

Activation measurements in support of the 14 MeV neutron calibration of JET neutron monitors

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# 1     **Activation measurements in support of the 14 MeV neutron calibration of** 2   **JET neutron monitors**

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## 21 22    **Abstract**

23  
24    In preparation for the upcoming deuterium-tritium campaign at the JET tokamak, the ex-vessel fission chamber  
25    neutron diagnostics and the neutron activation system will be calibrated in absolute terms at 14 MeV neutron  
26    energy, to a required accuracy of less than 10 %. Two identical DT neutron generators were chosen as the  
27    calibration sources, both of which were fully calibrated and characterised at the UK’s National Physical  
28    Laboratory (NPL). The neutron activation method was adopted as a complementary method for the purpose of  
29    determining the absolute value of the neutron yield from the neutron generators and to provide a means of cross  
30    check for the active detection methods being employed. The relative neutron intensity was measured utilising  
31    two Single Crystal Diamond Detectors with less than 1 % uncertainty. The work being presented here shows the  
32    derivation of the neutron emission rate from the neutron generators based upon experimental activation foil  
33    measurements. The reaction products chosen for the 14-MeV neutron measurements included the standard  
34    activation products: <sup>92m</sup>Nb, <sup>24</sup>Na, <sup>56</sup>Mn and <sup>27</sup>Mg; all of which were measured with an uncertainty less than 9%.  
35    The neutron generator yields were derived from the mean emission rate of the four different activation reactions,  
36    resulting in neutron yields of approximately  $2.4 \cdot 10^8 \text{ n} \cdot \text{s}^{-1}$  for the first neutron generator, with a standard  
37    deviation of 2.4-5.3 %, before it dropped permanently, during the experimental campaign, by 20% . For the same  
38    parameter settings, the second neutron generators mean neutron emission rate was calculated to be  
39    approximately  $2.2 \cdot 10^8 \text{ n} \cdot \text{s}^{-1}$  with a standard deviation in the range of 3.2-6.0 %.

40

41 **Keywords:** JET D-T campaign, neutron yield calibration, neutron generator, activation technique

42

## 43 1. Introduction

44

45 The absolute measurement of neutron yield ( $Y_n$ ), in a fusion device, is needed to provide the fusion power output  
46 along with other plasma parameters, such as the ion temperature and density.

47 The system of neutron yield monitors used to monitor the Joint European Torus (JET) consists of  $^{235}\text{U}/^{238}\text{U}$   
48 fission chambers (KN1), located outside the tokamak, and an internal, in-vessel, activation system (KN2). An  
49 absolute calibration of both KN1  $^{235}\text{U}/^{238}\text{U}$  fission chambers and KN2 was performed in 2013, using a  $^{252}\text{Cf}$   
50 spontaneous-fission source, having a mean energy of 2.1 MeV and a source strength of  $2.4 \cdot 10^8 \text{ n} \cdot \text{s}^{-1}$ . JET  
51 operating in deuterium (D) mode produces 2.5-MeV neutrons by the (d,d) fusion reaction, the  $^{252}\text{Cf}$  neutron  
52 energy spectrum is sufficiently similar to the (d,d) fusion energy distribution; that it serves as an adequate  
53 calibration measure for neutrons of such similar energies. Additionally, MCNP [1] calculations were used to  
54 determine the correctional factors arising from the differences in the neutron spectrum from that of a pure D  
55 plasma and other geometrically dependant calibration factors [2].

56 The neutron source (NS) was placed at different points inside the vacuum vessel, from which neutron induced  
57 activation and fission chamber pulses were recorded by KN1 and KN2 systems, respectively. In KN2 the  
58  $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$  nuclear reaction is used as the monitoring reaction in D operations. The cross section has a  
59 maximum at an energy of 2.7 MeV, which is useful for measuring the 2.5 MeV neutrons released during  
60 deuterium fusion, and has a threshold of approximately 0.4 MeV. The moderated  $^{235}\text{U}/^{238}\text{U}$  fission chambers can  
61 measure a broad energy range of neutrons and have a relatively flat response over these energies. During the  
62 2013 calibration campaign, both KN1 and KN2 were calibrated with a total uncertainty of approximately  $\pm 10\%$ ;  
63 these results were successfully verified during the following D campaign [S. Popovichev, private  
64 communication].

65 A new Deuterium-Tritium Experimental Campaign (DTE2) on the JET tokamak is planned in the near future [3];  
66 in which up to  $1.7 \cdot 10^{21}$ , 14.1 MeV neutrons will be produced, a new calibration of JET monitoring systems for  
67 higher energy neutrons therefore is required.

68 JET calibration, at 14.1 MeV neutron energy, requires the use of a different set of nuclear reactions, with higher  
69 energy thresholds, and at the same time, sufficiently high cross section and convenient decay times of the  
70 reaction products. Moreover, the tokamak transparency to neutrons alters as the neutron energy increases from  
71 2.5 MeV to 14.1 MeV, thus, causing a change in the response of the  $^{235}\text{U}$  fission chambers. To accurately  
72 determine calibration coefficients, it is therefore necessary to conduct a JET neutron diagnostic calibration with a  
73 NS that emits 14.1-MeV neutrons from a (d,t) reaction. The 14-MeV calibration will be based on the procedures  
74 and experience gained during the 2.5-MeV calibration [2]. The experience gained during the 14.1-MeV  
75 calibration of JET neutron diagnostics will serve as a good methodology when calibrations are carried out on  
76 ITER, which is currently under construction in Cadarache, France.

77 The ING-17 neutron generator (NG) [4] manufactured by the All-Russia Research Institute of Automatics  
78 (VNIIA) Moscow, Russian Federation [5] was chosen as the neutron source for neutron calibration of JET. It has  
79 a nominal yield of approximately  $2 \cdot 10^8 \text{ n} \cdot \text{s}^{-1}$ . The NG comprises of an accelerated beam consisting of deuterium  
80 and tritium ions and of ionized molecules, striking a target made of tritium and deuterium, in an approximate  
81 50/50 % ratio, implanted onto titanium. The yield of neutrons emitted is strongly dependent upon the beam  
82 acceleration voltage.

83 In order for the NG to be used as a calibration source, the yield must be known with a high accuracy, possibly  
84 better than  $\pm 5\%$ . The emitted neutron energy spectrum characteristics must also be known. The NG emission  
85 characteristics were measured during two experimental campaigns at the UK National Physical Laboratory  
86 (NPL) by the NPL Neutron Metrology Group, using their low-scatter cell neutron facility. Two nominally  
87 identical NGs (NG1 and NG2) were examined. They were mounted in the centre of the large hall (see fig. 1),  
88 where the conditions support the low scatter requirements. The emission rates and energy spectrums of both NGs  
89 were measured by “characterization” neutron detectors: an absolutely calibrated De Pangher long counter; an  
90 absolutely calibrated NPL long counter; two Single Crystal Diamond Detector (SDD) -neutron spectrometer; a  
91 NE-213 scintillator based neutron spectrometer [6] and activation foils. From these measurements, the two NGs  
92 total neutron yield in  $4\pi$  can be derived.

93



94

95 *Fig. 1* Experimental hall inside the Chadwick facility. The NG is located in the centre of the hall. The two long  
96 counters and the NE-213 scintillator are situated above the red rails in the centre of the above image.

97

98 The NG emission rate and energy spectrum vary over the course of a single run [7]. It is therefore necessary to  
99 monitor the varying yield during the whole calibration process. In order to do this, the NG was equipped with  
100 “monitoring” detectors, both active and passive. These comprised: i) a SDD and a Silicon diode in the first  
101 campaign, two SDD in the second campaign, and ii) a set of 12 activation foils, all located in well-defined, stable  
102 positions relative to the neutron generator target; where the neutrons are produced. These monitoring detectors  
103 were attached to the NGs by means of a mechanical support (see fig. 2).

104 The SDDs measurements, combined with the measurements by the absolutely calibrated long counter  
105 measurements carried out at NPL, provide the absolute time resolved emission rate from the NG. The activation  
106 foils provide a complementary and independent measurement of the absolute neutron emission rate ( $n \cdot s^{-1}$ ) for a  
107 given exposure period. This paper focuses on the measurement and analyses of the monitoring activation foils,

108 and on the comparison with the active monitoring detectors. The uncertainty of the derived absolute neutron  
109 emission rate of the NGs is also discussed.

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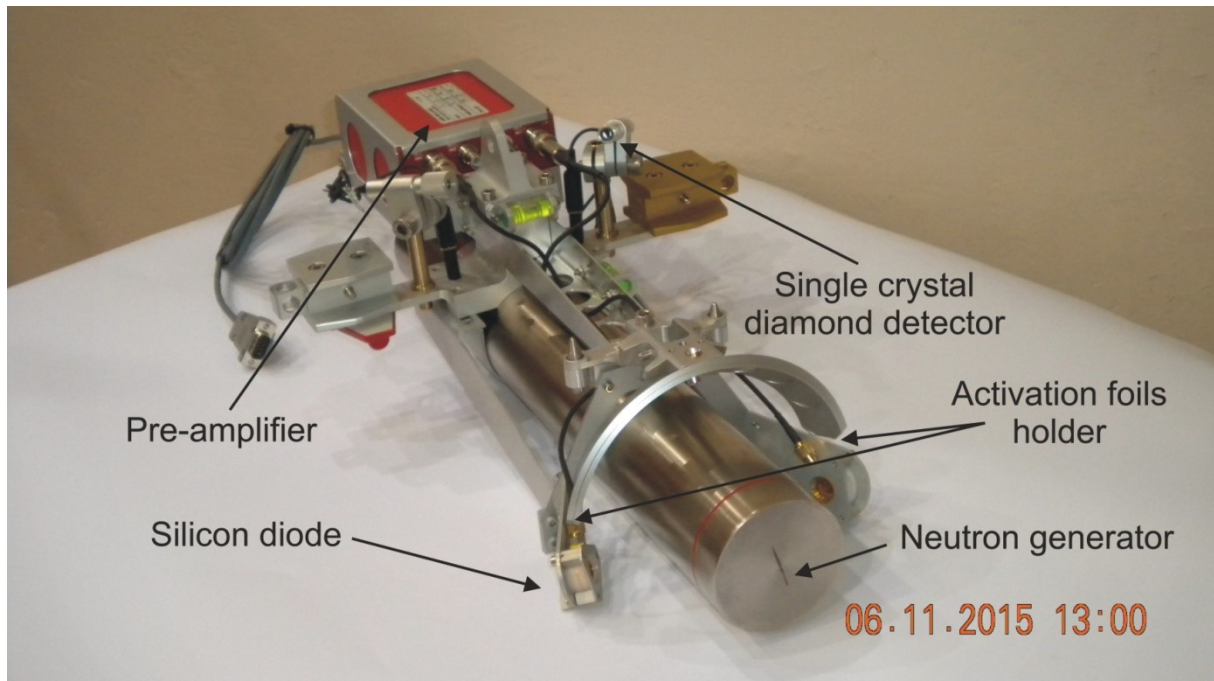
## 111 2. Experiment set up

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113 A set of monitoring activation foils were attached to a custom made holder and mounted on the NG mechanical  
114 support (fig. 2). The holder was designed to allow for retrieval by the JET remote handling system during the in-  
115 vessel calibration of the JET tokamak. The mechanical support used in the second campaign was a slight  
116 variation on the one used in the first campaign; which was modified to improve the positioning of monitoring  
117 detectors with respect to the NG target. Both the SDDs and the activation foils will be used during the in vessel  
118 calibration at JET, which will implement the same mechanical support and positioning system used in the second  
119 NPL campaign.

120 The NG irradiation schedule at NPL consisted of a series of 20-minute irradiations followed by 10 minutes of  
121 NG cooling. During the cooling periods, the positions of the non-attached neutron diagnostics were changed and  
122 other necessary anisotropy measurements were carried out. The daily operational cycle consisted of 11-13  
123 irradiations, except for the first day, where only two irradiations were completed. The monitoring activation foils  
124 were normally removed after the ninth irradiation cycle; to allow the gamma spectrometry measurements to be  
125 started at a practical time.

126



127

128 **Fig. 2** Neutron Generator with the mechanical support needed for remote handling gripping during the JET in  
129 vessel calibration, and to support the “monitoring detectors” and pre-amplifier (first NPL campaign).

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## 131 3. Activation measurements and analyses

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### 133 3.1 Neutron activation reactions and their products

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The activation reactions chosen for the monitoring foils were selected based on numerous requirements. Specifically, the cross section for the reaction products needed to be relatively large and well known. Also, 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 latter requirement mainly limits isotope selection to those of sufficiently long half-life and large branching intensities of the emitted photons to be useful for immediate post irradiation measurements. The reaction cross sections must also be from one of the standard Fusion dosimetry libraries. Finally, the nuclear reactions chosen for NG characterization should also parallel the foil reactions to be used during the DTE2 campaign in the JET KN2 diagnostic.

Several neutron-induced nuclear reactions were considered during the selection process for NS characterization. Given the above requirements, the following nuclear reactions were selected as activation monitors for 14.1 MeV neutrons:  $^{27}\text{Al}(n,p)^{27}\text{Mg}$ ,  $^{56}\text{Fe}(n,p)^{56}\text{Mn}$ ,  $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ , and  $^{93}\text{Nb}(n,2n)^{92m}\text{Nb}$ . It should also be noted that any interactions of high energy neutrons with the NG component materials slow the neutrons down and broaden their low-energy spectrum. Furthermore, the NG emits not only (d,t) neutrons but also trace amounts of neutrons from (d,d) and (t,t) reactions. Thus, detection of low-energy neutrons was necessary and they were monitored with the  $^{115}\text{In}(n,n')^{115m}\text{In}$  nuclear reaction. Finally, note that the niobium foil reaction,  $^{93}\text{Nb}(n,\alpha)^{90}\text{Y}$ , leads to  $\alpha$ -particle emission, which will not be incorporated into the yield calculations due to the relatively low production rate.

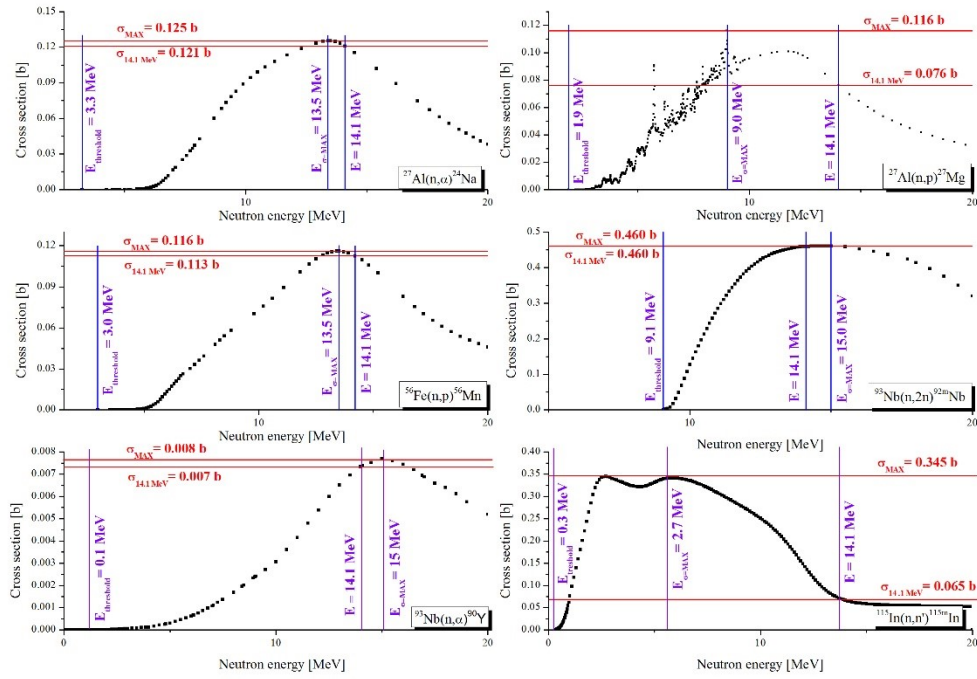
Nuclear data for analysis was taken from the International Reactor Dosimetry and Fusion File (IRDF, volume 1.05) [8]. Except for  $^{93}\text{Nb}(n,\alpha)^{90}\text{Y}$ , which was not listed in the IRDF-1.05 and was therefore taken from the TALYS-based Evaluated Nuclear Data Library (TENDL, volume 2014 [9]) instead. Fundamental Nuclear data parameters relating to the products of nuclear reactions, the gamma lines, intensities and half-lives were taken from the National Nuclear Data Center, Brookhaven National Laboratory, USA.

The cross sections for the above-mentioned reactions are plotted in fig 3. The main parameters for the radioactive products of selected nuclear reactions are listed in the table 1.

**Table 1.** Main parameters of nuclear reaction products.

Product of reaction	Half life	Energy of the most intense gamma lines [keV]	Intensity
$^{27}\text{Al}(n,p)^{27}\text{Mg}$	9.46 min	843.8	0.72
$^{56}\text{Fe}(n,p)^{56}\text{Mn}$	2.58 h	846.7	0.99
$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	14.99 h	1368.6	0.99
$^{93}\text{Nb}(n,2n)^{92m}\text{Nb}$	10.25 day	934.4	0.99
$^{93}\text{Nb}(n,\alpha)^{90}\text{Y}$	3.19 h	202.5	0.97
$^{115}\text{In}(n,n')^{115m}\text{In}$	4.49 h	336.2	0.46

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163

164 **Fig. 3** Cross sections for the selected nuclear reactions.  $E_{\text{threshold}}$  and  $E_{\sigma=\text{MAX}}$  are the neutron energy threshold  
 165 and the energy where the cross section has a maximum, respectively;  $\sigma_{\text{MAX}}$  and  $\sigma_{14.1 \text{ MeV}}$  are the maximum value  
 166 of the cross section and the value of the cross section at 14-MeV, respectively. The  $^{93}\text{Nb}(n, \alpha)^{90}\text{Y}$  data is taken  
 167 from the TENDL 2014 library. The remainder of the data is taken from the IRDFF v. 1.05 library.

168

### 169 3. 2 Neutron emission rate calculation

170

171 The neutron-induced radioactivity in a sample material can be expressed as:

$$172 A = Y_n \cdot R \cdot N_T (1 - \exp(-\lambda \cdot t_A)) \quad (1)$$

$$173 N_T = (m \cdot f \cdot A_v) / w \quad (2)$$

$$174 R = \int_0^{\infty} \varphi(E) \cdot \sigma(E) dE = \langle \varphi(E) \cdot \sigma(E) \rangle \quad (3)$$

175 where:  $Y_n$  is the neutron yield [ $\text{n} \cdot \text{s}^{-1}$ ],  $A$  is the activity of a particular isotope induced by neutron activation [Bq],  
 176  $R$  is the reaction rate [reaction  $\cdot \text{s}^{-1}$ ],  $m$  is the mass of activated sample [g],  $f$  is the abundance of target nuclei in  
 177 the sample [unitless],  $A_v$  is Avogadro's constant [ $\text{mol}^{-1}$ ],  $w$  is the atomic mass of the target nucleus [ $\text{g} \cdot \text{mol}^{-1}$ ],  $\lambda$  is  
 178 the decay constant of the activation product,  $t_A$  is the activation time,  $\varphi(E)$  is the distribution of neutrons as  
 179 function of energy, and  $\sigma(E)$  is the reaction cross section [b].

180 The radioactivity of  $i$ -th activations ( $t_{A_i} \neq t_{A_{i+1}}$ ) and the subsequent cooling time ( $t_{C_i} \neq t_{C_{i-1}}$ ) can be expressed as:

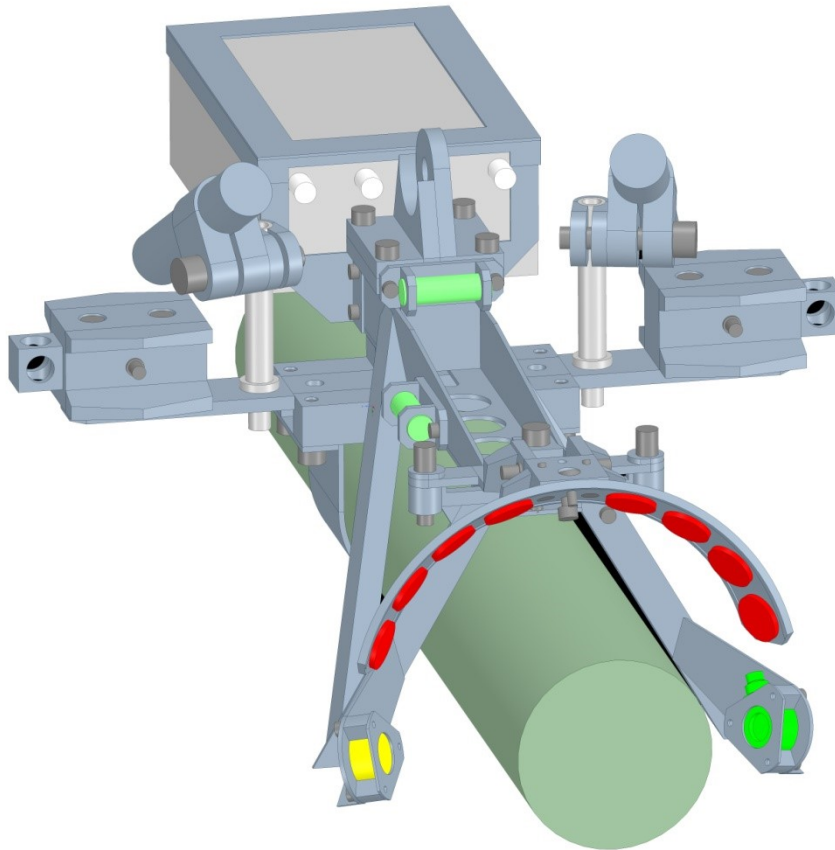
$$181 A_n = Y_n / t \cdot N_T \cdot \langle \varphi(E) \cdot \sigma(E) \rangle \cdot \sum_i B_i (1 - \exp(-\lambda \cdot t_{A_i})) \cdot \exp(-\lambda \cdot t_{C_i}) \quad (4)$$

182 where  $t$  is the total irradiation time,  $B_i$  is a normalization factor which takes into account changes in the neutron  
183 yield, recorded by the monitoring SDD during successive NG pulses of duration  $t_{A_i}$ . Note that in the case of a  
184 single NG pulse, eq. (4) simplifies to eq. (1).

185

### 186 3.3 Monte Carlo N-Particle calculation of the neutron spectra

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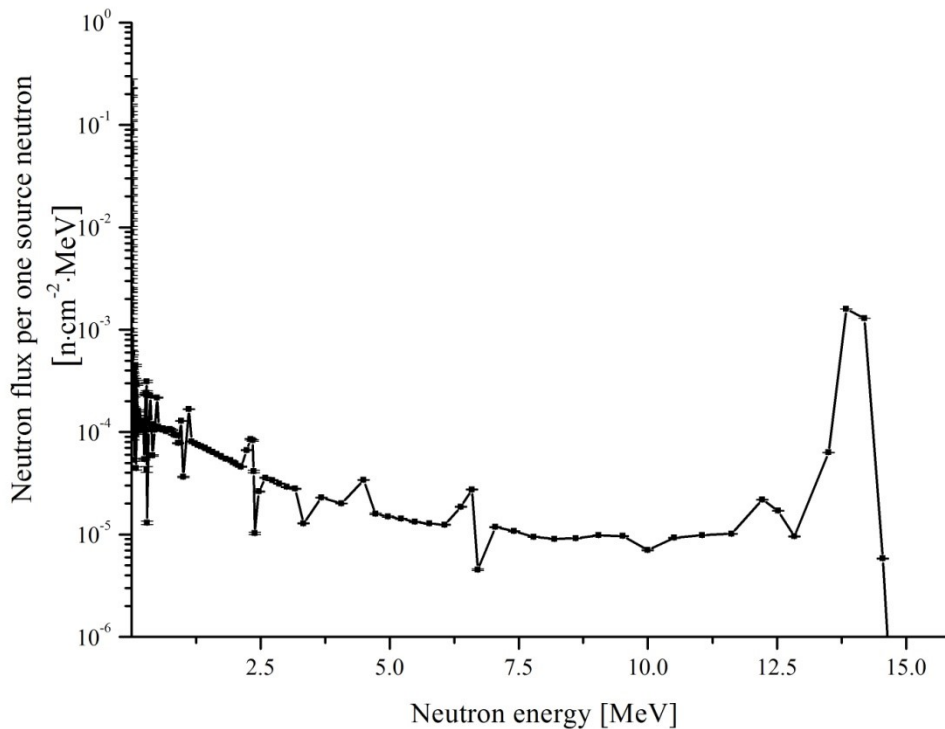
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189 **Fig. 4** MCNP model of the neutron generator (dark green) and holder (grey) with attached foils (red coins).

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191 A simplified CAD version of the NG, activation foils, monitoring detectors and attachments was created and  
192 converted to a Monte Carlo N-Particle Transport Code (MCNP) compatible geometry using the  
193 SuperMC/MCAM code [10,11] (see fig. 4). Neutron transport calculations, using MCNP, were performed to  
194 derive reaction rates in the activation foils being used. The neutron emission spectrum, used in the source  
195 routine, consisted of a weighted sum of expected source components corresponding to (d,t) and (t,d) reactions at  
196 different incident ion beam energies. Spectra of these source components were obtained through simulations  
197 using a custom source subroutine [12] implemented in MCNP. The weighting factors for different source  
198 components in the source description were determined by SDD spectral measurements during the first NPL  
199 campaign.

200 The results of the MCNP calculations of neutron energy distributions at the positions occupied by the activation  
201 foils can be seen in fig. 5. The neutrons with energies below 13 MeV are the result of scattering of source  
202 neutrons through the NG body.



203  
 204 **Fig. 5** The MCNP calculated neutron spectrum at the activation foil position.

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 206 **3.3 Gamma-ray spectrometry**

207  
 208 A high purity germanium (HPGe, Canberra) detector was used for the gamma-ray spectrometry measurements.  
 209 The detector had a relative efficiency of approximately 30 % for 1332-keV photons with a resolution 1.8-keV. It  
 210 was supplied with Canberra Laboratory Sourceless Calibration Software (LabSOCS) and numerical  
 211 characterisation, which allows for source-less energy-efficiency calibration. All the activation foils used for the  
 212 NPL measurement campaigns were of 18-mm diameter and 1-mm thickness, except for niobium foils which  
 213 were 2-mm thick. Four aluminium, four iron, and four niobium foils were mounted on the holder, activated and  
 214 subsequently measured sequentially. The gamma-ray measurements were conducted in two geometries. The  
 215 "cylindrical" geometry consisted of a circular plexiglass holder with a hole at its centre. The holder was mounted  
 216 on the detector endcap and the stack of foils was placed in the hole. The "rosette" geometry consisted of an  
 217 aluminium holder mounted on the detector end cap. A square indent was drilled in the plate so that the four  
 218 activation samples could be placed at opposing ends of the geometry. The efficiency of detecting a gamma-ray in  
 219 HPGe detectors depends on the photon energy, the sample size, and the measurement geometry. Thus, for each  
 220 foil set, the energy-efficiency calibration was calculated using LabSOCS. The option of measuring in two  
 221 geometries enables the selection of the maximum efficiency for the chosen gamma line being measured. The  
 222 following uncertainties, for the various photon energies measured, are assigned for the efficiency calibration:  
 223 7 % standard deviation (SD) for photons of less than 150 keV in energy, 6 % SD for photons between 150–  
 224 400 keV, and 4.3 % SD for photons between 400–7000 keV [13]. These are standard LabSOCS figures, while in  
 225 our studies using Marinelli sample geometries, an efficiency uncertainty of 0.1 % was observed [14]. On the

226 other hand, values of detection efficiency uncertainty rapidly increase with changing samples density. Based on  
227 the cross calibration of the above detector with point like source and measurements of metal samples activated  
228 during Neutron Source Calibration we deduced that the most reasonable efficiency uncertainty for photons  
229 between 400-7000 keV is 8 % [2].

230 All the aluminium foils were measured twice. One set of measurements was conducted 12 minutes after the  
231 irradiation had concluded. This 12 minute cooling time allowed for the decay of the short lived  $^{28}\text{Al}$ , from the  
232  $^{27}\text{Al}(n,\gamma)^{28}\text{Al}$  activation reaction. Then 40 minutes of measurement in the cylindrical geometry allowed for the  
233 recording of the  $^{27}\text{Mg}$  activity. The iron sample was then measured for 30 min with a cylindrical geometry to  
234 determine the activity of  $^{56}\text{Mn}$  present. The aluminium samples were then measured a second time in the rosette  
235 geometry for 900 min and the activity of  $^{24}\text{Na}$  was determined. Finally,  $^{92\text{m}}\text{Nb}$  metastable was measured in the  
236 four samples for 420 minutes in the rosette geometry. The presence of the  $^{90}\text{Y}$  radionuclide was also detected in  
237 the niobium sample, as unexpected. The low energy neutron monitoring foil, indium, was allowed to cool for 4 h  
238 before it's measurement, which allowed it to partly decay to  $^{116}\text{In}$  and to decrease the Compton background  
239 around 336.2-keV peak of full energy absorption being measured.

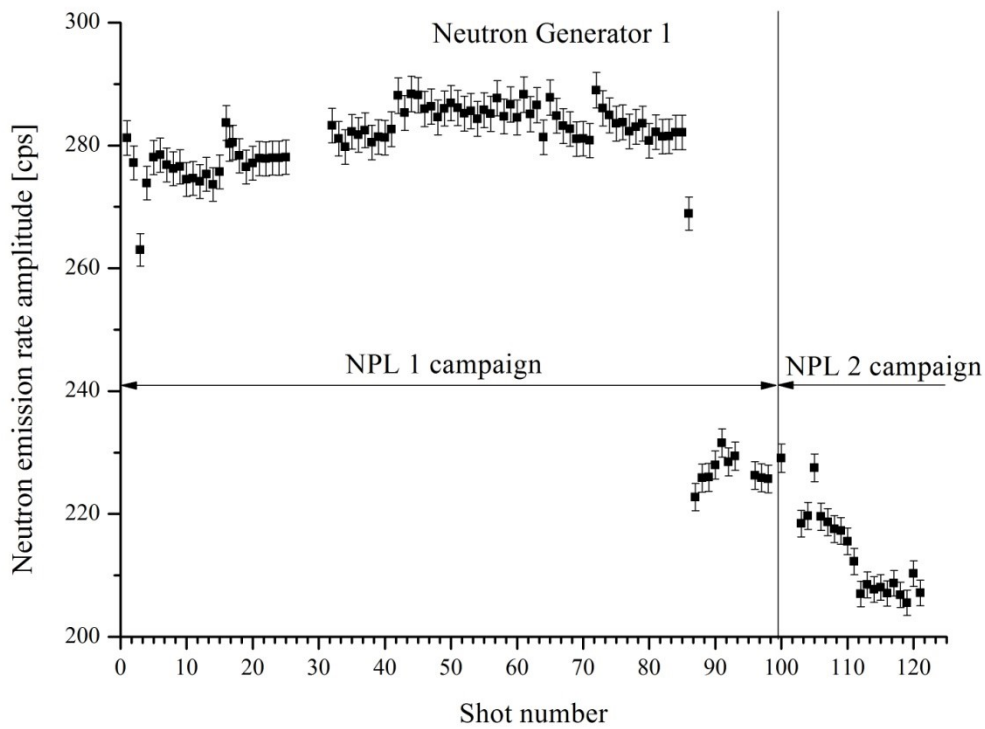
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#### 241 **4. Results**

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243 The normalized amplitudes of the neutron yield, for NG1 and NG2 are presented in fig. 6 and 7, as a result of the  
244 signal (counts per second) from the monitoring SDD. The shot numbers are presented on the horizontal axis. The  
245 irradiation duration was typically 1200 s; however, there were also shots with durations of 900 s and 600 s. The  
246 variations in  $Y_n$  amplitudes, measured with the SDD, were taken into account when deriving the  $B_i$  factors in eq.  
247 (4).

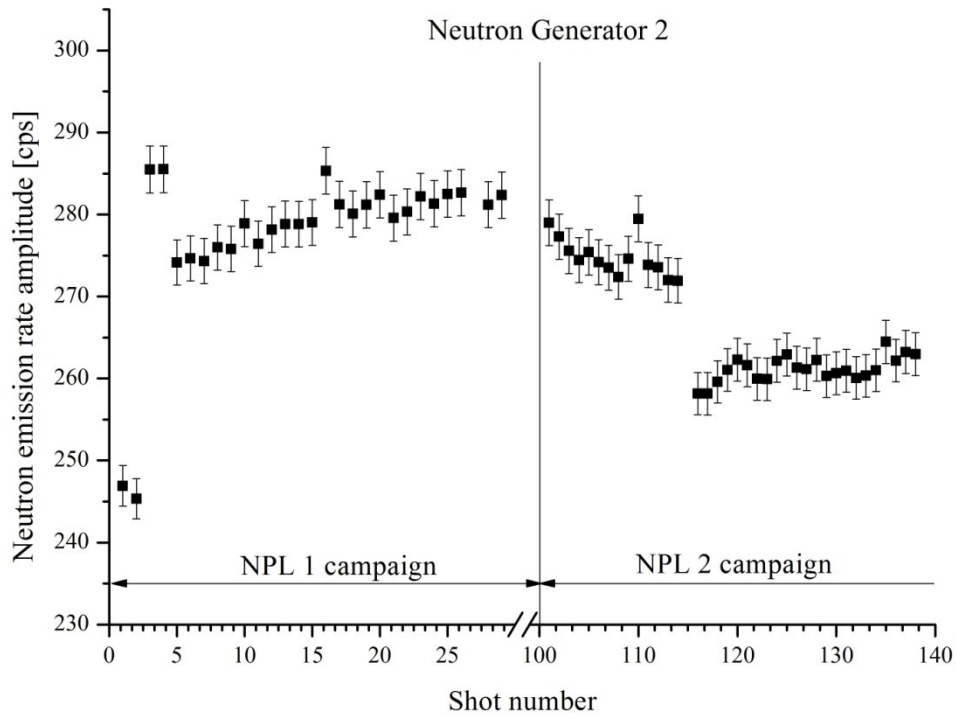
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250 **Fig. 6** Relative amplitude of  $Y_n$  for NG1 based on SDD measurements.

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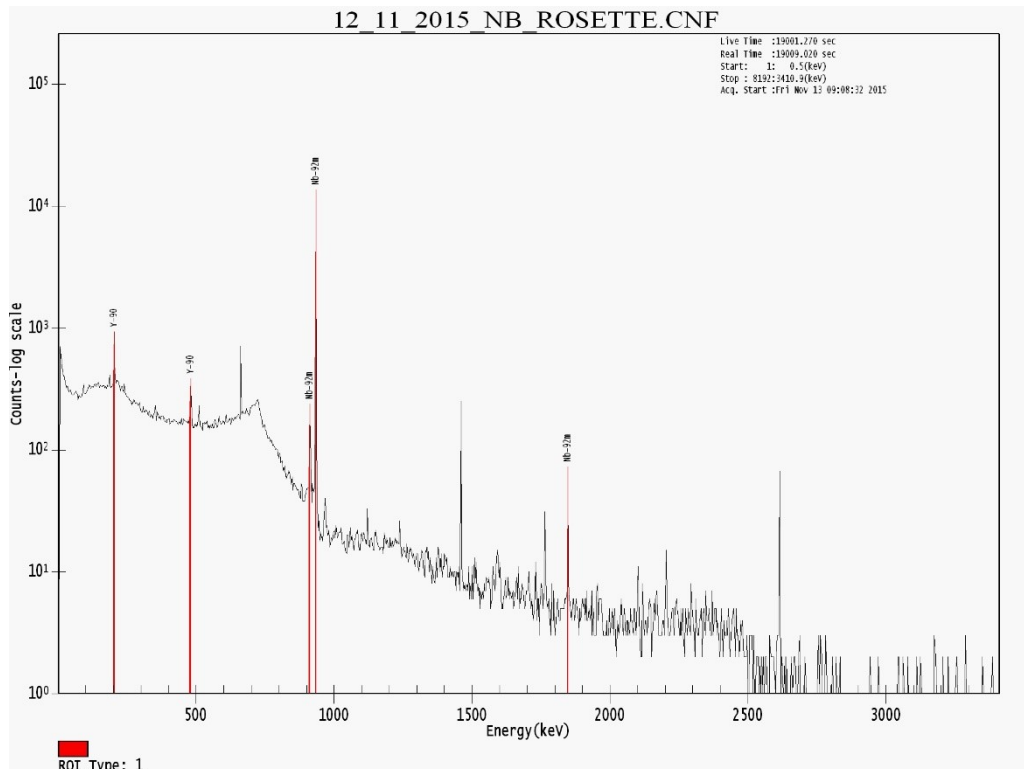


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253 **Fig. 7** Relative amplitude of  $Y_n$  for NG2 based on SDD measurements.

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The measured gamma-ray spectrum of the aluminum sample displayed the characteristic peaks of  $^{27}\text{Mg}$  and  $^{24}\text{Na}$ , whilst the standard iron sample showed full energy peaks resulting from the decay of  $^{56}\text{Mn}$ . The niobium was therefore identified as the most effective neutron monitor for the DTE2 experimental campaign. The decay gamma spectrum of the activated niobium, during the fourth day of the NPL campaign which is presented in fig. 8.

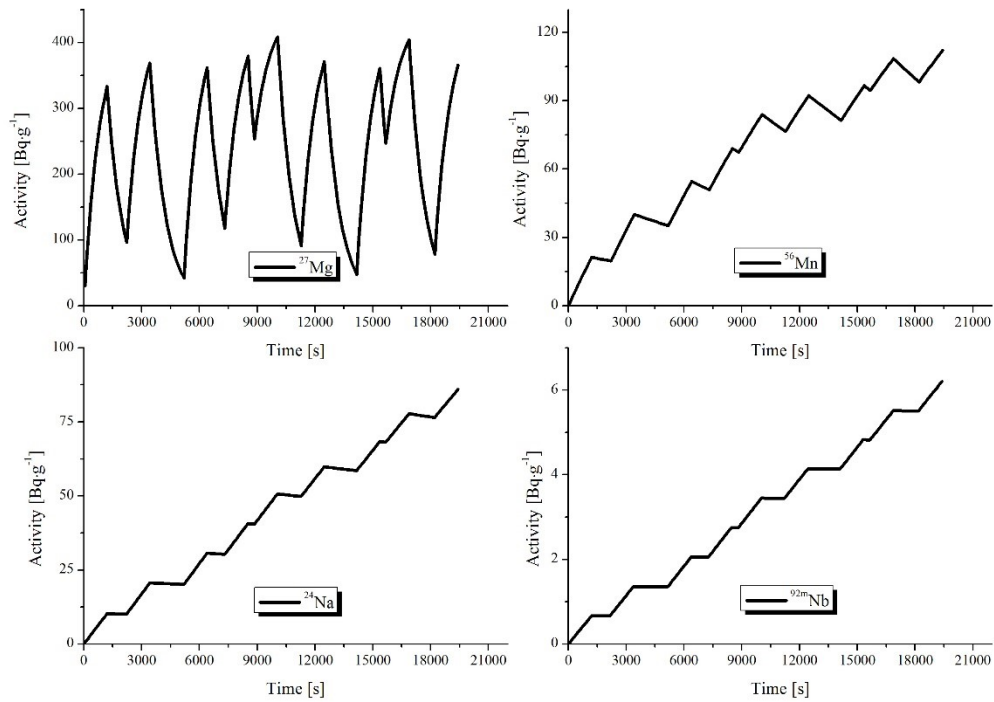


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**Fig. 8** Gamma-ray spectrum (original screenshot from Genie2000) of niobium activation foil irradiated on Nov 10<sup>th</sup> and measured the following day. In addition to  $^{92m}\text{Nb}$  and the natural background radionuclide peaks observed, two full energy absorption peaks for  $^{90}\text{Y}$  are visible (from left: two red peaks from  $^{90}\text{Y}$ , three red peaks from  $^{92m}\text{Nb}$ ).

As mentioned above, the  $^{90}\text{Y}$  radionuclide from the  $(n,\alpha)$  reaction was detected in the niobium sample, along with  $^{92m}\text{Nb}$ . This is evidence of a highly efficient activation process.

Fig. 9 shows the build-up of  $^{27}\text{Mg}$ ,  $^{56}\text{Mn}$ ,  $^{24}\text{Na}$  and  $^{92m}\text{Nb}$  radioactivity on the second day of the experimental campaign and is representative of the build-up pattern observed throughout the campaigns. The graphs show the result of calculations that took into account the observed variations in neutron yield, irradiation times and cooling times for each pulse. For  $^{27}\text{Mg}$ , the accumulated activity oscillates around a specific level with little variation due to its short half-life relative to the irradiation and cooling times. Saturated activity was not reached here. For the other radionuclides, the activity build-up is essentially linear due to their long half-lives relative to the irradiation and cooling times.

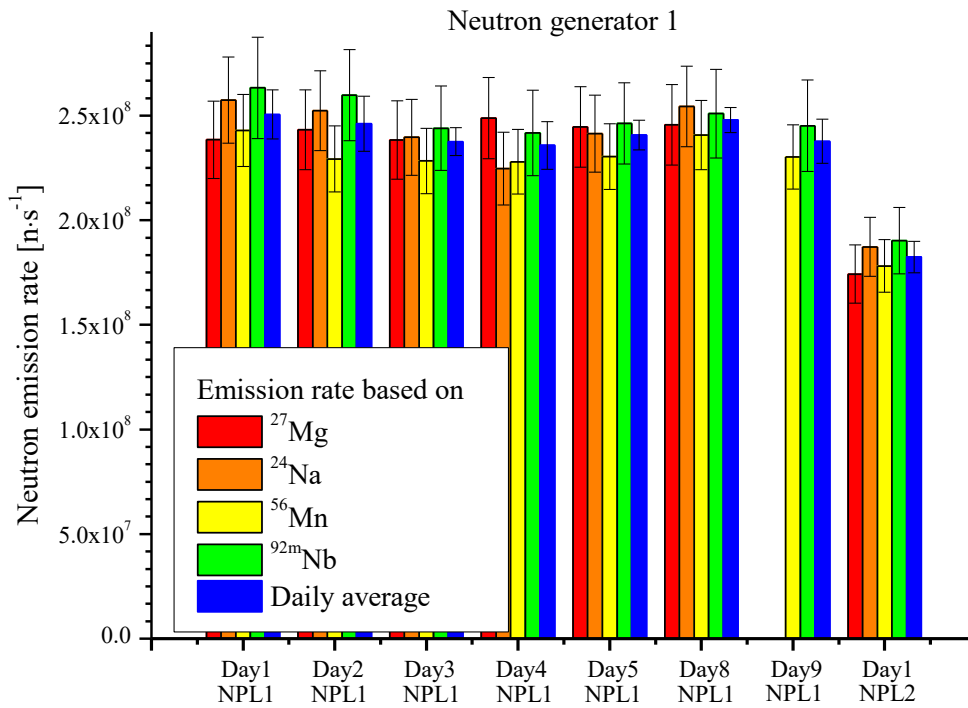


277  
 278 **Fig. 9** Time evolution of radioactivity for particular reaction products during the second day of irradiation  
 279 under real conditions.

280  
 281 Over both NPL experimental campaigns, the measured  $^{27}\text{Mg}$  radioactivity, after a single day's irradiation, was in  
 282 the range of 243–409  $\text{Bq}\cdot\text{g}^{-1}$ . The  $^{24}\text{Na}$  radionuclide was measured twice with identical results; however, the  
 283 uncertainty in the measured activity was lower for the longer measurement. The  $^{24}\text{Na}$  radioactivity was in the  
 284 range of 22–86  $\text{Bq}\cdot\text{g}^{-1}$ . For  $^{56}\text{Mn}$  formed during the irradiation of the iron sample, the measured radioactivity was  
 285 in the range of 44–126  $\text{Bq}\cdot\text{g}^{-1}$ . The results for  $^{92\text{m}}\text{Nb}$  varied over the range of 1.44–6.35  $\text{Bq}\cdot\text{g}^{-1}$ . During the last  
 286 day of the first experimental campaign at NPL, indium foils were used instead of aluminium foils. The  
 287 radioactivity of  $^{115\text{m}}\text{In}$  was 42  $\text{Bq}\cdot\text{g}^{-1}$ .

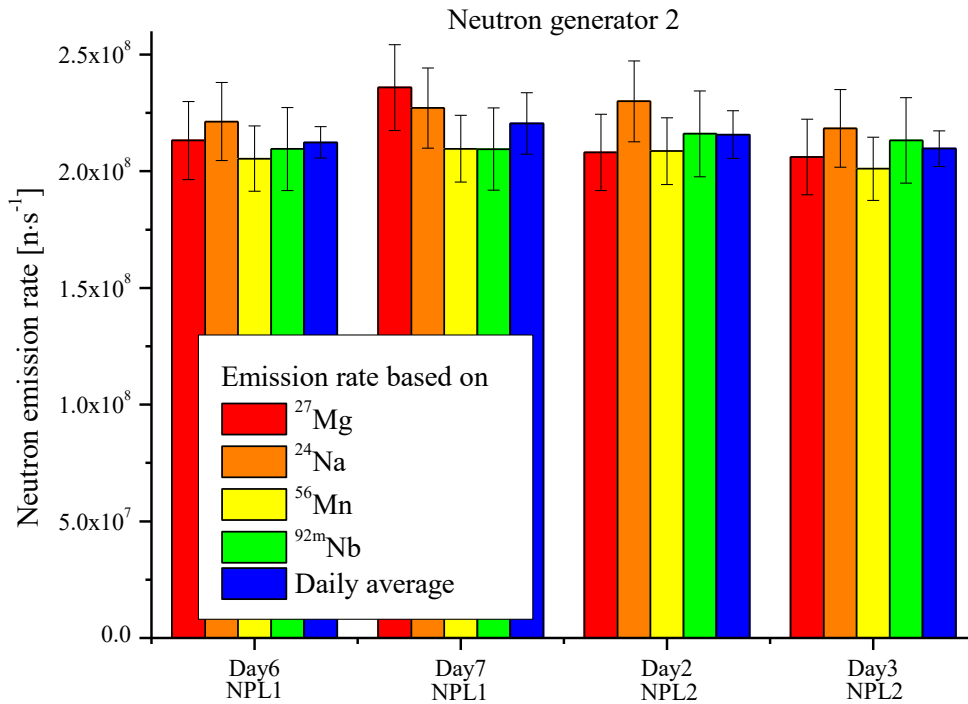
288 The estimated neutron emission rate was based on an MCNP-calculated neutron reaction rates at the foil  
 289 locations and on the measured radioactivity as given by eq.4, fig. 9 and 10, show plots of the estimated neutron  
 290 emission rates for particular reaction products for each day of the experimental campaigns. The calculated  
 291 reaction rates per one source neutron were  $8.34\cdot 10^{-5}$  for  $^{27}\text{Al}(n,p)^{27}\text{Mg}$ ,  $1.15\cdot 10^{-4}$  for  $^{56}\text{Fe}(n,p)^{56}\text{Mn}$ ,  $1.24\cdot 10^{-4}$  for  
 292  $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ , and  $4.45\cdot 10^{-4}$  for  $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ . Fig. 9 showing NG1, and fig. 10 showing NG2.

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**Fig. 10** Estimated neutron emission rates for NG1 based on MCNP-calculated neutron spectra for the foils. The error bars represent the total uncertainty ( $1\sigma$ ).



298

299 **Fig. 11** Estimated neutron emission rates for NG2 based on MCNP-calculated neutron reaction rates for the  
300 foils. The error bars represent the total uncertainty ( $1\sigma$ ).

301

302 The total uncertainty in the neutron emission rate was calculated as the quadratic sum of different contributions,  
303 including:

- 304 ○ The statistical uncertainty in the activity, the branching ratio, and the computed decay correction factor.  
305 This uncertainty amounts to 8.3% for  $^{27}\text{Mg}$ , 8.1% for  $^{24}\text{Na}$ , 7.5% for  $^{56}\text{Mn}$  and 8.9% for  $^{92\text{m}}\text{Nb}$ .
- 306 ○ The uncertainty in the number of target nuclei, which is directly related to the precision of the sample  
307 mass measurement, which is equal to 0.01 g for the foil samples used here. This uncertainty amounts to  
308 0.39% for Al samples, 0.12% for Fe samples and 0.06% for Nb samples.
- 309 ○ The uncertainty of the sums in eq. 4 was estimated to be Mg: 1.51%, Na: 1.16%, Mn: 1.16%, Nb:  
310 1.16%, because all components in this part of the equation were correlated to each other. The highest  
311 uncertainty was for magnesium sample due to its short half-life.
- 312 ○ The uncertainty on the reaction rates calculated by MCNP is less than 0.1%. The uncertainties of cross  
313 sections in the activation calculation were not taken into account.

314 The resulting total uncertainty of the neutron emission rate based on singular nuclear reaction is in the range 6.7-  
315 9.2%. The discrepancies between the reactions on the same day have been observed, outside the combined  
316 uncertainties of the measurements. The SD for the daily average neutron emission rates for NG1 was within the  
317 range of 2.5-4.9 %, with the exception of day 2 of the NPL 1 campaign, where it was greater than 5 %. For NG2  
318 the SD was in the range of 3.2-6.0 %, where more than 5 % was observed only on the seventh day of the NPL 1  
319 campaign. It should be noted that when the ion beam current intensity changes, the neutron emission rate is  
320 affected. The monitoring foils are distributed approximately 180 degrees, asymmetrically across the main axis of  
321 the NG. Deviations of the ion beam in the radial direction result in neutron emissions that are no longer  
322 symmetric about the centre of the NG target. Which can result in variations in the measured neutron fluence at  
323 the foil positions.

324 The neutron yields measured by the activation foils were compared with the signals obtained by the calibrated  
325 monitoring SDD, on a day to day basis, and they were found to agree in all cases within 8%.

326

## 327 **5. Conclusions**

328

329 A 14.1 MeV neutron generator was selected as the NS for the forthcoming in-vessel calibration of neutron  
330 diagnostics on the JET tokamak in preparation for DT operations. After detailed analysis of the nuclear reaction  
331 parameters. the following reactions were selected for the purpose of measurements:  $^{27}\text{Al}(n,p)^{27}\text{Mg}$ ,  
332  $^{56}\text{Fe}(n,p)^{56}\text{Mn}$ ,  $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ ,  $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ . Two NGs have been characterized in terms of neutron emission  
333 (rate) and angular distributions at the National Physical Laboratory. The activation technique has been used to  
334 measure the NGs neutron emission rates. The same methodology will be used as a complementary technique for  
335 NG neutron yield monitoring during the in vessel process. Throughout the NPL campaigns', the activity of the  
336 reaction products has been measured using gamma-ray spectrometry with less than 10 % uncertainty. The  
337 exception was the measurements with  $^{115}\text{In}$ . due to the larger uncertainty in determining the detector efficiency at  
338 lower energies. The NG emission rates have been derived using MCNP-calculated reaction rates. The

339 uncertainty for these values was in the range 6.7-9.2 %. The SD for the daily average neutron emission rate for  
340 NG1 was greater than 5 % on a solitary occasion; this was on the second day of the NPL 1 campaign. The NG2  
341 SD was more than 5 % only once, on the seventh day of the NPL 1 campaign. The neutron yields measured by  
342 the activation foils were in agreement within 8% with the yields obtained by the calibrated monitoring SDD.

343

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#### 349 **References**

- 350 [1] X-5 Monte Carlo Team, MCNP - A General N-Particle Transport Code, Version 5., Los Alamos National  
351 Laboratory, 2003.
- 352 [2] D.B. Syme, S. Popovichev, S. Conroy, I. Lengar, L. Snoj, C. Sowden, L. Giacomelli, G. Hermon, P. Allan, P.  
353 Macheta, D. Plummer, J. Stephens, P. Batistoni, R. Prokopowicz, S. Jednorog, M.R. Abhangi, R. Makwana, JET  
354 EFDA contributors, Fusion Yield measurements on JET and their Calibration, *Fusion Eng. Des.* 89 (2014) 2766–  
355 2775. doi:10.1016/j.fusengdes.2014.07.019.
- 356 [3] P. Batistoni, 15.5 Nuclear fusion technology in conjunction with DT operations at JET in support of ITER,  
357 in: 29<sup>th</sup> Symp. Fusion Technol., Prague, 2016: p. 17.
- 358 [4] E.P. Bogolubov, V.I. Ryzhkov, D.I. Yurkov, VNIIA research, engineering, and manufacturing capabilities to  
359 develop neutron generators and equipment on their basis, in: *Int. Sci. Tech. Conf. Portable Neutron Gener.*  
360 *Technol. Their Basis*, Moscow, 2012: pp. 22-26.
- 361 [5] <http://www.vniia.ru/> (accessed November 21, 2016).
- 362 [6] A. Klix, M. Angelone, P. Batistoni, A. Cufar, Z. Ghani, L. Giacomelli, S. Jednorog, E. Laszynska, I. Lengar,  
363 S. Lorenti, A. Milocco, L.W. Packer, M. Pillon, S. Popovichev, M. Rebai, S.D. Rigamonti, H. Roberts, L. Snoj,  
364 E. Tardocchi, D. Thomas, P1.066 Characterization of a neutron generator for the JET monitoring system  
365 calibration with NE-213 spectrometer, in: 29<sup>th</sup> Symp. Fusion Technol., Prague, 2016: p. 137.
- 366 [7] E. Laszynska, S. Jednorog, A. Ziolkowski, M. Gierlik, J. Rzakiewicz, Determination of the emission rate for  
367 the 14 MeV neutron generator with the use of radio-yttrium, *Nukleonika*. 60 (2015) 319-322. doi:  
368 10.1515/nuka-2015-0040.
- 369 [8] R. Capote, K.I. Zolotarev, V.G. Pronyaev, A. Trkov, E.M. Zsolnay, H. K. Nolthenius, (2014, October).  
370 *International Reactor Dosimetry and Fusion File IRDFF v.1.05*, (2012). <https://www-nds.iaea.org/IRDFF/>  
371 (accessed June 10, 2016).
- 372 [9] A. J. Koning, D. Rochman, S.C. van der Marck, J. Kopecky, J.Ch. Sublet, S. Pomp, H. Sjostrand, R. Forrest,  
373 E. Bauge, H. Henriksson, O. Cabellos, S. Goriely, J. Leppanen, H. Leeb, A. Plompen, R. Mills, S. Hilaire,  
374 *TENDL-2014:TALYS-based evaluated nuclear data library*, (2015). <ftp://ftp.nrg.eu/pub/www/talys/tendl2014>  
375 (accessed June 10, 2016).
- 376 [10] Y. Wu, FDS Team, CAD-based interface programs for fusion neutron transport simulation, *Fusion Eng.*  
377 *Des.*, 84 (2009) 1987-1992. doi:10.1016/j.fusengdes.2008.12.041.

- 378 [11] Y. Wu, J. Song, H. Zheng, G. Sun, L. Hao, P. Long, L. Hu, FDS Team, CAD-Based Monte Carlo Program  
379 for Integrated Simulation of Nuclear System SuperMC, *Ann. Nucl. Energy.*, 82 (2015) 161-168.  
380 doi:10.1016/j.anucene.2014.08.058.
- 381 [12] A. Milocco, A. Trkov, M. Pillon, A Monte Carlo model for low energy D–D neutron generators, *Nucl.*  
382 *Instruments Methods Phys. Res. Sect. B Beam Interact. With Mater. Atoms.* 271 (2012) 6-12.  
383 doi:10.1016/j.nimb.2011.10.009.
- 384 [13] F. L. Bronson, Validation of the accuracy of the LabSOCS software for mathematical efficiency calibration  
385 of Ge detectors for typical laboratory samples, *Radioanal. Nucl. Chem.* 255 (2003) 137–141.  
386 doi:10.1023/A:1022248318741.
- 387 [14] S. Jednorog, A. Szydłowski, M. Scholz, M. Paduch, B. Bienkowska, Preliminary determination of angular  
388 distribution of neutrons emitted from PF-1000 facility by indium activation, *Nukleonika.* 57 (2012) 563–568.