Activation measurements and modelling on MAST Upgrade

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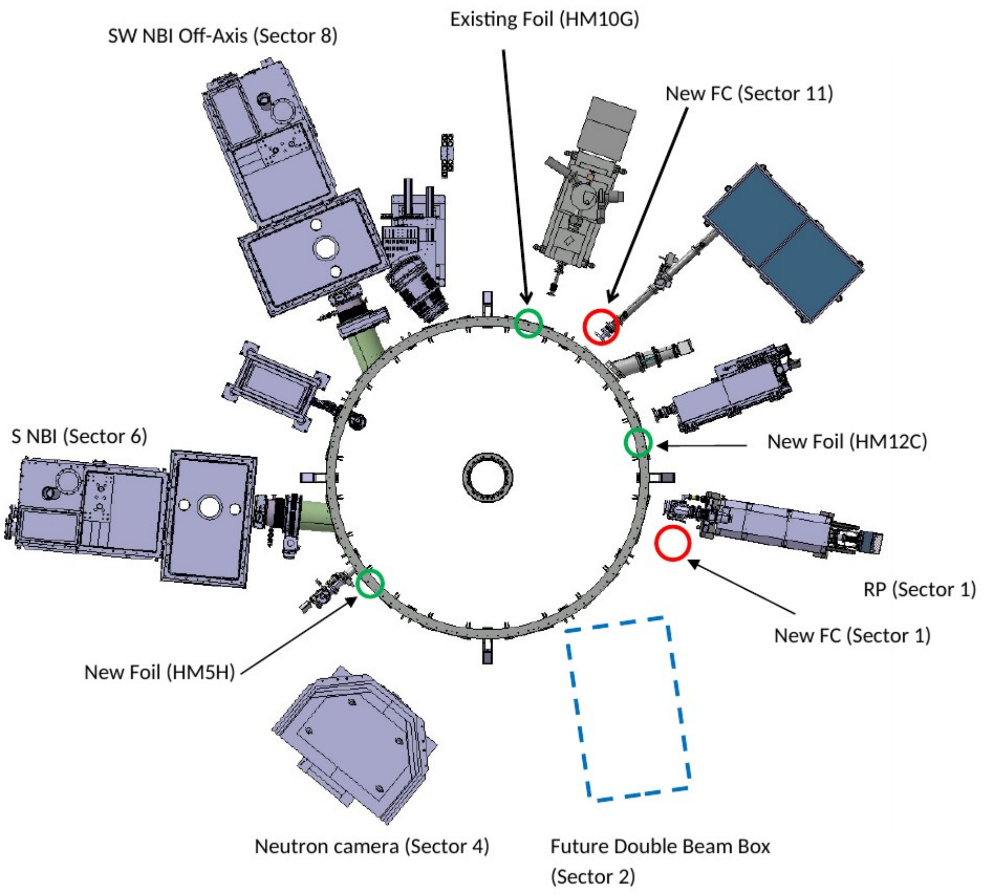
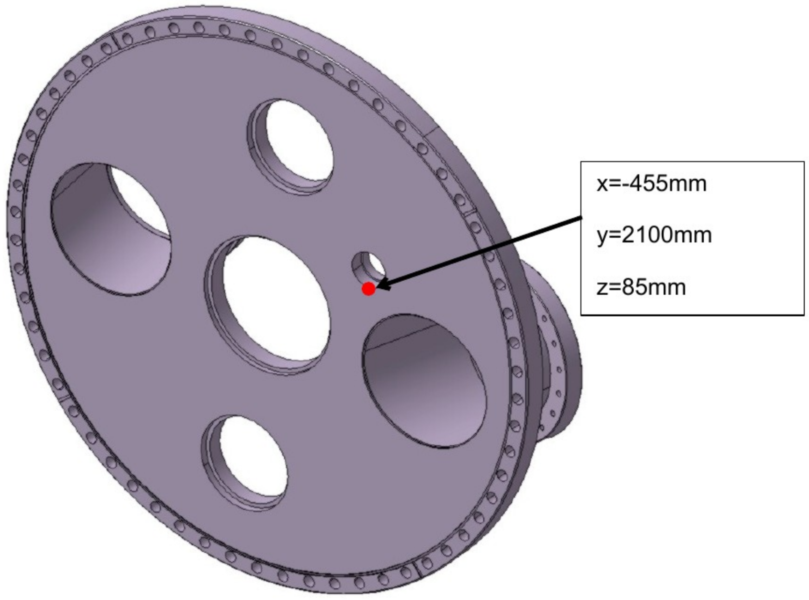
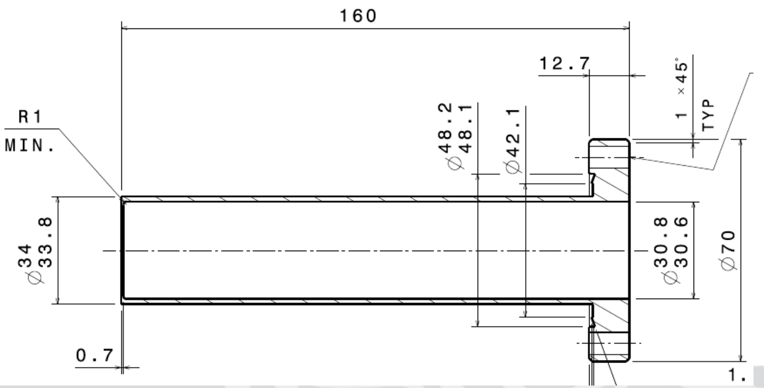
Activation foil measurements at MAST Upgrade

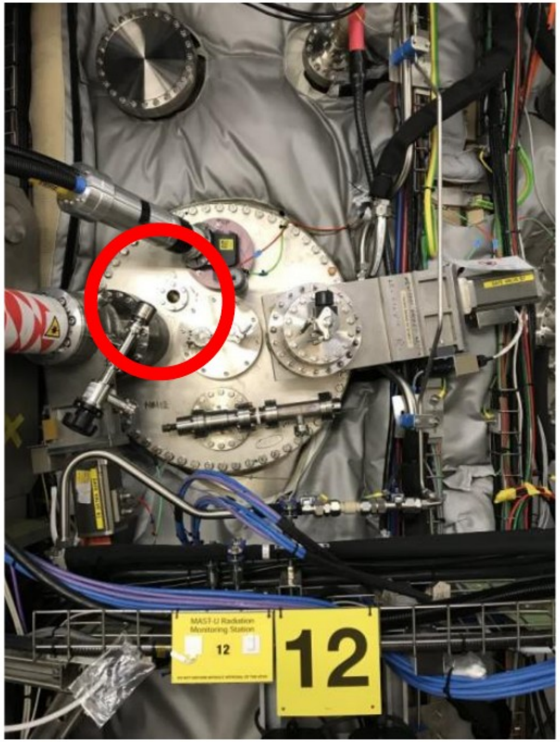


- HM12-C





^{115}In activation foil (HM12-C)



^{115}In foils properties:

- Diameter, Thickness — 25 mm, 4 mm
- Volume — 1.9635e-06 m^3
- Mass — 14.35 g
- Isotopic fraction — 0.9571 % ^{115}In and 0.0429 % ^{113}In
- Number of ^{115}In atoms — 7.2075×10^{22}
- Atomic density n — 3.6708×10^{28} m^{-3}
- Half-life — 4.486 h
- Position (centre) — R = 201.17 cm, Z = 10 cm

^{115}In activation campaign at MAST U:

Indium activation foils used on 4 days in October of MU01: **8^{th}**, 15^{th}, 22^{nd} and 28^{th}

Pulse	Pulse Time	Time (s)	SS Δt (s)	SW Δt (s)	FC Δt (s)	FC Δt (s)	FC Δt (s)	FC Yield (x 10^13)	Scaling Factor
45212	11:56:00 AM	0	0.340	0.340	0.728	0.323	0.405	0.548	1.712
45214	12:44:00 PM	2880	0.343		0.703	0.323	0.380	0.276	0.916
45215	01:42:00 PM	6360		0.600	0.700	0.100	0.600	0.1456	0.000
45216	02:14:00 PM	8280	0.556	0.597	0.760	0.160	0.600	1.152	3.478
45218	02:43:00 PM	10020	0.277	0.600	0.717	0.105	0.612	0.3458	1.120
45219	03:03:00 PM	11220	0.600	0.298	0.719	0.100	0.619	0.8672	2.645
45220	03:42:00 PM	13560		0.299	0.706	0.403	0.303	0.07365	0.000
45221	04:02:00 PM	14760	0.599	0.300	0.707	0.104	0.603	0.5276	1.652
			2.7145	**3.034**			4.122	**3.93585**	
44863								0.7054	
45006								0.3419	
45083								0.109	

Reference pulses

Gamma-rays measurements

γ-ray spectra	Start time	End time
Start	04:26:50 PM	16250
End		102767.65

TRANSP runs for reference pulses

NBI Setup	Reference Pulses	Estimated Flux (1/m2s)	at time (s)
SW	45083U12	1.152E+11	0.4
SS	45006U13	1.097E+12	0.4
SS + SW	44863U10	1.639E+12	0.4
SS + SW	45212U03	1.560E+12	0.4

Activation

Rate at which activation interactions occur in the foil:

$$R = \phi V \Sigma$$

ϕ average flux [m^{-2} s^{-1}]
V foil volume [m^3]
Σ macroscopic cross-section averaged over neutron spectrum [m^{-1}]

Assumptions:

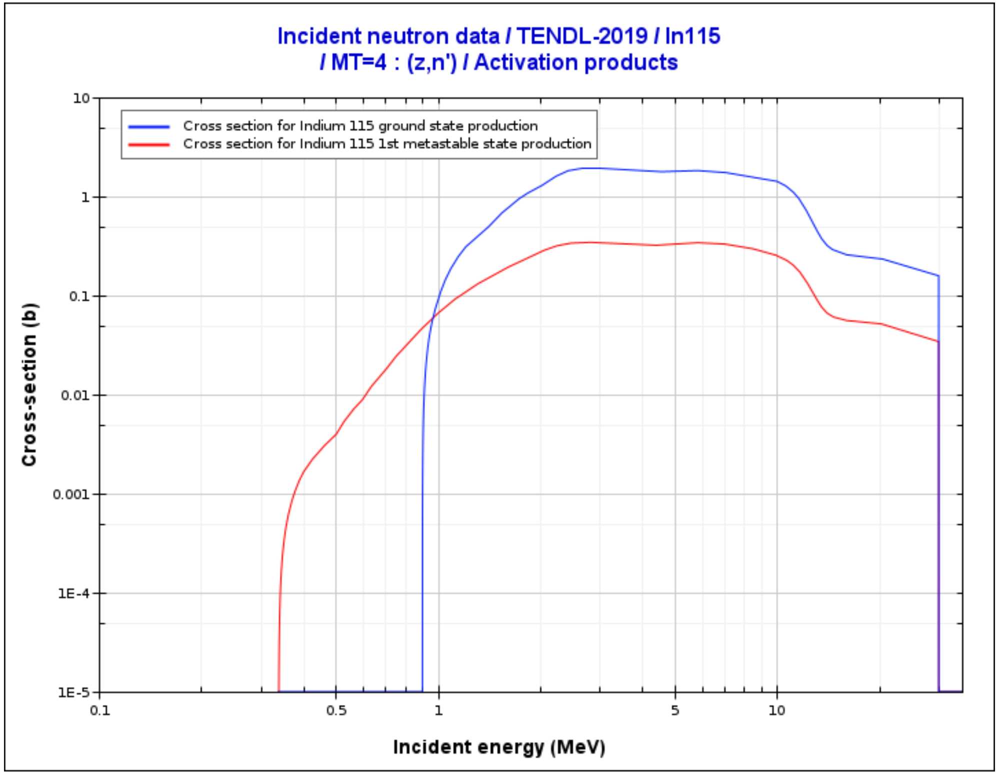
- Foil is so thin that ϕ is not perturbed,
- ϕ is constant,
- Target burn-up is negligible.

Rate of target nuclei being activated

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = R - \lambda N(t)$$

$\lambda = ln(2)/t_{1/2}$ decay constant [s^{-1}].

^{115}In activation



Threshold at about $E_n = 0.35$ MeV

$$^{115}\mathrm{In} + n \rightarrow ^{115m}\mathrm{In}$$

$$\begin{cases} ^{115m}\mathrm{In} \rightarrow ^{115}\mathrm{In} + \gamma & 95\ \%,\ E_\gamma = 0.336\ \mathrm{MeV} \\ ^{115m}\mathrm{In} \rightarrow ^{115}\mathrm{Sn} + \beta^- & 5\ \% \end{cases}$$

(branching ratio 46 %)

Average cross-sections:

$$<\sigma>= 0.3074 \quad \mathrm{barn} \qquad E_\mathrm{n} \in [2;3] \quad \mathrm{MeV}$$

$$<\Sigma>=<\sigma>n = 1.1285 \quad 1/\mathrm{m}$$

Activation after single irradiation

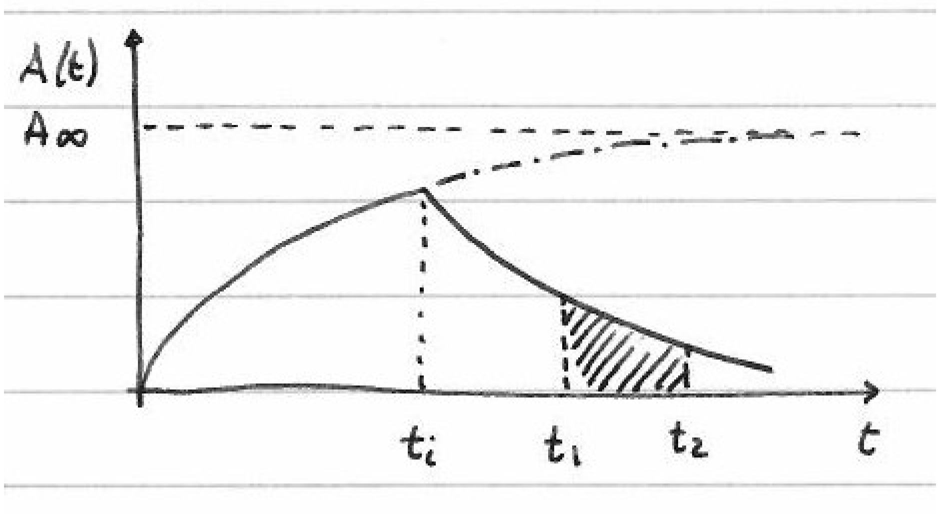
Number of target nuclei being activated after and irradiation time t_i (assuming $N = 0$ at the start of the irradiation):

$$N(t_i) = \frac{R}{\lambda}\left(1 - e^{-\lambda t_i}\right)$$

Activation after and irradiation time t_i

$$A(t_i) = A_\infty \left(1 - e^{-\lambda t_i}\right)$$

$A = \lambda N$	activity
A_∞	saturated activity ($t = \infty$)



Counts on detector (after single irradiation)

Post-irradiation detector counts with measuring time between $[t_1,\, t_2]$:

$$C = \epsilon A(t_i) \int_{t_1}^{t_2} e^{-\lambda(t-t_i)} \mathrm{d}t + B$$

ϵ	detector efficiency (at appropriate energy)
B	background counts

$$C = \epsilon \frac{A_\infty}{\lambda} \left(1 - e^{-\lambda t_i}\right) e^{\lambda t_i} \left(e^{-\lambda t_1} - e^{-\lambda t_2}\right) + B$$

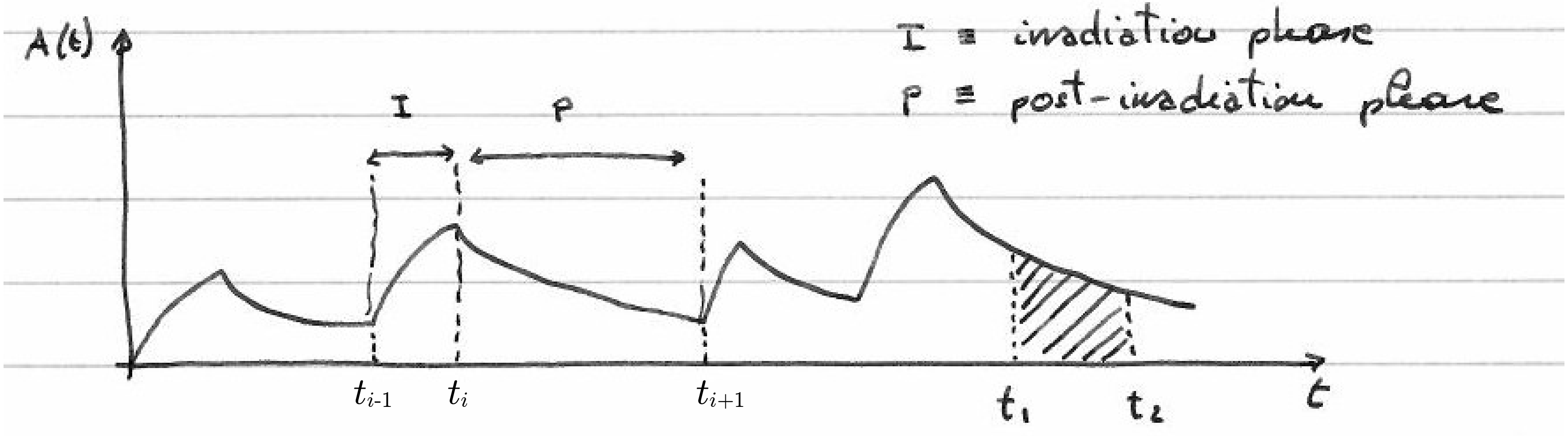
Saturated activity:

$$A_\infty = \frac{\lambda(C-B)}{\epsilon\left(1 - e^{-\lambda t_i}\right) e^{\lambda t_i} \left(e^{-\lambda t_1} - e^{-\lambda t_2}\right)}$$

Neutron flux from measured counts:

$$\phi = \frac{A_\infty}{\Sigma V}$$

Activation after multiple irradiation



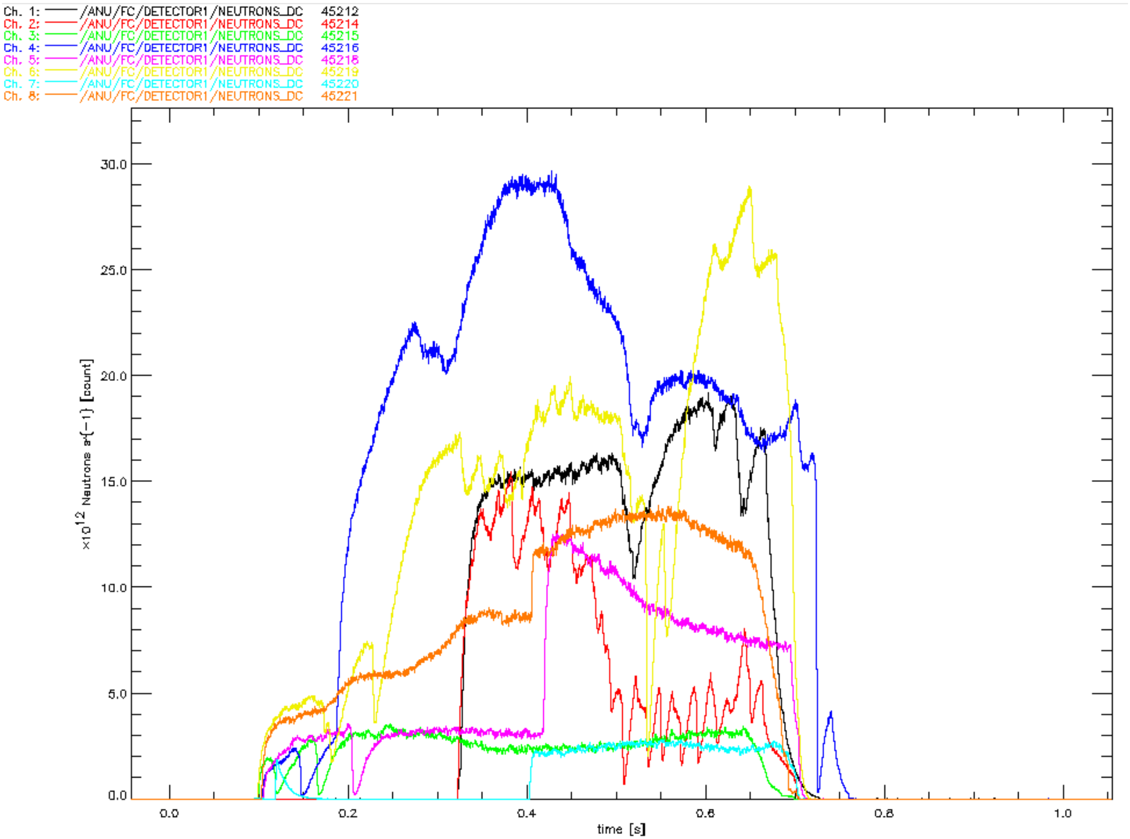
Irradiation phase: $N(t_i) = N(t_{i-1})e^{-\lambda(t_i - t_{i-1})} + \frac{R}{\lambda}\left[1 - e^{-\lambda(t_i - t_{i-1})}\right]$ since $\lambda(t_i - t_{i-1}) \approx 2 \times 10^{-5} \ll 1$

$$\approx N(t_{i-1}) + R(t_i - t_{i-1})$$

Post-irradiation phase: $N(t_{i+1}) = N(t_i)e^{-\lambda(t_{i+1} - t_i)}$ $\lambda(t_{i+1} - t_i) \approx 8.6 \times 10^{-2} < 1$

$$\approx N(t_i)[1 - \lambda(t_{i+1} - t_i)]$$

Neutron rates for the 8th of October



Neutron flux is not constant during irradiation!

$$R(t) = \phi(t) V \Sigma$$

Activation with non constant neutron flux

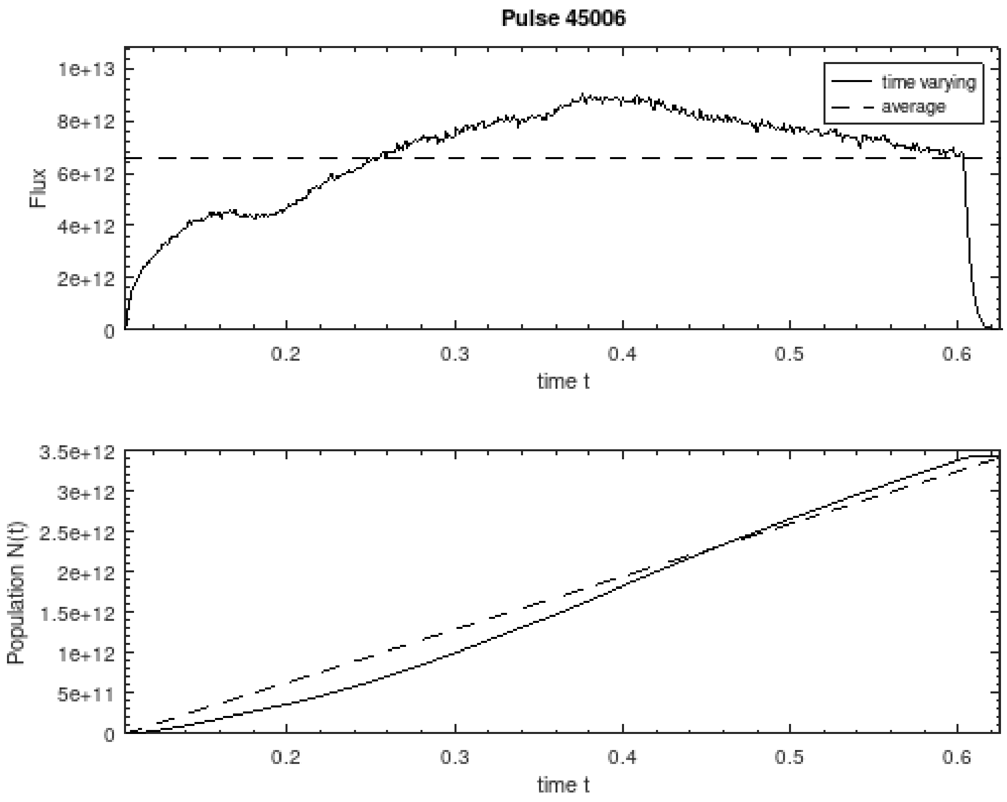
Rate of target nuclei being activated

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = R(t) - \lambda N(t)$$

Assuming that the neutron flux is equal to the neutron rate (unit area) and ignoring units:

- Exact numerical solution with time dependent $Y_n(t)$
- Approximate solution with time independent $Y_n = <Y_n(t)>$

0.3 % difference in the final activation.



Estimate of the neutron flux at the activation foil

Two different approaches:

- TRANSP/NUBEAM for direct neutron flux with the addition of the scattered contribution either from “best guess” or MNCP,
- MCNP to provide the flux per simulated particle at the activation foil and at the FC which is then scaled to match the neutron counts on the absolutely calibrated FC.

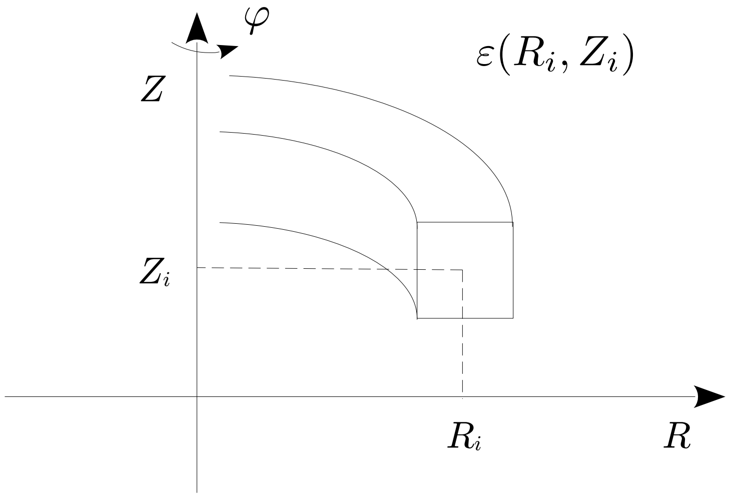
Estimate of the neutron flux at the activation foil

- TRANSP/NUBEAM used to estimate the 2.5 MeV direct neutron flux (with 44/44 energy fractions),
- Scattered neutron flux (ideally via MCNP) or assumed to be a certain % of the direct one,
- Attenuation due to the 0.7 mm thick SS thin flange,
- Neutron/γ-ray self-shielding in the ^{115}In foil.

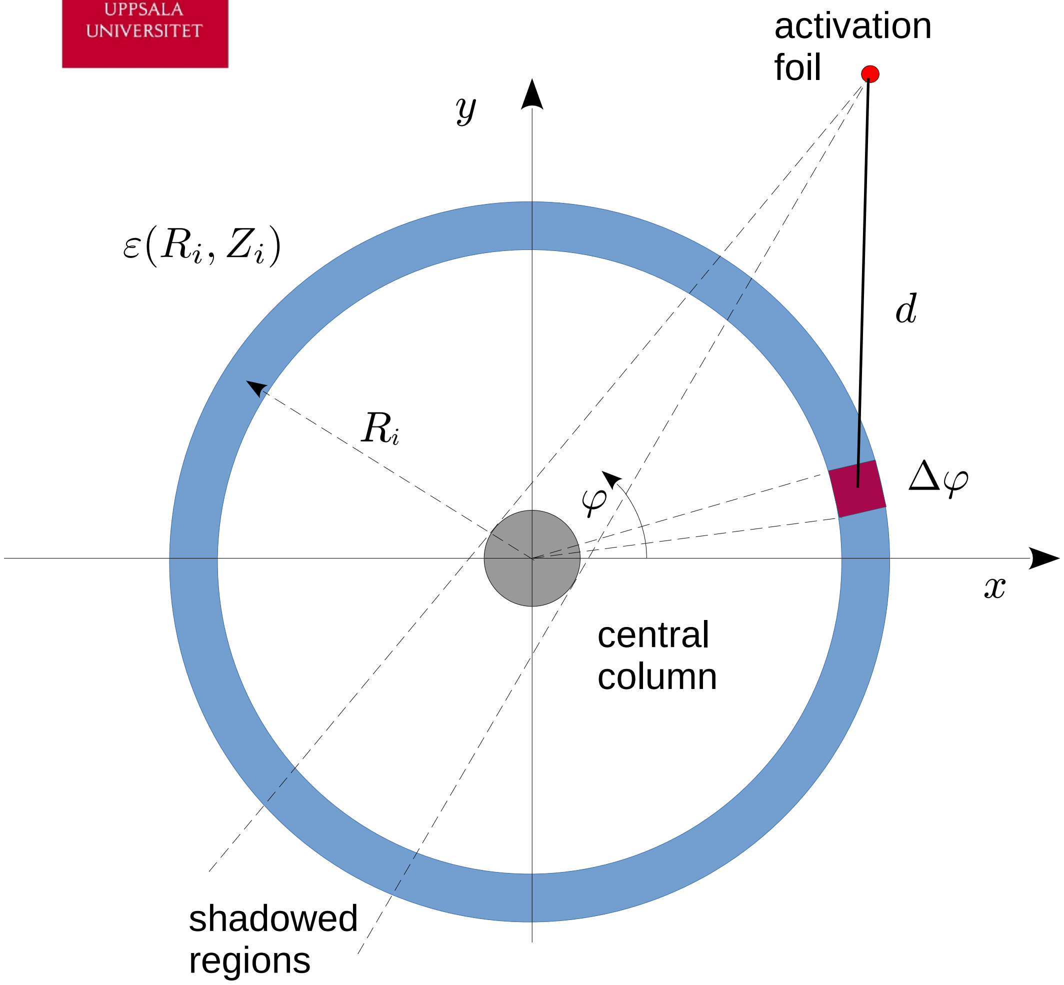
$$R(t) = \phi(t) V \Sigma$$

TRANSP/NUBEAM calculates the axis-symmetric neutron emissivity in toroidal tubes:

$\varepsilon(R_i, Z_i)$	[cm^{-3}s^{-1}]
V_ε	volume



Direct neutron flux at the activation foil



Isotropic neutron emission from each volume

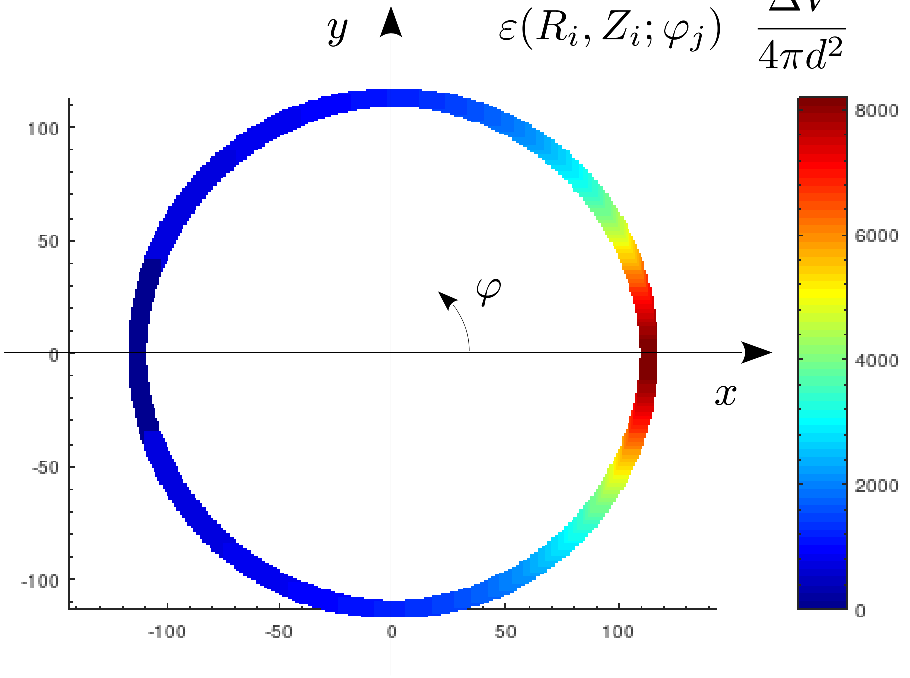
$$\Delta V = \frac{\Delta\varphi}{2\pi} V_\varepsilon$$

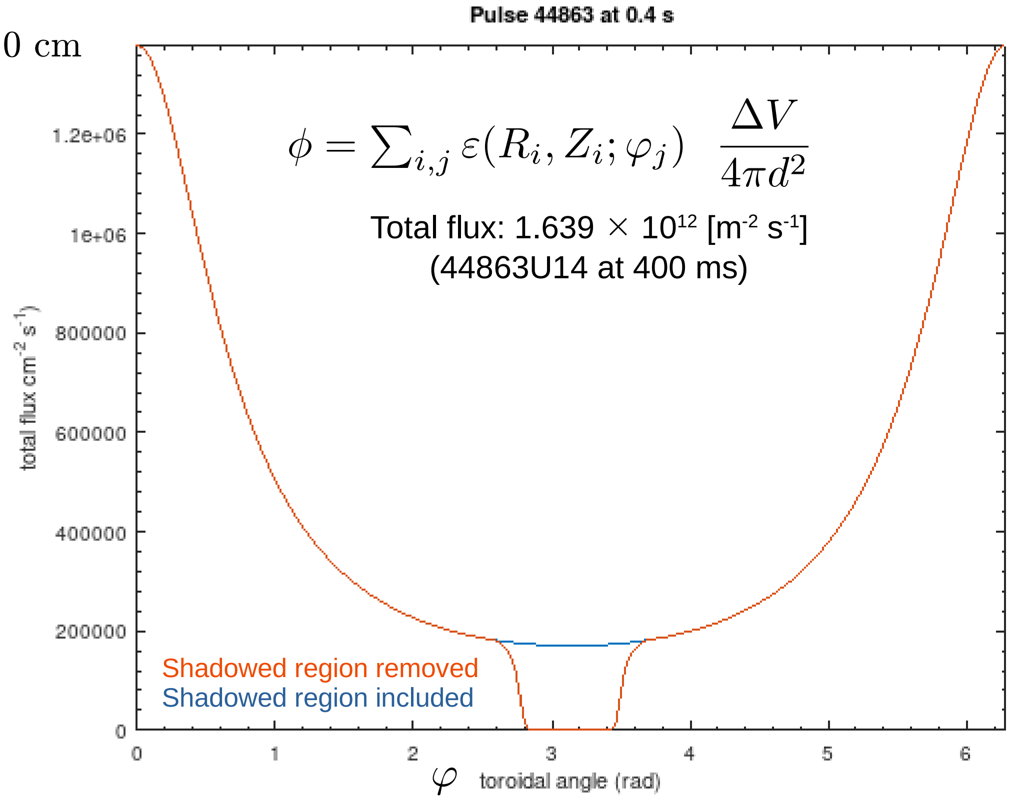
$$\phi = \sum_{i,j} \varepsilon(R_i, Z_i; \varphi_j) \frac{\Delta V}{4\pi d^2}$$

with the exception of the emission from the shadowed region.

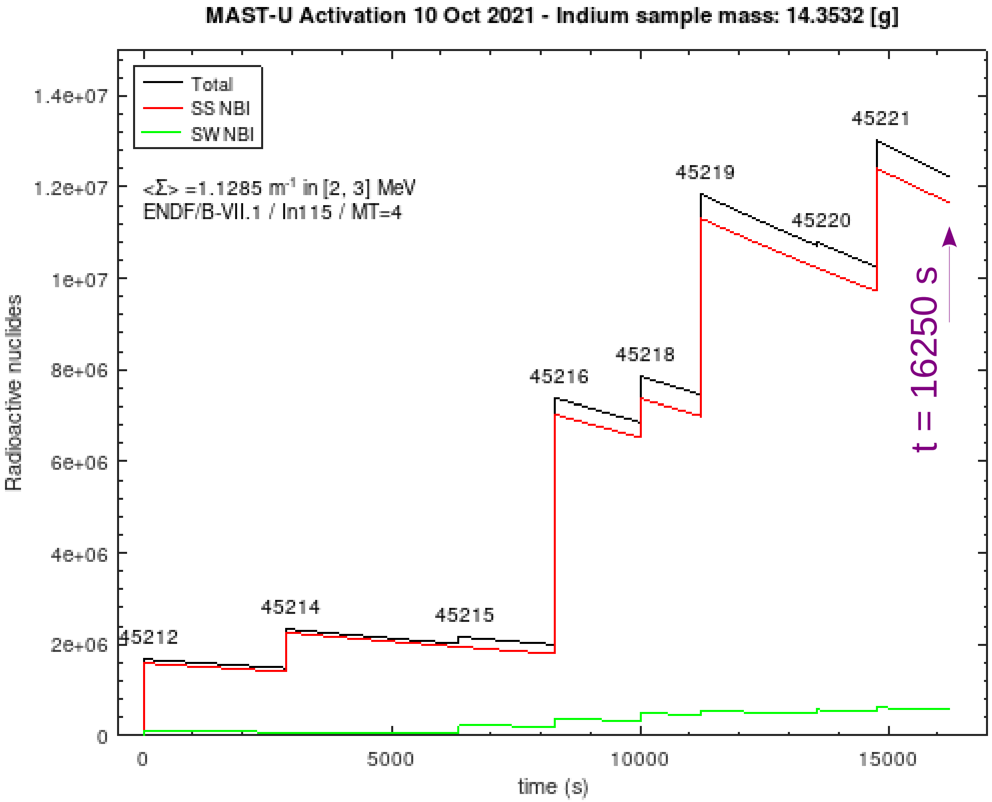
Direct neutron flux at the activation foil

- Non-flux averaged neutron emissivity at a fixed time in the discharge (assumed to be representative for the whole plasma discharge) for reference plasmas
- Activation foil at $\varphi = 0\,\text{rad},\ x = 201.17\ \text{cm},\ z = 10\ \text{cm}$





Estimated total activation on Oct, 8th



- Based on TRANSP/NUBEAM runs for reference pulses scaled to match the neutron rates of the actual pulses;
- Individual contributions from SS and SW NBIs;
- 44/44 energy fractions for the SS NBI;
- Assumed $Z_{\mathrm{eff}} = 1.5$;
- Scattered neutron flux at 10 % of direct one with averaged cross-section in [0, 2] MeV;
- Start of activation foil γ-rays measurements at t = 16250 s (after the start of the 1st pulse).

Estimated counts at the detector

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- Uncertainty in the TRANSP/NUBEAM neutron emissivity is assumed to be 10 % (input profiles);
- Uncertainty in the cross-section from FENDL is 15 %;
- Detector absolute efficiency at 0.336 MeV is $\epsilon = 0.076$ (8% uncertainty);
- Branching ratio is $B_R = 0.46$;
- Averaged self-attenuation of 0.336 MeV γ-rays in ^{115}In foil is $k_{SA} = 0.82$;
- Correction factor for over-estimate of neutron rate due to GC approximation in TRANSP/NUBEAM $k_{GC} = 0.4$ - 0.65;
- Neutron attenuation in thin flange is $f_n = 0.96$.

Expected counts:

$$N_E = \epsilon f_n B_R k_{\text{SA}} k_{\text{GC}} N_{\text{TRANSP}}$$

$$N_E = (1.3 \pm 0.2) \times 10^5 \qquad k_{GC} = 0.4$$

$$N_E = (2.1 \pm 0.4) \times 10^5 \qquad k_{GC} = 0.65$$

Measured counts:

$$N_E = (1.740 \pm 0.004) \times 10^5$$

On- and off-axis NBI heating

L-mode plasmas in double-null divertor configuration with a 600 kA plasma current.

Selected since they exhibited time intervals free of the typical MHD instabilities affecting the fast ions.

No fast ion anomalous diffusion.

Scaling factor to match TRANSP and NCU is:

$$k = 0.4$$

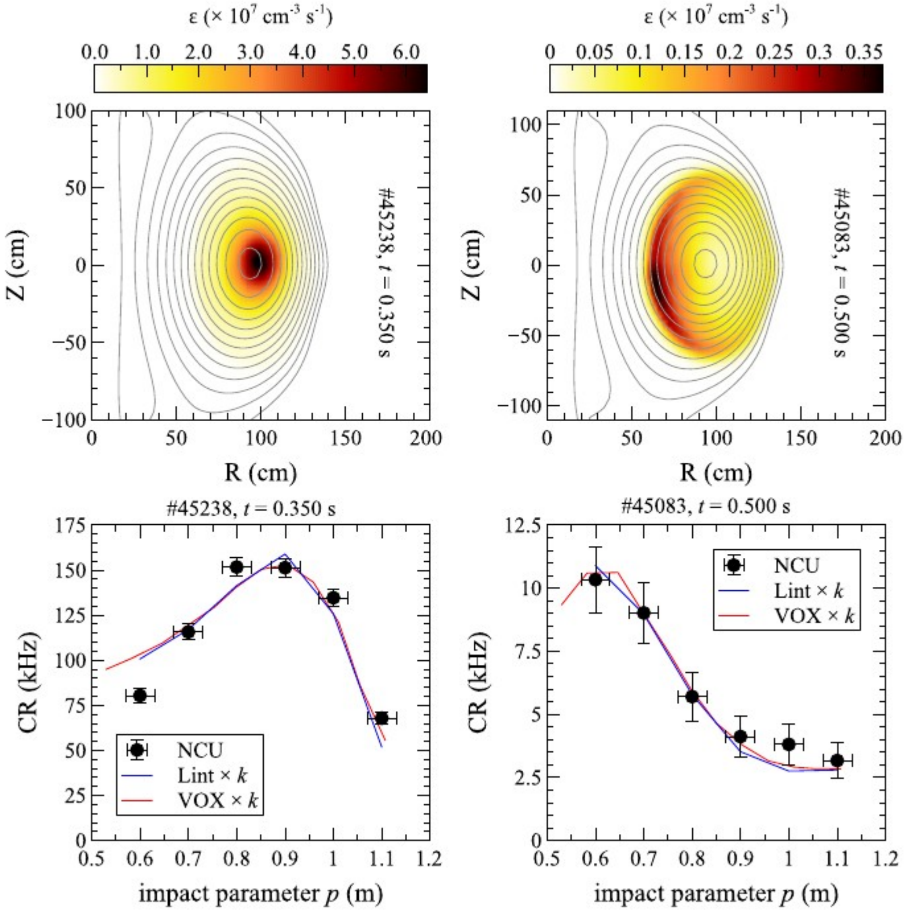
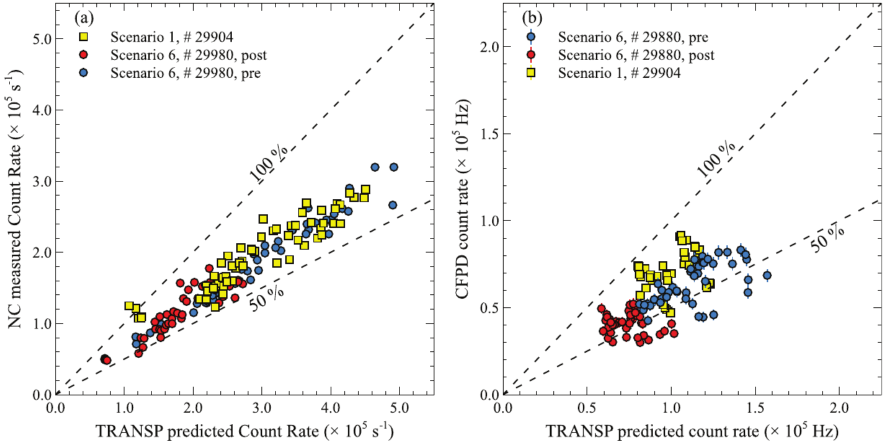


Figure 4 – Top row: TRANSP/NUBEAM calculated neutron emissivity for pulses #45006 at $t = 0.350$ s with on-axis NBI heating only (left panel) and #45083 at $t = 0.500$ s with off-axis NBI heating only. Bottom row: comparison between NCU measurements (black solid circle) and predictions based on the neutron emissivities shown above using simple line of sight integrals (Lint, blue line) and the full 3D field of view geometry (VOXels, red line). The scaling factor is $k = 0.4$.

Scaling factor in MAST and MAST U



Scenario	k_{NC}	k_{PD}
S1	0.69 ± 0.01	0.72 ± 0.02
S2	0.70 ± 0.01	0.71 ± 0.01
S3	0.59 ± 0.01	—
S4	0.68 ± 0.01	—
S5	0.64 ± 0.01	—
S6 (pre)	0.63 ± 0.01	0.57 ± 0.01
S6 (post)	0.64 ± 0.01	0.56 ± 0.02

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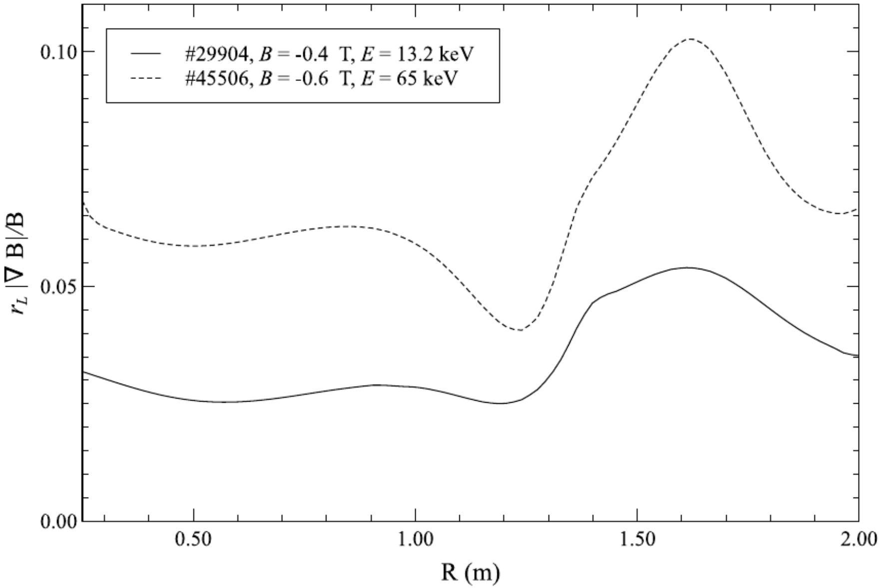
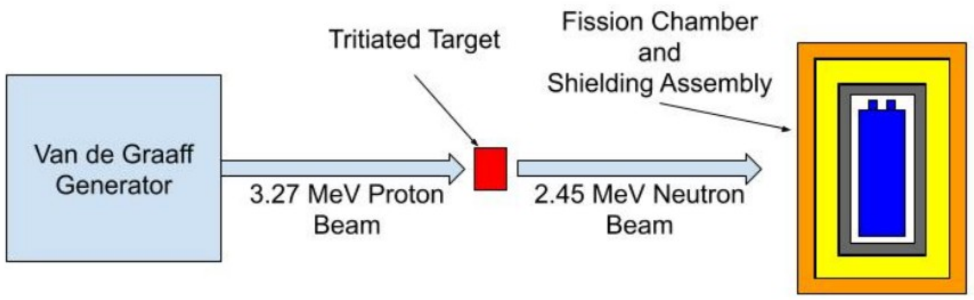


Figure 5 – Example of the relation $r_L|\nabla B|/B$ calculated for MAST (#29904, solid line) and MAST-U (#45006, dahsed line) equilibria at $t = 240$ ms along the major radius for $Z = 0$ m for fast ions with equal $\sqrt{E}/B^2$ and with $\lambda = -0.8$.

Fission chamber

- Two ^{235}U fission chambers (Centronic FC765/1670/235) for 2.45MeV neutron measurements.
- Absolute calibration at NPL combined with MCNP model of MAST Upgrade to transfer the calibration at location on MAST Upgrade (Mid-plane Sectors 1 and 11).
- Shielding:

Material + Thickness	Purpose
Lead (t=45mm)	Block γ rays
HDPE (t=50mm)	Slow neutrons to thermal energies (<1eV)
Cadmium (t=0.5mm)	Block incident thermal neutrons
Aluminium (t=12mm)	Structural support



Fission chamber: MAST vs MAST-U

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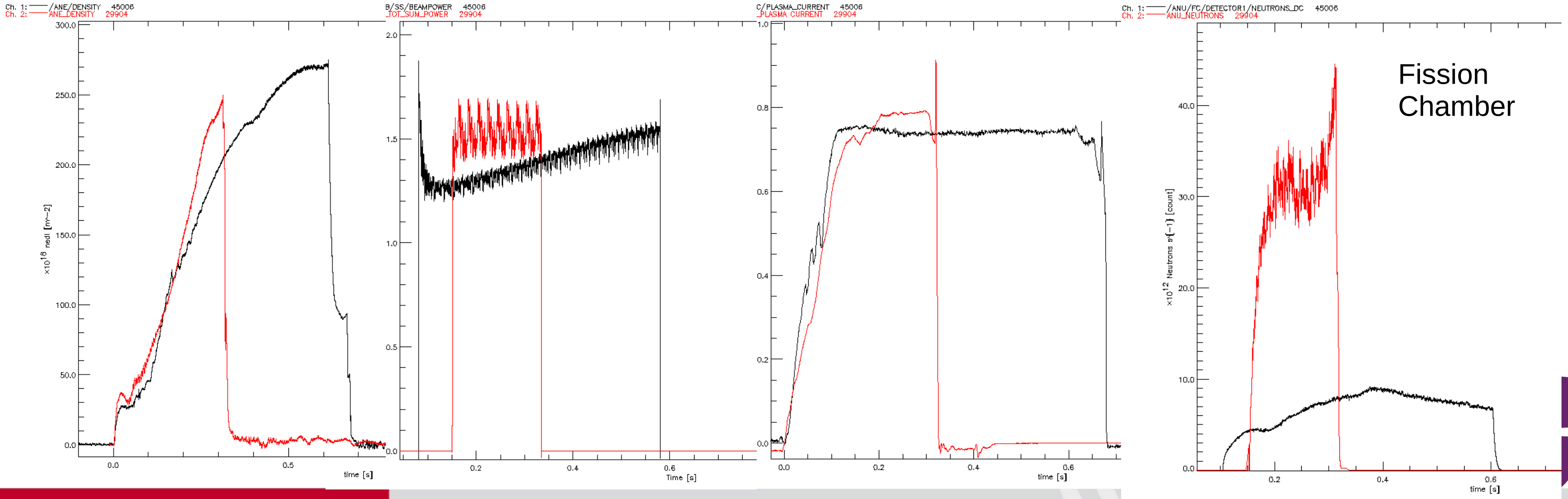
MAST — SS only, quiescent, high density, 750 kA, E_{NBI} = 60 keV, $T_e(0)$ = 1 keV, $n_e(0) = 6 \times 10^{19}$ m^{-3}

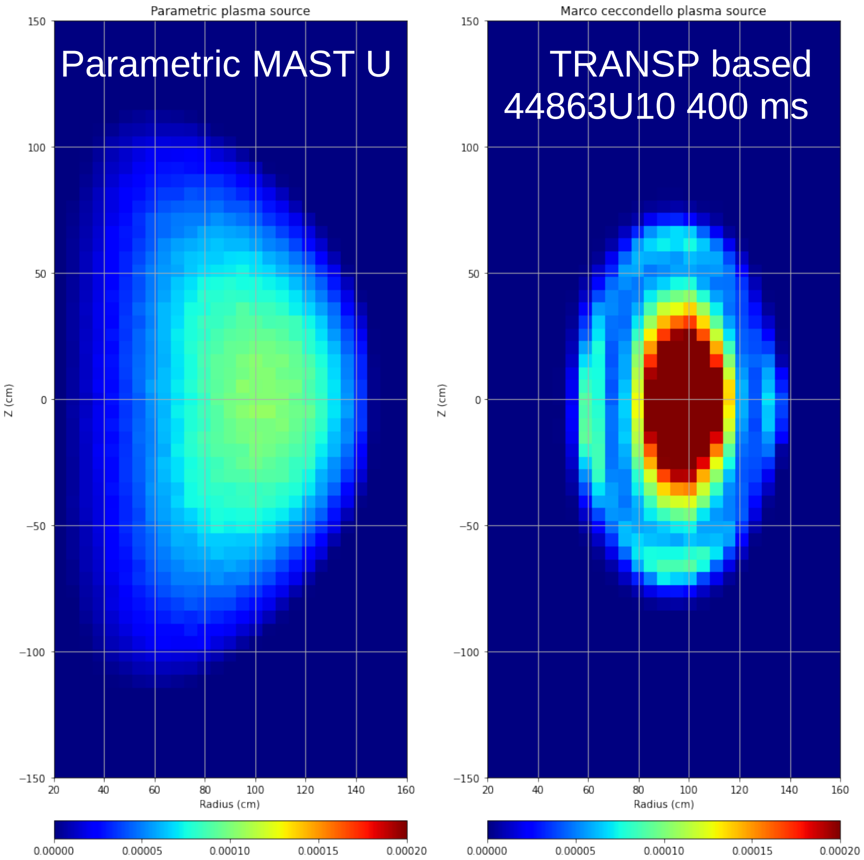
MAST U — SS only, quiescent ?, high density, 750 kA, E_{NBI} = 65 keV, $T_e(0)$ = 1.1 keV, $n_e(0) = 4 \times 10^{19}$ m^{-3}

Reactivity: $\langle \sigma v \rangle = 1.8 \times 10^{-24}$ m^3/s

$\langle \sigma v \rangle = 2.1 \times 10^{-24}$ m^3/s

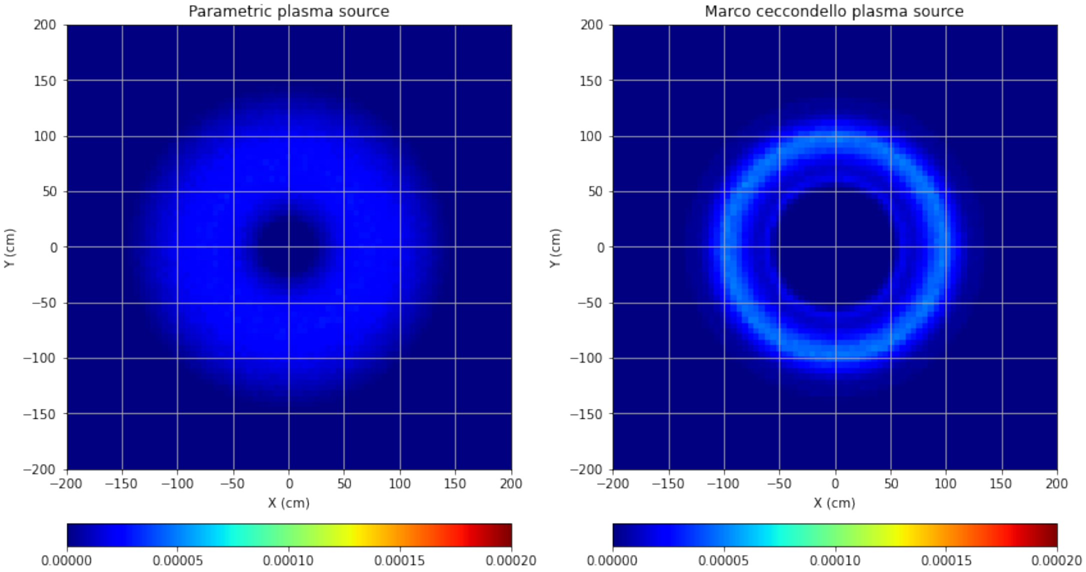


MCNP modelling: neutron source



Parametric MAST U

TRANSP based



MCNP modelling: neutron flux at fission chamber location (F2 tally)

Original Point Source(*) (source neutrons / neutron $cm^{-2} \times 10^5$)	43644 MCNP Source (source neutrons / neutron $cm^{-2} \times 10^5$)	MU01 MCNP Source (source neutrons / neutron $cm^{-2} \times 10^5$)
7.85	5.38	5.12

Using more accurate MCNP source results in a 5 % difference in the flux ...

(*)neutron source was a point at the centre of the vessel which emitted spherically out to the fission chamber which was taken to be at a radius of 2.5m

Conclusions

TRANSP/NUBEAM modelling of the activation in relatively good agreement with experimental measurements of the Indium foil.

FC calibration transfer from beam-target facility to tokamak environment not as simple as expected.

MAST Upgrade calibration to proceed with neutron activation system coupled to MCNP and TRANSP/NUBEAM modelling.

In-situ calibration with neutron source pending results from current calibration campaign with In foils.

Additional material

Comparing NC and NCU collimation geometry and predicted count rates

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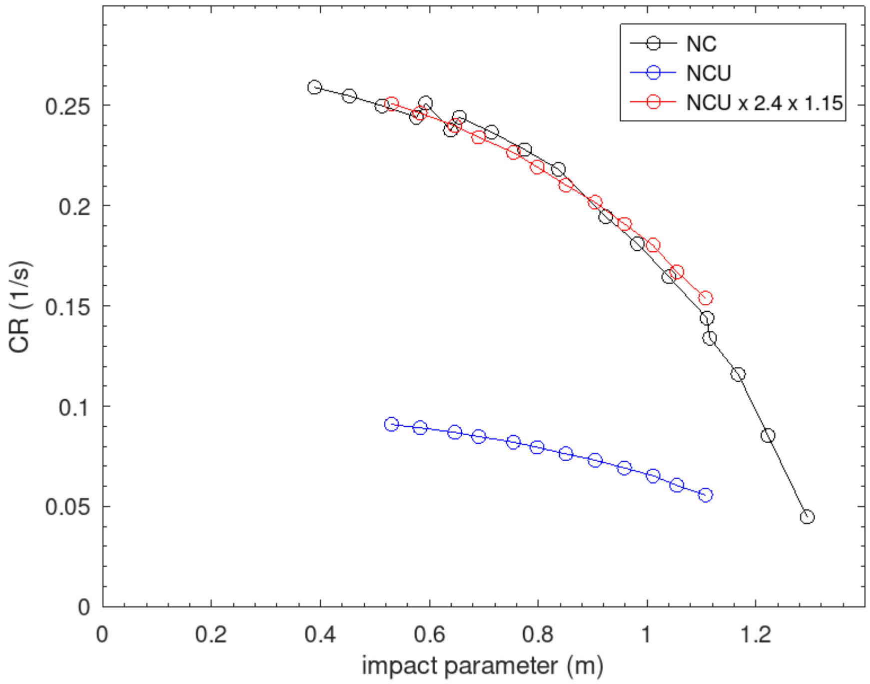
$$\nu_{\mathrm{n}}(p) = \eta\epsilon \sum_{i,j} \varepsilon_{\mathrm{n}}(R_{i,j}, Z_{i,j})\Omega(p; R_{i,j}, Z_{i,j})$$

- $\eta\epsilon$ **is the same** for both NC and NCU
- the solid angles Ω (collimators) are not, but
- assuming constant, **unit emissivity** allows the comparison of the solid angles by using an
- analytical expression for the count rates allows to compute the expected ratio between the solid angles:



$$\nu_{\mathrm{NC}} = k(a,b,L) \int_p \varepsilon(\ell)\mathrm{d}\ell$$

$$\nu_{\mathrm{NCU}} = k(D,L) \int_p \varepsilon(\ell)\mathrm{d}\ell$$

$$\Rightarrow \quad \frac{k(a,b,L)}{k(D,L)} \approx 2.76$$

Predicted neutron count rates

TRANSP neutron emissivity

Field of view/Solid angle...

Integration over the poloidal cross-section

… dependent on the impact parameter

$$\nu_{\mathrm{n}}(p) = \eta\epsilon\sum_{i,j}\varepsilon_{\mathrm{n}}(R_{i,j},Z_{i,j})\,\Omega(p;R_{i,j},Z_{i,j})$$

Impact parameter

Trasmission of neutron through flange and detector casing

Detector efficiency for 2.45 MeV neutrons including the effect of DAQ threshold

Measured neutron count rates

Number of single neutron events
in the given time interval

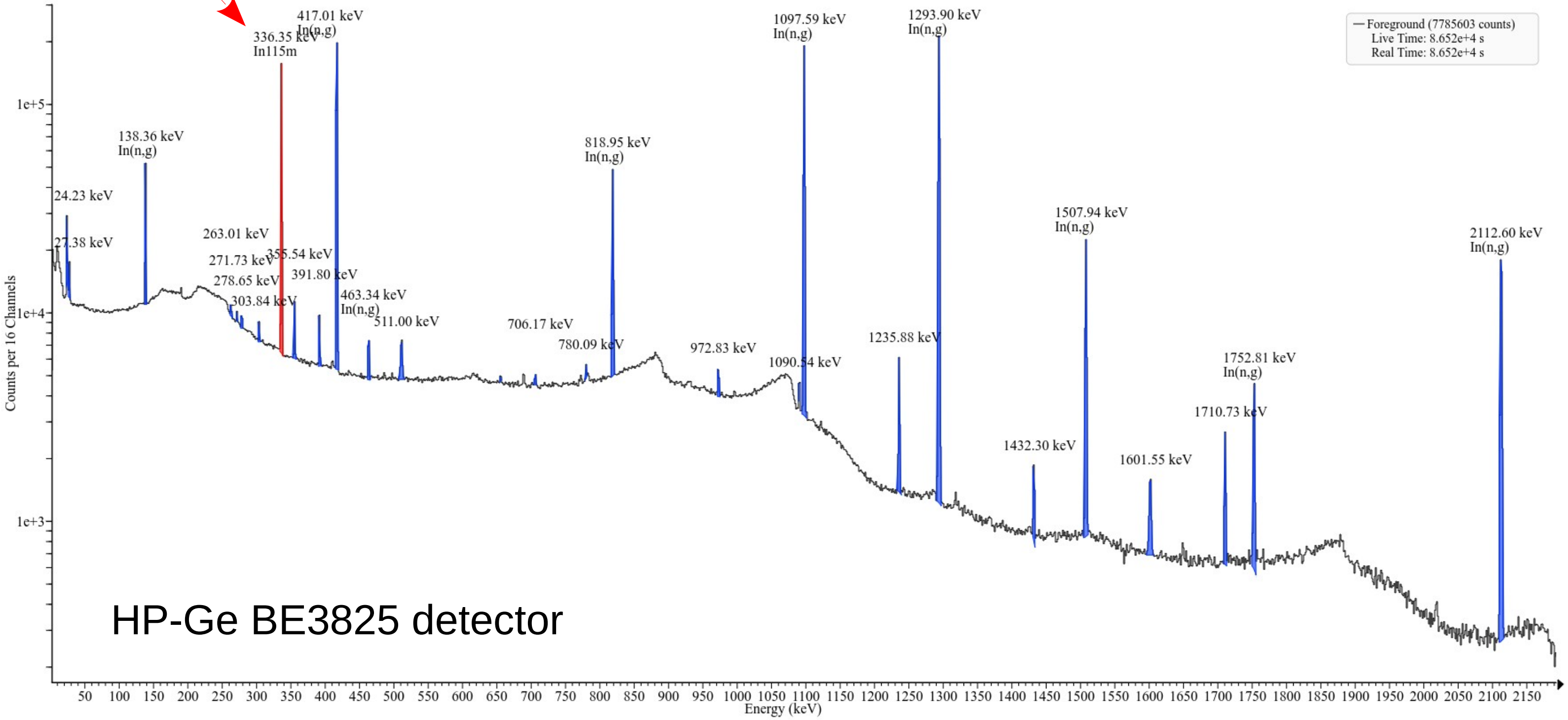
$$\nu_{\mathrm{NC}}(t_i) = \rho \frac{N(t_i)}{\Delta t}$$

Correction factor to account for pile-up
and DAQ dead time (typically 1.05 – 1.10)

Measured counts at the detector

Measured counts: $N_E = (1.740 \pm 0.004) \times 10^5$

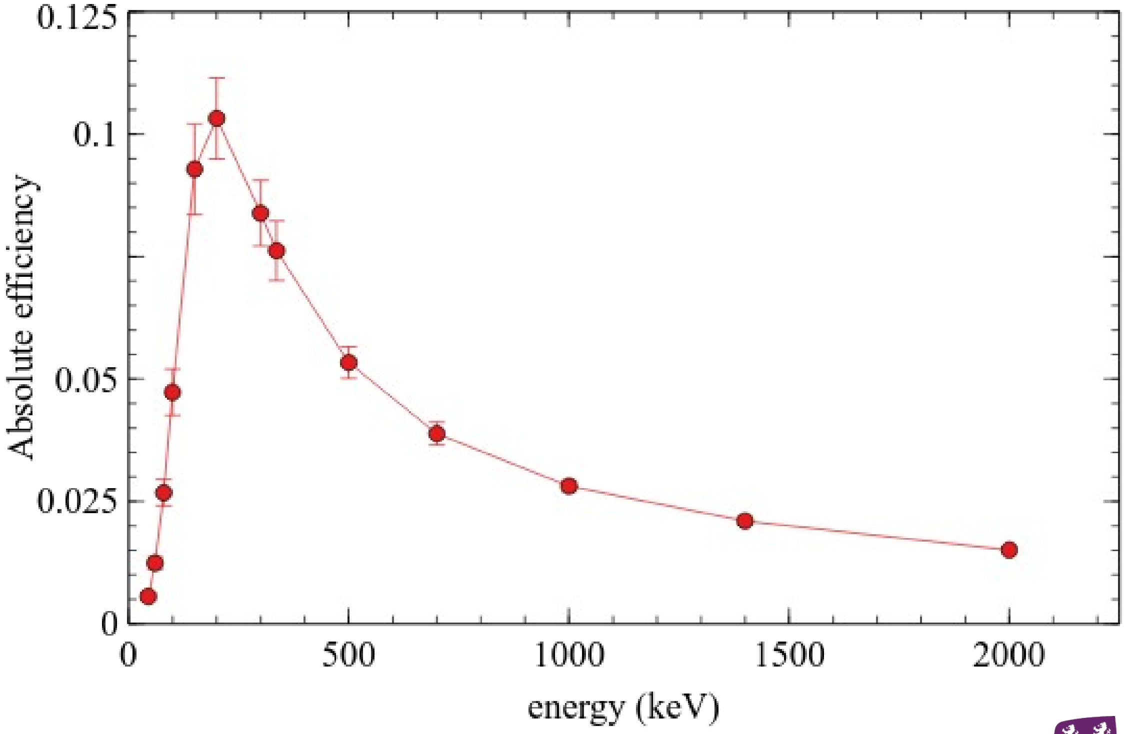
Delayed gamma-rays from induced neutron capture



HP-Ge BE3825 detector

BEGe efficiency

- Efficiency calculated with Canberra LabSOCS software (based on MCNP)
- Detector absolute efficiency at 0.336 MeV is $\epsilon = 0.076189$ (8% uncertainty)



Delayed gamma-rays from induced neutron capture

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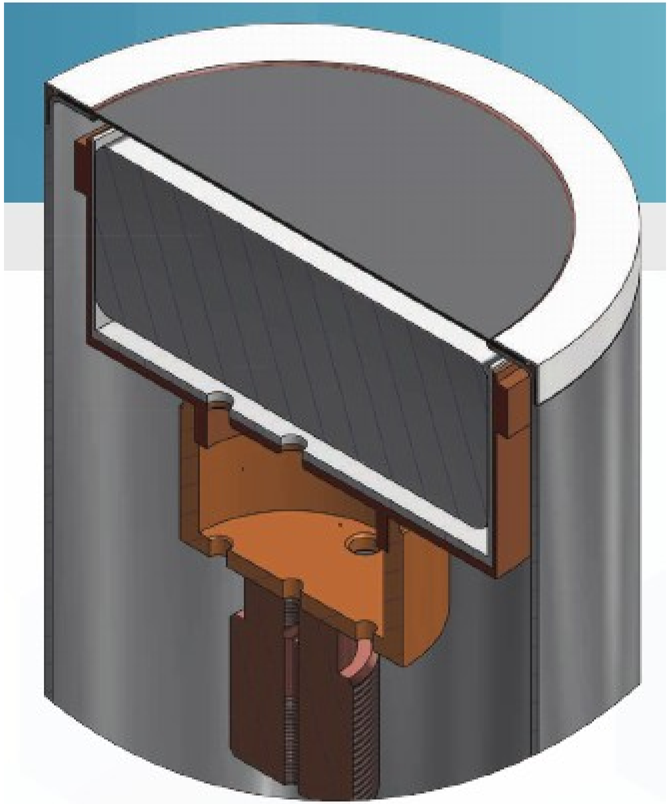
Table 3 Delayed gamma rays induced by neutron capture

E_γ(keV)	$I_{E\gamma}$(%)	$P_{E\gamma}/\varepsilon E_\gamma \cdot f_\gamma$($\times10^{-8}$) (Count)	$\langle\sigma_{E\gamma}\rangle$(mb)	$\langle\sigma_{int}\rangle$(b)	$\sigma_{E\gamma,th}$ (b)
^{116m}In					
138.3	3.29	3.9 ± 0.3	17.6 ± 1.5	0.53 ± 0.04	5.34 ± 0.19
416.9	27.7	30 ± 1	135 ± 6	0.49 ± 0.02	44.9 ± 0.2
463.3	0.83	0.89 ± 0.08	4.0 ± 0.4	0.48 ± 0.05	1.33 ± 0.08
818.7	11.5	14.0 ± 0.5	63 ± 3	0.55 ± 0.03	18.6 ± 0.7
1097.3	56.2	64.7 ± 1.9	291 ± 13	0.52 ± 0.02	91.2 ± 0.2
1293.6	84.4	96.9 ± 2.9	437 ± 20	0.52 ± 0.02	137 ± 3
1507.6	10.0	10.7 ± 0.4	48.3 ± 2.5	0.48 ± 0.02	16.2 ± 0.5
1752.2	2.46	2.7 ± 0.1	12.2 ± 0.6	0.50 ± 0.02	3.99 ± 0.12
2111.8	15.5	17.3 ± 0.6	78.0 ± 3.9	0.50 ± 0.02	25.2 ± 0.7
^{116m2}In					
162.4	37.2	19.1 ± 0.7	74.8 ± 3.8	0.20 ± 0.01	16.5 ± 0.8

E_γ is the gamma-ray energy, $I_{E\gamma}$ the gamma-ray intensity, $P_{E\gamma}/\varepsilon E_\gamma \cdot f_\gamma$ the net count in the gamma-ray peak divided by the full-energy-peak efficiency and the gamma-ray self-absorption factor, $\langle\sigma_{E\gamma}\rangle$ the neutron spectrum-averaged isotopic cross section for gamma ray production by Eq. (4), $\langle\sigma_{int}\rangle$ is the neutron spectrum-averaged cross section for the reaction calculated by means of Eq. (6) and $\sigma_{E\gamma,th}$ is the isotopic cross section for gamma ray production from thermal neutron capture [14].

Broad Energy Ge detector



- Energy range from 3 keV to 3 MeV combines the spectral advantages of Low Energy and Coaxial HPGe detectors
- Detection efficiencies and energy resolutions are optimized in the 3 keV to 662 keV energy region where most tightly-grouped gamma lines of interest are located
- Flat, non-bulletized crystals offer optimum efficiencies for samples counted close to the detector
- Thin, stable entrance window allows the detector to be stored warm with no fear of low energy efficiency loss over time
- Equipped with Intelligent Preamplifier
- USB 2.0 Serial Interface

Backward activation calculation

Measured counts: $N_E = (1.740 \pm 0.004) \times 10^5$

Then the number of nuclides that have decayed is:

$$N_D = \frac{N_E}{\epsilon B_R}$$

and the number of nuclides at the start of the measurements is

$$N_S = \frac{N_D}{1 - e^{-\lambda(t_{m,2} - t_{m,1})}}$$

from which one can estimate the number of activated nuclides at the end of the irradiation

$$N_I = \frac{N_S}{e^{-\lambda(t_{m,1} - t_{i,2})}}$$

which means that R as quoted in Scott's presentation is:

$$RR_{\text{exp}} = \frac{\lambda N_I}{1 - e^{-\lambda(t_{i,2} - t_{i,1})}}$$

INCORRECT

and since the irradiation time is 4.67 s, this gives the following value which is close to the one reported by Scott.

$$RR_{\text{exp}} = 1.1618 \times 10^6 \quad \text{s}^{-1}$$

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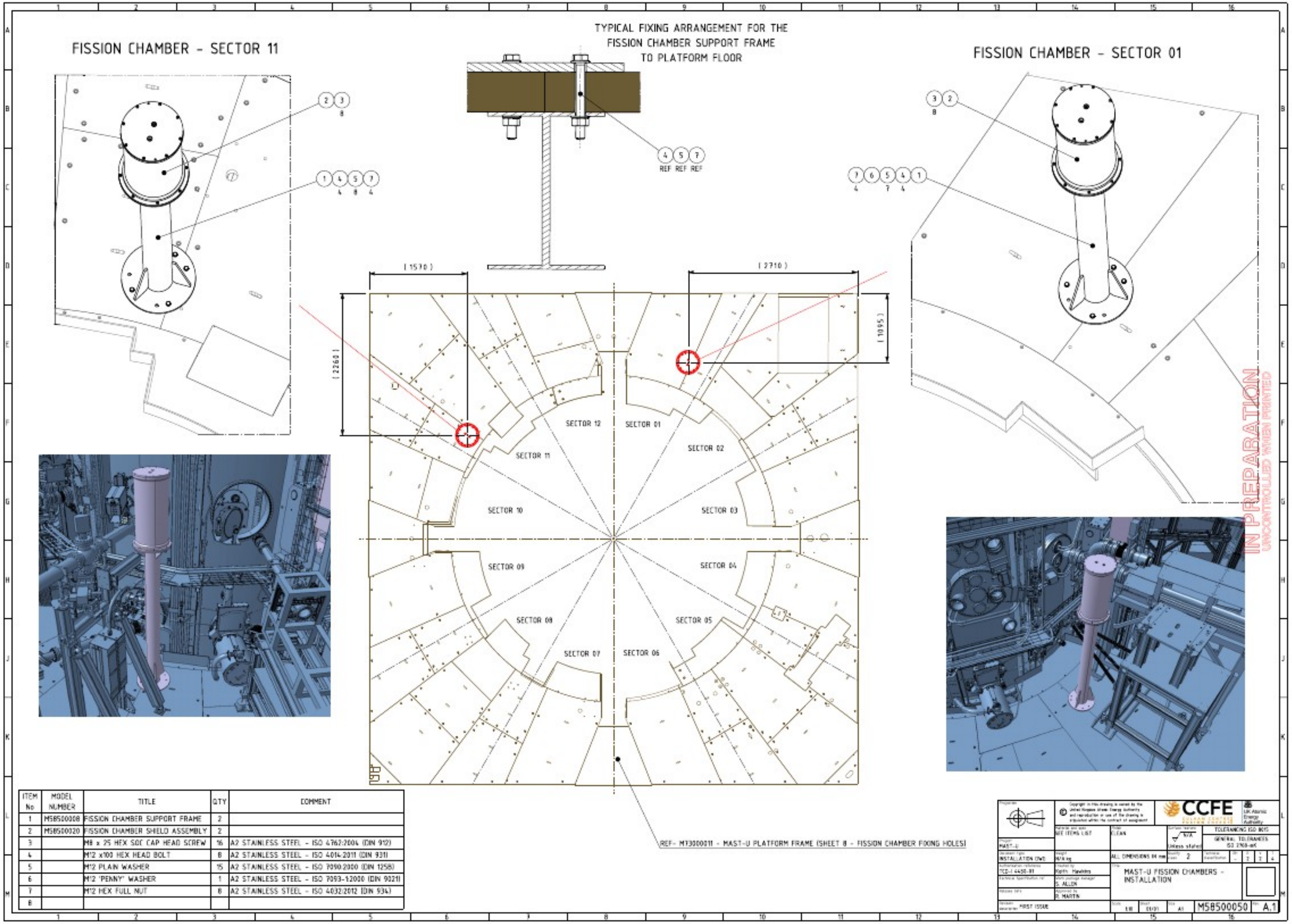

ITEM No	MODEL NUMBER	TITLE	QTY	COMMENT
1	M58500008	FISSION CHAMBER SUPPORT FRAME	2	
2	M58500020	FISSION CHAMBER SHIELD ASSEMBLY	2	
3		M8 x 25 HEX SOC CAP HEAD SCREW	16	A2 STAINLESS STEEL - ISO 4762:2004 (DIN 912)
4		M12 x100 HEX HEAD BOLT	8	A2 STAINLESS STEEL - ISO 4014:2011 (DIN 931)
5		M12 PLAIN WASHER	15	A2 STAINLESS STEEL - ISO 7090:2000 (DIN 125B)
6		M12 'PENNY' WASHER	1	A2 STAINLESS STEEL - ISO 7093-1:2000 (DIN 9021)
7		M12 HEX FULL NUT	8	A2 STAINLESS STEEL - ISO 4032:2012 (DIN 934)
8				