EUROfusion

Prediction of damage doses of irradiated samples based on the correlation with activation inventories

ICFRM-21| Oct 22-27, 2023

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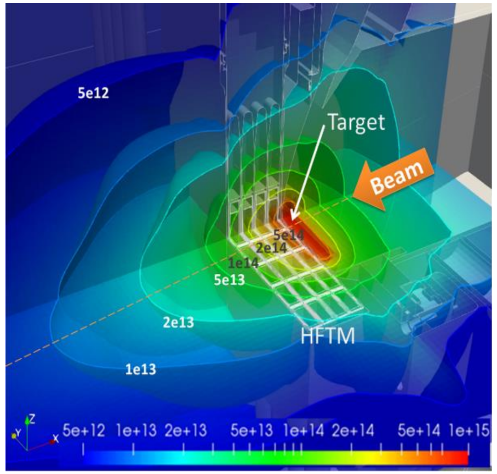
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European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

Outline

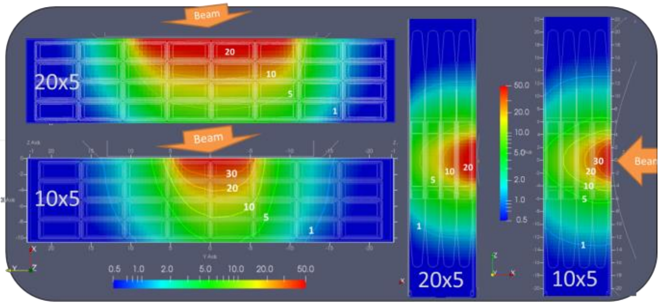
- Introduction and Motivations
- Simulation methods
- Correlation studies
- Conclusions and discussions

Introduction and Motivations

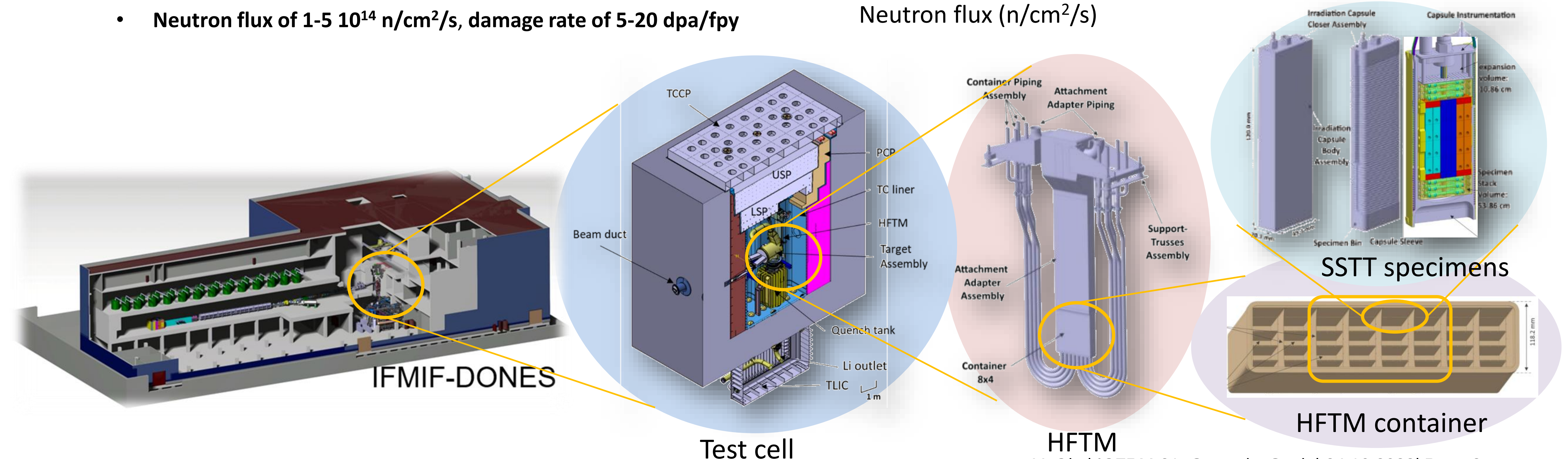
- IFMIF-DONES: Accelerator-based neutron source (D+: 125 mA, 40 MeV), generating fusion-relevant neutrons through Li(d,xn) reactions
- DONES and material irradiation
  - Test cell (TC) houses the target assembly and the High Flux Test Module (HFTM)
  - **HFTM** container provide **4 x 8 sample slots**, 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)

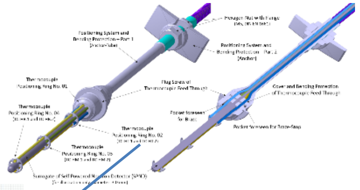


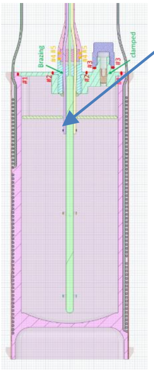
DPA (dpa/fpy) distribution

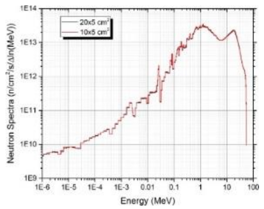


Introduction and Motivations

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







Neutron detector
(SPND, activation foils)

↓

Neutron flux spectra (unfolding)

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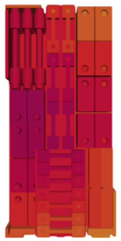
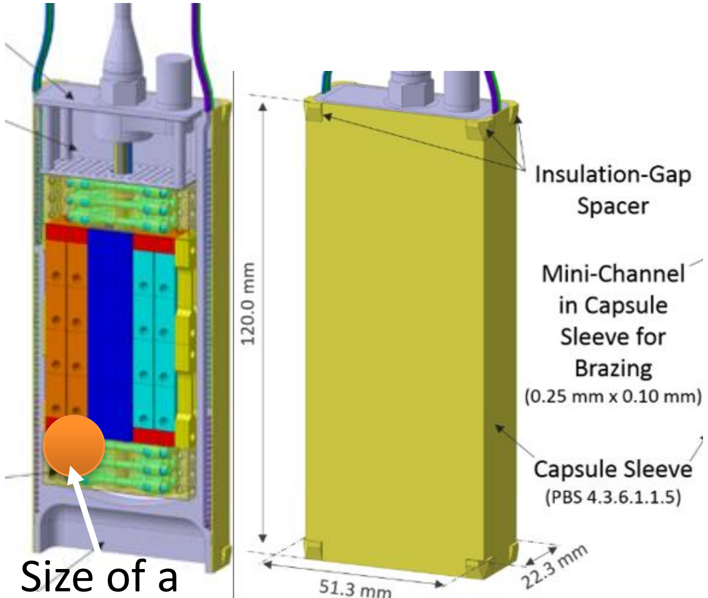
Displacement cross section ⇒ $DPA = \int \varphi(E)\sigma_d(E)dE$

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

Neutron flux distribution (n/cm^2/s) (I. Álvarez et.al.)



Size of a typical foil

- Motivation: an alternative way to measure the DPA with high spatial resolution (sample-wise).
- Any useful correlation between activation and flux, or damage dose? And How can it help us?

Outline

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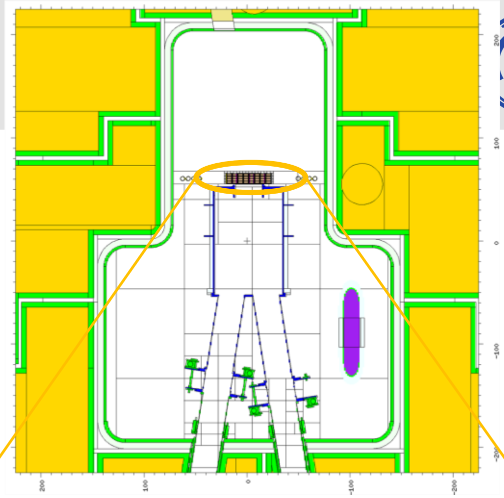
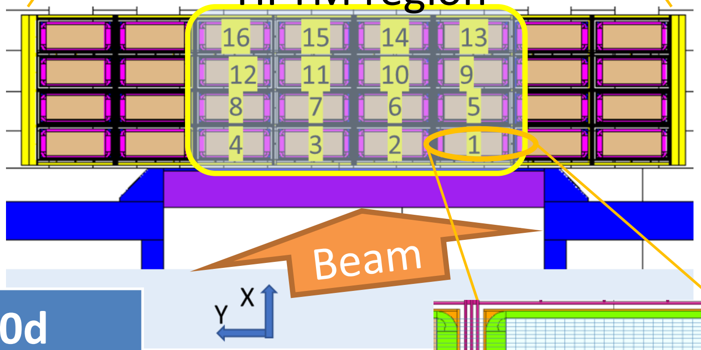
Simulation methods

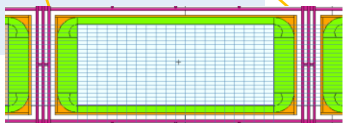
- Simulation codes and data
  - Neutronics model: Detailed HFTM and Li target
  - Simulation code: McDeLicious-MCNP(v6.2), **FISPACT-II.5** (API version)
  - Nuclear data: FENDL3-1d for neutron transport, TENDL-2017 for neutron activation, special displacement cross section [1] for EUROFER.
- Simulation 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 (t): parametric study of 1, 30,…360,…1080 days
  - Cooling time (t'): from 1 hour to 1 year
- Studied regions and quantities
  - **HFTM region**, **Capsule 1-16**, **mesh** (6x8x8)
  - Activity, gamma intensity, decay heat

	1d	30d	…	1080d
1 h	$A_{1d,1h}$	$A_{30d,1h}$		$A_{1080d,1h}$
1 d	$A_{1d,1d}$	$A_{30d,1d}$		$A_{1080d,1d}$
…			$A_{i,j}$	
1 y	$A_{1d,1d}$	$A_{30d,1y}$		$A_{1080d,1y}$

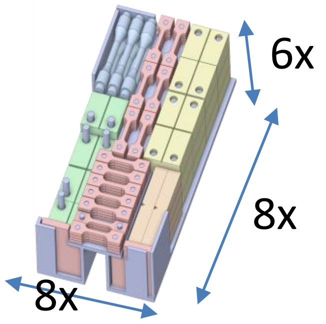


HFTM region



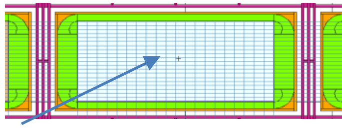


Mesh in Capsules



[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]

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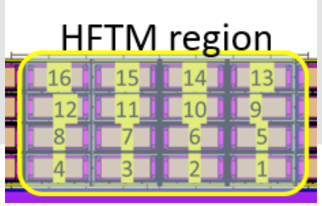
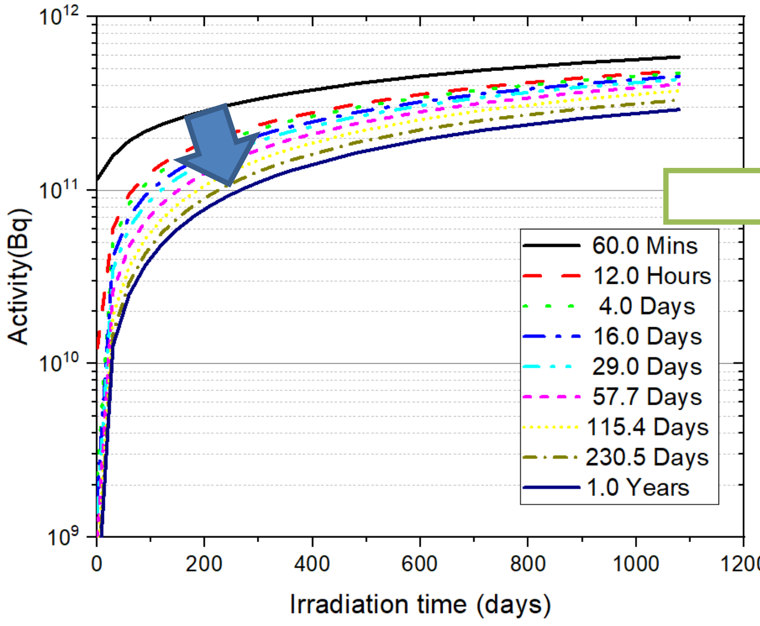
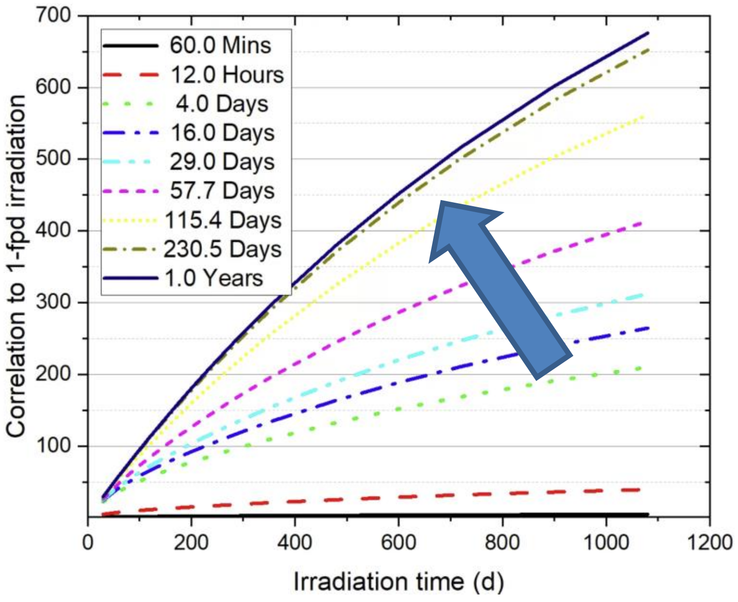
HFTM region: Activity inventory



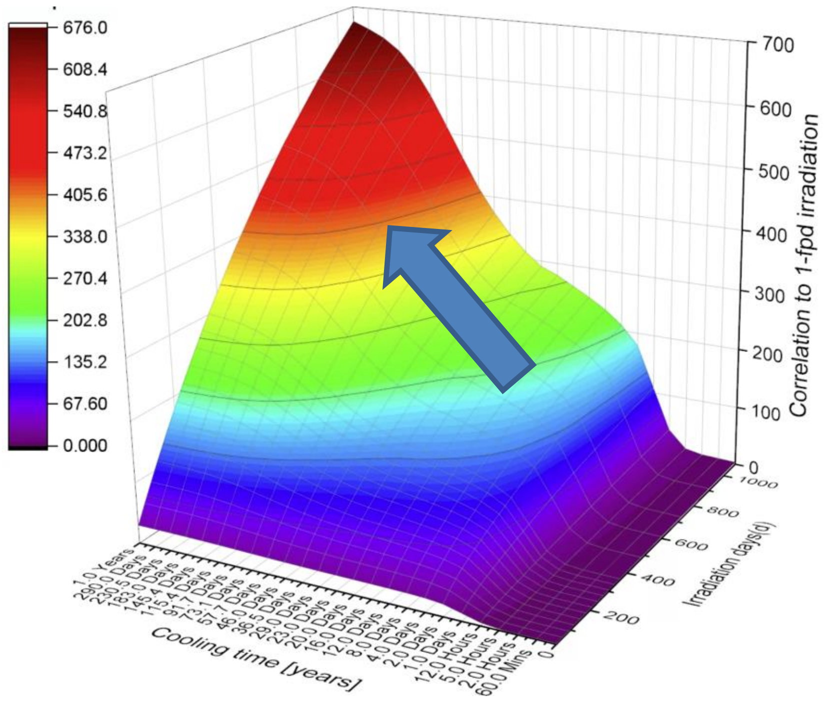
- Total activities of 1 cm^3 EUROFER under irradiation in HFTM region
  - Activity A(t, t') increasse with **irradiation time t** , and decrease with **cooling time t'**
  - Normalizing to one full power day (t=1d) activities: non-linear, slope increase with decay time.
  - Total activity: not a favorable measurement quantity.



Activity: A(t, t')

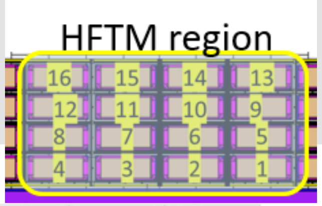


Correlation: $A(t,t'_l)/A(t=1\ d, t')$

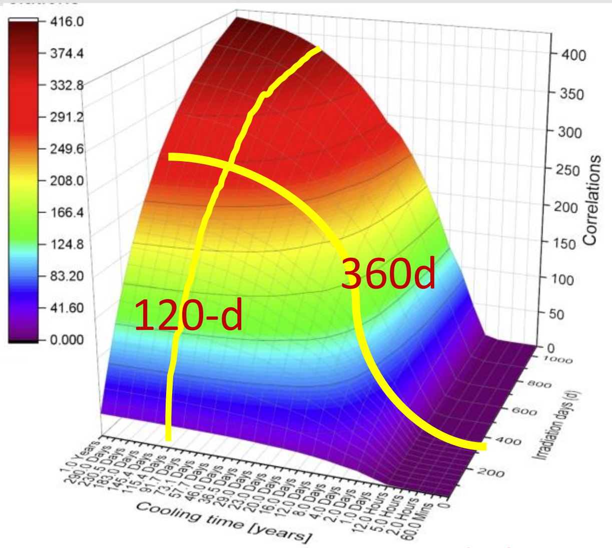


Correlation map: $A(t,t'_l)/A(t=1\ d, t')$

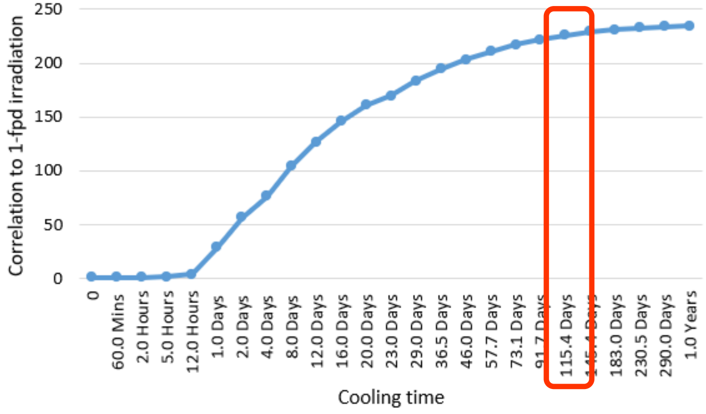
HFTM region: decay heat and decay gammas



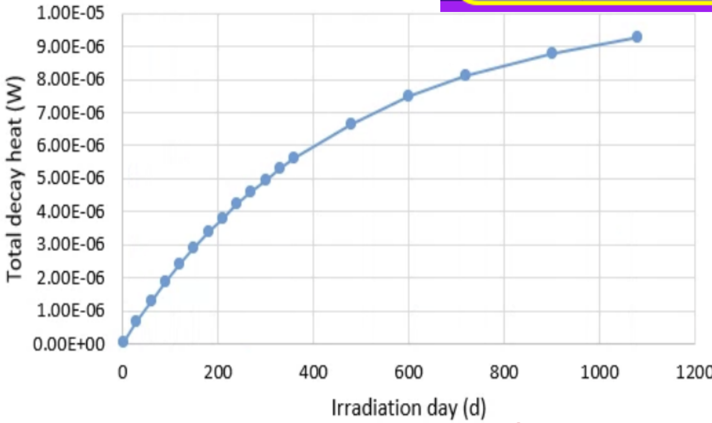
Total heat



Correlation map of **decay heat (H)**: H(t, t')/H(t=1d, t')

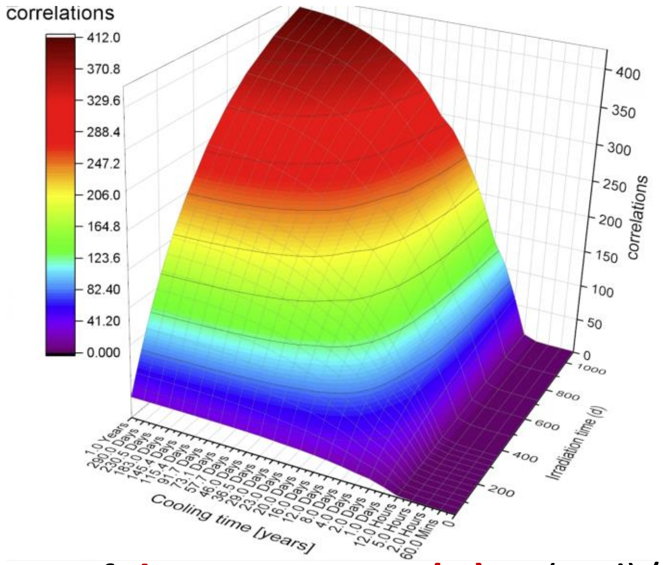


Correlation map: H(t=360d, t')/H(t=1d, t')

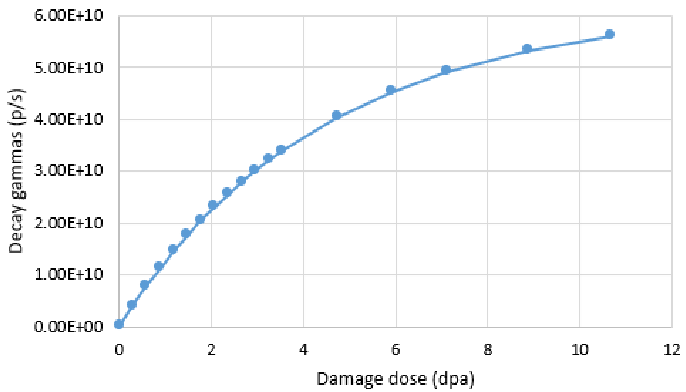


decay heat at t' =**120 d (~4 month)** cooling

Decay gammas



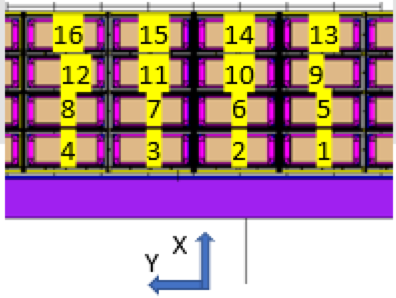
Correlation map of **decay gammas (G)**: G(t, t')/G(t=1d, t')



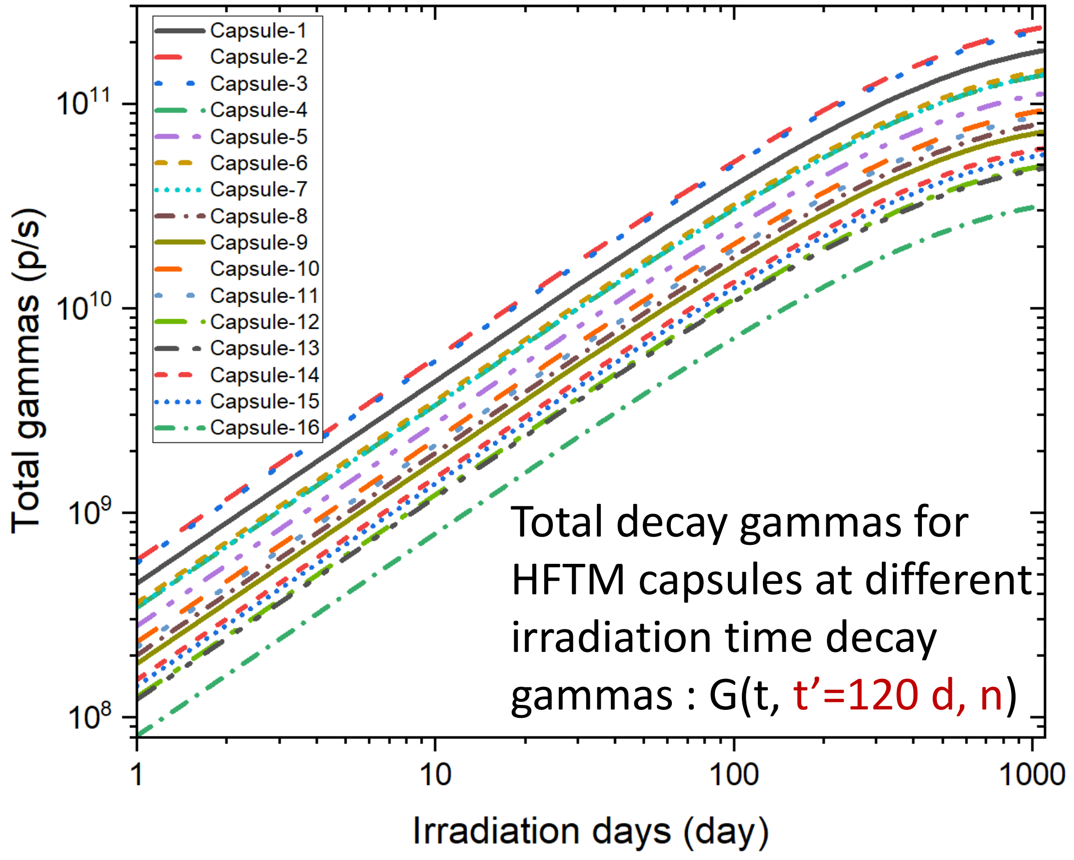
Gammas at t' =**120 d** cooling

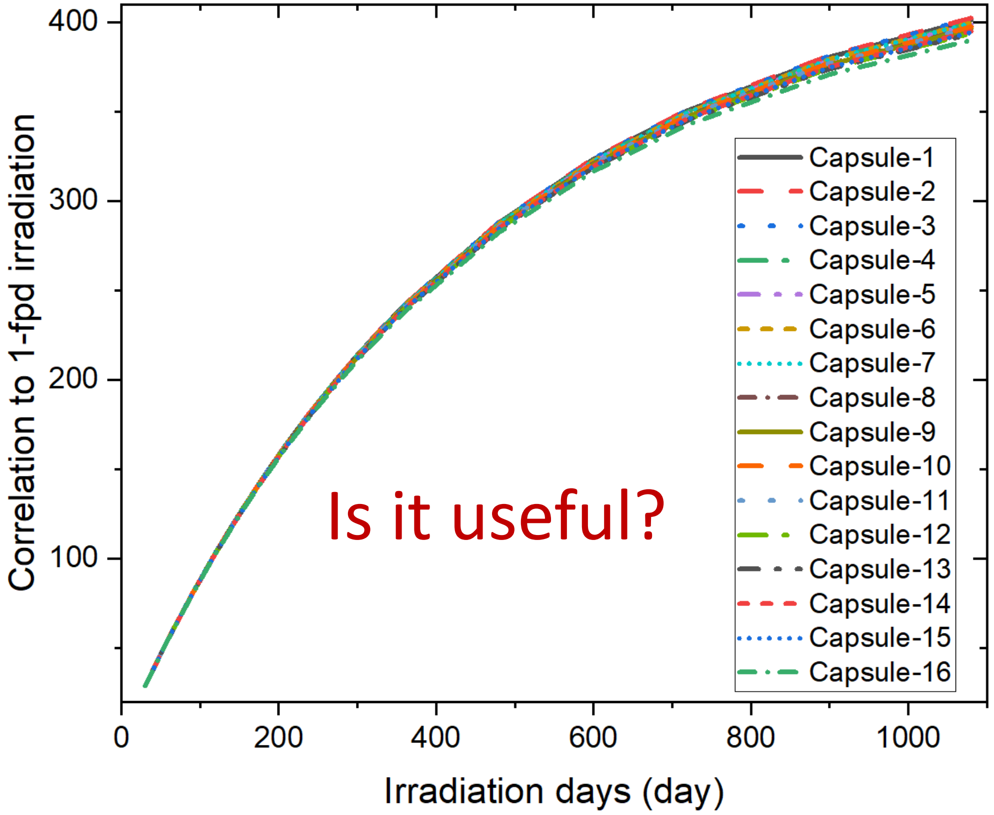
- **Decay heat 10^{-6} -10^{-7} W/cm^3 too low for measurement**: typical specimen volume 0.2-0.5 cm^3 (tensile: 0.03 cm^3). Current libs are provided >10mW measurement sensitivity
- **Decay gammas 10^{10} p/s: favorable for measurements for HPGe detector**.

HFTM capsules : decay gammas



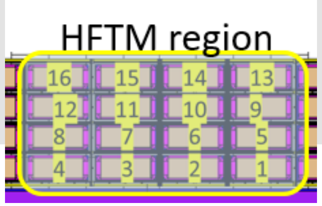
- Decay gamma in capsules (capsule-n)
  - Similar trend: non-linear.
  - Good news: by normalizing to G(t=1d, t'=120 d, **n**), the curve are very similar.

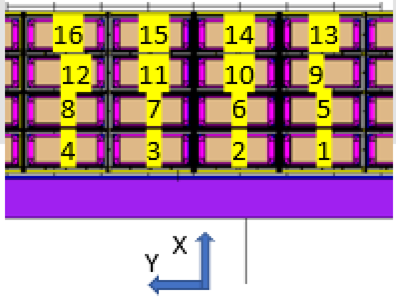




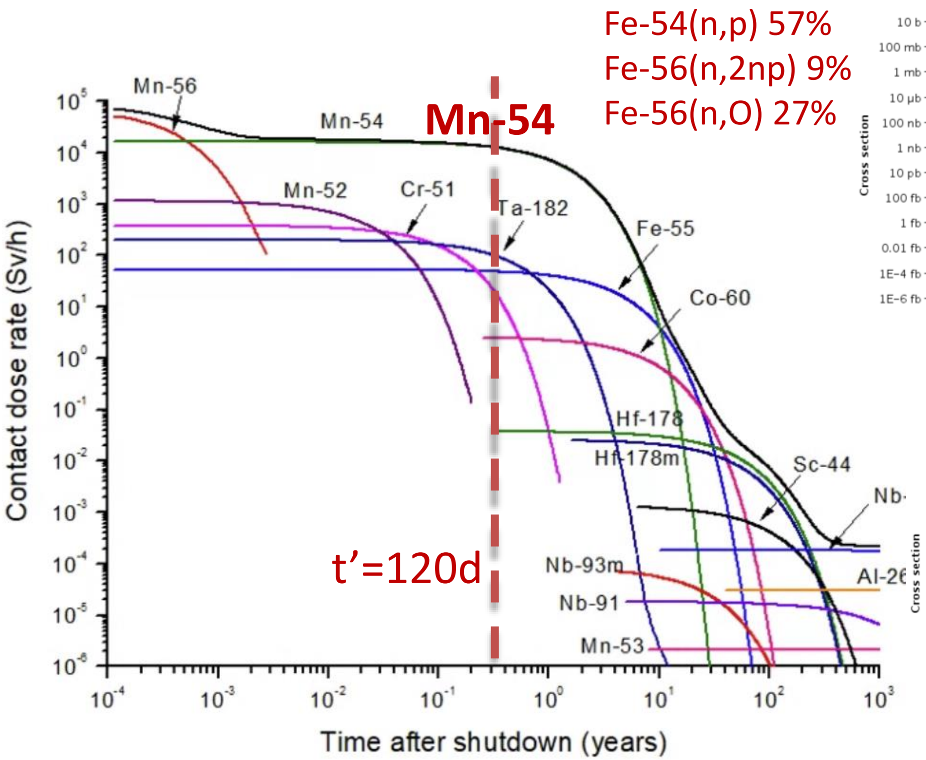
Correlation G(t, t'=120 d, n)/G(t=1d, t'=120 d, n)

HFTM region: dominant isotopes

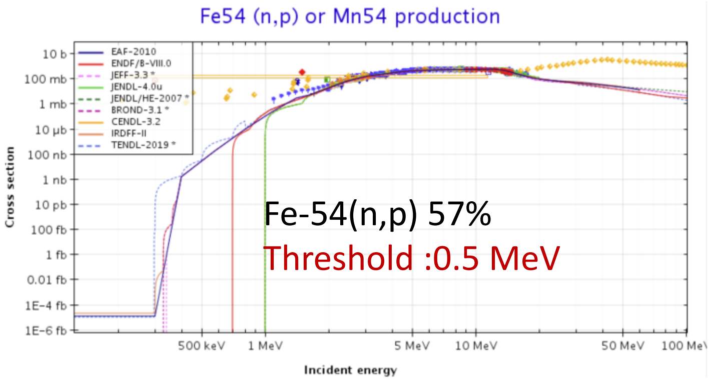


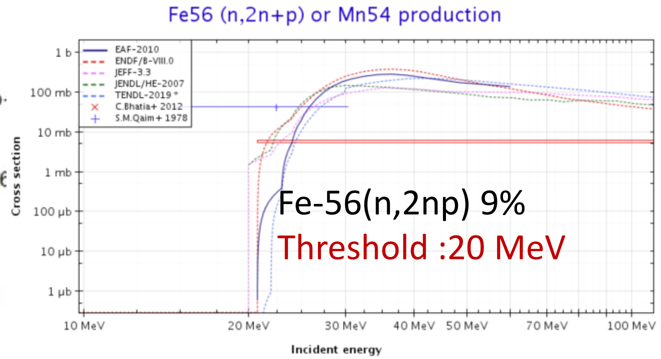


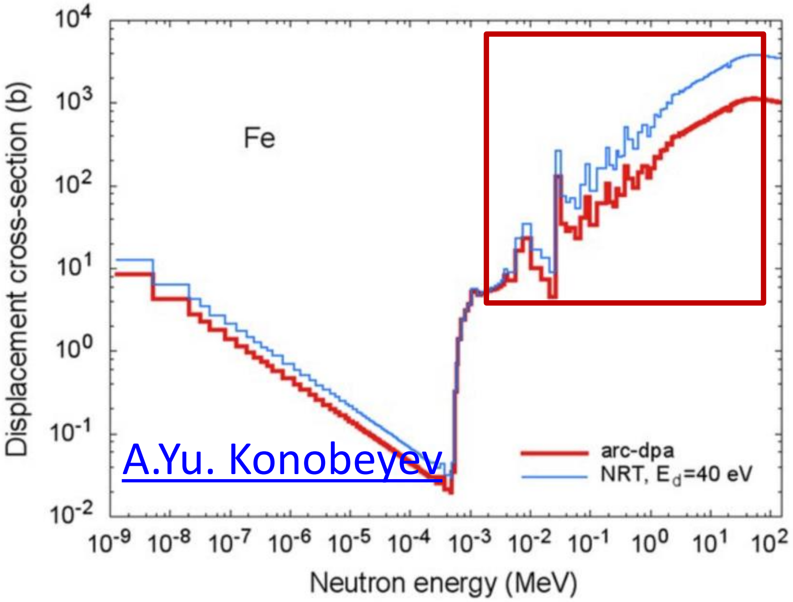
- Dominant isotopes for decay gammas
  - More than **95% gammas dominant by Mn-54** between cooling time 1day -1 year
  - Both DPA and gammas production are dominant in high neutron energy (>0.01 MeV), **relevant for DPA cross section**



Dominant isotopes for gammas

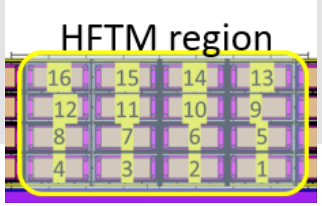






Displacement cross section of Fe

Mn-54 inventory analysis



- **Bateman differential equation**
  - N : Atoms of Mn-54 during irradiation
  - N' : Atom of Mn-54 during decay
  - Σ : Total marco cross section
  - t : Irradiation time
  - t' : decay cooling time
- Comparison of calculated Mn-54 gammas and FISPACT output gammas shows reasonable agreement

$$\frac{dN}{dt} = \Sigma\,\phi - \lambda N \qquad \frac{dN'}{dt'} = -\lambda N'$$

Irradiation   Cooling

$$\Rightarrow N(t,t') = \frac{\Sigma\phi}{\lambda}\left(1 - e^{-\lambda t}\right) e^{-\lambda t'}$$

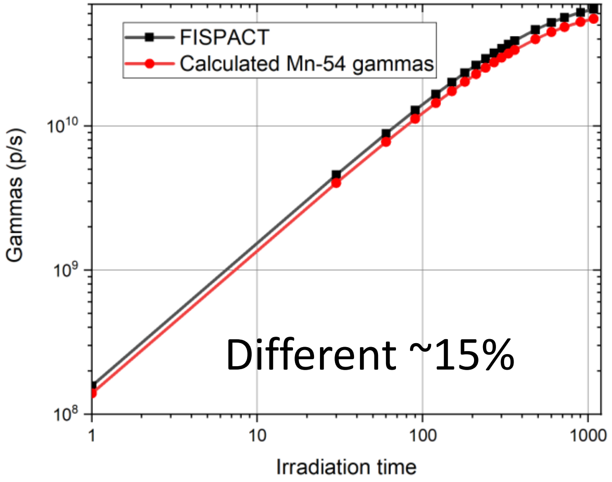
Activity $A = \lambda N = \Sigma\phi\left(1 - e^{-\lambda t}\right) e^{-\lambda t'} = G$

Fe54	5	(n,O	) =	3.8189e-04
Fe54	103	(n,p	) =	1.1620e-01
Fe56	5	(n,O	) =	3.2100e-03
Fe56	32	(n,nd	) =	2.6851e-04
Fe56	41	(n,2np	) =	1.1404e-03
Fe56	105	(n,t	) =	2.6206e-04
Mn55	5	(n,O	) =	3.0876e-03
Mn55	16	(n,2n	) =	1.1399e-01

1-group Micro cross sections (barn-cm) of Mn-54 production

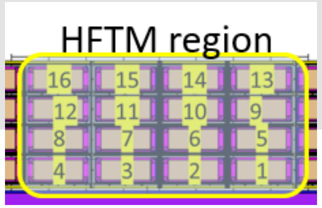
Energy (keV)	Intensity (%)	Type
834.848 (3)	99.9752 (5)	γ
5.41479 (-)	15.02 (27)	$X_{K\alpha1}$
5.40557 (-)	7.65 (14)	$X_{K\alpha2}$
5.9669 (-)	3.05 (7)	$X_{K'\beta1}$
0.59889 (-)	0.65 (13)	X_L
511 (-)	0.00000114 (-)	γ±

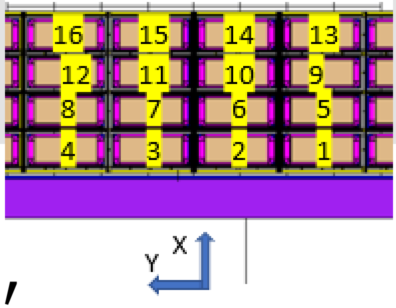
Mn-54 decay



Gammas (p/s) by analog Cal. v.s. FISPACT

Mn-54 gammas and flux correlations





- Relation between HFTM region and capsule
  - For the same irradiation time t=360 d and cooling time t'=120 d, compare the flux and Mn-54 gammas
  - Σ: Macro cross section consist of neutron spectra information
  - If spectra consider the same, macro cross section Σ is the same.
  - Consider $\phi(HFTM)$ is known from detectors, we can estimate the $\phi(n)$.

$$G = \Sigma\phi(1 - e^{-\lambda t})\, e^{-\lambda t'}$$

$$\frac{G(HFTM)}{G(n)} = \frac{\Sigma(\mathrm{HFTM})\phi(HFTM)}{\Sigma(n)\phi(n)}$$

$$\Sigma = \sum_i \int \sigma_i(E) N_i \varphi(E) dE$$

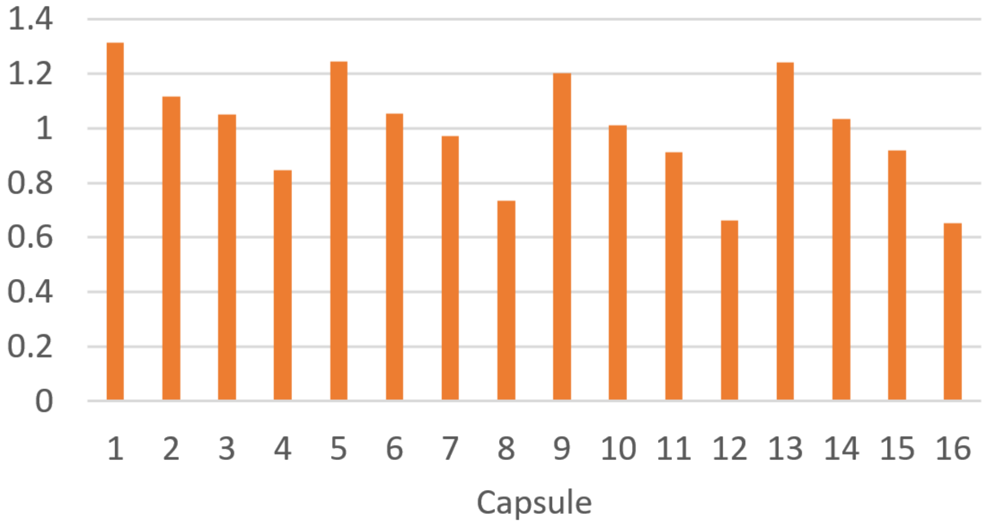
i: parent nuclei (Fe-54, Fe-56, Mn-55)

$$if\ \Sigma(\mathrm{HFTM}) \approx \Sigma(n) \ \Rightarrow$$

$$\frac{G(HFTM)}{G(n)} = \frac{\phi(HFTM)}{\phi(n)}$$

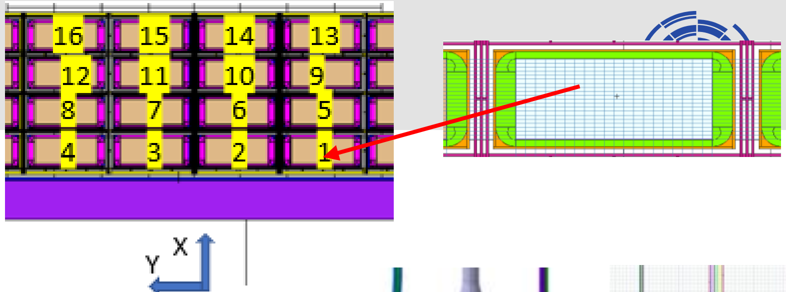
?

Results are not very promising…

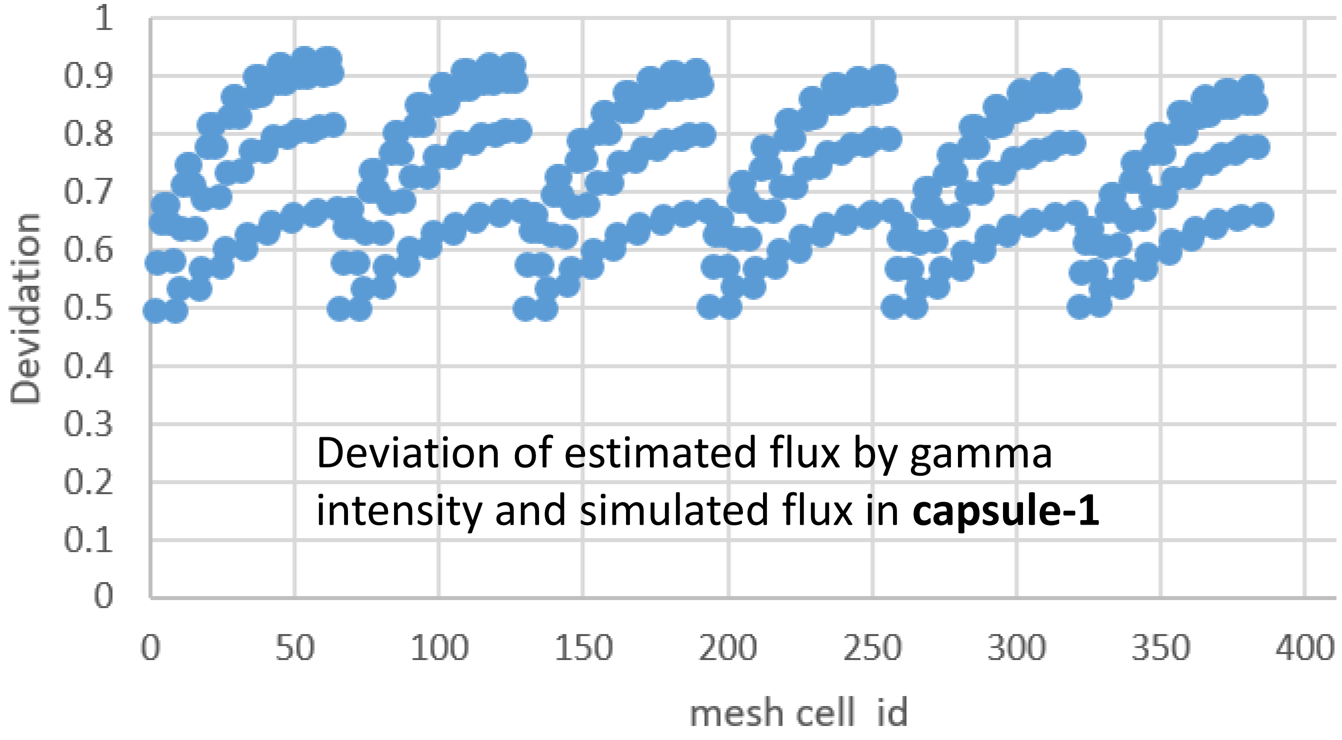


Deviation of estimate flux to the actual simulated flux

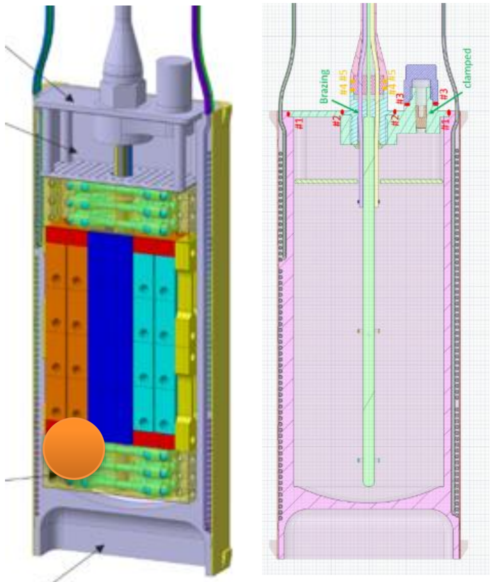
Mn-54 gammas and flux inside capsule-1



- Mesh cell in capsules
  - Take the capsule-1 for first investigation, the estimated flux by gamma intensity and simulated flux (10-50% difference).
  - From the **spatial patterns** it seems that the deviation is impacted by the **spectra**.

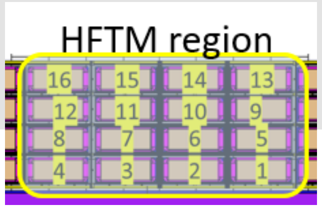


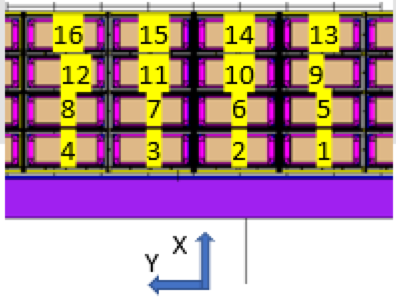
Deviation of estimated flux by gamma intensity and simulated flux in **capsule-1**



Activation foils   SPND

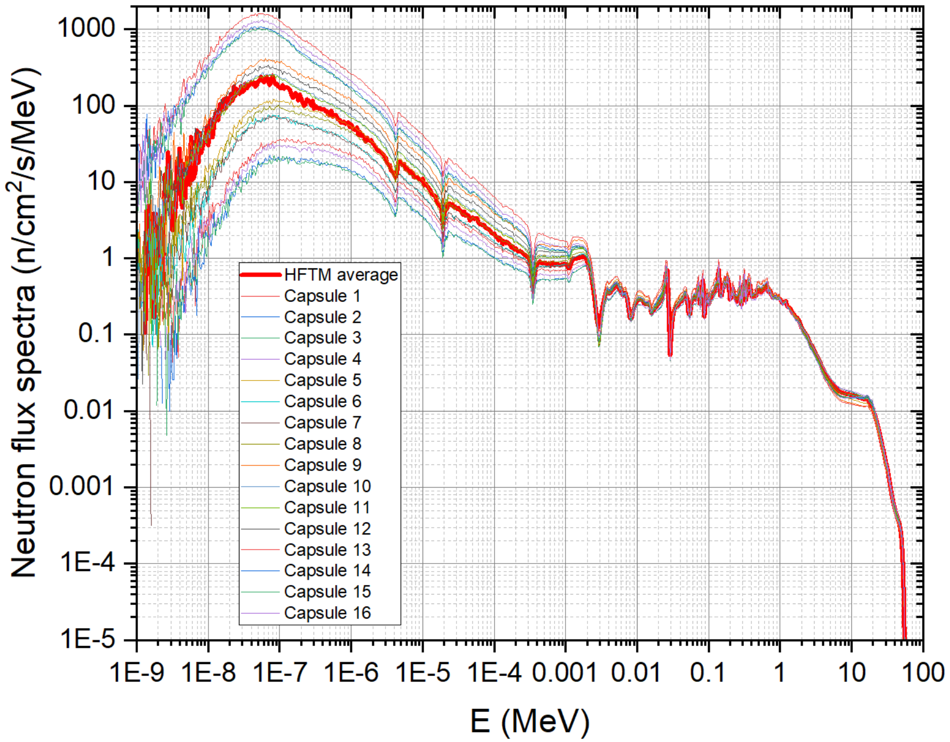
HFTM region and capsule neutron spectra



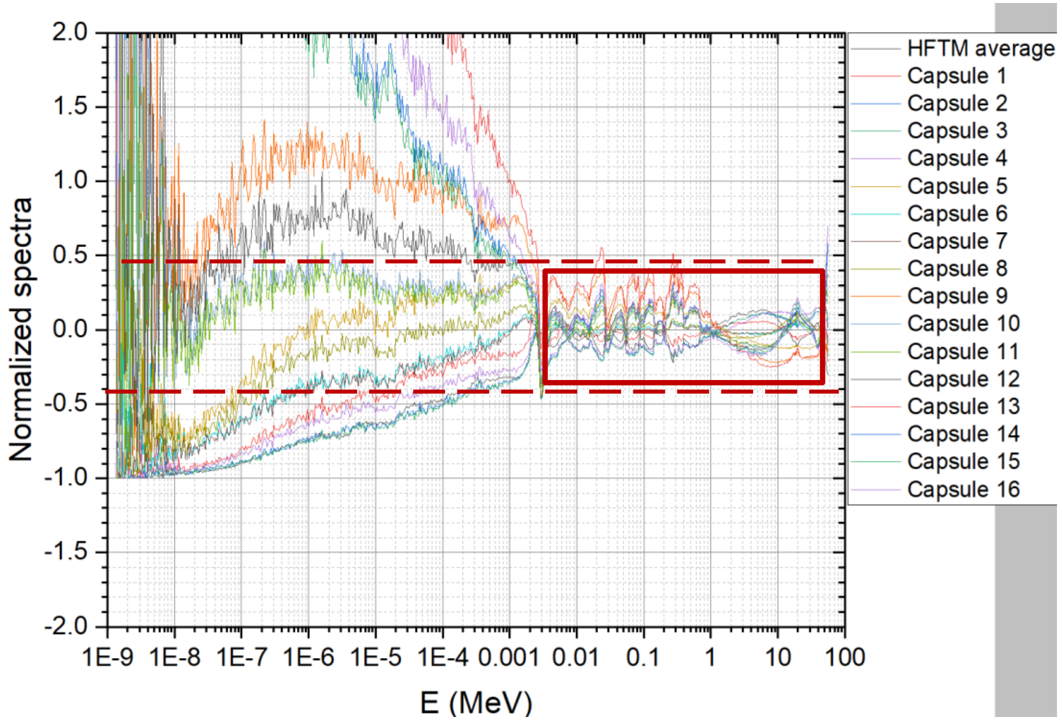


- Spectra different of HFTM region and capsules
  - Spectra difference of **25-50%** for the DPA important energies.
  - This might account for the difference of estimated flux deviation
  - Work is still ongoing for further reasons, and how this flux estimation to predict the DPA.

$$DPA = \Sigma_{dpa}\phi$$



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



Neutron spectrum difference in capsules compare to HFTM average spectrum

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Conclusions and discussions

- Conclusions
  - The measurement of flux/DPA in HFTM is challenging.
  - This work proposed an idea to **predict the flux/DPA by the decay gamma intensity**.
  - It is found that the **Mn-54 decay gammas is dominant** at the practical measurement time (~4 months).
  - Through analog analysis we found these gammas are helpful, but the resulting **difference** to the actual simulated flux is large **(25%-50%)**, which might be due to the **spectra difference**.
  - Work is still ongoing to justify this approach.
- Discussions on further developing this method
  - Accurate measurement of the **EUROFER compositions and impurities**.
  - Detector calibration for the sample of different shapes
  - Self-shielding during the gamma counting
  - Irradiation uniformity
  - **SPND and activation foil developments for the HFTM**

Thank you!

IFMIF DONES GRANADA | THE KEY TO THE FUTURE

FAIRNESS

Transparency

Collaboration

Loyalty

OPENNESS

Open doors

Open hearts

Open minds

Open ears

COMMITMENT

Ownership

Critical thinking

Determination

Respect

DIVERSITY

Cooperation

Equal opportunities

Inclusion