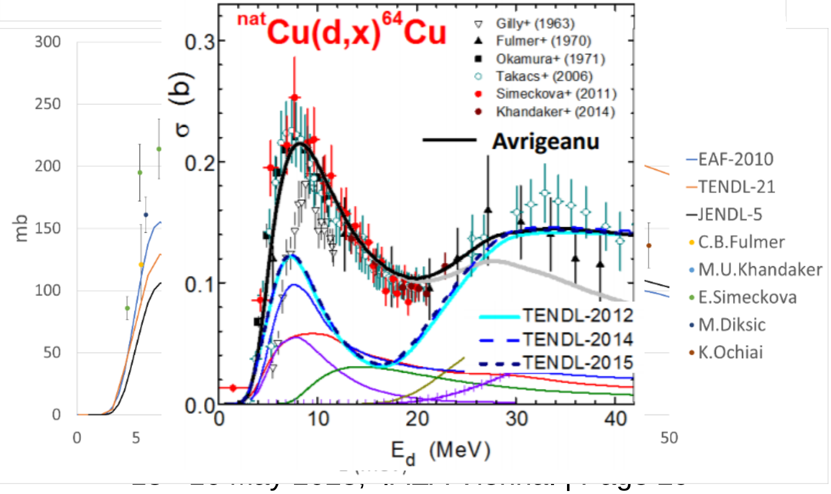
- TENDL tend to underestimate the neutron yield, except C-nat.
- JENDL-5 data is used in DONES as long as available
- Systematic reviews of the data are urgently needed

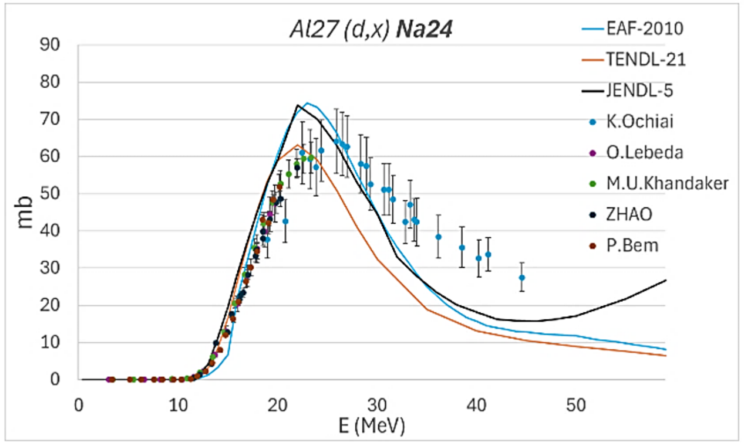
Deuteron activation data

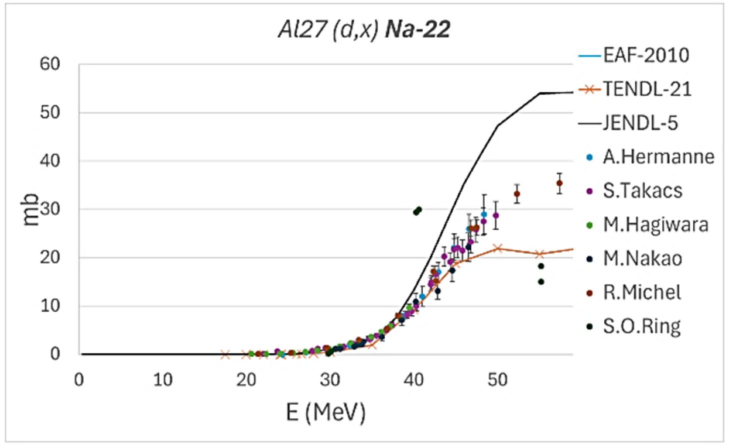
- TENDL deuteron activation libraries
  - **New nuclear models** have been updated by M. Avrigeanu et.al. [1] in the new version of the TALYS code.
  - TENDL cannot be produced with this update, since this TALYS version has to be combined with the FRESCO code in the workflow.
- JENDL activation data
  - reconstructed from secondary particle yield data
  - Not suitable for activation calculations.
- Ongoing activities
  - Collaboration with QST/JAEA on the JENDL-5 deuteron data V&V under the EU-JA bilateral agreement. Aiming at a systematic review and improvement.
  - 40 MeV d-Li activation (Be-7 and Tritium) and d-Cu activation measurement at GANIL/NFS in 2025.











Summary and discussion

- These isotopes need to be further reviewed: ^{6}Li, ^{9}Be, **^{10}B, ^{11}B,** ^{28}Si, ^{58}Ni, ^{60}Ni, ^{62}Ni, **^{180}W,** ^{183}W, ^{184}W.
- **^{10}B, ^{11}B** data are deviating significantly between FENDL3.1d and FENDL3.2b, and **^{180}W** which significant different of several order of magnitude between FENDL3.2b and JEFF-3.3.
- Impacts of changing Fendl3.1d to FENDL3.2b: **neutron flux at 15-20 MeV** decreases for ~5% at target and HFTM, and 20-40% at Concrete and steel liner. The **nuclear heating** increases instead by 5-7%.
- Gas production uncertainty data is missing for energy above 30 MeV, cross section data are spread in +- 15%-30% for IFMIF-DONES HFTM.
- Impact of using FENDL3.2b increases the He production by **15%**, which needs to be further investigated.
- TENDL deuteron data overall underestimate the neutron yield, and the activation data can benefit from M. Avrigeanu's work on deuteron break-up enhancement. JENDL-5 provides good estimations on neutron yield, but the drawback is a short list of isotopes and the absence of activation libraries.
- Discussion
  - Other nuclear responses besides of neutron flux in the JADE leakage sphere benchmark.
  - Gas production uncertainty: key impact on the DONES irradiation performance.

Thank you!

IFMIF DONES GRANADA

THE KEY TO THE FUTURE

Back-up slides

Stack, Row-Column	Neutron flux (/cm^2/s)	DPA (dpa/fpy)	Nuclear heating (W/g)	H production (appm/fpy)	He production (appm/fpy)	H-ratio (appm/dpa)	He-ratio (appm/dpa)
1-3	2.57E+14	9.30	8.92E-01	4.71E+02	1.16E+02	50.6	12.4
1-4	3.91E+14	14.90	1.43E+00	7.82E+02	1.92E+02	52.5	12.9
1-5	4.01E+14	15.36	1.48E+00	8.10E+02	1.99E+02	52.7	13.0
1-6	3.04E+14	11.75	1.13E+00	6.33E+02	1.56E+02	53.8	13.3
2-3	1.68E+14	5.61	6.22E-01	2.80E+02	6.90E+01	49.9	12.3
2-4	2.56E+14	9.30	1.02E+00	4.95E+02	1.22E+02	53.2	13.1
2-5	2.65E+14	9.70	1.07E+00	5.20E+02	1.29E+02	53.6	13.2
2-6	2.04E+14	7.50	8.24E-01	4.09E+02	1.01E+02	54.5	13.5