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EUROfusion

In-vessel calibration of JET neutron diagnostics - results and experience gained during calibration of the neutron activation system

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Content

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Why is an accurrate estimation of the neutron yield necessary?

$$\mathbf{D + D = {}^{3}He\ (0{,}817\ MeV) + n\ (2{,}452\ MeV) + 3{,}269\ MeV}$$

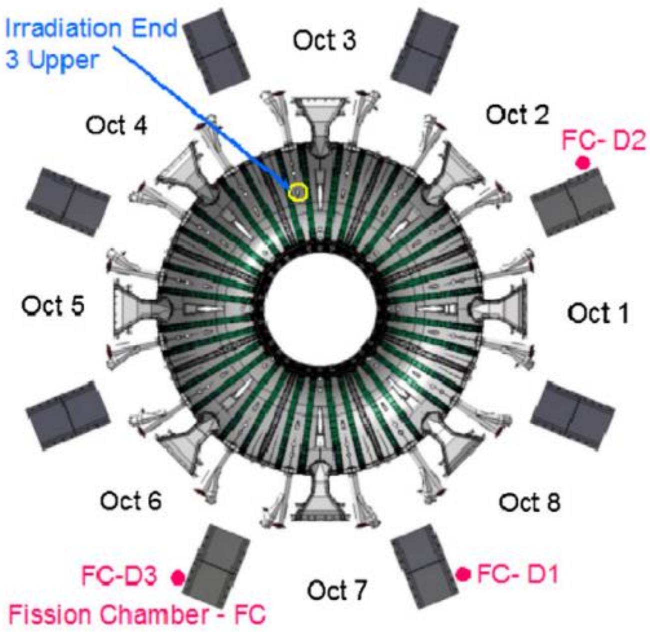
$$\mathbf{D + T = \alpha\ (3{,}518\ MeV) + n\ (14{,}072\ MeV) + 17{,}590\ MeV}$$

- The absolute measurement of neutron yield is needed to provide the fusion power output, and fuel ratio along with other plasma parameters, such as the ion temperature and density.

- The neutron yield is also needed to support the operational safety case and is the prime input to operational and maintenance doses.

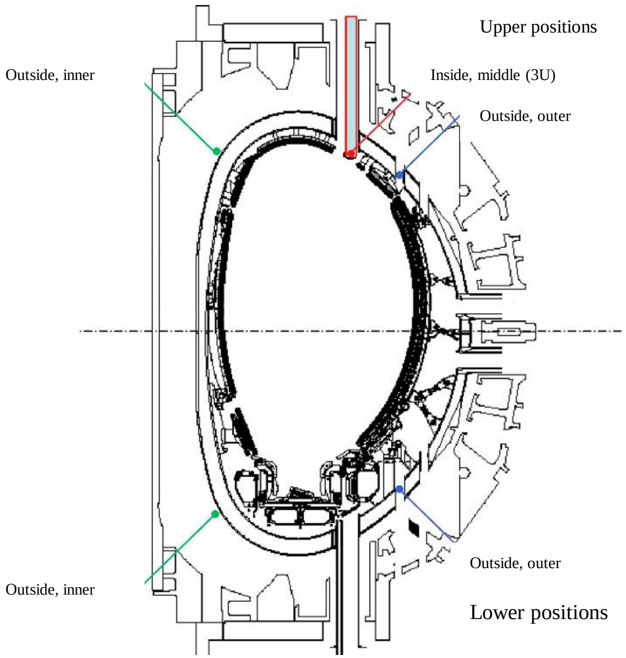
Neutron systems calibrated at JET

KN1 system



- 3 pairs of ^{235}U/^{238}U fission chambers – located outside tokamak [1].

KN2 system



- Activation system [2].
- 8 irradiation ends – only one located inside the tokamak (KN2 3U).

These systems were absolutely calibrated in:

- 2013 – ^{252}Cf as the neutron calibration source (D-D).
- 2017 – 14 MeV neutron generator as the calibration source (D-T).

[1] Jarvis, O. N. (1992). Neutron measurements from the preliminary tritium experiment at JET. *Review of Scientific Instruments*, *63*(10), 4511-4516.
[2] Murari, A. et al (2008). Measuring the radiation field and radiation hard detectors at JET: Recent developments. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *593*(3), 492-504.

Why we need a 14 MeV neutron calibartion of the JET neutron monitors?

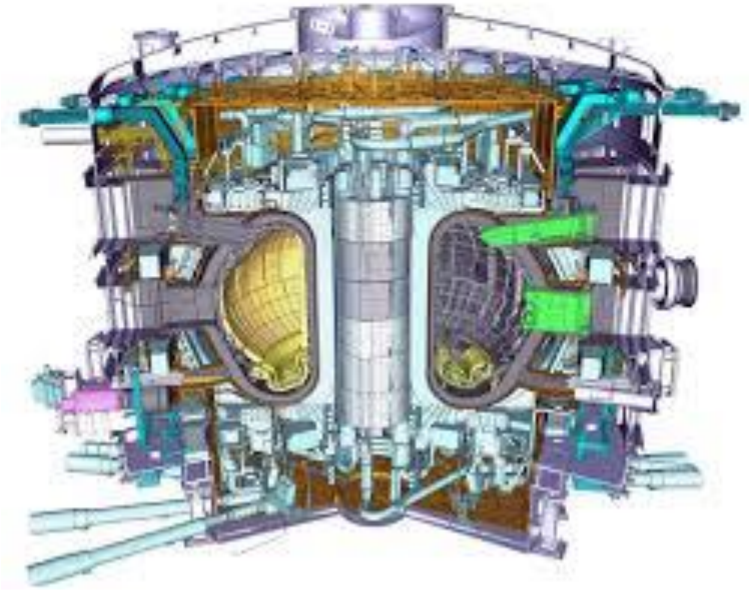
- A new Deuterium-Tritium Experimental Campaign on the JET tokamak was performed in 2021– high fluxes of 14-MeV neutrons were produced.

- Extrapolation of the D-D calibration factors to D-T calibration factors for fission chambers - could increase the calibration uncertainty and influents the overestimation of the neutron budget for the fusion device.

- The experience gained during the 14 MeV calibration of neutron diagnostics will be used when calibrations are carried out on **ITER**.

- 14-MeV neutron generator (NG) – the calibration source.

- 14-MeV NG has been characterized in terms of its **emissivity** and **angular distribution** – the activation method applied to the monitoring of the neutron emission rate of the NG.



ITER tokamak

Selection of monitoring reactions

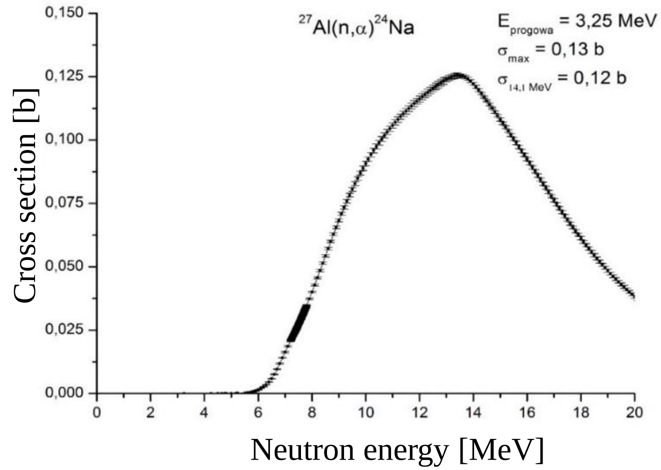
The activation reactions chosen for the monitoring foils were selected based on following requirements:

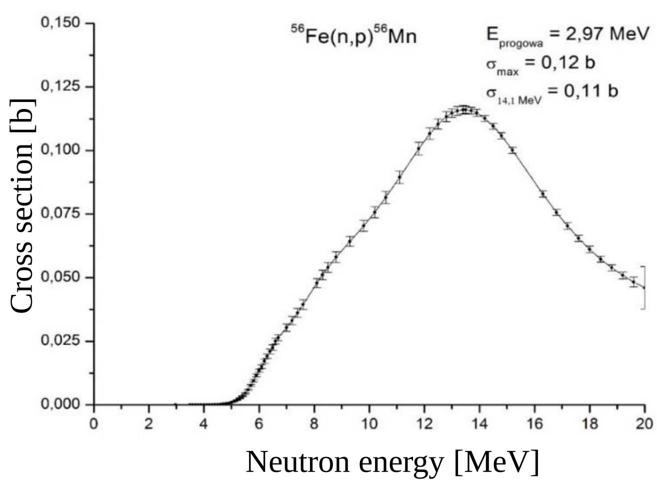
- ✓ **The cross section** for the selected reactions needed to be relatively large and well know (must also be from one of the standard fusion dosimetry libraries).
- ✓ **The reaction thresholds** should be sufficiently high in order to discriminate lower energy neutron scatter.
- ✓ The reaction products should emit **gamma radiation** that can be clearly measured using **gamma spectrometry methods**.
- ✓ The reaction product should has **sufficiently long half-life** and large **branching intensities** of the emitted photons (post irradiation measurements).

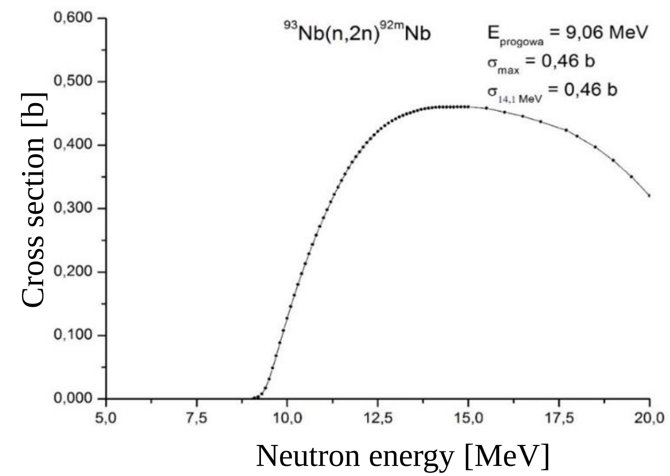
Selected nuclear reactions

Main parameters of nuclear reaction products [3]

Reaction	Half-life	Energy of gamma qunata [keV]	Intensity of gamma quanta [%]
$^{24}Mg(n,p)^{24}Na$	15,00 h	1368,6	99,9
$^{27}Al(n,p)^{27}Mg$	9,46 min	843,8	71,8
$^{27}Al(n,\alpha)^{24}Na$	15,00 h	1368,6	99,9
$^{56}Fe(n,p)^{56}Mn$	2,58 h	846,8	98,9
$^{58}Ni(n,2n)^{57}Ni$	35,60 h	1377,6	81,7
$^{90}Zr(n,2n)^{89}Zr$	78,41 h	909,2	99,0
$^{93}Nb(n,2n)^{92m}Nb$	10,15 days	934,4	99,2



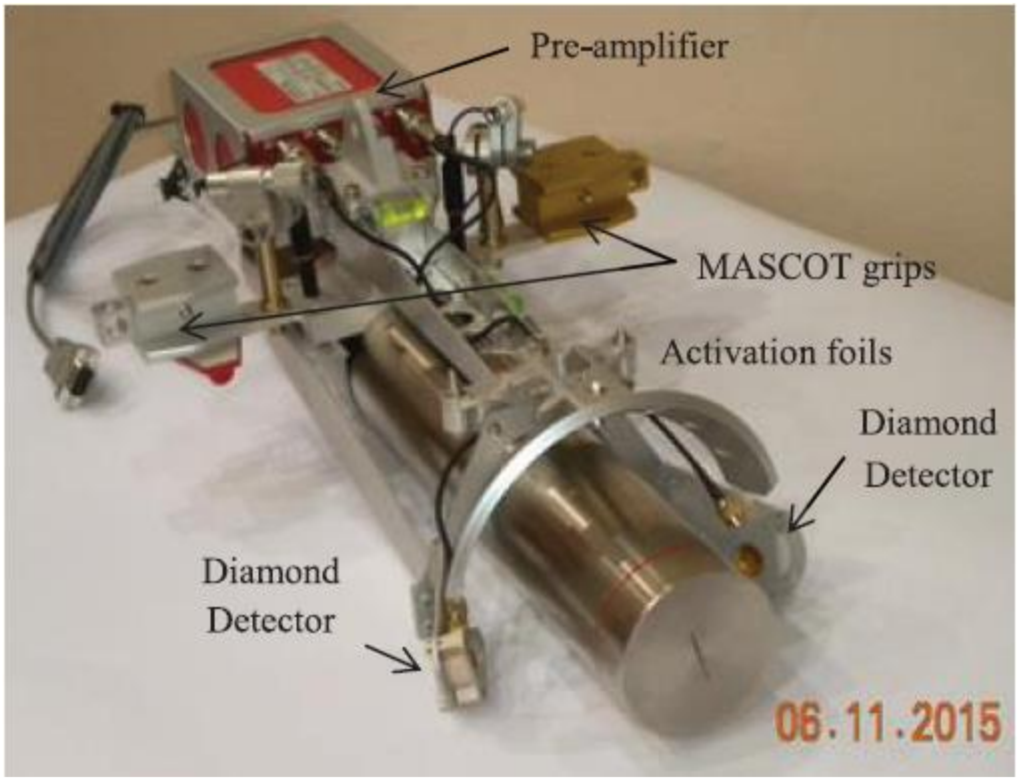




[3] National Nuclear Data Center, Brookhaven National Laboratory. "http://www.nndc.bnl.gov/nudat2/"
[4] International Reactor Dosimetry and Fusion File IRDFF v.1.05. (2014). "https://www-nds.iaea.org/IRDFF/"

Characterization of the 14 MeV NG

Left: The two Neutron Generators. Right: The Power Supply and Control Unit [5].



Neutron generator and the monitoring detectors [5].

The 14 MeV neutron generator type **ING-17** (provided by VNIAA) was identified as a suitable source complying with the JET physical and technical requirements.
In the NGs, a mixed $D_x^+/T_y^+/D_xT_y^+$ **beam** (x, y = 1, 2, 3 …), with nominally **50 % D** and **50% T**, is accelerated to a nominal energy of 100 keV onto a **titanium target** containing **T/D (nominally 50%/50%)** inside a sealed tube thus producing beam–target fusion reactions.

- **The NG intensity** can be subject to fluctuations due to variations in the voltage/current, target heating or general aging of the target and other components.
- Achieving stability of emission down to a few percent level is still very challenging in present neutron generator technology.
- Therefore, **during the in-vessel calibration** the neutron emission intensity, or the NG total neutron yield, **needs to be monitored** by compact detectors mounted in suitable positions close to the NG.
- The NGs have been characterized during **2 experimental campaigns** carried out in National Physical Laboratory.

[5] Batistoni, P., Popovichev, S., Cufar, A., Ghani, Z., Giacomelli, L., Jednorog, S., ... & Packer, L. (2017). 14 MeV calibration of JET neutron detectors—phase 1: calibration and characterization of the neutron source. *Nuclear Fusion*, *58*(2), 026012.

In-vessel calibration of the JET neutron monitors

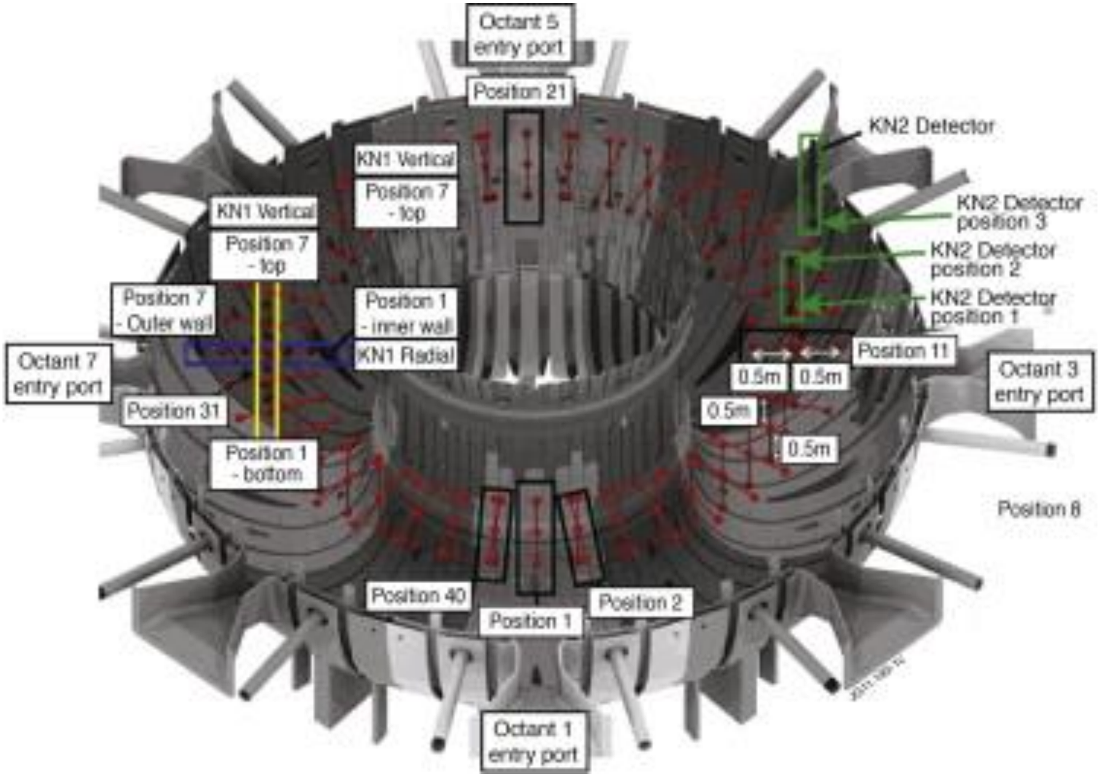
The in-vessel calibration of the JET neutron monitors, with using previously characterized 14 MeV NG as the neutron source, was performed 28 January – 8 February 2017. During 10 days of operations 227 shots were made.

Transport of the NG and control unit inside JET vacuum vessel by means of Remote Handling System [6].

The 14 MeV NG with attached monitoring detectors and control unit were transported inside the vacuum vessel on Octant 1 Remote Handling boom tray. The NG was placed in previously defined positions by MASCOT robot

[6] Batistoni, P., Popovichev, S., Ghani, Z., Cufar, A., Giacomelli, L., Hawkins, P., ... & Peacock, A. (2018). 14 MeV calibration of JET neutron detectors—phase 2: in-vessel calibration. *Nuclear Fusion*, *58*(10), 106016.

Calibration of KN1, KN2 systems



Draft of in-vessel scan pattern. There are 5 points at each toroidal location round the vessel, i.e. 5 rings of points, plus some subsidiary points at other particular locations. Only part of the JET structure is shown. KN1 denotes external neutron monitors and KN2 denotes the JET activation neutron monitoring system [6].

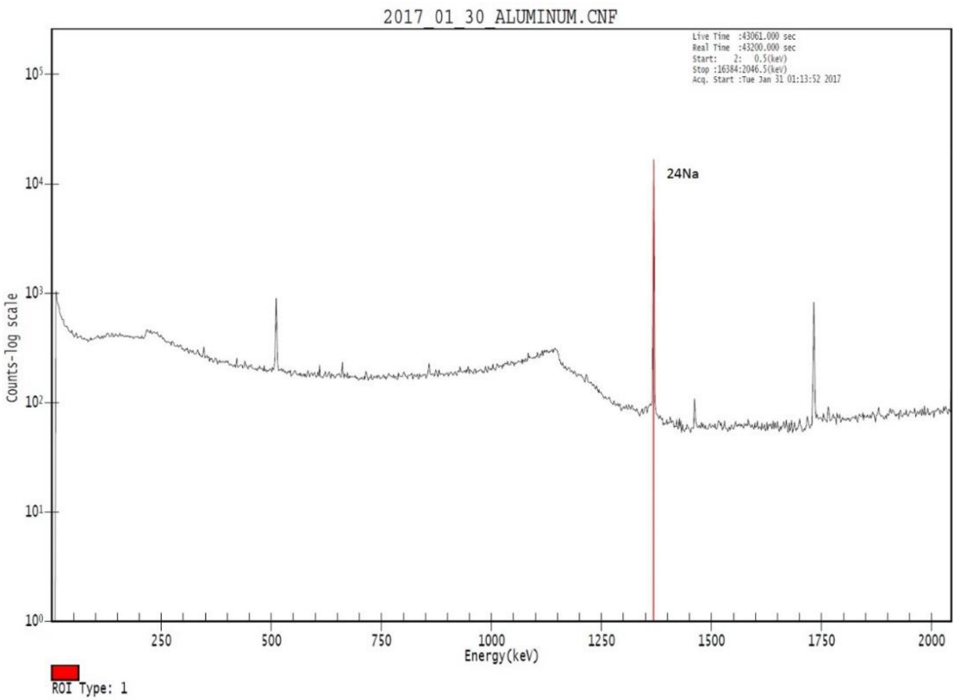
- In order to **calibrate KN1 system** the neutron source was located in 40 toroidal positions. 3 radials and vertical scans at 9 positions each have been performed.

- In order to **calibrate KN2 system** 9 irradiations have been carried out (3 upper, 3 middle and 3 lower). Typically 4 Nb foils and 1 Al foil were present in the capsule during irradiation in KN2 irradiation end. Foils were irradiated for 10-15 shots of 1200 s duration.

Monitoring of the NG neutron emission

Radioactivity of irradiated samples measured with using HPGe detector (relative efficiency equals 38% and resolution 1.7 keV at 1.33 MeV) loaned from ADRIANA laboratory (CCFE).

HPGe detector with shielding used during in-vessel calibration of JET neutron monitors.



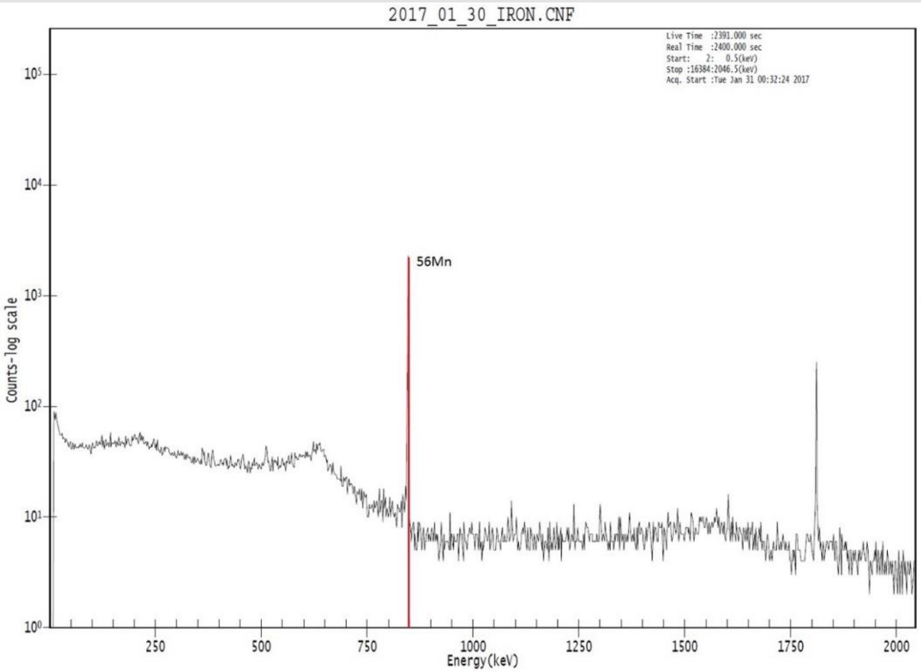
Typical gamma spectrum emitted from the aluminium foils.

Uncertainty of net peak area for ^{24}Na was in the range **0.17 - 0.21%**

Radioactivity of ^{24}Na measured during in-vessel calibration

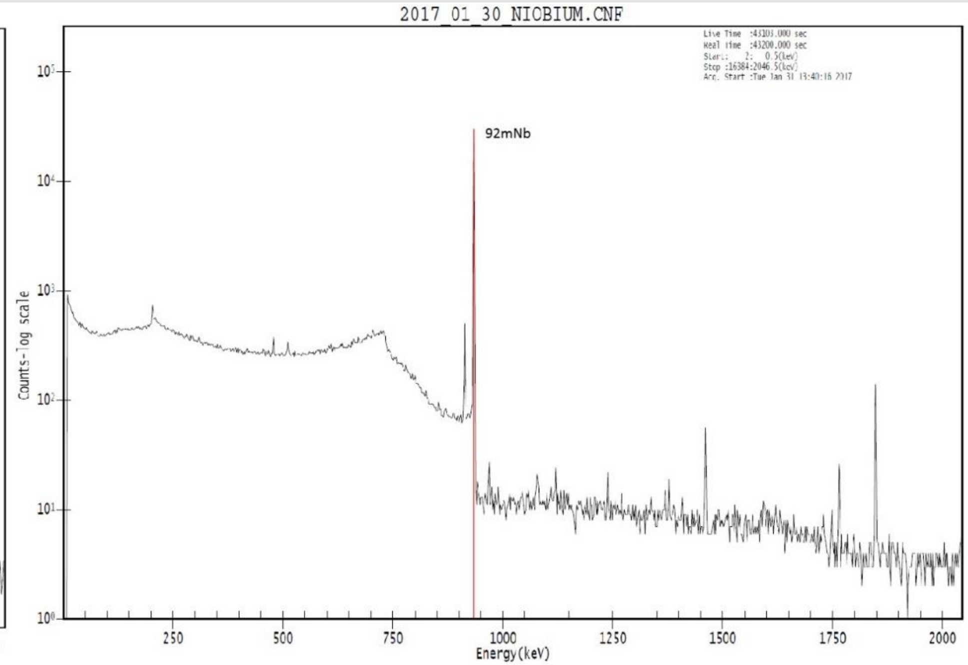
Al foils	Activity [Bq/g]	Unc. [%]
Day 1,2	156.7	6.78
Day 3,4	214.6	6.78
Day 5	172.3	6.78
Day 6	158.8	6.78
Day 7	221.6	6.78
Day8	186.4	6.78

Activation measurements



Typical gamma spectrum emitted from the iron foils.

Uncertainty of net peak area for ^{56}Mn was in the range **0.39 - 0.60%**



Typical gamma spectrum emitted from the niobium foils.

Uncertainty of net peak area for ^{92m}Nb was in the range **0.10 - 0.21%**

Radioactivity of ^{56}Mn measured during in-vessel calibration

Fe foils	Activity [Bq/g]	Unc. [%]
Day 1,2	147.4	6.68
Day 3,4	153.4	6.67
Day 5	152.5	6.67
Day 6	158.9	6.67
Day 7	194.4	6.66
Day8	168.0	6.67

Radioactivity of ^{92m}Nb measured during in-vessel calibration

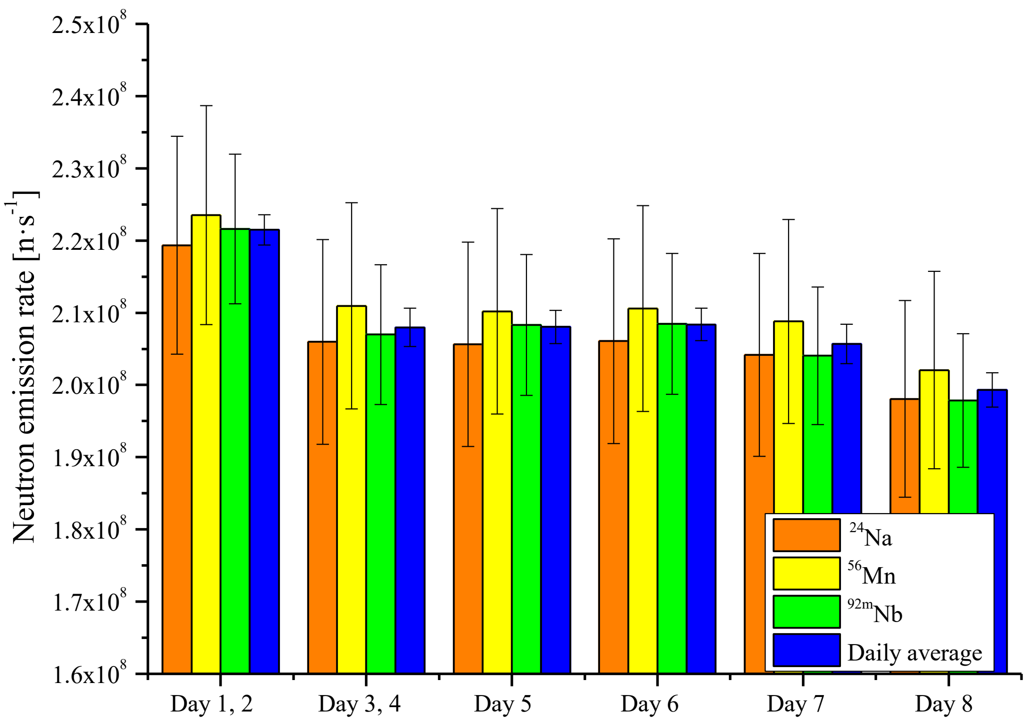
Nb foils	Activity [Bq/g]	Unc. [%]
Day 1,2	20.7	4.53
Day 3,4	31.5	4.53
Day 5	16.8	4.53
Day 6	14.6	4.53
Day 7	21.7	4.53
Day8	17.8	4.53

Neutron emission rate of the NG

The radioactivity of i-th activations ($t_{Ai} \neq t_{Ai+1}$) and the subsequent cooling time ($t_{Ci} \neq t_{Ci-1}$) can be expressed as:

$$A_n = Y_n / t \cdot N_T \cdot \langle \varphi(E) \cdot \sigma(E) \rangle \cdot \sum_i B_i \left(1 - \exp(-\lambda \cdot t_{Ai})\right) \cdot \exp(-\lambda \cdot t_{Ci})$$

where t is the total irradiation time, B_i is a normalization factor which takes into account changes in the neutron yield, recorded by the monitoring SDD during successive NG pulses of duration t_{Ai}.



Neutron emission rate of the NG during in-vessel calibration campaign.

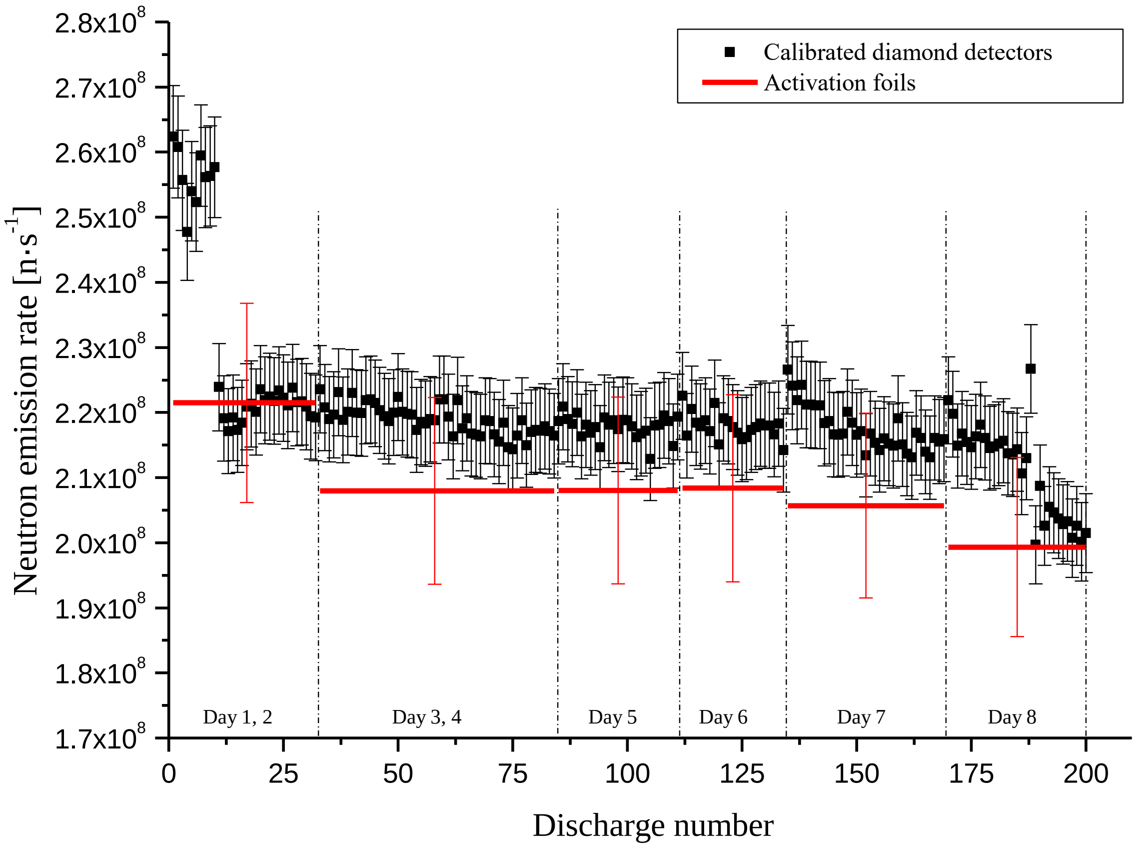
- Average value of neutron emission rate was $2.08 \cdot 10^8$ n/s (except 1-st and last day).

- Uncertainty of neutron emission rate:
  - ✓ 4.7 % - ^{92m}Nb
  - ✓ 6.8 % - ^{56}Mn
  - ✓ 6.9 % - ^{24}Na

- SD expressing the level of discrepancy between values calculated based on radioactivity of particular reaction products is in the range of 1% - **high agreement** between reactions!!!

Neutron emission rate of the NG – comparison with other systems

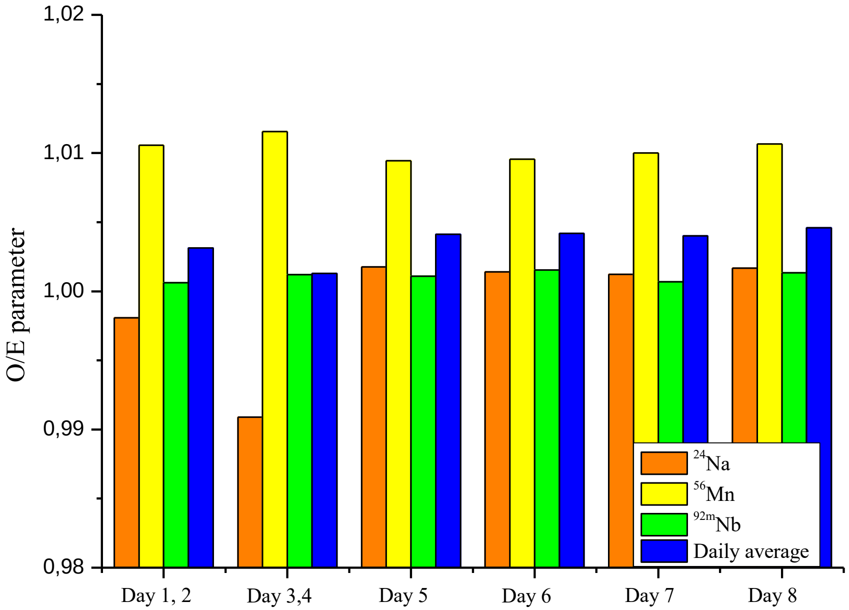
The IPPLM activation results were compared with diamond detector results – the agreement within 3% has been achieved.



The comparison of neutron emission rates estimated based on IPPLM and diamond detector results .

FISPACT-II calculations

- An independent analysis of the activation measurements used to determine the neutron emission rate of the NG has been performed.
- The neutron emission rates of NG from monitoring activation results were obtained using a detailed MCNP model of the NG and its neutron source properties. In the second case, they were calculated using the FISPACT-II code with neutron flux spectra calculated by MCNP code.



Calculated values of neutron emission rate were compared to values estimated based on the activation measurements.

- The calculated and measured values of neutron emission rate were similar.
- The discrepancy between calculated and measured values of neutron emission rate was in the region of 1%.

KN2 Activation coefficients and KN1 calibration factors

Target accuracy for the JET DT calibration was set to ±10%.

- **KN1 calibration factors**

	D1 / Oct 8	D2 / Oct 2	D3 / Oct 6
Integral of Central Ring (n/count) measured	$3.97 \cdot 10^8$	$7.28 \cdot 10^8$	$3.71 \cdot 10^8$
Correction $R_{DT,ring}/R_{NG+RH,ring}$	1.07	1.10	1.19
Correction $R_{DT,plasma}/R_{DT,ring}$	0.98	1.00	1.00
TOTAL Correction Factor	*1.04*	*1.10*	*1.19*
DT plasma (n/count) (2017)	$\mathbf{3.81 \cdot 10^8}$	$\mathbf{6.61 \cdot 10^8}$	$\mathbf{3.11 \cdot 10^8}$
DD plasma (n/count) (2014)	$3.631 \cdot 10^8$	$5.261 \cdot 10^8$	$2.948 \cdot 10^8$
DD plasma (n/count) (2016)	$3.64 \cdot 10^8$	$6.98 \cdot 10^8$	$3.25 \cdot 10^8$
DT(2017) / DD(2016)	1.05	0.95	0.96

Total uncertainty on KN1 calibration factors: NG intensity 3.5%, FCs counting statistics<0.8%, NG postions <2% →4.2% + uncertainty on modeling.

- **KN2 activation coefficients**

Measured saturated activity in Nb and Al foils compared to activity calculated by MCNP show C/E=1.036 ± 6.2%.

Activation coefficients have been derived for DT plasmas: $2.66 \cdot 10^{-31}$ activated nuclei/(target nuclei·neutron) for Nb and $8.04 \cdot 10^{-31}$ activated nuclei/(target nuclei·neutron) for Al.

[7] Z. Ghani, „NC14 Lessons learnt", presentation during WPPrIO meeting

Cross-calibration of KN2 3U and KN2 6U irradiation ends

- Due to the foreseen high demand of the KN2 3U position for operations during JET T-T and D-T campaigns, a particular focus has been given to characterise another irradiation end position KN2 6U (more available for WPJET3 subprojects in future campaigns).

- In order to characterize of KN2 6U irradiation end, cross-calibration of 3U with 6U along with supplementary measurements with dosimetry foils providing insight on the neutron spectrum has been planned.

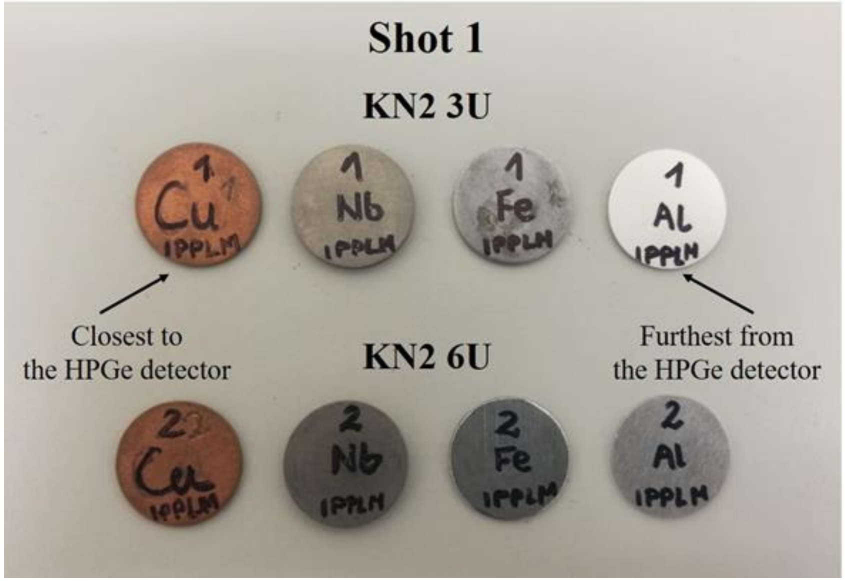
- Selection of threshold dosimetry reactions spanning the entire neutron energy range of interest.

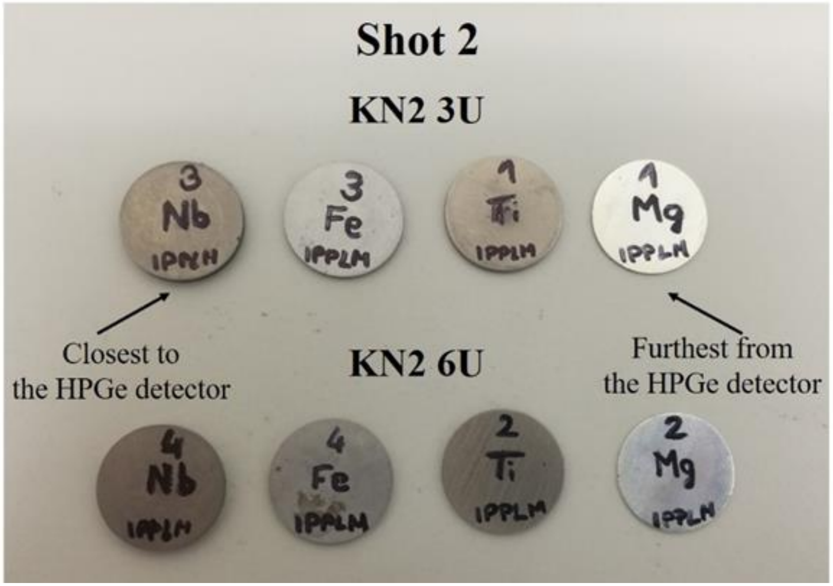
Selected threshold reactions

KN2 6U/3U dosimetry reactions and main characteristics.

Foil	Reaction	Threshold [MeV]	Half-life	Gamma energy [keV]
Cu	$^{65}Cu(n,2n)^{64}Cu$	11	12.7 h	511
Nb	$^{93}Nb(n,2n)^{92m}Nb$	9	10.15 d	934
Fe	$^{54}Fe(n,p)^{54}Mn$	1.8	312 d	835
Fe	$^{56}Fe(n,p)^{56}Mn$	7	2.58 h	847
Al	$^{27}Al(n,a)^{24}Na$	5.4	15 h	1368.9
Ti	$^{47}Ti(n,p)^{47}Sc$	1.8	3.3 d	159
Mg	$^{24}Mg(n,p)^{24}Na$	5	15 h	1368.9
In	$^{115}In(n,n')^{115m}In$	0.5	4.49 d	336
Zn	$^{64}Zn(n,p)^{64}Cu$	1.8	12.7 h	511
Zr	$^{90}Zr(n,2n)^{89}Zr$	13	78.4 h	909

Activation foils





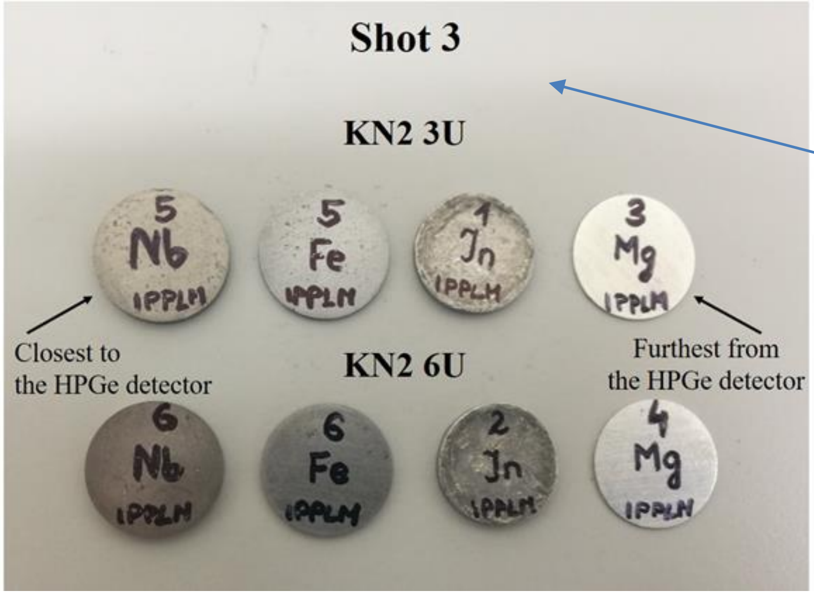
Irradiated during **#95899**:

Total neutron yield $2{\cdot}10^{16}$
Irradiation time: 7 s

Irradiated during **#96099**:

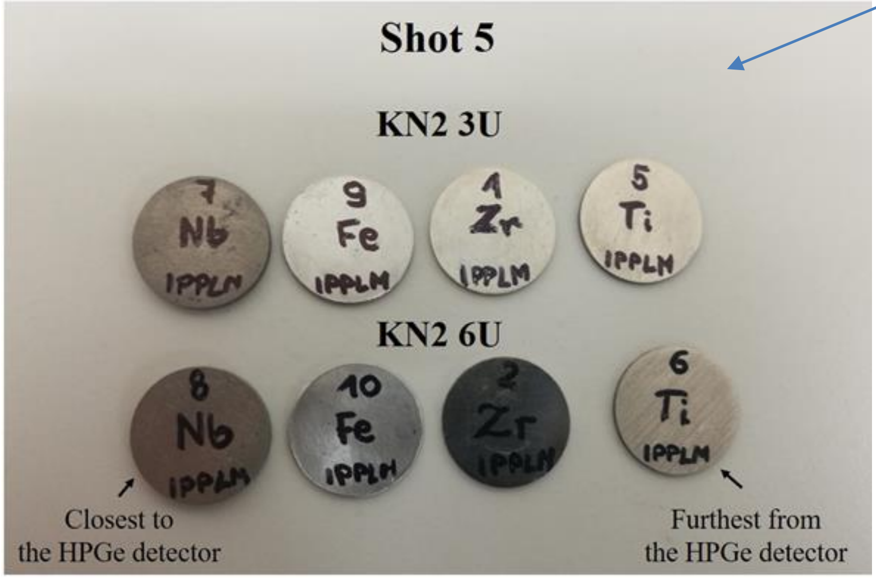
Total neutron yield $2.5{\cdot}10^{16}$
Irradiation time: 6 s

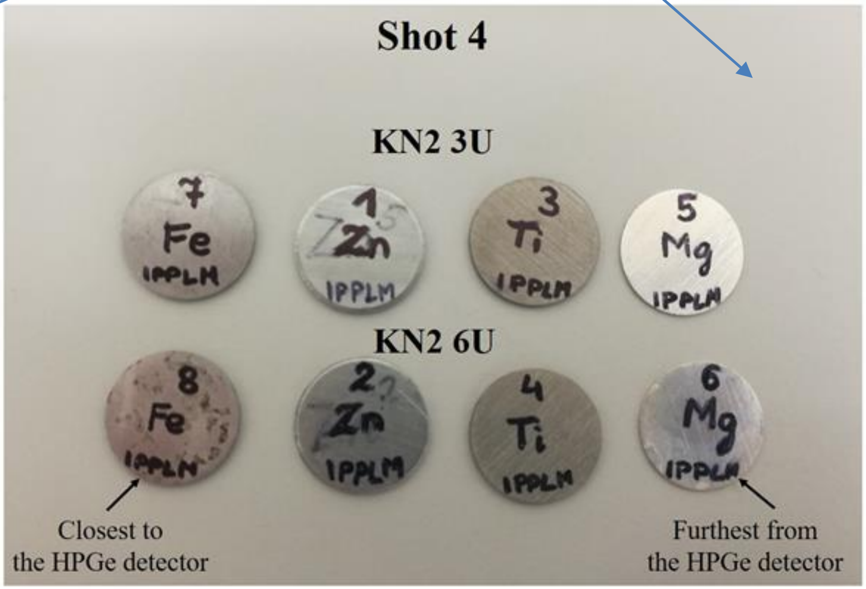
Activation foils



Irradiated during C38b – capsule for KN2 3U has been lost in the transfer system.
The gamma-ray spectrum for KN2 6U recorded and saved in „listmode”.

Planned shots – depends if DD campaign will be continued and the problem with the capsule transfer system will be solved.





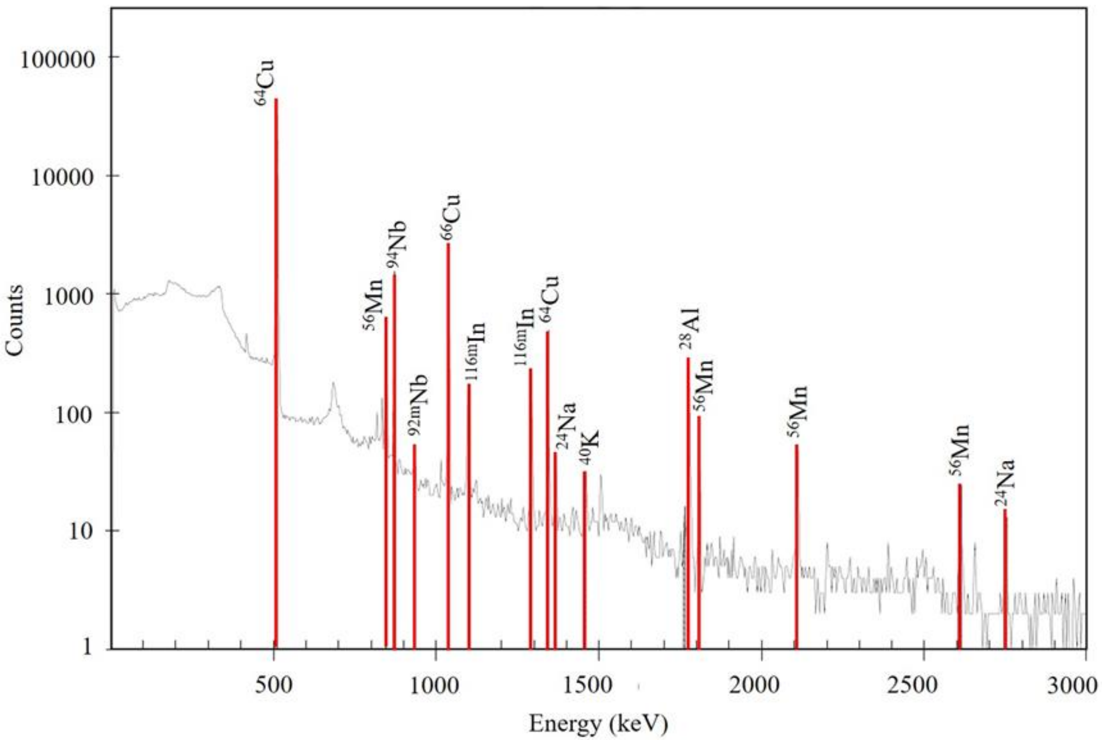
Gamma spectrometry measurements

- After each discharge capsules were transported to KN2 lab where gamma-ray spectra were recorded using HPGe detector (ORTEC).

- All gamma-ray spectra recorded in „listmode” format which allow to extract gamma-ray spectra for considered radionuclide with using a processing tool (this tool developed by CCFE).

- Capsule with foils irradiated at KN2 6U was measured first – due to lower neutron flux.

Recorded gamma spectra



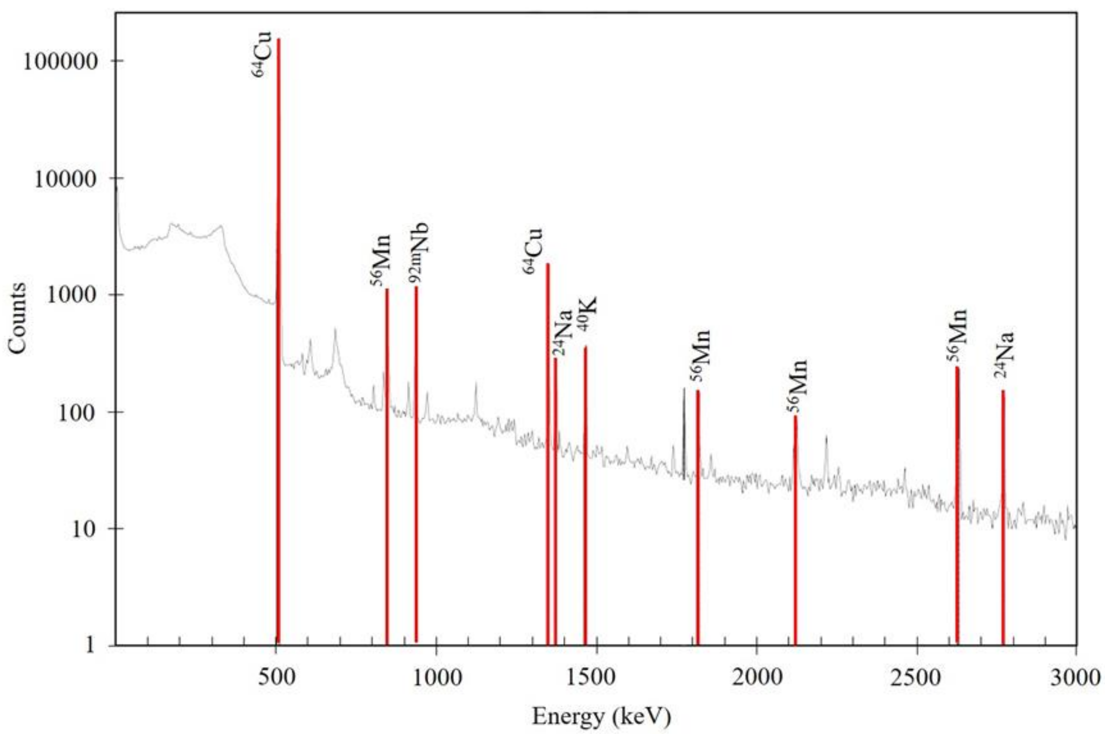
Gamma-ray spectrum measured for dosimetry foils (Cu, Nb, Fe, Al) irradiated in KN2 6U during #95899 discharge. Gamma-ray spectrum recorded using .spc format file.

- The full energy gamma peaks for ^{64}Cu, ^{56}Mn, ^{92m}Nb and ^{24}Na radionuclides are well visible

- ^{66}Cu, ^{28}Al and ^{94}Nb which are the products of (n,γ) reactions will not be taken into further considerations – generated primarily via low energy neutrons.

- The presence of ^{116m}In in the gamma-ray spectrum shows evidence of some contamination of used dosimetry foils, or the transfer capsule itself.

Recorded gamma spectra



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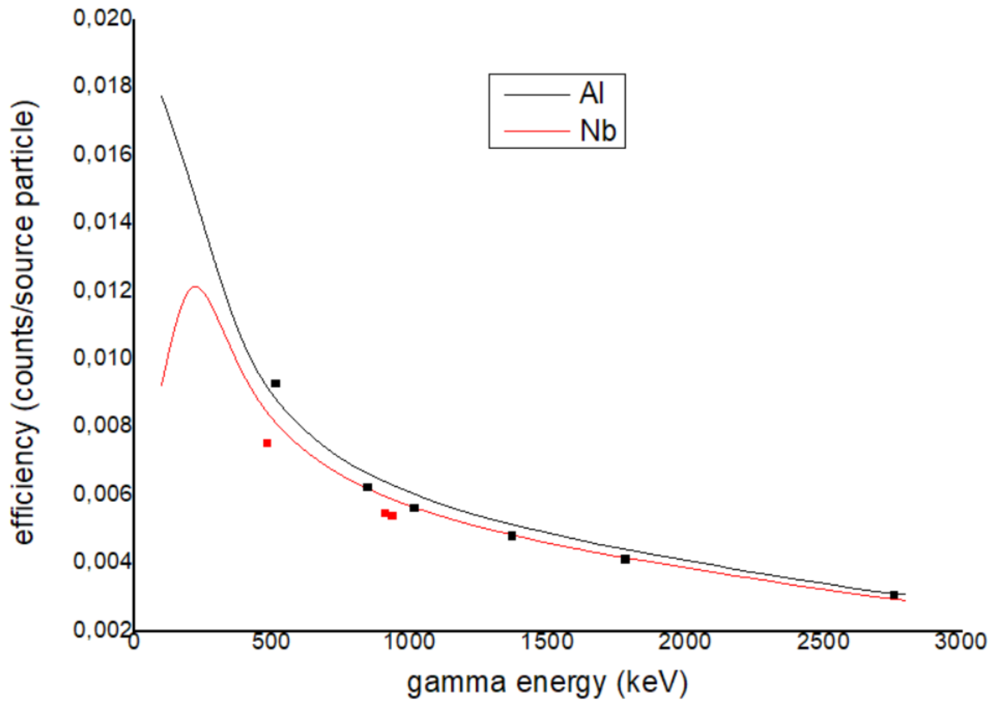
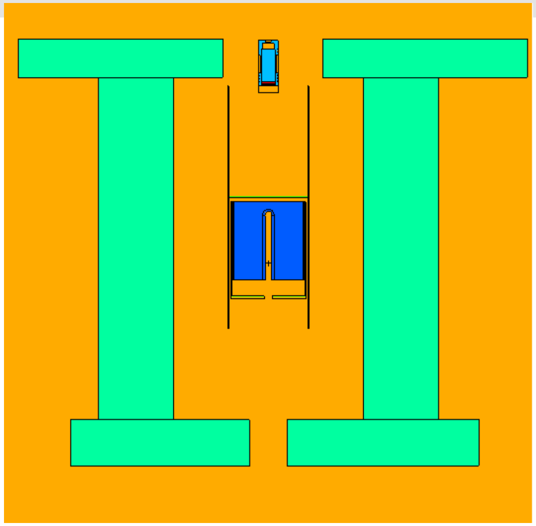
- The full energy gamma peaks for ^{64}Cu, ^{56}Mn, ^{92m}Nb and ^{24}Na radionuclides are well visible
- KN2 3U capsule measured after KN2 6U capsule.

Energy-efficiency calibration

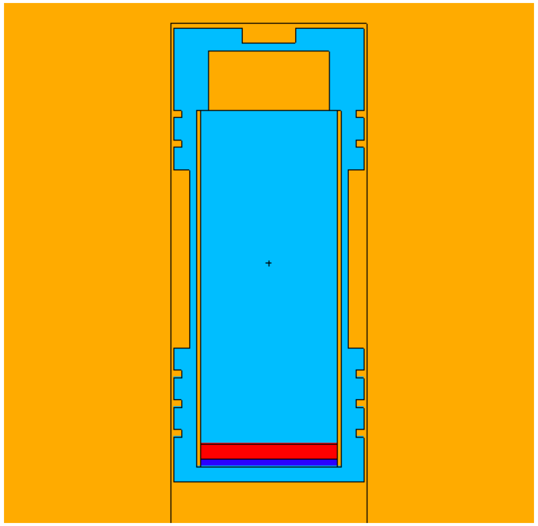
In order to assess radioactivity of reactions products, the ***detection efficiency at the peak energy*** in question was determined from a calibration measurement using a traceable reference source and supporting MCNP calculations using a model of the HPGe detector.



Energy-efficiency calibration curve for Al and Nb samples.



The MCNP model of detector with foils.



The MCNP model of capsule with foils.

Comparison of results

C/E 3U/6U ratios determined based on the FISPACT-II calculations and measurements.

#95899						
Nuclide	KN 2 3U/6U ratio based on calculations	Uncertainty [%]	KN2 3U/6U ratio based on measurements	Uncertainty [%]	C/E 3U/6U ratio	Uncertainty [%]
^{64}Cu	1.22	1.88	1.11	1.70	1.10	2.53
^{56}Mn	2.34	11.83	2.30	1.58	1.02	11.94
^{92m}Nb	2.43	22.44	1.64	10.15	1.48	24.63
^{24}Na	2.40	13.34	2.26	7.26	1.06	15.19
#96099						
Nuclide	KN2 3U/6U ratio based on calculations	Uncertainty [%]	KN2 3U/6U ratio based on measurements	Uncertainty [%]	C/E 3U/6U ratio	Uncertainty [%]
^{56}Mn	2.37	11.72	1.91	15.18	1.24	19.18

The overall weighted average KN2 3U/6U C/E ratio considering all five results was 1.10 ± 0.02. This preliminary result indicates that the MCNP geometrical model of KN2 6U should be modified.

Summary

- The 14 MeV neutron generator had been very well characterized in advance, in terms of its emissivity and angular distribution (with 3.5% uncertainty) – activation foils were used to the monitoring of NG emission stability.

- The 14-MeV calibration of JET neutron monitors has been successfully achieved using a neutron generator deployed inside the JET vacuum vessel by the remote handling system.

- The calibration factors for the fission chambers (KN1) have been estimated with a total uncertainty of ±5%.

- The activation coefficients for Al, and Nb foils have been calculated with uncertainty within ±6-8%.

- An additional HPGe detector is recommended for gamma spectrometry measurements. All HPGe detectors should be monitored with a calibration source.

Thank you for your attention!

The 14 MeV neutron calibration team.