EUROfusion

# Prediction of DPA of irradiated samples based on the correlation with activation inventories

3rd DONES User Workshop| 1st Oct. 2024 | Zagreb

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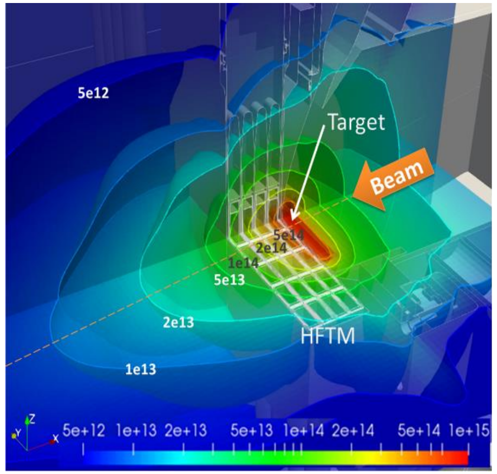
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

# Outline

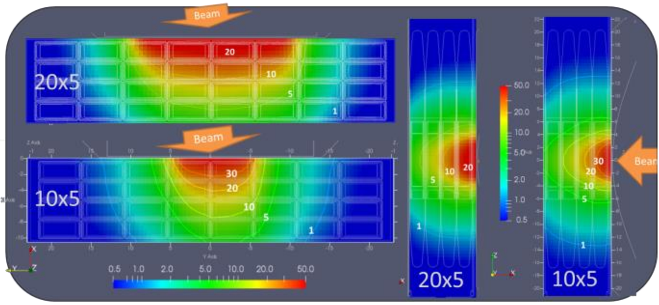
- Introduction and Motivations
- Simulation methods
- Correlation studies
- Conclusions and discussions

# Introduction and Motivations

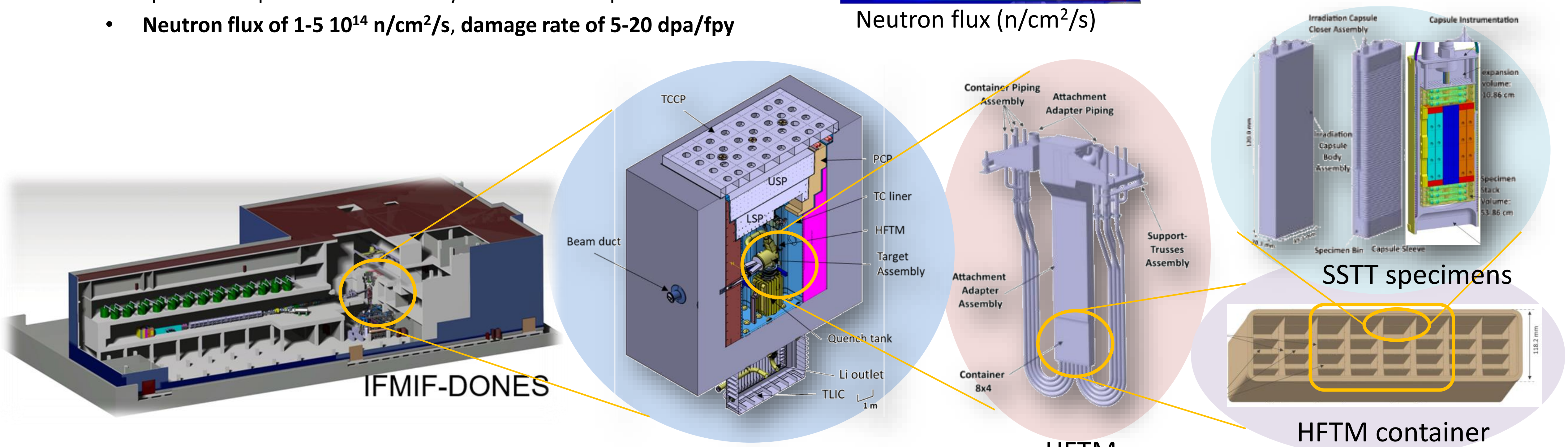
- IFMIF-DONES: Accelerator-based neutron source (D+: 125 mA, 40 MeV), generating fusion-relevant neutrons through Li(d,xn) reactions
- DONES and material irradiation
  - Test cell (TC) houses the target assembly and the High Flux Test Module (HFTM)
  - **HFTM** container provide **4 x 8 sample slots**, with the center 4 x 4 slots material samples and other as reflectors
  - Small Specimen Testing Technique **(SSTT ) samples** are located in specimen capsules surrounded by heaters for temperature control.
  - **Neutron flux of 1-5 $10^{14}$ n/cm$^2$/s, damage rate of 5-20 dpa/fpy**




Neutron flux (n/cm$^2$/s)




DPA (dpa/fpy) distribution




Test cell

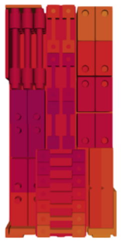
HFTM

SSTT specimens

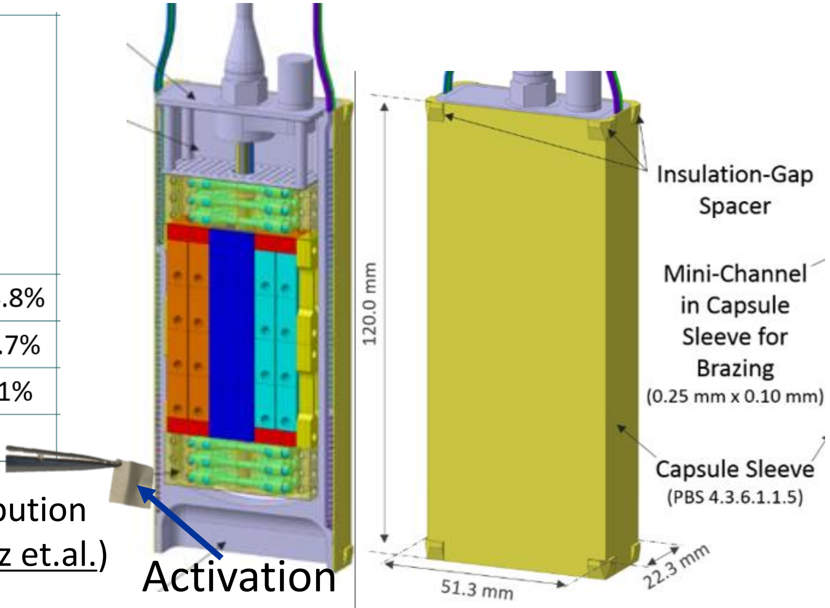
HFTM container

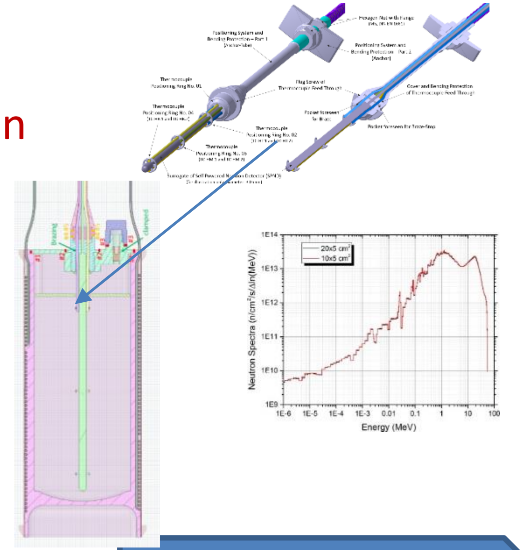
# Introduction and Motivations

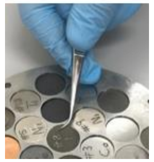
- Current detectors in HFTM : **Self-powered neutron detector** (SPND), **Activation foils** (Au, Ni, Y, Co, and Fe)
- Current issue:
  - **SPND**: online diagnostics, **1D resolution**, **low signal** $10^{-20}$ A/(n cm$^{-2}$ s$^{-1}$), no spectra info, sensitive to thermal neutron and gamma, occupying space.
  - **Activation foils**: neutron spectra, less space, **off-line**, multiple foils needed, limited resolutions, attaching and retrieval of foils

| | | |
|---|---|---|
| Layout |  | |
| Min | 1.58E14 | -44.8% |
| Max | 4.54E14 | 58.7% |
| Average | 3.12E14 | 9.1% |
| SPND | 2.86E14 | |

Neutron flux distribution (n/cm²/s) (I. Álvarez et.al.)



Neutron detector (activation foils)

↓

Neutron flux spectra $\varphi(E)$ (unfolding)

↓

Displacement cross section $\sigma_d(E)$ → $DPA = \int \varphi(E)\sigma_d(E)dE$

***Alternative way to measure the DPA with high spatial resolution (sample-wise)?***

***Any useful correlation between activation and DPA?***

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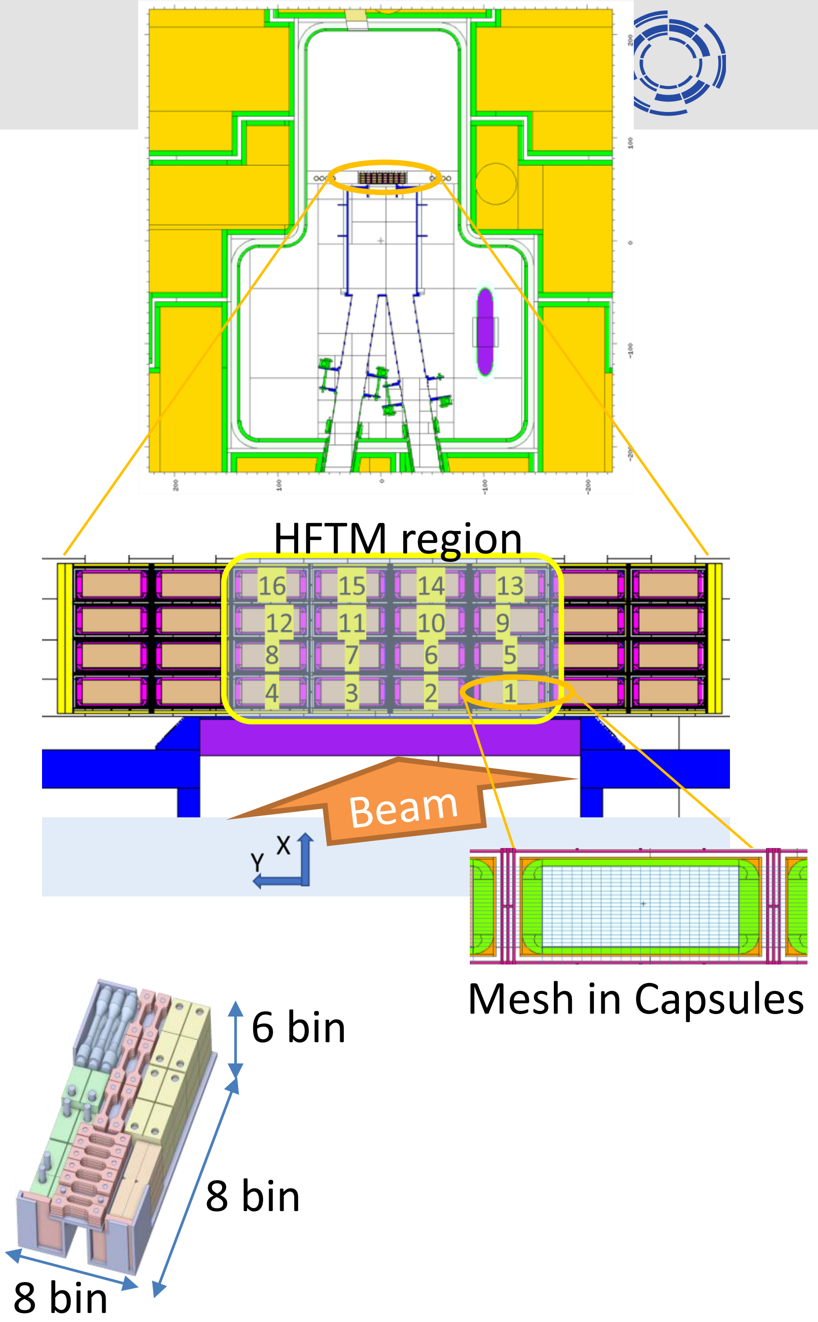
# Simulation methods

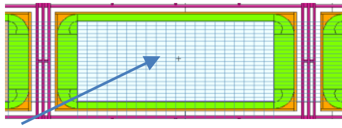
- Simulation codes and data
  - Neutronics model: Detailed HFTM and Li target
  - Simulation code: McDeLicious-MCNP(v6.2), **FISPACT-II.5** (API version)
  - Nuclear data: FENDL3-1d for neutron transport, **TENDL-2017 for neutron activation**, special displacement cross section [1] for EUROFER.
- Simulation setup
  - Calculation of the average flux in the **HFTM center regions**, average flux in the HFTM capsules.
  - Neutron flux spectra: CCFE 709 group.
  - Irradiation time : 345 days
  - Cooling time : from 1 hour to arbitrary long (1000 years).
- Studied regions and quantities
  - **HFTM region**, **Capsule 1-16**, **mesh** (**6x8x8**)
  - Activity, **gamma intensity (counts)**

***DPA and activation calculation on the same mesh.***




[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.

# Simulation materials



Homogenous ( EUROFER 75% Na 25%)

- Materials used for the simulations
  - For HFTM capsule: a homogenous mixture of EUROFER 75% Na 25%;
  - For activation: **1 $cm^3$** of 100% EUROFER (density 7.87 $g/cm^3$)

| Element | Min. wt% $[10^{-2}g/g]$ | Max. wt% [10-2g/g] | Target wt% $[10^{-2}g/g]$ | Recommended (*) $[10^{-2}g/g]$ |
|---|---|---|---|---|
| **Alloying elements** | | | | |
| **Fe** | balance | balance | balance | **balance** |
| **C** | 0.09 | 0.12 | 0.11 | **0.11** |
| **Mn** | 0.2 | 0.6 | 0.4 | **0.4** |
| **Cr** | 8.5 | 9.5 | 9.0 | **9.0** |
| **V** | 0.15 | 0.25 | 0.2 | **0.2** |
| **Ta** | 0.10 | 0.14 | 0.12 | **0.12** |
| **W** | 1.0 | 1.2 | 1.1 | **1.1** |
| **N** | 0.015 | 0.045 | 0.03 | **0.03** |

| Element | Min. wt% $[10^{-2}g/g]$ | Max. wt% [10-2g/g] | Target wt% $[10^{-2}g/g]$ | Recommended (*) $[10^{-2}g/g]$ |
|---|---|---|---|---|
| **Impurities** | | | | |
| **Ti** | | 0.02 | | **0.02** |
| **P** | | 0.005 | | **0.005** |
| **Si** | | 0.05 | | **0.05** |
| **S** | | 0.005 | | **0.005** |
| **Ni** | ALAP | 0.01 | | **0.01** |
| **Mo** | ALAP | 0.005 | | **0.005** |
| **Cu** | ALAP | 0.01 | | **0.01** |
| **Nb** | ALAP | 0.005 | | **0.005** |
| **Al** | ALAP | 0.01 | | **0.01** |
| **B** | ALAP | 0.002 | | **0.002** |
| **Co** | ALAP | 0.01 | | **0.01** |
| **As(**)** | As+Sn+Sb+Zr(**) | 0.05 | | **0.05** |
| **Sn(**)** | | | | **0.05** |
| **Sb(**)** | | | | **0.05** |
| **Zr(**)** | | | | **0.05** |
| **O** | | 0.01 | | **0.01** |

EUROFER compositions (2006)
[EFDA_D_2MM3A6 v1.2]

# HFTM region: dominant isotopes

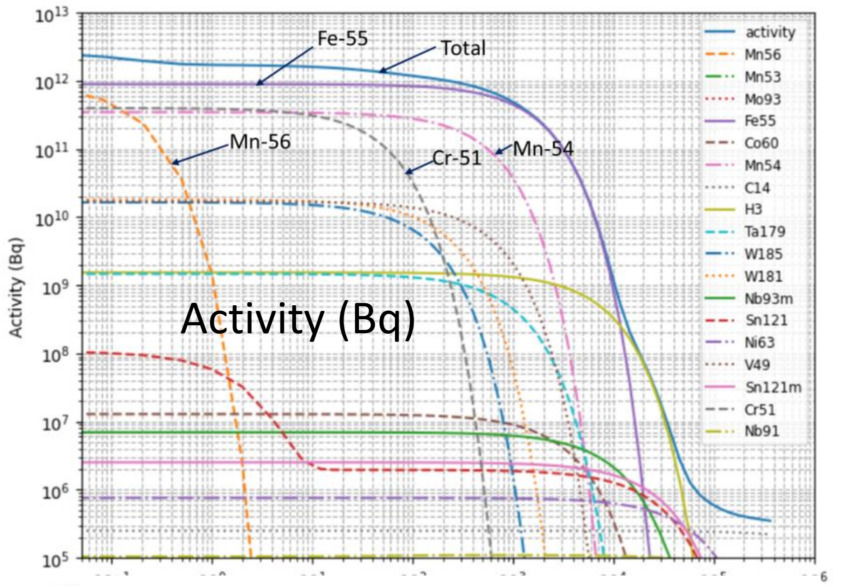
- Activation calculations
  - Capsule-3, 345 day irradiation.
- Dominant nuclei
  - Fe-55: x-ray emitter
    - T1/2 : 2.74 year, X-ray : 5-6 keV
  - Mn-56: short-lived gamma emitter
    - T1/2 : **2.58 hour**, γ-ray : 1810 keV(27%) and 2113 keV (14%)
  - Cr-51: strong gamma emitter
    - T1/2 :**27.7 d** , γ-ray : 320.1 keV(9.91%)
  - **Mn-54**: strong gamma emitter,  important isotope
    - T1/2 :**312 day** , **γ-ray : 834.8 keV(99.98%)**
- For the time of **200-2000 days**, the Mn-54 gammas dominant the total gammas by more than 99%.

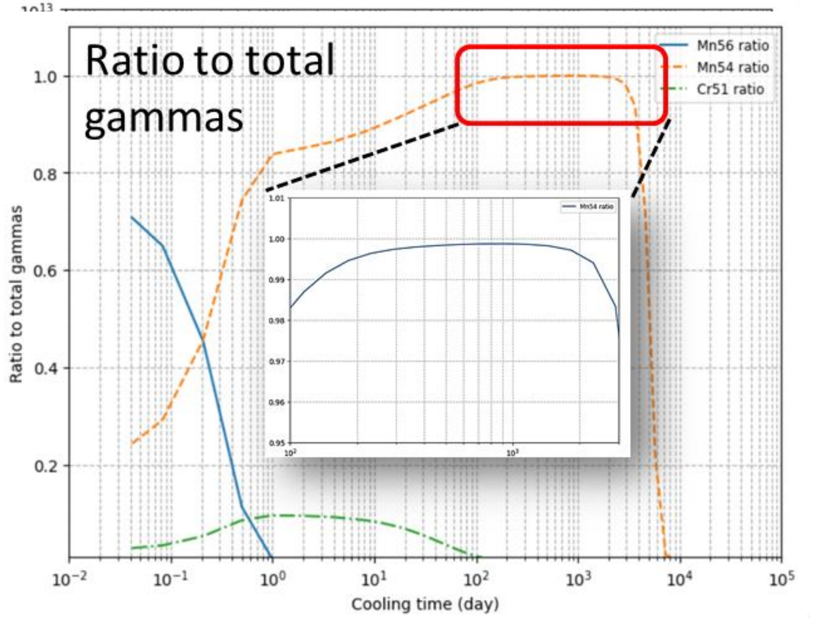
***Mn-54 is suitable for accumulate neutron flux, as well as decay gamma measurement.***

**Gamma**

| # | $E_\gamma$ [keV] | $I_\gamma$ (abs) [%] |
|---|---|---|
| 1 | 834.848 3 | **99.976 1** |

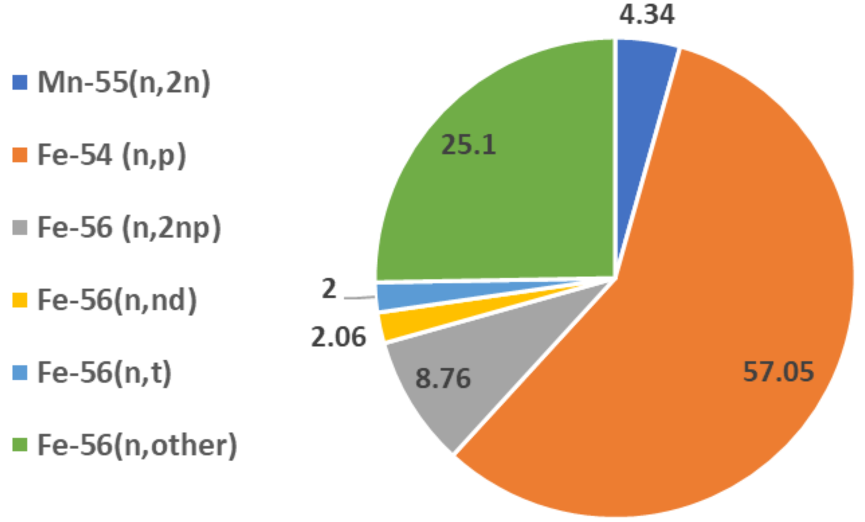
Mn-54 decay gamma

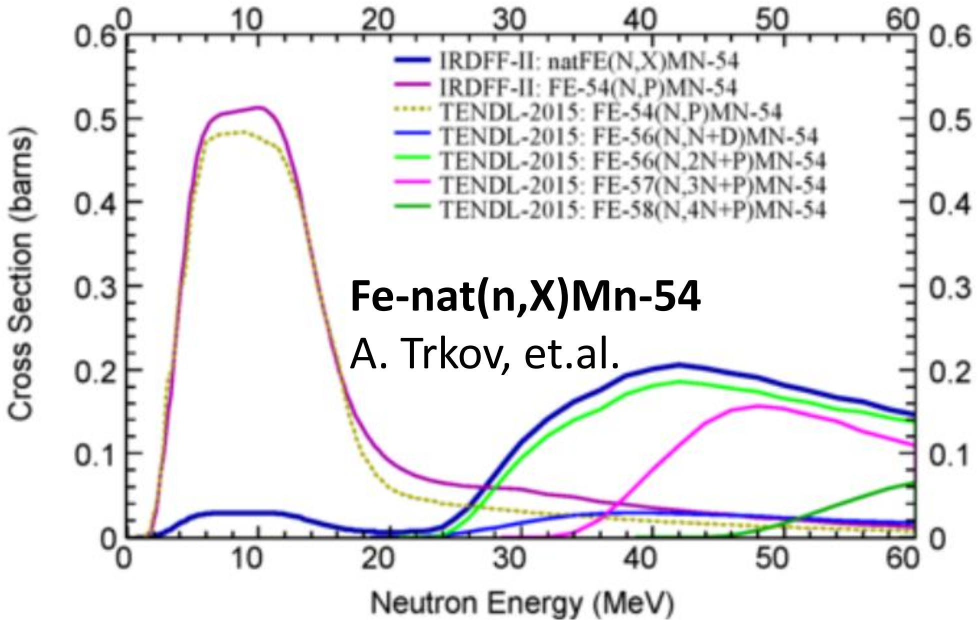


# Reaction pathways contribute to Mn-54 production

- The pathways contribute to Mn-54
  - Fe-54 (n,p): 57.05%
  - Mn-55(n,2n): 4.34%
  - Fe-56 (n,2np): 8.76%
  - Fe-56(n,nd) 2.06% (n,t) 2.00%
    (n,other) 25.10%
  - Threshold reactions sensitive to neutrons > 1 MeV.
  - Production from Fe-56 will be the main uncertainty.
    - Multiple pathways, low qualities of nuclear data.
    - Consider to use IRDFF-II *Fe-nat(n,X)Mn-54* data.

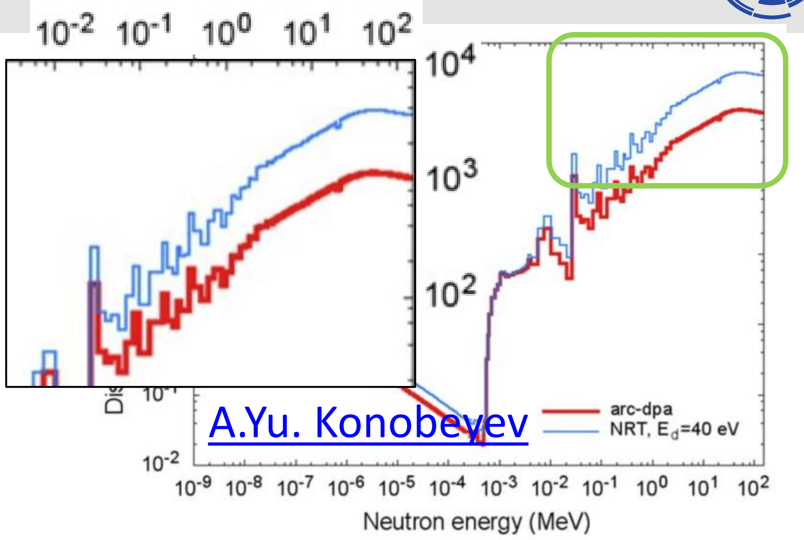



***95% of Mn-54 are produced from Fe.***
***Threshold reaction dominant at 1-20 MeV.***

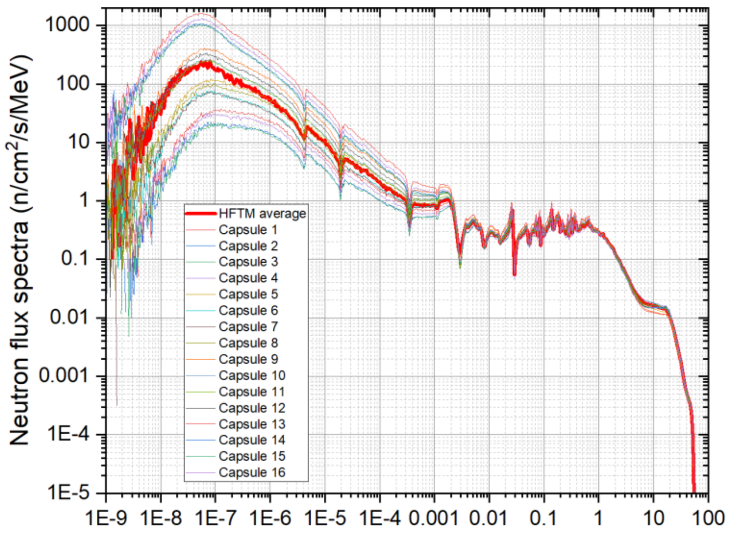
# Displacement cross section and neutron spectra

- Displacement cross section for Fe
  - Dominant in the high energy, consistent with Mn-54 production
  - Flux spectra different for >0.1 MeV : 25-50%. How this will impact on DPA and Mn-54 production.
- Two approach for study the correlations
  - **Direct DPA to Activation correlations**
  - Mn-54 -> unfolding neutron spectra -> DPA cal.

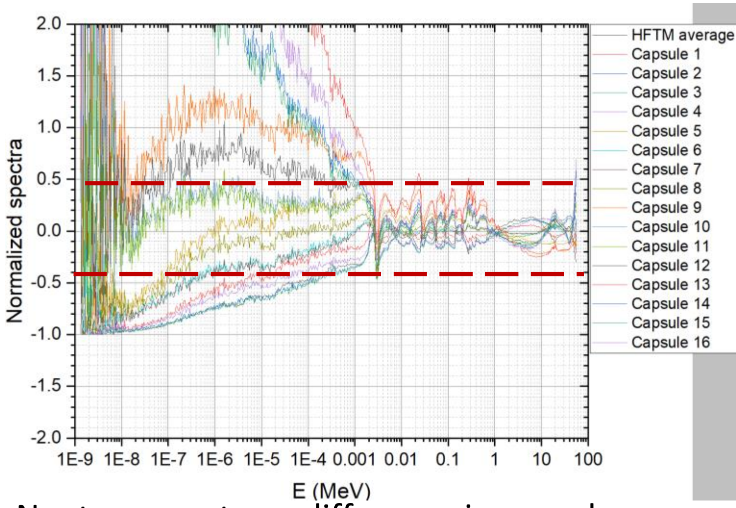


Displacement cross section of Fe

***Mn-54 production is in a similar trend with displacement (DPA) cross section.***



Neutron spectra (n/cm$^2$/s/MeV) in capsules



Neutron spectrum difference in capsules compare to HFTM average spectrum

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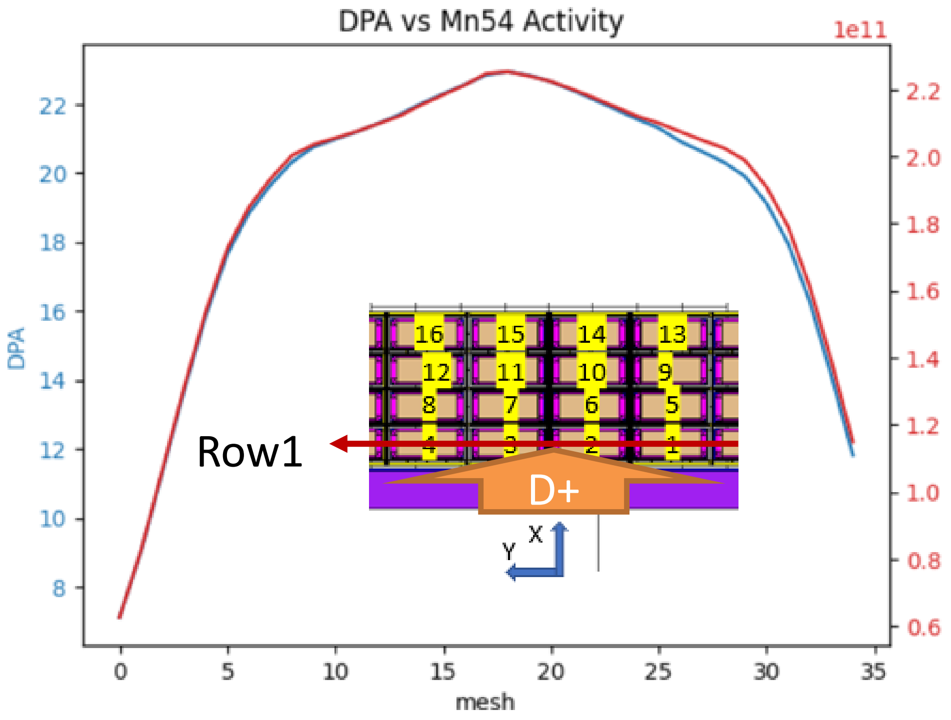
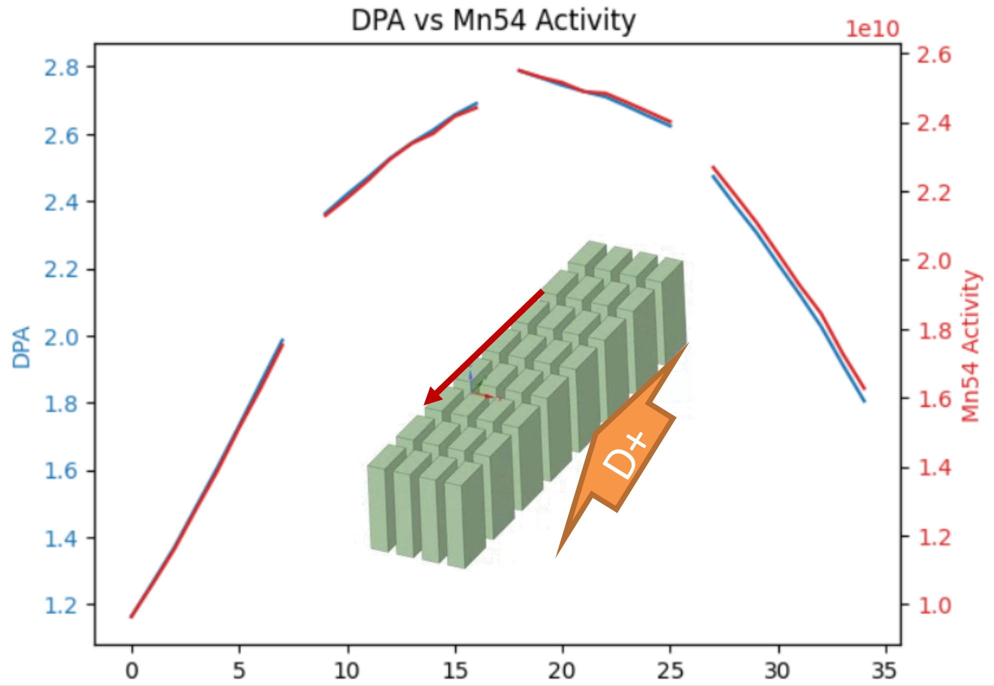
# DPA and Mn-54 activity correlations

- What happened when plot DPA together with Mn-54 activity
  - Cooling time: **180 days** (6 month)
  - Highly correlated distribution, in linear scale
  - A correlation ratio can be obtained at the measurement point.
  - This correlation is also observed at the far-source cells.

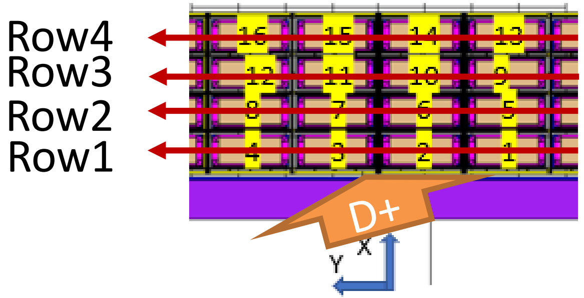
***Liner correlation between DPA and Mn-54 Activities!***



# DPA and Mn-54 activity correlations

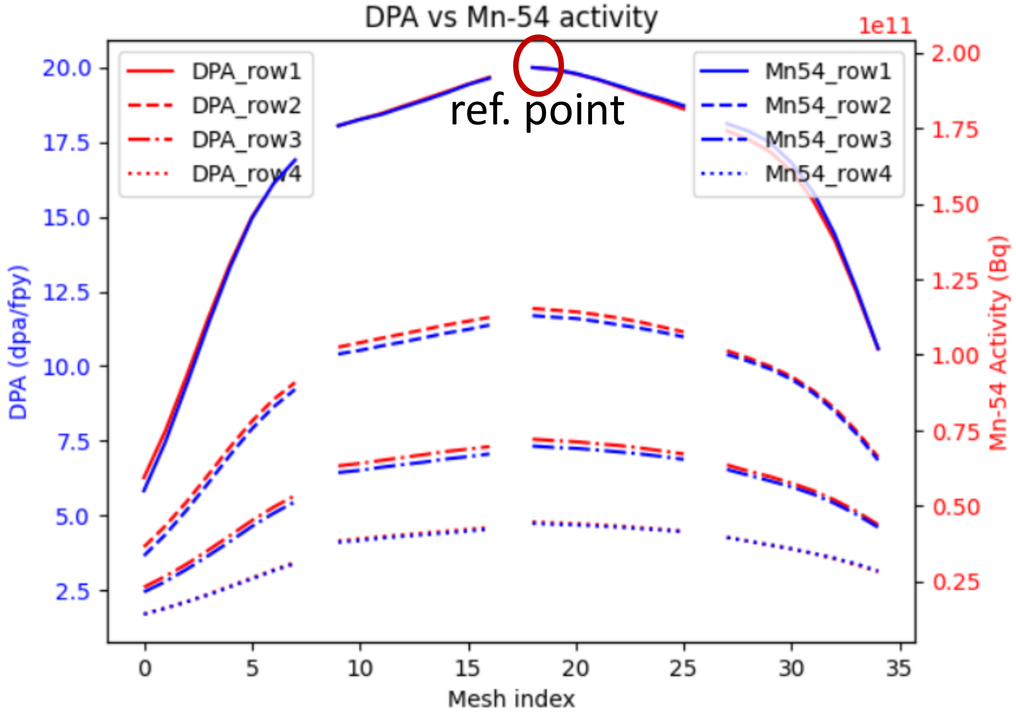
- Overall correlation studies at beam level
  - One measurement point (ref. point) : max DPA and Mn-54 activity point
  - Using correlation factor at the ref. point as base, evaluating over entire HFTM.



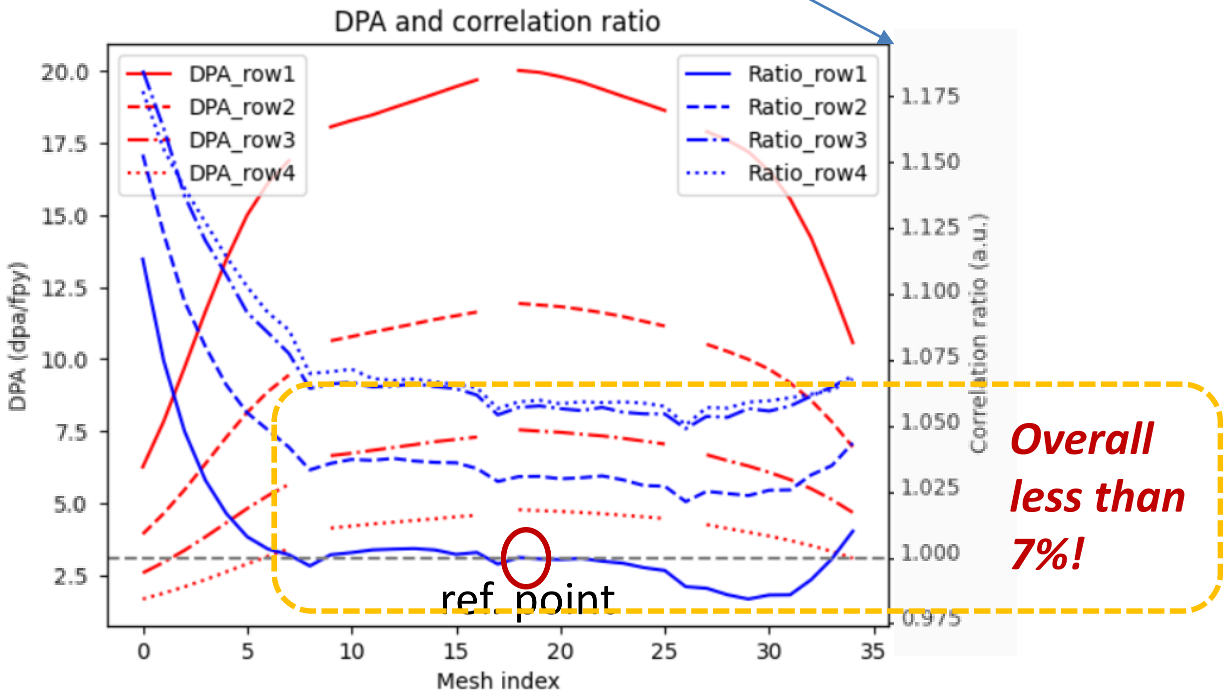

***Correlation_ref = DPA_ref / Act_Mn-54_ref***

***Ratio = Correlation_i/ Correlation_ref***

$$C^{ref} = \frac{D^{ref}}{A^{ref}} \qquad R = \frac{C^{\vec{r}}}{C^{ref}}$$



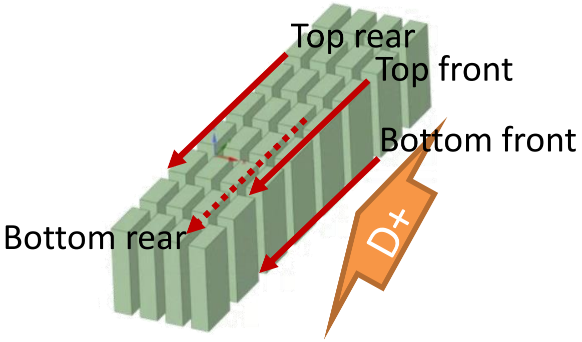

DPA and Mn-54 activities



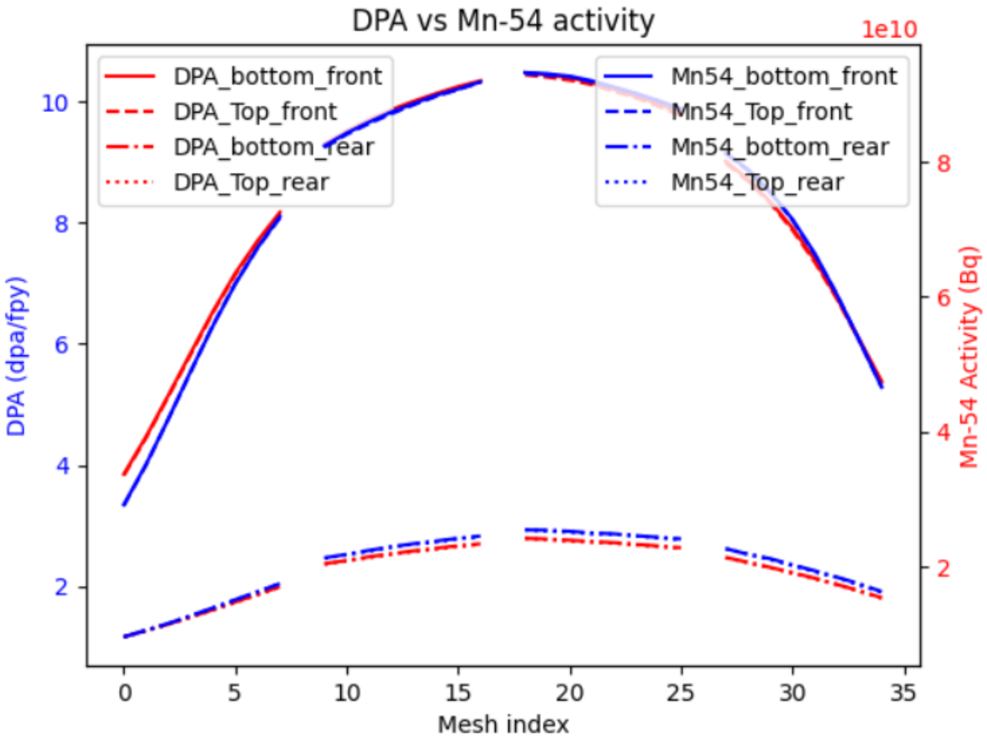

Correlation ratio compare to the ref. point

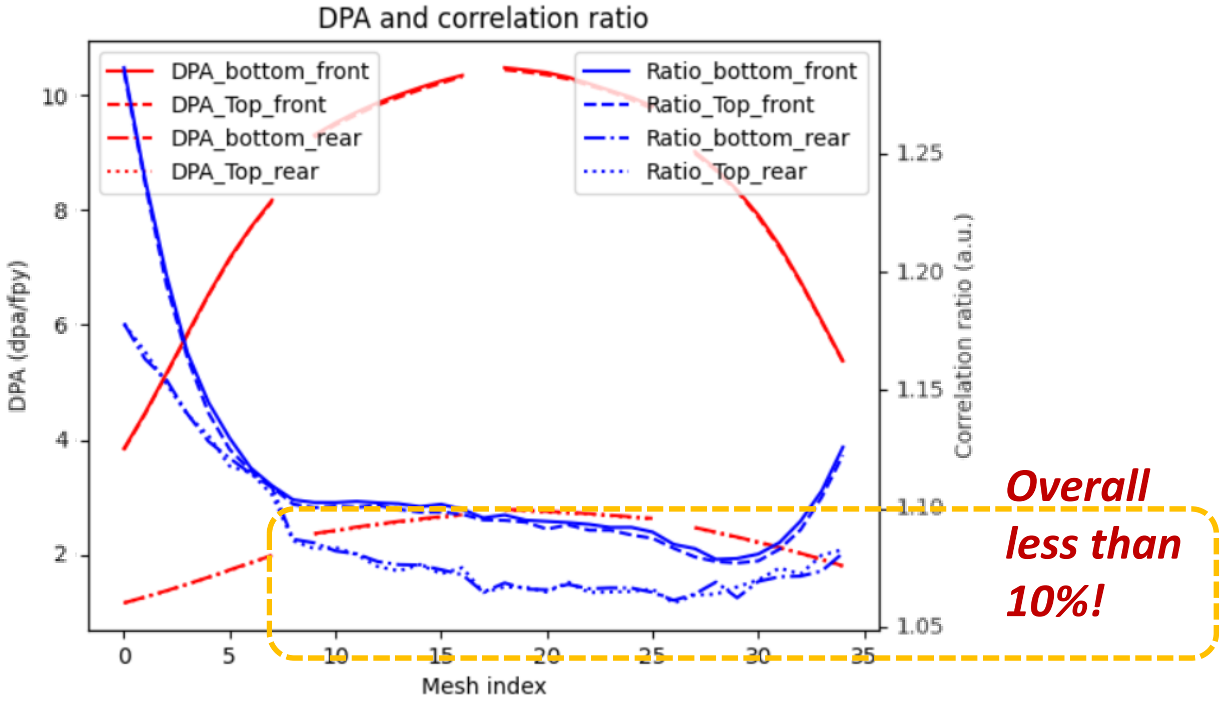
# DPA and Mn-54 activity correlations

- Extreme locations
  - Still using correlation factor of the previous ref. point
  - Overall less than 10%! Adding more local ref. point (measurement point) can help to improve accuracy of correlation factor.



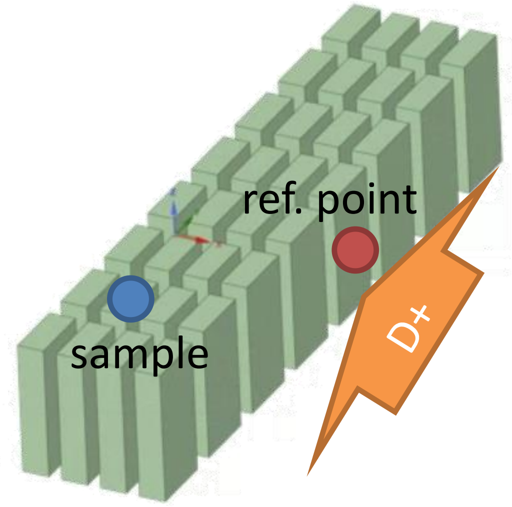

***One neutron flux measurement can used for predicting entire HFTM sample!***



# DPA prediction method

- Methodologies of predicting DPA using Mn-54 activity




Measure n-flux at ref. point (SPND/Foil)

↓

Compute the DPA and Mn-54 activity at ref. Point (red marker)

↓

Measure Mn-54 gamma at ref. point for validation (optional)

↓

Compute correlation Factor $C^{ref}$

→

Measure of Mn-54 gamma from sample (blue marker)

↓

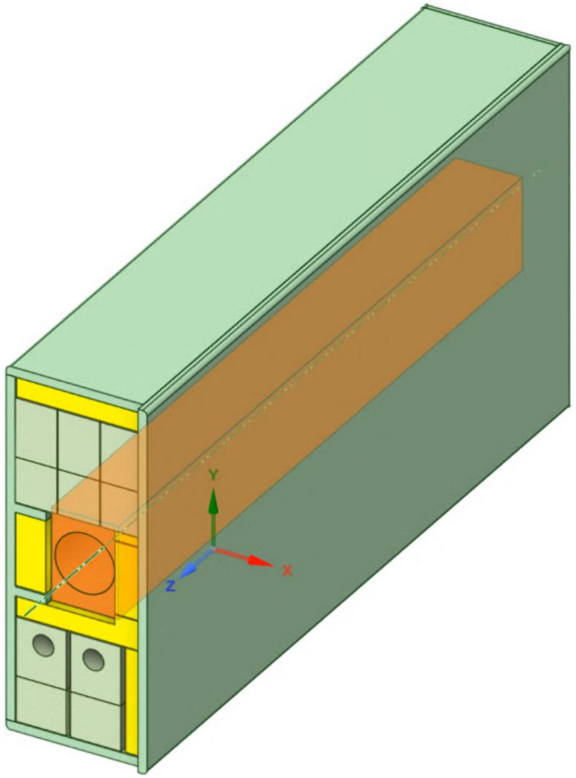
Estimate the $DPA^{i}$ = $A^{i}_{Mn54}$ * $C^{ref}$

***Prediction procedure is simple!***

***Measurement is necessary for some typical locations.***

# Benefit of new DPA measurement approach

- Benefit of new DPA measurement approach
  - One capsule with 8.0 x 4.0 x 1.46 cm = 46.7 cm$^3$, we can **save 5.8 cm$^3$** high flux volume (12.4%)
  - DONES provide 16 x 46.7 cm$^3$ = 747 cm$^3$ high flux irradiation volume with a total cost of 700-800 MEURO : ~**1 M EURO per cm$^3$ high flux volume**
  - Using the new DPA approach to reduce the SPND, which save 16 x 5.8 cm$^3$ = 92.8 cm$^3$



***Saving of more than 90 M EURO!!***

***Another 50-60cm$^3$ provide by using backplate as sample!***

# Summary and outlook

- Summary
  - The Mn-54 gammas dominant the gamma activitity for a long period, it emits a high single energy gamma, and have long half-live of 312 days.
  - The gammas from the sample (mostly from Mn-54) has good correlation with DPA, due to both cross section are dominant above 1 MeV
  - Using one measurement point of flux spectra, we can predict sample DPA with 10% uncertainty in the center rows, and <20% near the edges.
  - This approach could reduce the neutron diagnostics, and save around 12% of irradiation volume.

- Outlook
  - Further studies have to be continued on the uncertainties from material compositions, irradiation compaigns, gamma measurements, nuclear data, etc.
  - Experimental validation should be conducted before final adoption of this measure, using existing neutron source, and STUMM.

# Thank you!

IFMIF DONES GRANADA | THE KEY TO THE FUTURE

## FAIRNESS

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Collaboration
Loyalty

## OPENNESS

Open doors
Open hearts
Open minds
Open ears

## COMMITMENT

Ownership
Critical thinking
Determination
Respect

## DIVERSITY

Cooperation
Equal opportunities
Inclusion