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**ABSOLUTE NEUTRON EMISSION MEASUREMENTS FOR TWO
NEUTRON GENERATORS**

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ABSTRACT:

In order to calibrate the fission chamber neutron monitors and activation systems within the Joint European Torus, JET, two compact deuterium-tritium neutron generators were acquired. Prior to their deployment in JET they were brought to NPL for determination of the neutron emission. Measurements were performed with a precision long counter to determine the angle dependence of the emission on an absolute scale, and with activation foils to derive the total emission rate into 4π steradian. Agreement between the long counter values and the mean of the activation results for the total emission rates of the two generators was within the assigned uncertainties of 3 % to 4 %. This was for both the emission rate per monitor count, based on a diamond monitor detector attached to the neutron generator, and for the total emission rate although this latter quantity varied with time.

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Approved on behalf of NPLML by
Giuseppe Schettino, Knowledge Leader, CMES.

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1 Introduction

The Joint European Torus (JET) is a large tokamak used to study magnetically-confined plasmas with the ultimate aim of generating energy via nuclear fusion. It is collectively used by all European fusion laboratories under the EUROfusion consortium, and operated by the Culham Centre for Fusion Energy via a contract between the European Commission and the UK Atomic Energy Authority.

During January/February 2017 a compact deuterium-tritium (d+T) fast neutron generator (NG) was deployed within JET to calibrate the fission chamber neutron monitors and activation systems⁽¹⁾. Prior to this the neutron emission characteristics of the NGs, i.e. the total neutron emission and the angle dependence of the fluence were determined to an accuracy of better than 5 % at the National Physical Laboratory, NPL. Measurements were performed using a precision long counter (LC) and various activation foils. The experimental details, analysis techniques, and results of these measurements are presented here.

2 Neutron generators

Two nominally identical generators were purchased for potential use in the measurements at JET. Both were characterised at NPL. They are referred to throughout this document as NG1 and NG2. They were type ING-17 produced by VNIIA⁽²⁾ in Russia. Each one had two serial numbers; NG1 was body 0001600 and tube 5596228, while NG2 was body 0001601 and tube 5596227.

In this type of generator an accelerated mixed beam of deuterons and tritons is incident on a target of tritium and deuterium absorbed in a thin titanium layer. The reference accelerating potential used was 100 kV. For the measurements at NPL and during deployment within JET the cylindrical NG tubes were mounted in a jig, see Figure 1. The jig housed one or more diamond monitor detectors together with their preamplifier, and an arc of activation foils in a fixed geometry. These were designed to act as monitors, positioned at accurately reproducible positions, to link the present measurements to those made in-vessel at JET.

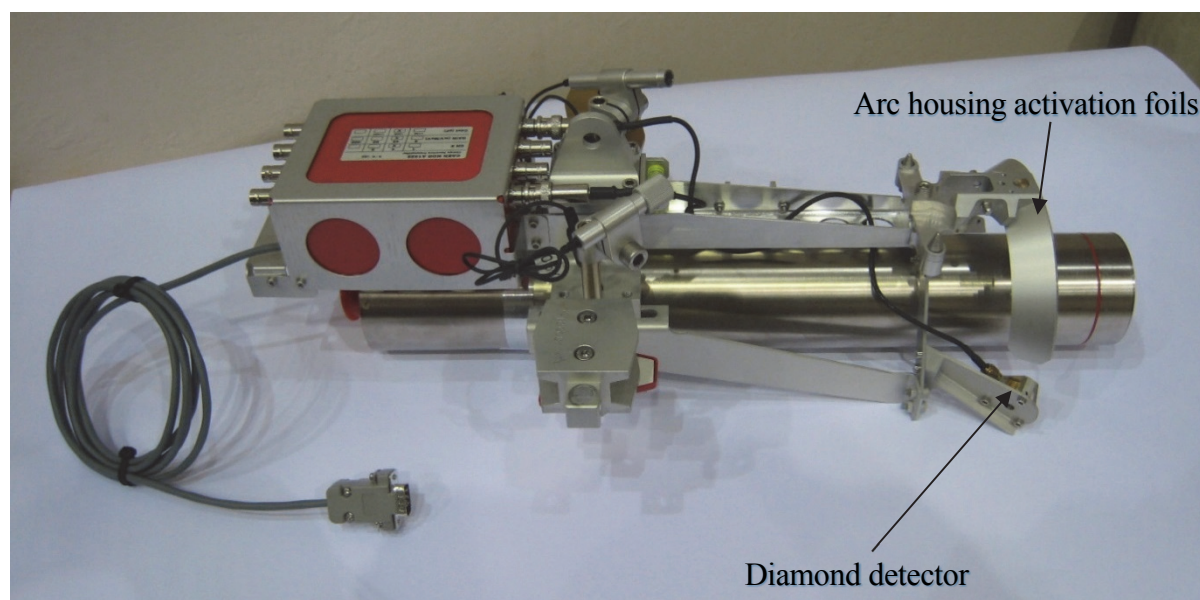


Figure 1. ING-17neutron generator with support for monitoring equipment. The target layer is close to the red line seen near the end of the generator tube to the right in the picture. The arc arrangement slightly to the left of this ring housed activation foils, while the diamond or silicon monitors are visible on wings just outboard of this arc. Equipment mounted on the opposite end of the tube to the target include the preamp for the active monitors (red box) and positioning lasers.

The measurements at NPL involved collaborators from several different institutions. The NGs were operated by personnel from the Culham Science Centre, and the diamond monitors by scientists from the Department of Fusion and Nuclear Safety Technology, ENEA, Frascati, Italy, while the activation foils in the arc were counted and analysed by personnel from the Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland. In addition spectrum measurements were performed with another diamond detector operated by staff from two establishments in Milan, Italy, namely the Istituto di Fisica del Plasma “P. Caldirola”, CNR, and the Università degli Studi di Milano-Bicocca. Finally further spectrometry measurements were performed by a staff member from the Karlsruhe Institute of Technology, Germany using a liquid scintillation detector.

This report is confined to the LC and activation foil measurements performed by NPL. All data were logged relative to the counts from the monitor diamond detectors which were operated by the collaborators from ENEA.

3 Modelling of the neutron generator

As part of the extensive neutronics analyses required to derive the JET neutron detectors' calibration, a detailed computational model of the NG was created using the multi-particle Monte Carlo code MCNP. The results were used extensively in the analysis of the NPL measurements.

Initially the MCNP model was based on a schematic diagram of the NG target area as supplied by manufacturer and simple assumptions about the ion beam composition. During the measurement campaign additional information was acquired and incorporated in improved versions of the model. Information on the primary spectrum from the deuteron and tritium beams striking the target was obtained from measurements, made with high-resolution diamond detectors⁽³⁾. These provided data on the ratios of neutrons from the various possible reactions, i.e. deuterons on tritium, tritons on deuterium, for both atomic and molecular beams. This information provided an estimate of the primary spectrum from the target⁽⁴⁾, and this in turn was used as a source term within MCNP. Improvements to the information about the construction of the NG in particular in the region near the target were also obtained during the measurement campaign and incorporated in the model – see section 7.

The calculations⁽⁵⁾ provided estimates of the neutron spectra incident on the LC as a function of angle relative to the NG axis. These spectra were used to calculate the efficiencies and effective centres for the LC; parameters that are used in deriving the neutron fluence. The spectrum consisted of a main peak in the 14 MeV region and a continuum extending down to essentially zero energy. The calculations also provided values for the expected activation in the NPL foils per neutron from the NG target; and the measured activity essentially provided a normalisation of these calculations to the actual number of neutrons produced.

In addition to providing an estimate of the spectral shape at different angles relative to the axis of the NG the MCNP calculations provided an estimate of the fluence at these angles. By integrating these angular fluence values around 4π sr the total fluence emitted could be derived. The value obtained was 1.012 which, in view of the fact the calculations were for a single neutron from the target, indicated that there were more neutrons emitted from the NG as a whole than from the target. Various effects within the target backing and the body of the NG can increase or decrease the total number of neutrons seen, and it would appear the neutron production, e.g. by (n,2n) reactions in high Z materials, is greater than the total absorption of neutrons.

It is important to take account of these additional neutrons when comparing results from the LC and the activation measurements because the LC results for the total emission into 4π sr include this additional 1.2 % whereas the activation measurements provide a normalisation for the neutron production from the target which does not include this 1.2 %

4 The long counter

Long counters (LCs) have been used for measuring neutron fluence since they were first proposed in 1947. They have the advantages of: high sensitivity, negligible gamma response in most situations, and a fluence response that is relatively constant over the energy region from roughly 1 keV to 7 MeV. Above this energy the response decreases monotonically. In the early days the constant (flat) response was a very important feature allowing the response at one energy to be predicted from a measurement at other energies. With the advent of modern neutron transport codes this has become less important as response function shapes can be calculated reliably. The present measurements were undertaken with a LC built to the tight specifications of De Pangher and Nichols⁽⁶⁾ and its response function has been determined to an accuracy of about 2.5 % (at 1σ) up to energies of about 17 MeV using radionuclide sources, neutron transport calculations⁽⁷⁾, and international fluence comparison exercises⁽⁸⁾.



Figure 2. The De Pangher LC, top left in the picture, mounted in the NPL low-scatter area with the NG to the right and a shadow cone between these two devices. The device in the foreground to the left is a diamond detector. The target of the NG is positioned at the centre of the circle about which the LC was rotated.

The LC is cylindrical in shape, consisting of a central thermal neutron detector, a BF_3 proportional counter in the present case, surrounded by a moderating layer and an outer shield layer. It is designed to be used with the source of neutrons on the axis and in front of the ‘front face’ which is at one end of the cylinder. This maximises the response to neutrons from the source and minimises the response to room and air scattered neutrons which are always present in a calibration room. At NPL a large low-scatter area, referred to as the Main Bay, with dimensions of $24 \text{ m} \times 18 \text{ m} \times 18 \text{ m}$ is available, but scatter corrections still have to be made. These are achieved by making measurements with an absorbing shadow cone between the source of neutrons and the LC in addition to the measurement without the cone. The counts due to direct neutrons are obtained by subtracting those measured with the cone present from those with it absent. Figure 2 shows the arrangement with the shadow cone in position.

A LC is a physically large instrument, the De Pangher type being roughly 43 cm long by 40 cm in diameter. It is, however, normally calibrated to provide the fluence at a fixed distance from a small, or a point, source of neutrons and this involves determination of the effective centre distance

from the LC front face. ('Front face' is taken here to mean the front face of the moderator, i.e. source distances are measured with the front cadmium shield temporarily removed.) The effective centre, like the efficiency, varies with neutron energy. The precise solid angle presented by the front face is difficult to define because the detection efficiency for a neutron striking the sensitive area depends on the neutron energy and the distance from the central axis. The area inside the shield annulus is, however, only 20 cm in diameter which corresponds, when the LC is 3 m from the source as it was in these measurements, to a half angle of less than 2° , and a solid angle of 0.0035 sr.

5 Long counter efficiencies and effective centres

Although tables have been derived at NPL for the De Pangher LC efficiency and effective centre as a function of neutron energy the fact that the spectrum from a NG of the type used in these measurements is not monoenergetic, because of scattering within the target backing and the body of the device, meant that spectrum averaged values needed to be used. Spectra were obtained from the MCNP model of the NG and were provided in terms of the fluence ϕ_i in n energy bins so that the total fluence Φ is given by:

$$\Phi = \sum_{i=1}^n \phi_i \quad (1)$$

The spectra consisted of a main peak in the 14 MeV region and a continuum extending down to essentially zero energy. Figure 3 shows the calculated spectra, normalised to one neutron from the target, at three different angles. The energy of the primary peak, which from the data obtained with two separate diamond detector measurements actually consists of a number of closely spaced peaks (not visible with the resolution of Figure 3) corresponding to the various reactions, decreases with angle because of the kinematics, and at 180° the overall intensity is reduced by absorption and scattering along the length of the generator tube which is between the target and the LC.

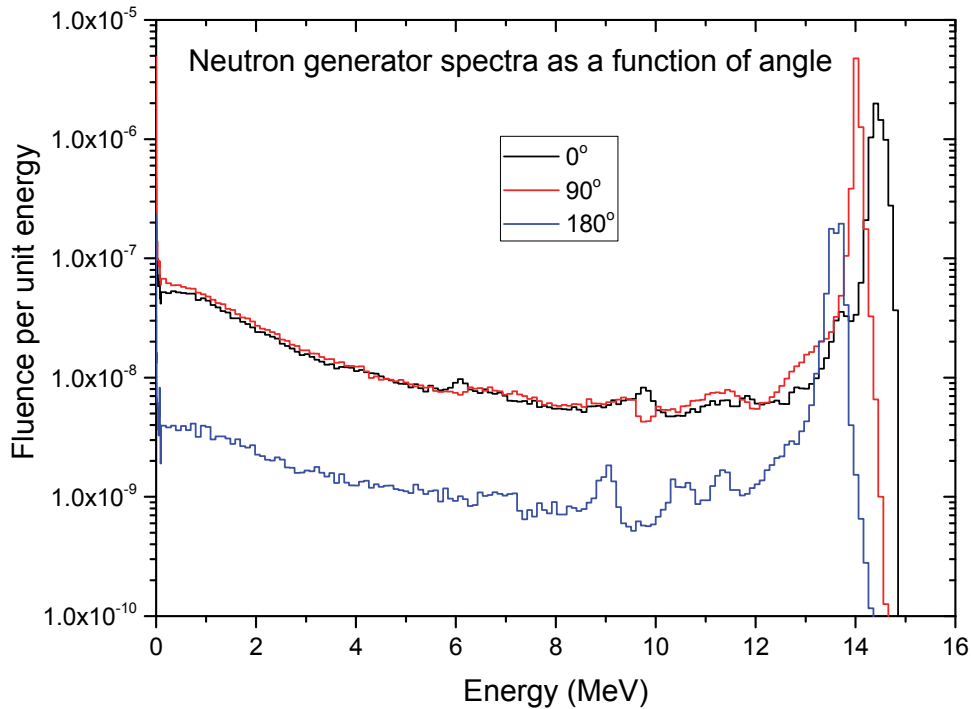


Figure 3. Neutron generator spectra calculated for 0° , 90° , and 180° relative to the NG axis. They are plotted per neutron from the target.

The normal equation for deriving the fluence Φ in terms of neutrons per cm² at a reference distance r_{ref} cm when a long counter is used to measure monoenergetic neutrons is:

$$\Phi = \frac{P \cdot F_A \cdot (r_0 + r)^2}{r_{ref}^2 \cdot \varepsilon} \quad (2)$$

where:

- P is the long counter counts corrected for in-scatter and dead-time,
- F_A is the air attenuation factor correcting for air out-scatter,
- r_0 is the target to long counter front face distance,
- r is the long counter effective centre value at the relevant energy,
- ε is the long counter efficiency at the relevant energy.

The inclusion of the air attenuation correction F_A means that the fluence is the idealised value, i.e. the value that would be seen in a vacuum.

Different approaches are possible for calculating the average efficiencies and effective centres when the long counter is used in a broad spectrum. If the variations of these two parameters over the spectrum are not large approximations are possible and average values, $\bar{\varepsilon}$ and $\bar{r}$ respectively can be defined by:

$$\bar{\varepsilon} = \frac{\sum_{i=1}^n \phi_i \cdot \varepsilon_i}{\Phi} \quad (3)$$

$$\bar{r} = \frac{\sum_{i=1}^n \phi_i \varepsilon_i r_i}{\sum_{i=1}^n \phi_i \varepsilon_i} \quad (4)$$

where: ε_i and r_i are the efficiencies and effective centres at the energy of the mid point of bin i .

In a similar way an effective air attenuation correction $\bar{F}_A$ can be defined by:

$$\bar{F}_A = \frac{\sum_{i=1}^n \phi_i \cdot F_{Ai}}{\Phi} \quad (5)$$

where: F_{Ai} is the air attenuation for neutrons at the mean energy of bin i .

An alternative approach considers the efficiency, effective centre, and air attenuation as interlinked quantities. The long counter total counts, expressed as the sum of the counts, p_i , due to neutrons in each bin of the spectrum, can be written as:

$$P = \sum_{i=1}^n p_i = r_{ref}^2 \sum_{i=1}^n \phi_i \cdot \varepsilon_i / [F_{Ai} \cdot (r_0 + r_i)^2] \quad (6)$$

To relate Φ and P using a single parameter, Δ say, so that

$$\Phi = P / (\Delta \cdot r_{ref}^2) \quad (7)$$

then:

$$\Delta = P / (\Phi \cdot r_{ref}^2) = \frac{r_{ref}^2 \sum_{i=1}^n \phi_i \cdot \varepsilon_i / [F_{Ai} \cdot (r_0 + r_i)^2]}{(\Phi \cdot r_{ref}^2)} = \frac{\sum_{i=1}^n \phi_i \cdot \delta_i}{\Phi} \quad (8)$$

where:

$$\delta_i = \varepsilon_i / [F_{Ai} \cdot (r_0 + r_i)^2] \quad (9)$$

A comparison of Δ with $\bar{\varepsilon} / [\bar{F}_A \cdot (\bar{r}_0 + \bar{r})^2]$ revealed differences of the order of 0.1 % so although the calculation of Δ is the more exact approach, individually averaged efficiencies, effective centres, and air attenuation factors can also be used, and are probably more illustrative when considering the variations of the long counter counts with angle.

Spectrum averaged efficiencies and effective centres are shown in Figure 4. Error bars of 0.2 % in the efficiency and 0.3 % in the effective centre have been assigned to these values in the plots for illustration and the fact that a smooth line can be drawn through the points to pass within the error bars indicates that the relative random uncertainties for adjacent points due to statistics in the spectrum calculations and the uncertainty introduced by the averaging are of this order or smaller. Relative uncertainties between the averaged efficiencies or effective centres at angles that are some way apart will depend on the accuracy of the calculational model at these different angles, and may well be larger than the rather small uncertainties shown in Figure 4. The systematic uncertainty of about 2.5 % in the absolute combined efficiency and effective centre values is excluded from consideration of the uncertainties just from the process of averaging over the calculated spectra.

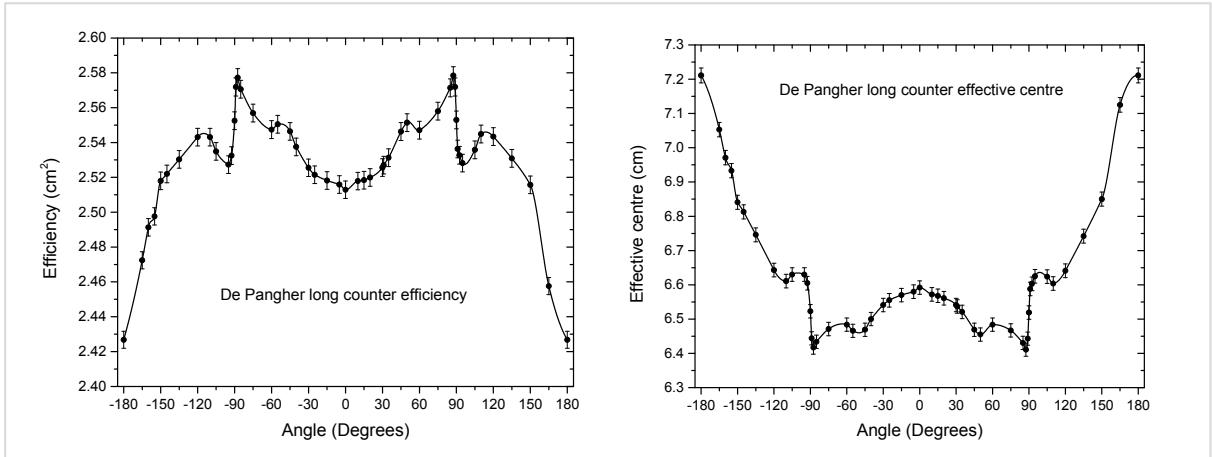


Figure 4. Spectrum averaged efficiencies and effective centres. The error bars represent uncertainties of 0.2 % for the efficiencies and 0.3 % for the effective centres. They indicate that point to point relative uncertainties are probably of this order although the actual uncertainties, e.g. those due to uncertainties in the model, are expected to be larger.*

6 Long counter measurements

Two measurement campaigns were undertaken, in November 2015 and June 2016. Measurements consisted of ‘shots’ where the NG was run for 10, 15, or 20 minutes with a break in between shots to allowed the generator to cool down and to move the instruments characterising the NG to different angles. Measurements were performed for both NGs during both campaigns.

* Note: The data plotted in Figure 3 and Figure 4 are based on calculations with MCNP. During the measurements at NPL improved information about the construction of the NGs was obtained and the MCNP model was adjusted accordingly. The data plotted in these figures is for the final version of the model including this additional information.

Because the measurements at NPL needed to be linked to the operation of the NG when within JET all the LC measurements were related to the reading of a monitor attached to the NG. During the 2015 measurements a diamond detector and a silicon detector were positioned on the framework attached to the NG – see Figure 1. The silicon detector did not function reliably so only the diamond detector data were used. For the 2016 measurements a second diamond detector replaced the silicon device. All the results presented here are relative to the readings of the first diamond detector, designated Dia0, although the ratio to the second diamond detector Dia1 as recorded in 2016 is presented from which the LC data can be related to the readings of the second diamond detector.

The spectrum in the diamond detector shows a number of features including, at the upper end, a peak due to the $^{12}\text{C}(\text{n},\alpha)^9\text{Be}$ reaction. The diamond monitor counts were derived by placing a window to define a region of interest, ROI, around this peak.

The low-scatter area at NPL is associated with a Van de Graaff accelerator and beamlines from this facility and the presence of other detector transport arms limited the angular range of the De Pangher long counter to -45° to 135° , via 0° , relative to the axis of the NG when mounted as shown in Figure 2. For the NG the 0° direction is defined as being along the line of the charged particle beam impinging on the target, and for the orientation shown in Figure 2 this coincides with the angle conventions in the low-scatter area. This orientation is described as the NG facing west. The angular range from 135° to -45° , via 180° , was covered by using the same range of low-scatter area angles, but rotating the NG through 180° , an orientation described as the NG facing east.

The De Pangher long counter was positioned at a nominal distance of 300 cm from the neutron-producing target. Although the detector transport system is designed so that the angle can be changed while keeping the distance constant, measurements taken over the two campaigns indicated that there were slight changes in the distance with angle – see Figure 5.

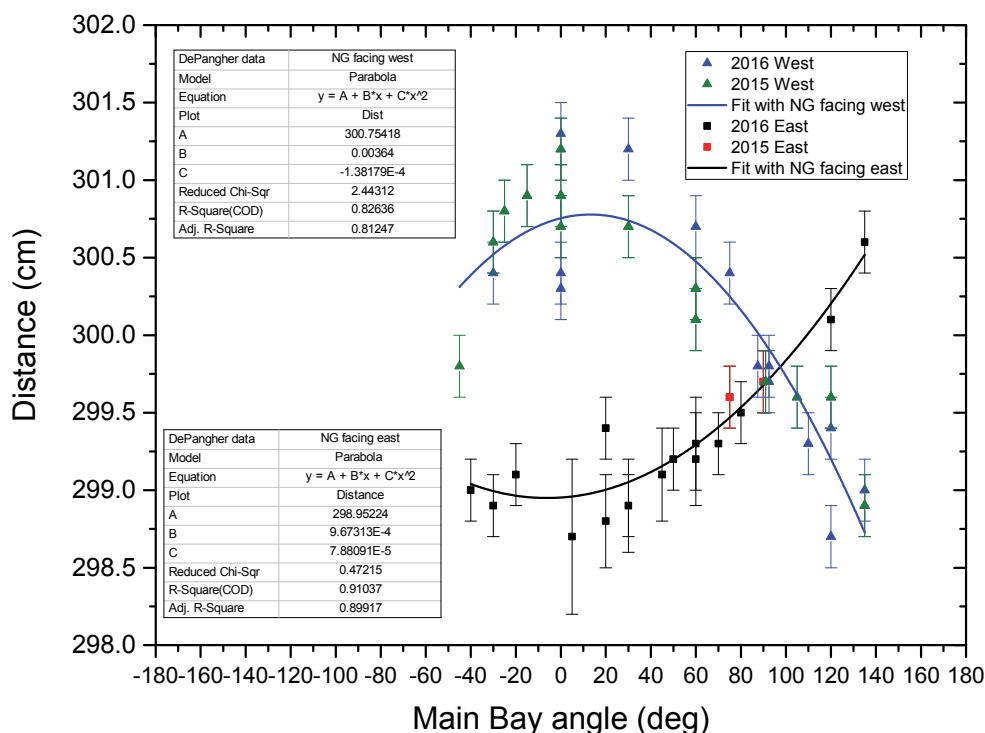


Figure 5. Variation of distance between De Pangher long counter front face and the neutron-producing target on altering the angle. The angles are those marked around the circle in the low-scatter area.

The variations in the distance had a different pattern for the NG facing east compared to when it was facing west. The two sets of distance variations for the two orientations were fitted with polynomial functions and these were used for correcting the distances as a function of angle. The correction was small. A 1 cm correction to the distance only corresponds to a 0.7 % correction to the measured fluence.

7 Long counter results

Values for the neutron fluence per monitor diamond count as measured in 2015 are presented for NG1 in Figure 6. The picture for NG2 is very similar. The uncertainties indicated by the error bars on the measured points (which are smaller than the symbol in many cases) are essentially the random errors in the measurements. They do not include the 2.5% uncertainty in the LC efficiency since this is assumed to be common to all the points.

The LC data were acquired by recording the counts from the BF₃ over 1 minute intervals during each NG shot. This provided a measure of the constancy of the fluence over a shot. The build-up of the NG to full output was clearly visible; the first cycle counts always being lower than the subsequent ones. The statistical uncertainty in the total and in the scatter counts were derived from Poisson statistics and was usually consistent with the uncertainty derived from the standard deviation of the 1 minute counts (excluding the first minute), indicating that the output over a shot was very constant.

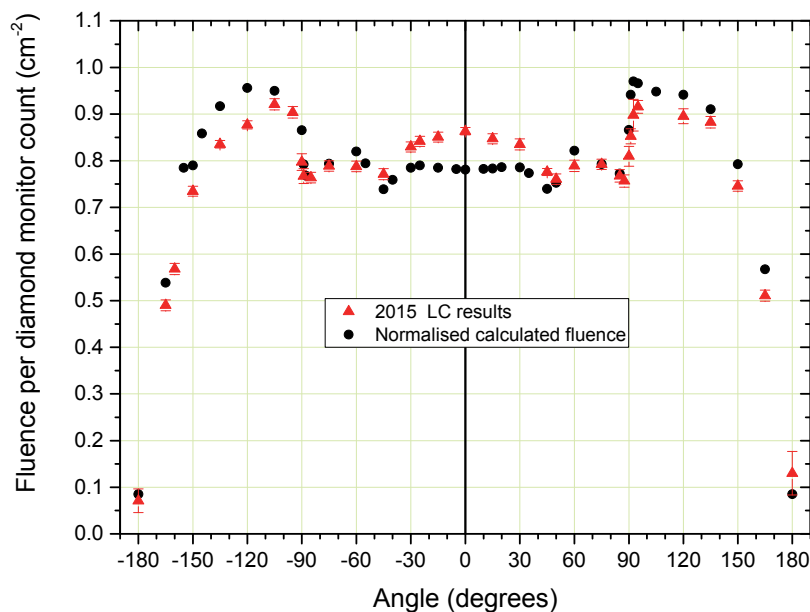


Figure 6. Comparison of fluence per diamond monitor count measured in 2015 for NG1 with the normalised MCNP calculated values

The direct counts were obtained by subtracting the scatter counts from the total and the uncertainties combined in quadrature. Dead-time corrections were made using previously determined values for the dead-time per BF₃ counter pulse. Two uncertainty components were added to the counting statistics for the scatter counts. The measured scatter contribution at angles other than 0° are probably too large because the LC sees neutrons scattered in un-shadowed parts of the NG body which should be part of the direct component and hence should not be subtracted. For example the measured scatter at 90° was 20% compared to 16% at 0°. To allow for the uncertainty caused by this effect the scatter subtraction was chosen to be mid way between the minimum possible percentage value, 16% measured at 0°, and the measured value at a particular angle, and an uncertainty was assigned that was large enough to just cover both extremes.

When performing shadow cone measurements at NPL an uncertainty component of 5 % is assigned to the scatter counts in addition to the uncertainty derived from statistics. This is to allow for inexact shadowing as the alignment and positioning of the shadow cone can never be perfect. For most neutron fields produced at NPL this 5 % contribution to the uncertainty in the scatter subtraction is unimportant because this correction is usually much smaller than in the present case, where the LC at 300 cm was further from the source of neutrons than usual, and the source was producing high-energy neutrons almost isotropically thus producing a significant scatter component. For the present measurements this 5 % uncertainty in the scatter was in most cases the largest contributor to the final statistical uncertainties in the direct counts. These varied between 1.2 % and 1.4 % for angles between 0° and 150° although they increased on approaching 180°.

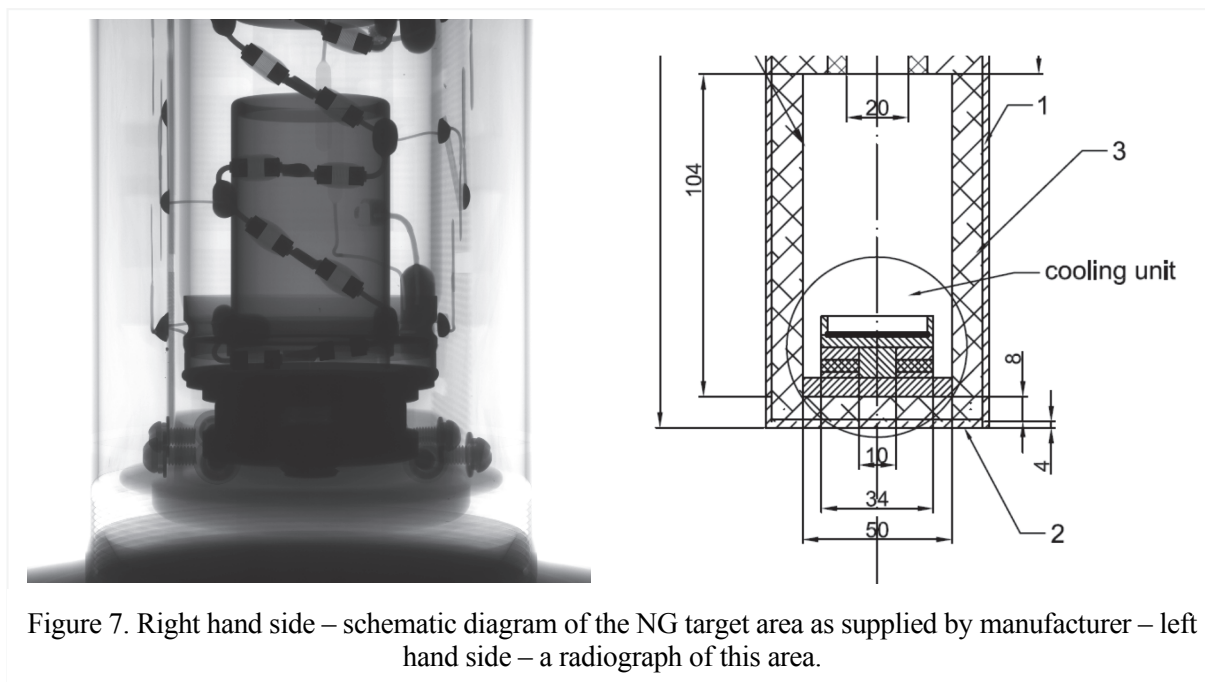
Because the shadow cone has to be close to the source of neutrons, the mounting arrangements of the NG meant that shadow cone scatter measurements were not possible at 180°. Estimates for the scatter were therefore made by interpolating the data for scatter counts per diamond count as a function of angle and also by interpolating the scatter/total values. The predictions of the two approaches did not agree well so a scatter correction corresponding to the mean from these two approaches was adopted with an uncertainty large enough to cover both values. This resulted in an uncertainty in the direct counts per diamond count of about 40%. This is largely due to the direct count being so small at this angle (about 14% of that at 0°), and this is because the neutrons have to traverse the full length of the NG. The contribution of the neutrons at this angle (and also that at 0°) to the total emission into 4π sr is, however, very small because the solid angle about these two angles is small.

The fluence at 300 cm from the NG target was calculated from the LC direct counts using the spectrum averaged LC efficiencies and effective centres. Corrections were made for small variations in the target to LC distance as the angle varied, and for air out-scatter. Uncertainties in these corrections were added in quadrature with the statistical uncertainties in the direct counts. One additional uncertainty component was added to allow for uncertainty in the LC angle, θ . Values for the rate of change of the fluence with angle ($d\Phi/d\theta$) were taken from the MCNP calculations. The final values for the random uncertainties in the fluence (excluding the systematic uncertainty in the LC efficiency and effective centre) were between 1% and 2% in the majority of cases although they increased approaching 180° due to the uncertainty in the scatter correction at this angle.

Figure 6 also includes results from the MCNP calculations. The calculations were for the fluence per neutron from the target so had to be normalised for comparison with the LC data which are for the fluence at 300 cm from the target. This was achieved by multiplying the MCNP data by the average of the ratio of the measured over calculated results for all angles where there was both measured and calculated data.

Although there is agreement on the general shape of the variation of the fluence with angle, there are clear differences; the calculations being lower than measurements between -60° and +60° and higher in the range from $\pm 60^\circ$ out to $\pm 160^\circ$. The initial MCNP model was based on a schematic diagram of the NG construction in the area around the target. This had been supplied by the manufacture, VNIIA, and is illustrated on the right in Figure 7. In view of the differences evident in Figure 6 it was thought that this might not be an exact representation of the actual construction.

During the 2016 campaign one of the NGs was taken to the Dimensional Metrology section at NPL and X-ray Computed Tomography (XCT) scans were carried out using a Nikon XT H 225M micro XCT system that employs a cone-beam X-ray source with a maximum energy of 225 kV. These scans revealed, in 3D, details that were not readily available from the manufacturer's documentation. The CT scan results, together with additional information eventually provided by



the manufacturer, was used to create a much more detailed model of the NG target, backing and housing, left hand picture in Figure 7 and the MCNP calculations rerun. The final MCNP model also contained more precise information about the neutron spectrum produced in the target. This was derived from further analysis of the spectrometry measurements made with a diamond detector which gave improved the ratios of the neutron production from the different reactions, atomic deuteron ions on tritium, ionised deuteron molecules on tritium, tritium on deuterium, etc.

With the revised MCNP model the agreement between calculations and measurements improved dramatically as shown in Figure 8 and Figure 9.

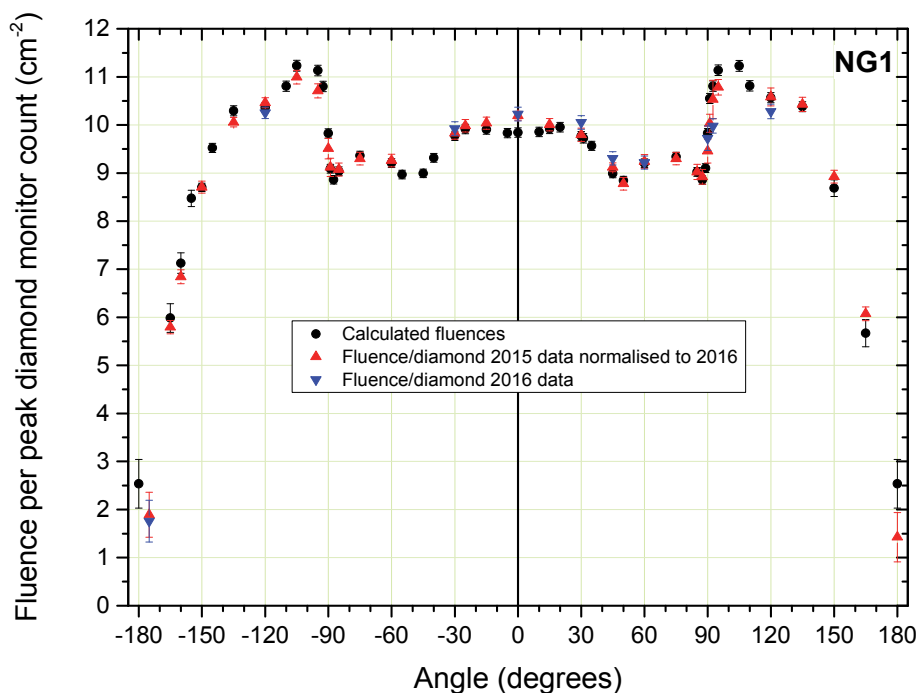


Figure 8. Measured fluence per diamond monitor count (Dia0) at 300 cm from the neutron-producing target compared to normalised calculated values for NG1.

Several conclusions can be drawn from the data in these two figures. There were differences (to be discussed later in this section) between the absolute values obtained in 2015 and 2016. However, after adjustment of the 2015 results to match those in 2016 the agreement between the two measured data sets and the normalised calculations for the shape of the variation of fluence with angle is excellent. The fluence also appears, as expected, to be symmetric in that results at negative angles (to the left of the 0° line) agree with those at positive angles (to the right of the 0° line). The overall shape can be explained qualitatively by considering the construction of the NG. The target is mounted on a solid cooling block so neutrons emitted with angles less than $\pm 90^\circ$ are attenuated in the metal of this block. This attenuation is not present for angles greater than $\pm 90^\circ$ so the fluence increases only to decrease again as the angle approaches 180° because of attenuation along the length of the neutron generator.

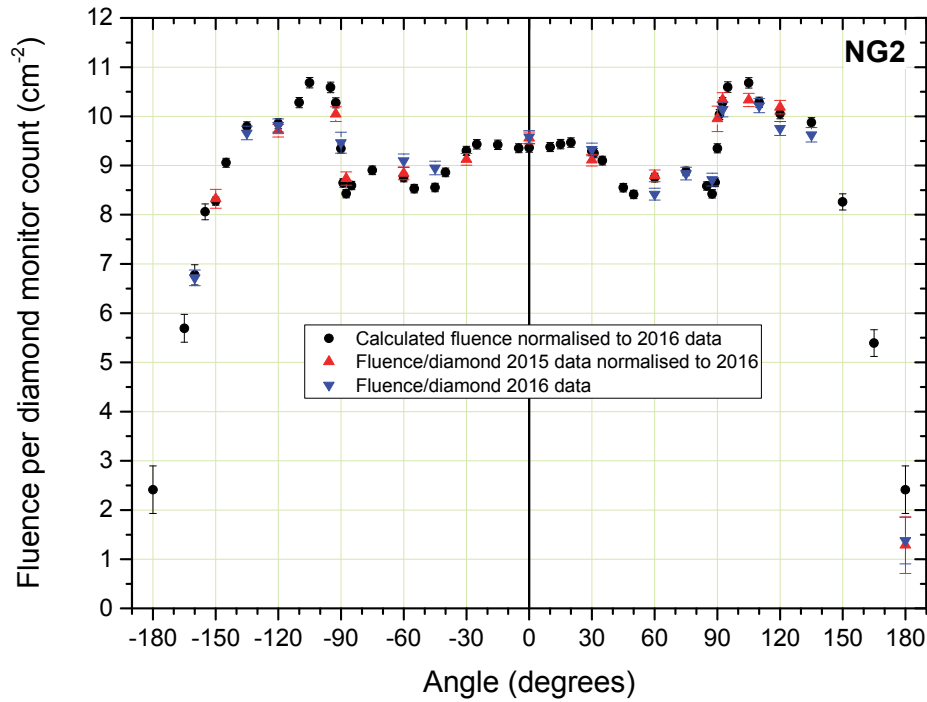


Figure 9. Measured fluence per diamond monitor count (Dia0) at 300 cm from the neutron-producing target compared to normalised calculated values for NG2

The MCNP calculated values were adjusted to the measured values by using a normalisation factor N derived by taking a weighted mean of the measured/calculated ratios for all angles, n , where there were both measurements and calculations:

$$N = \frac{\sum_{i=1}^n (M_i / C_i) / (\sigma_{C_i}^2 + \sigma_{M_i}^2)}{\sum_{i=1}^n 1 / (\sigma_{C_i}^2 + \sigma_{M_i}^2)} \quad (10)$$

where:

- M_i is the measured fluence
- C_i is the MCNP calculated fluence
- σ_{M_i} is the uncertainty in the measured fluence
- σ_{C_i} is the uncertainty in the calculated fluence

The ratio for 180° was excluded from this process because of large uncertainties in both the measurements and the calculations. Values for the measurement uncertainty, σ_{Mi} , were derived as explained earlier. Those for the calculations are difficult to estimate. The statistical component is small, but a component must be present for inaccuracies in the model. Various options were tried for this component, and to test them a χ^2 value was determined from:

$$\chi^2 = \sum_{i=1}^n (N \cdot C_i - M_i)^2 / (\sigma_{Ci}^2 + \sigma_{Mi}^2) \quad (11)$$

A value for χ^2 per degree of freedom ($\chi^2/(n-1)$) close to unity implies that the combined uncertainties are reasonably correct. For angles near 180° the model is likely to be inaccurate because of uncertainties about the construction and the effect of the cable attached to the NG at this point and uncertainties of 5%, 3% and 2% were therefore assigned to the calculations for angles of 165°, 160° and 150° respectively. Values for χ^2 close to 1 were obtained when all the other angles were assigned an uncertainty of 1% for the calculations implying uncertainties of this order in the calculated shape of the angular distribution at angles away from 180°.

An examination of all the available LC data revealed differences for the fluence per Dia0 between 2015 and 2016, and between NG1 and NG2. Information on the ratios 2016/2015 and NG1/NG2 were available from, a) data where LC results were available at a particular angle for both campaigns and/or for both NGs, b) the factors derived to normalise the MCNP calculations to the measurements, c) ratios of slab detector counts to diamond counts. The slab detector is a high-sensitivity neutron detector positioned permanently on the wall of the NPL low-scatter area and used routinely as a monitor when producing monoenergetic neutrons using the Van de Graaff accelerator. All three measurements gave very similar results and the average values are summarised in Table 1. The tabulated uncertainties are based on the uncertainties in the individual measurements and the spread of results between the three approaches.

Table 1. Ratios of fluences per Dia0 for 2016/2015 and NG1/NG2

Quantity	Ratio
2016/2015 from NG1 data	1.074 ± 0.004
2016/2015 from NG2 data	1.084 ± 0.005
NG1/NG2 from 2015 data	1.056 ± 0.007
NG1/NG2 from 2016 data	1.052 ± 0.004

The differences between 2105 and 2016 and between NG1 and NG2 were assumed to be due largely to positioning of the diamond monitor which is very close to the target and the counts are thus very sensitive to the exact positioning, in particular the distance from the target. Because of the difference between the results from the two campaigns the data from 2015 were adjusted by the average ratio to 2016 data for plotting in Figure 8. This was because the method of positioning of the diamond was reassessed and improved after the 2015 measurements and it is assumed that the positioning for the 2016 measurements was the same as for the measurements within JET.

After the adjustment the shape of the variation of fluence with angle and the absolute values are in excellent agreement as evidenced in Figure 8 and Figure 9.

8 Derivation of the total emission rate from the long counter fluence measurements

For an anisotropically emitting neutron source, the neutron fluence, $\phi(r, \theta, \alpha)$, at a distance r , and at angle, $\Omega(\theta, \alpha)$, in vacuum, is related to the total source emission, B , by the double integral:

$$B = \int_{\alpha=0}^{2\pi} \int_{\theta=0}^{\pi} \phi(r, \theta, \alpha) r^2 \sin(\theta) d\theta d\alpha \quad (12)$$

The spherical coordinate system in which the angles are defined is shown schematically in Figure 10.

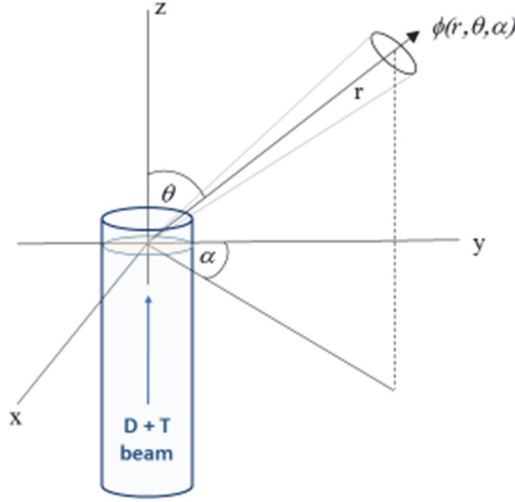


Figure 10. System of spherical co-ordinates for neutron emission from the target position on the NG.

If the neutron emission is independent of the azimuthal angle, α , i.e. the source has rotational symmetry about its cylindrical axis, the following simpler relationship holds:

$$B = 2\pi r^2 \int_{\theta=0}^{\pi} \phi(r, \theta) \sin(\theta) d\theta \quad (13)$$

This simpler relationship was assumed to apply in the present situation. The integral was performed by using a numerical algorithm (NAG) integration routine, or by using an Excel spreadsheet to calculate:

$$B = 2\pi r^2 \sum_{i=1}^n \phi_i \{ [\cos(\theta_l) - \cos(\theta_i)] + [\cos(\theta_i) - \cos(\theta_h)] \} \quad (14)$$

where:

θ is the angle at which the fluence was measured

θ_l is the angle $(\theta_{i-1} + \theta_i) / 2$ half way between θ_{i-1} and θ_i ($\theta_l = 0^\circ$ for $i = 1$ where $\theta_l = 0^\circ$),

θ_h is the angle $(\theta_i + \theta_{i+1}) / 2$ half way between θ_i and θ_{i+1} ($\theta_h = 180^\circ$ for $i = n$ where $\theta_h = 180^\circ$)

Both approaches gave near identical results, the advantage of the spreadsheet approach being that uncertainties introduced by the summation process could be estimated using values for the uncertainties in the individual measured fluences. The uncertainty varied depending on the number of angles measured. The number of points for NG1 in 2016 and NG2 in 2015 were limited and the uncertainties when integrating the measured data were thus higher.

In view of the good agreement between measurements and calculations for the shape of the angular dependence of the fluence the total fluence into 4π sr was also derived by integrating the MCNP calculated data after normalising to the measurements.

The variations in the results from the different approaches to performing the integration, and between the results obtained from the measurements and from the normalised calculations were taken as an indication of uncertainty introduced when deriving the total emission rate, and this was of the order of 1%. To this uncertainty must be added the systematic uncertainties, the predominant ones being those associated with the LC efficiency and effective centre. Other systematic components such as for air-out-scatter, distance, dead-time, or LC stability are almost negligible when added in quadrature. The final estimated uncertainty in the total emission per diamond detector count is 3%. The results are presented in Table 2

Table 2. Neutron emission rate for NGs into 4π sr per diamond count rate (peak ROI Dia0). N.B. the emission rates are for all neutrons emitted from the NG which according to the MCNP calculations corresponds to 1.012 times the number from the target.

Configuration	Total neutron emission per Dia0 count	Average Dia0 count rate (s^{-1})	Average total emission (s^{-1})
NG1 in 2015	$(1.011 \pm 0.030) \times 10^7$	$26.41 \pm 0.05^*$	$(2.672 \pm 0.080) \times 10^8$
NG1 in 2016	$(1.090 \pm 0.032) \times 10^7$	19.32 ± 0.16	$(2.106 \pm 0.065) \times 10^8$
NG1 all data normalised to 2016	$(1.094 \pm 0.033) \times 10^7$		
NG2 in 2015	$(9.67 \pm 0.029) \times 10^6$	26.25 ± 0.17	$(2.538 \pm 0.077) \times 10^8$
NG2 in 2016	$(1.035 \pm 0.031) \times 10^7$	23.90 ± 0.13	$(2.474 \pm 0.075) \times 10^8$
NG2 all data normalised to 2016	$(1.038 \pm 0.031) \times 10^7$		

* Data are for measurements performed before the decrease in the neutron emission rate at the end of the 2015 campaign

The average diamond count rates in column 3 of Table 2 are the average values over all the shots used in deriving the total neutron emission for a particular configuration. Shot to shot variations were sometimes quite large due to variations in the NG output. For example in 2015 the diamond count rates for NG1 varied by more than 10% between the highest and lowest values. Day to day variations of the average values tended to be smaller. For NG1 in 2015 the difference between the highest and lowest values on the different days was 3.4%.

From the data taken in 2016 the average ratio of Dia0/Dia1, over all shots, was 1.1700 ± 0.0049 for NG1, and 1.1732 ± 0.0027 for NG2, and these ratios can be used to derive neutron emission per Dia1.

Since the shape of the angular dependence of the fluence from the measurements with the two NGs appears to be the same, and this shape agrees with the MCNP calculations, a best estimate of the shape was derived by combining all these data sets. The measured data used were the shapes as measured both in 2015 and 2016, but with the 2015 data normalised to 2016 values. As the total emission per Dia0 was similar for both NGs, with a value close to 10^7 , the data were normalised to a total emission per Dia0 of 1.0×10^7 neutrons. The calculated data were also normalised to the same total emission per Dia0 and optimum values for the shape of the fluence per Dia0 at 300 cm in vacuum were derived using all measured and calculated data – see Table 3.

Table 3. Averaged values for fluence per Dia0 at 300 cm from the NG target in vacuum for a total emission into 4π sr of 1.0×10^7 neutrons. The uncertainties refer only to the shape of the variation of the fluence with angle.

Angle	Fluence/Dia0	Angle	Fluence/Dia0
-180°	1.57 ± 0.38	0°	9.21 ± 0.12
-175°	1.61 ± 0.40	10°	9.011 ± 0.090
-165°	5.33 ± 0.12	15°	9.101 ± 0.072
-160°	6.39 ± 0.10	20°	9.099 ± 0.091
-155°	7.75 ± 0.16	30°	8.953 ± 0.062
-150°	7.967 ± 0.062	31°	8.890 ± 0.089
-145°	8.706 ± 0.087	35°	8.746 ± 0.087
-135°	9.304 ± 0.080	45°	8.312 ± 0.087
-120°	9.458 ± 0.053	50°	8.068 ± 0.067
-110°	9.880 ± 0.099	60°	8.416 ± 0.058
-105°	10.19 ± 0.10	75°	8.527 ± 0.060
-95°	10.04 ± 0.18	85°	8.252 ± 0.072
-92.5°	9.817 ± 0.087	87.5°	8.18 ± 0.11
-90°	8.96 ± 0.10	89°	8.322 ± 0.083
-89°	8.317 ± 0.075	90°	9.00 ± 0.18
-87.5°	8.19 ± 0.15	91°	9.54 ± 0.20
-85°	8.274 ± 0.069	92.5°	9.78 ± 0.21
-75°	8.541 ± 0.070	95°	10.08 ± 0.15
-60°	8.487 ± 0.078	105°	10.15 ± 0.15
-55°	8.199 ± 0.082	110°	9.876 ± 0.080
-45°	8.34 ± 0.18	120°	9.661 ± 0.078
-40°	8.517 ± 0.085	135°	9.455 ± 0.082
-30°	8.945 ± 0.073	150°	8.08 ± 0.11
-25°	9.091 ± 0.072	165°	5.48 ± 0.15
-15°	9.104 ± 0.071	180°	1.57 ± 0.38
-5°	8.988 ± 0.090		

For angles where there was more than one datum a weighted mean of the results was taken. Best vales for the total fluence for each NG, at any of the angles in the table, can be obtained by multiplying the tabulate numbers by the ratio of the total emission as given in Table 2 to 1.0×10^7 .

9 Activation measurements

Measurement of the neutron output from the NG was performed by irradiating thin iron and aluminium foils of diameter 25.4 mm. They are routinely used at NPL for measuring neutrons from the d+T reaction in the energy range 14 to 20 MeV, and have been used in international neutron fluence comparison exercises^(8,9,10).

The foils were held in paper attached to lightweight aluminium holders mounted in an aluminium ring for the 2015 campaign and in a foam board disc for the 2016 campaign (as shown in Figure 11) at approximately 15 cm from the target of the NG. Some foils were also irradiated in contact with the surface of the NG, wrapped in cigarette paper (see Figure 12). Foils were positioned at 15° steps from -120° to +120° with 0° corresponding to the direction of the deuterium-tritium beam in the NG. The distance of each foil from the surface of the NG was measured using a measuring rod with the foil at either the 0° or ±90° position, before rotating the aluminium ring or foam board disc to set the foil at the desired angle. The height of each foil was set using a laser installed on the laboratory wall.



Figure 11: Mounting arrangement of the foils in the 2015 (left) and the 2016 (right) campaign



Figure 12: Mounting of foils on surface of NG

Foil irradiations ranged from 1 to 6 shots in length, depending on which reaction was being used and the position of the foil. The diamond detectors on the NG jig and other detectors in the low scatter area were used to monitor the NG output during each shot. In total 29 aluminium and 52 iron foils were irradiated over the two campaigns.

The start time and stop times of each irradiation were taken from the NPL scaler data files recording the LC counts, the PC clock having been checked against the speaking clock periodically during the two campaigns.

The activities of the foils were measured as soon as possible after the end of the irradiation. Four separate highly-efficient gas-flow proportional counters were used to determine the activities of the foils from the beta particles emitted in the decay. The counters use a 90:10 Ar/CH₄ gas mixture and two out of the four used have anti-coincidence rings to suppress the background. Foils were placed on gold-coated VYNS plastic mounts and counted for cycles of a fixed time period until sufficient β counts had been recorded to give an acceptably low statistical uncertainty. Where possible the foils were also counted in more than one counter to provide an additional measurement of the activity. The background rates of the counters were measured before and after each measurement campaign.

Corrections are made for the counter's additional sensitivity to gamma rays from the foil (K-correction), for variations in the beam flux during the irradiation, for the non-saturation of the activity and for the decay since the end of the irradiation.

A least squares fitting program (MHLIFE) was used to analyse the decay data. The program calculates the saturated β count rate, $N_{\beta(sat)}$ (i.e. that which would be obtained during an infinitely long irradiation at the mean fluence rate). Each β -count cycle is first dead-time corrected, then decay corrected to the end of the irradiation. The decay correction is performed by considering the following integral expression for the counts in each cycle, C :

$$C = \int_{t_1}^{t_2} N_{\beta} e^{-\lambda t} dt \quad (15)$$

where:

- t_1 is the time from the end of the irradiation to the start of the cycle,
- t_2 is the time from the end of the irradiation to the end of the cycle,
- N_{β} is the β count rate at the end of the irradiation,
- λ is the decay constant of the foil activity.

Solving equation (15) yields the following expression:

$$N_{\beta} = \frac{C\lambda}{(e^{-\lambda t_1} - e^{-\lambda t_2})} \quad (16)$$

Values for N_{β} for each β counting cycle are obtained from eq. (16). The β count rate at saturation, $N_{\beta(sat)}$, is related to the β count rate, at the end of the irradiation, N_{β} , by:

$$N_{\beta(sat)} = \frac{N_{\beta}}{(1 - e^{-\lambda T})} \quad (17)$$

where:

T is the length of the irradiation, including breaks between shots.

Another program (NVVARY) analysed the monitor data to calculate the small correction factor for the variation of the fluence rate during the irradiation, F_T .

The saturated activity, N_0 , is related to the β count rate at saturation, $N_{\beta(sat)}$ by:

$$N_0 = \frac{N_{\beta(sat)}}{\varepsilon_{\beta}' F_T F_a(d)} \frac{T}{T_{NG}} \quad (18)$$

where:

- ε'_β is the effective β -efficiency $\varepsilon'_\beta = \varepsilon_\beta(1 + K)$ (allowing for the γ -ray sensitivity of the β -detector by means of the K -correction),
 F_T is the fluence rate variation correction factor,
 $F_a(d)$ is the self-shielding factor for a foil, thickness d ,
 T_{NG} is the time during the irradiation for which the NG was switched on.

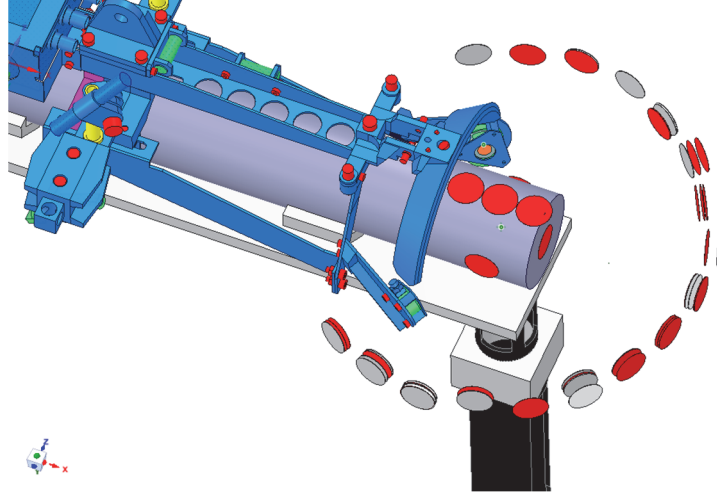


Figure 13: MCNP model of NG and NPL activation foils around the head of the neutron generator.

For the foil thicknesses used the self-shielding is negligible, hence $F_a(d)=1$, and the effect of the front foils shielding the back ones is also negligible where two foils were placed together in a mount.

In the standard approach in use at NPL the total neutron fluence, Φ , is derived from the saturated foil activity, N_0 . However, because of the extended geometry of the NG, the variation in the energy spectrum with angle, and the fact that the main purpose of the exercise was to validate the MCNP model of the NG, it was considered more appropriate to compare the measured saturated activities of each foil with the calculated reaction probability for each foil obtained from the MCNP simulation, R , normalised to the mass of the modelled foil (in mg) and to the total number of neutrons emitted by the NG into 4π sr, Q , derived from the model. All the foils were added to a single MCNP input file, the geometry of which is shown in Figure 13.

The measured activity of each foil was divided by the mass of the foil (in mg), m , and the mean count rate in Dia0, for the time during the foil irradiation for which the NG was switched on. When divided by the MCNP calculated reaction rate, each activity yielded a value for the total number of neutrons emitted by the NG into 4π sr per Dia0, as follows:

$$\frac{Q}{D} = \frac{N_0}{m} \frac{T_{NG}}{D} \frac{1}{R} \quad (19)$$

where:

D is the total count in Dia0 during the foil irradiation.

No correction was made for room and air scattered neutrons and there are two reasons why this correction was deemed unnecessary. Firstly, the target to detector distance was small so that the scattered fluence component was only a very tiny fraction of the direct, and secondly the fact that

the cross section decreases rapidly below 13 MeV, going to zero at about 6 MeV, means that the detection efficiency for scattered neutrons is low. The parameters used in the analysis of the foils are given in Table 4.

Table 4. Parameters used in the analysis of the foils

	Al(n,p) ²⁷ Mg		Al(n,α) ²⁴ Na		Fe(n,p) ⁵⁶ Mn
Nominal thickness (mm)	0.3	0.6	0.3	0.6	0.1
Mass range (mg)	395-411	811-818	395-413	811-818	369-424
ϵ_{β} range	0.7837- 0.7738	0.6202- 0.6160	0.7337- 0.7232	0.5382- 0.5359	0.7270- 0.7125
(1+K)	1.002	1.005	1.007	1.017	1.016
λ (s ⁻¹) ⁽¹¹⁾	1.2209×10^{-3}		1.2866×10^{-5}		7.4664×10^{-5}

Total emission rates were derived from each foil using the MCNP calculations of reaction probabilities. The spread of the points is quite large (about $\pm 10\%$) and this is believed to be primarily due to the positioning of the foils. As they were close to the NG small changes in the distance or angle of the foil could make a significant difference to the activity, particularly for foils which were mounted for several shots where they may have been disturbed while other equipment was moved and checked between shots. Despite this the large drop in the NG1 output in 2015 is very evident. Foils which were attached to the surface of each NG give an even greater spread of emission rate values and this is probably due to their closeness to the source of neutrons making them even more sensitive to position. The mean values for the neutron emission rates from the targets of the NGs are given in Table 5 and Table 6, with the 2015 values for NG1 split into pre- and post- the large decrease in output that occurred near the end of the first campaign. Values derived from the long counter measurements are included for comparison. Note that the LC data from Table 4 have been reduced by a factor of 1.012 for comparison with the foil data which is per neutron from the target rather than from the whole NG body.

Table 5. Mean values for neutron emission rate from target of NG1. Standard uncertainties are shown in brackets, corresponding to the least significant digit(s).

	Al(n,p) $\times 10^8 \text{ s}^{-1}$	Al(n,α) $\times 10^8 \text{ s}^{-1}$	Fe(n,p) $\times 10^8 \text{ s}^{-1}$	Mean $\times 10^8 \text{ s}^{-1}$	Long counter $\times 10^8 \text{ s}^{-1}$
2015, pre decrease	2.54(11) (7 foils)	2.68(10) (13 foils)	2.53(9) (13 foils)	2.59(9)	2.64(8)
2015, post decrease	-	-	2.11(12) (2 foils)	2.11(12)	
2016	1.95(14) (3 foils)	2.13(8) (2 foils)	2.01(10) (4 foils)	2.01(9)	2.08(6)

Table 6. Mean values for neutron emission rate from target of NG2. Standard uncertainties are shown in brackets, corresponding to the least significant digit(s).

	Al(n,p) $\times 10^8 \text{ s}^{-1}$	Al(n,α) $\times 10^8 \text{ s}^{-1}$	Fe(n,p) $\times 10^8 \text{ s}^{-1}$	Mean $\times 10^8 \text{ s}^{-1}$	Long counter $\times 10^8 \text{ s}^{-1}$
2015	-	2.58(12) (4 foils)	2.31(8) (12 foils)	2.38(9)	2.51(8)
2016	-	2.43(10) (4 foils)	2.27(9) (7 foils)	2.33(9)	2.44(7)

The total uncertainties in the reported foil emission rates include components for the following:

- distance from NG to foil (± 2 mm) which equates to $\pm 2.67\%$,
- foil parameters m ($\pm 0.06\%$), $\varepsilon\beta$ ($\pm 0.2\%$), $1+K$ (± 0.1 - 0.2%), λ ($\pm 0.1\%$), cross section ($\pm 0.5\%$),
- R as calculated from the model of the NG ($\pm 2\%$),
- background in the foil beta counters ($\pm 0.33\%$),
- timing of length of irradiation and time to start of foil counting (± 0.11 - 0.35%),
- correction for flux variations F_T (± 0.0 - 0.5%),
- statistical uncertainty in N_0/R from standard error on the mean.

The neutron emission per Dia0 was determined for each angle and reaction by averaging results where more than one foil of the same type had been irradiated at the same angle (taking positive and negative angles to be equivalent) for the same NG and during the same campaign. These are plotted in Figure 14, Figure 15 and Figure 16, with the error bars corresponding to the statistical error in the foil counting or the standard deviation where more than one foil of the same type was irradiated at the same angle. The mean values shown on the figures are the simple means of the angular points plotted and will differ from the final weighted means presented later. There is no apparent trend in the emission rate as a function of angle indicating that the MCNP model has the correct angular distribution of neutrons from the NG.

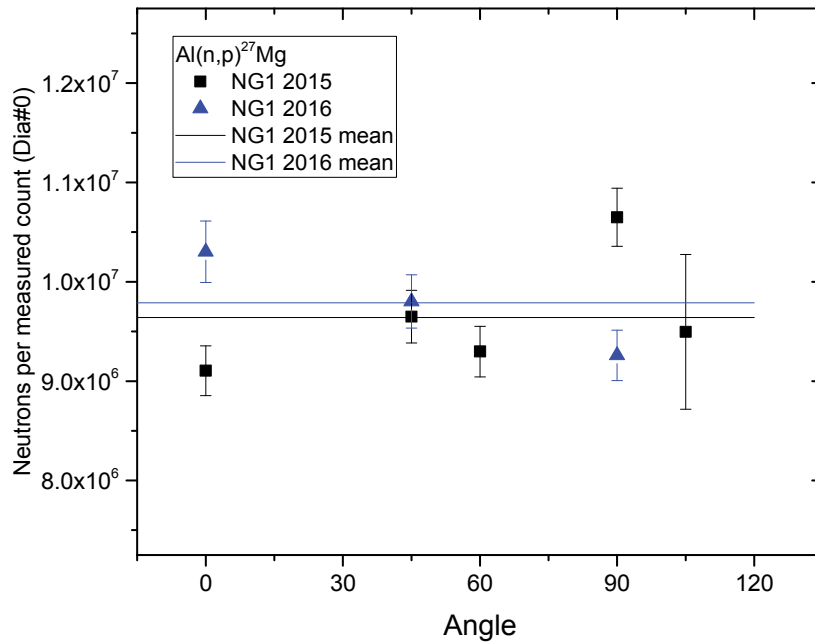


Figure 14: Neutron emission per Dia0 for the $\text{Al}(n,p)^{27}\text{Mg}$ reaction

Mean values of the neutrons emitted from the target of each NG per Dia0 for each reaction (excluding those foils placed on the surface of the NG) are given in Table 7 and Table 8 and plotted in Figure 17 and Figure 18. Values from the long counter measurements have been included for comparison. Values from 2015 have been normalised to the 2016 campaign using the overall mean of Slab 1/Dia0, Slab 2/Dia0 and LC/Dia0 (1.080) where Slab 1 and Slab 2 are two independent subsystems within the wall-mounted slab monitor. To derive neutron emission per Dia1 the average ratio of Dia0/Dia1 over all shots should be used (1.1700 ± 0.0054 for NG1 and 1.1732 ± 0.0027 for NG2).

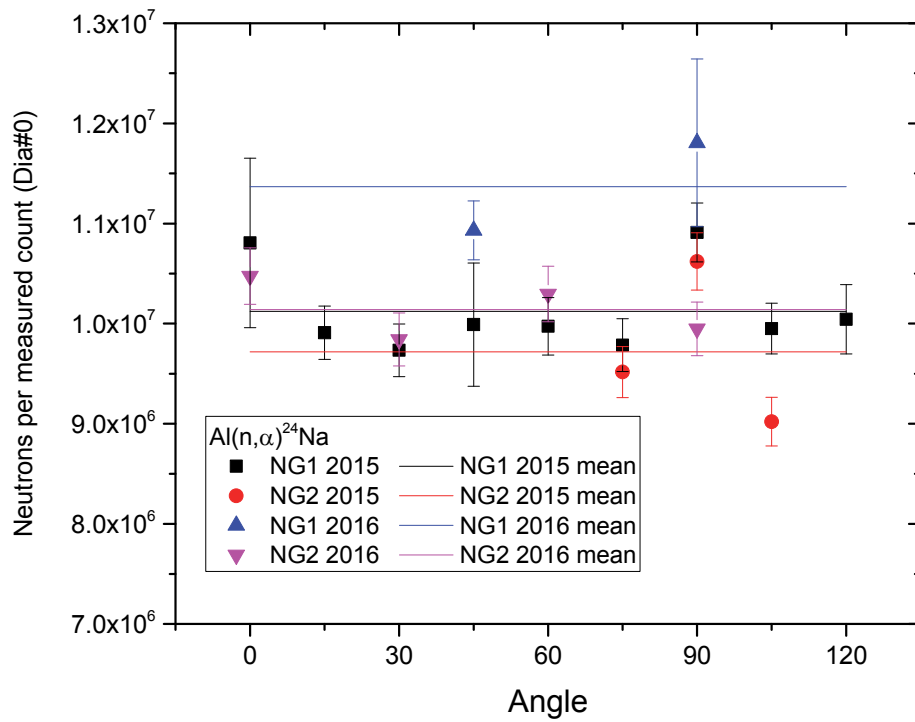
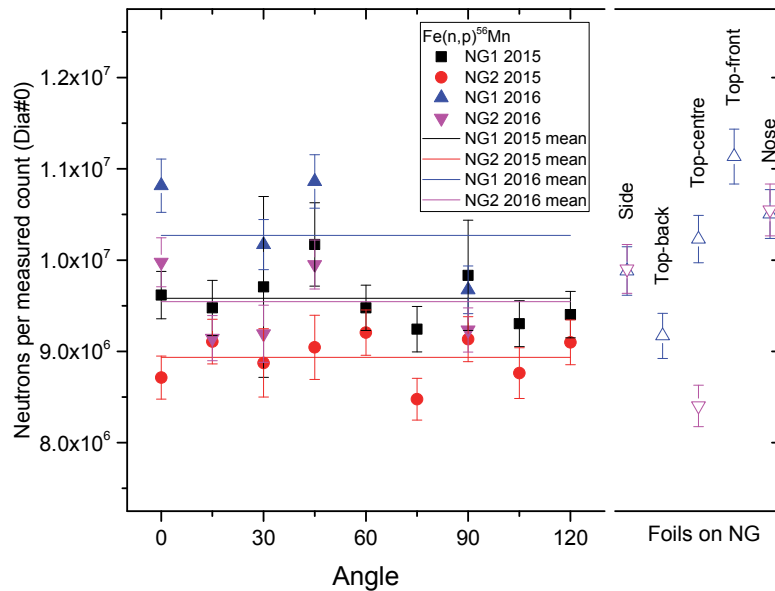
Figure 15: Neutron emission per Dia0 for the $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ reactionFigure 16: Neutron emission per Dia0 for the $^{56}\text{Fe}(n,p)^{56}\text{Mn}$ reaction. Open points correspond to foils on the surface of the NG, positions indicated by the corresponding labels.

Table 7. Mean values for neutrons emitted from target of NG1 per Dia0, normalised to 2016 campaign. Standard uncertainties are shown in brackets, corresponding to the least significant digit(s).

	Al(n,p) $\times 10^7 \text{ Dia0}^{-1}$	Al(n, α) $\times 10^7 \text{ Dia0}^{-1}$	Fe(n,p) $\times 10^7 \text{ Dia0}^{-1}$	Mean $\times 10^7 \text{ Dia0}^{-1}$	Long counter $\times 10^7 \text{ Dia0}^{-1}$
2015	1.051(45) (7 foils)	1.102(40) (13 foils)	1.037(38) (15 foils)	1.064(39)	1.076(34)
2016	0.979(46) (3 foils)	1.109(58) (2 foils)	1.038(46) (4 foils)	1.034(43)	1.077(32)
Mean	1.030(43)	1.103(40)	1.037(37)	1.058(37)	1.076(33)

Table 8. Mean values for neutrons emitted from target of NG2 per Dia0, normalised to 2016 campaign. Standard uncertainties are shown in brackets, corresponding to the least significant digit(s).

	Al(n,p) $\times 10^7 \text{ Dia0}^{-1}$	Al(n, α) $\times 10^7 \text{ Dia0}^{-1}$	Fe(n,p) $\times 10^7 \text{ Dia0}^{-1}$	Mean $\times 10^7 \text{ Dia0}^{-1}$	Long counter $\times 10^7 \text{ Dia0}^{-1}$
2015	-	1.053(51) (4 foils)	0.964(34) (12 foils)	0.986(37)	1.026(31)
2016	-	1.014(38) (4 foils)	0.942(36) (7 foils)	0.968(37)	1.023(31)
Mean	-	1.033(40)	0.956(34)	0.979(36)	1.024(31)

The overall mean value for NG1 is 1.7% lower than the LC value once the 1.012 correction for neutrons from the NG (rather than the target) is included. For NG2 the foil value is 4.6% lower than the LC value.

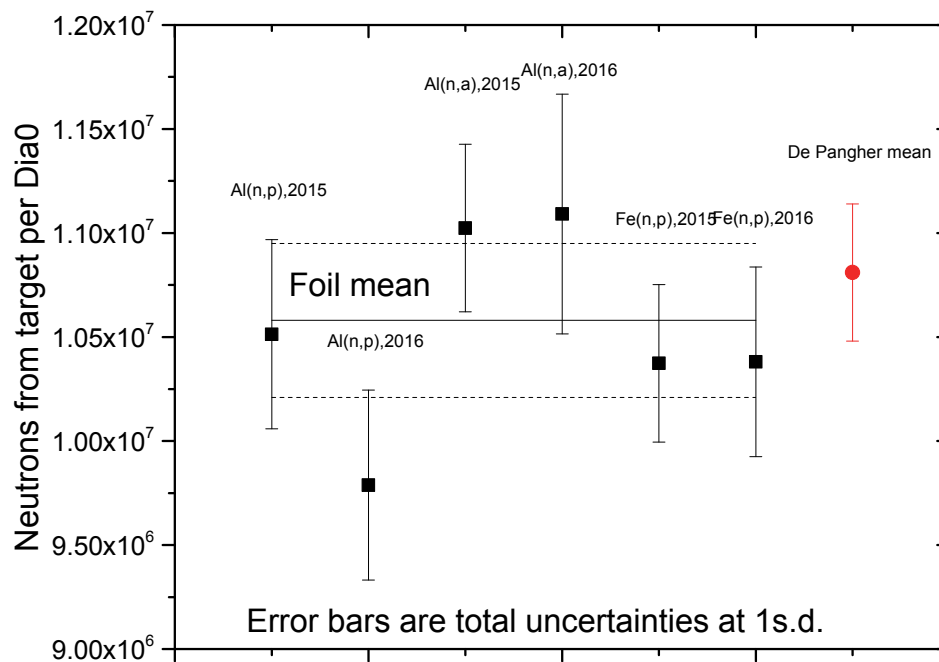


Figure 17: Comparison of foil and long counter values for neutrons per Dia0 for NG1

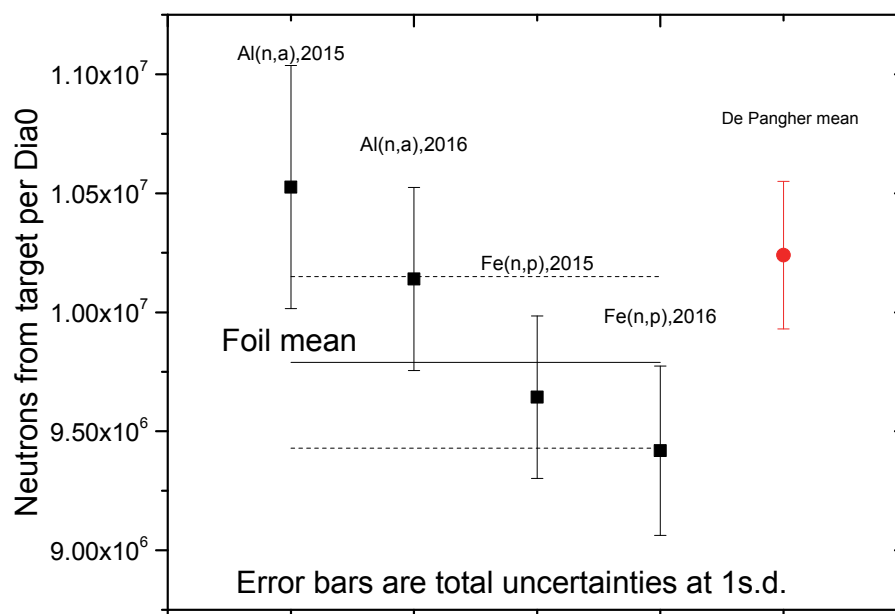


Figure 18: Comparison of foil and long counter values for neutrons per Dia0 for NG2

10 Conclusions

A De Pangher LC has been used to measure the variation of the neutron fluence with angle around two NGs. Data from both NGs show very similar features. After renormalisation of the data taken during the first campaign in 2015, to allow for what is presumed to be a change in the position of the diamond monitor detector, the results from the two campaigns agree within the uncertainties estimated. (These exclude the systematic uncertainty of about 2.5% in the LC efficiency). The uncertainties vary with angle and are at present dominated by that in the scatter correction where there are possibilities of improvement.

The total emission into 4π sr, for both NGs, was about 1.0×10^7 per diamond monitor count. For the average diamond count rate of 26 s^{-1} at the beginning of the first campaign this corresponds to a total emission rate of about $2.6 \times 10^8 \text{ s}^{-1}$ in agreement with the manufacturers estimate. The output did, however, fall by about 24% during a shot near the end of the 2015 campaign, and did not recover. The fluence per diamond monitor count nevertheless remained constant if allowance is made for the change between 2015 and 2016 is made. At the beginning of the 2015 campaign the total neutron emission of NG2 was similar, i.e. about $2.5 \times 10^8 \text{ s}^{-1}$, and dropped during the two campaigns, but only by about 12%.

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11 Appendix – Individual foil results

11.1 Iron foils

NG1, November 2015

Angle	Distance (mm)	Shot numbers	Foil ID	Mass, m (mg)	Diamond 0 rate, D/T_{NG} (s^{-1})	T_{NG} (s)	F_T	Saturated activity, N_0/m (Bq mg^{-1})	$\sigma(N_0/m)$ (Bq mg^{-1})	MCNP reaction rate, R ($\times 10^{-10}$ mg^{-1})	Neutrons per Dia0 count, Q/D ($\times 10^6$)
-90	141.8	65-67	Fe902	420.876	26.782	2700	1.0129	0.10842	0.00092	3.9473	10.2555
-90	144.8	91-96	Fe912	410.430	21.275	4200	1.0051	0.07584	0.00043	3.7747	9.4436
-60	139.0	65-67	Fe901	414.325	26.782	2700	0.9728	0.09597	0.00081	3.7612	9.5269
-60	139.7	26-28	Fe907	408.168	26.252	3600	0.9962	0.08866	0.00040	3.7189	9.0811
-45	140.1	3-8	Fe902	420.876	25.751	7200	1.0129	0.09149	0.00044	3.5878	9.9024
-30	143.5	42-44	Fe911	413.108	26.854	3600	0.9972	0.09126	0.00051	3.7642	9.0283
-15	144.5	81-84	Fe907	408.168	26.261	3000	1.0165	0.09586	0.00050	3.7990	9.6084
0	150.1	32-34	Fe909	411.998	26.545	3600	1.0016	0.08911	0.00047	3.4905	9.6171
15	146.6	32-34	Fe910	407.933	26.545	3600	1.0016	0.09149	0.00061	3.6886	9.3437
30	145.1	91-96	Fe910	407.933	21.275	4200	1.0051	0.08135	0.00048	3.6820	10.3856
45	141.9	81-84	Fe909	411.998	26.261	3000	1.0165	0.08911	0.00041	3.4962	10.4399
60	152.6	42-44	Fe912	410.430	26.854	3600	0.9972	0.07902	0.00045	3.1213	9.4275
75	145.7	17-25	Fe906	407.722	26.143	10800	1.0033	0.08301	0.00045	3.4347	9.2444
90	101.7	Test 2 -2	Fe901	414.325	-	2700	1.0060	0.18515	0.00077	7.7175	-
90	139.4	73-76	Fe904	404.449	26.773	3600	1.0060	0.11104	0.00050	4.0572	10.2223
105	147.3	9-14	Fe904	404.449	25.948	7200	1.0129	0.10047	0.00060	4.1616	9.3040
120	143.1	73-76	Fe906	407.722	26.773	3600	1.0060	0.10477	0.00048	4.1619	9.4027

NG2, November 2015

Angle	Distance (mm)	Shot numbers	Foil ID	Mass, m (mg)	Diamond 0 rate, D/T_{NG} (s ⁻¹)	T_{NG} (s)	F_T	Saturated activity, N_0/m (Bq mg ⁻¹)	$\sigma(N_0/m)$ (Bq mg ⁻¹)	MCNP reaction rate, R ($\times 10^{-10}$ mg ⁻¹)	Neutrons per Dia0 count, Q/D ($\times 10^6$)
-105	144.9	4-7	Fe46	410.938	26.375	4800	1.0043	0.09876	0.00046	4.3329	8.6416
-90	142.5	1-2	Fe31	385.172	23.182	2400	1.0002	0.08266	0.00043	3.9037	9.1343
-60	135.7	4-7	Fe43	412.017	26.375	4800	1.0043	0.09595	0.00090	3.9515	9.2067
-45	138.9	1-2	Fe38	380.116	23.182	2400	1.0002	0.07819	0.00084	3.6520	9.2360
-30	138.1	10-11	Fe36	387.410	26.159	2400	1.0004	0.09672	0.00072	4.0685	9.0876
0	136.6	16-19	Fe68	388.614	26.709	4800	1.0098	0.09836	0.00051	4.2266	8.7132
15	148.1	20-22	Fe82	406.302	26.341	3600	0.9983	0.08661	0.00070	3.6103	9.1078
30	145.9	25-26	Fe40	384.328	26.629	2400	1.0007	0.08387	0.00094	3.6364	8.6608
45	148.1	20-22	Fe83	405.942	26.341	3600	0.9983	0.07436	0.00051	3.1882	8.8541
75	142.2	16-19	Fe72	386.104	26.709	4800	1.0098	0.08165	0.00045	3.6066	8.4762
105	142.9	25-26	Fe51	385.640	26.629	2400	1.0007	0.10467	0.00104	4.4247	8.8834
120	146.1	10-11	Fe32	369.094	26.159	2400	1.0004	0.09500	0.00085	3.9911	9.0997

NG1, June 2016

Angle	Distance (mm)	Shot numbers	Foil ID	Mass, m (mg)	Diamond 0 rate, D/T_{NG} (s^{-1})	T_{NG} (s)	F_T	Saturated activity, N_0/m (Bq mg^{-1})	$\sigma(N_0/m)$ (Bq mg^{-1})	MCNP reaction rate, R ($\times 10^{-10} \text{ mg}^{-1}$)	Neutrons per Dia0 count, Q/D ($\times 10^6$)
-ve side	35	20	Fe906	407.722	19.190	900	1.0002	1.20540	0.00337	63.5693	9.8810
Top- back	0	8	Fe36	387.410	19.626	900	1.0001	0.78603	0.00368	43.6730	9.1704
Top	35	8	Fe38	380.116	19.626	900	1.0001	1.27219	0.00539	63.5474	10.2004
Top	35	20	Fe904	404.449	19.190	900	1.0002	1.25122	0.00591	63.5474	10.2602
Top- front	0	8	Fe40	384.328	19.626	900	1.0001	0.87177	0.00346	39.8939	11.1341
Nose	33	6	Fe32	369.094	19.807	900	1.0002	1.50533	0.00546	72.6021	10.4680
Nose	33	20	Fe901	414.325	19.190	900	1.0002	1.46874	0.00420	72.6021	10.5417
-45	152.3	2-4	Fe902	420.876	20.251	2700	0.9947	0.06699	0.00077	3.0458	10.8612
0	143.8	13-16	Fe82	406.302	18.678	3600	1.0001	0.07803	0.00063	3.8627	10.8161
30	144.1	13-16	Fe46	410.938	18.678	3600	1.0001	0.07136	0.00048	3.7565	10.1708
90	153.1	6-8	Fe43	412.017	19.720	2700	0.9939	0.06455	0.00074	3.3836	9.6742

NG2, June 2016

Angle	Distance (mm)	Shot numbers	Foil ID	Mass, m (mg)	Diamond 0 rate, D/T_{NG} (s ⁻¹)	T_{NG} (s)	F_T	Saturated activity, N_0/m (Bq mg ⁻¹)	$\sigma(N_0/m)$ (Bq mg ⁻¹)	MCNP reaction rate, R ($\times 10^{-10}$ mg ⁻¹)	Neutrons per Dia0 count, Q/D ($\times 10^6$)
-ve side	35	10	Fe51	385.640	25.602	900	1.0002	1.61171	0.00471	63.5693	9.9028
+ve side	35	37	Fe915	406.908	23.413	900	1.0002	1.27112	0.00276	63.5728	8.5401
Top	35	37	Fe912	410.430	23.413	900	1.0002	1.25027	0.00691	63.5474	8.4034
Nose	33	10	Fe31	385.172	25.602	900	1.0002	1.96100	0.00729	72.6021	10.5499
Nose	33	37	Fe913	424.240	23.413	900	1.0002	1.42209	0.00215	72.6021	8.3661
-90	148.4	2-4	Fe83	405.942	24.786	2700	1.0110	0.08350	0.00084	3.6290	9.2829
-45	146	2-4	Fe72	386.104	24.786	2700	1.0110	0.08188	0.00091	3.3195	9.9514
-30	142	20-24	Fe908	414.733	23.254	4500	0.9717	0.08411	0.00059	3.8708	9.3443
0	151.3	20-24	Fe910	407.933	23.254	4500	0.9717	0.08027	0.00048	3.4599	9.9768
15	145	7-9	Fe909	411.998	24.829	2700	0.9949	0.08603	0.00038	3.7888	9.1448
30	148.7	20-24	Fe911	413.108	23.254	4500	0.9717	0.07402	0.00084	3.5202	9.0423
90	149.8	7-9	Fe907	408.168	24.829	2700	0.9949	0.08093	0.00040	3.5480	9.1865

11.2 Aluminium foils $^{27}\text{Al}(\text{n},\alpha)^{24}\text{Na}$ reaction

NG1, November 2015

Angle	Distance (mm)	Shot numbers	Foil ID	Mass, m (mg)	Diamond 0 rate, D/T_{NG} (s^{-1})	T_{NG} (s)	F_T	Saturated activity, N_0/m (Bq mg^{-1})	$\sigma(N_0/m)$ (Bq mg^{-1})	MCNP reaction rate, R ($\times 10^{-10} \text{ mg}^{-1}$)	Neutrons per Dia0 count, Q/D ($\times 10^6$)
-120	145.4	68-71	Al40	395.090	26.536	3600	1.0007	0.23636	0.00079	8.7220	10.2123
-60	144.4	86-89	Al83	412.460	21.957	3600	1.0001	0.16542	0.00052	7.6306	9.8734
-45	140.2	3-8	Al83	412.460	25.751	7200	1.0016	0.21031	0.00148	7.8362	10.4223
-30	148.7	50-56	Al79	410.950	26.777	8400	0.9972	0.19954	0.00050	7.6559	9.7335
-15	153.4	32-39	Al28	395.560	26.420	9600	0.9972	0.19251	0.00071	7.3535	9.9089
0	145.4	50-56	Al80	410.640	26.777	8400	0.9972	0.22321	0.00052	8.1414	10.2390
0	151.6	5	Al69	812.955	26.138	1200	1.0000	0.22144	0.00500	7.4484	11.3743
45	139.9	86-89	Al78	411.350	21.957	3600	1.0001	0.16601	0.00062	7.8900	9.3537
45	143.1	21	Al62	811.223	26.143	1200	1.0000	0.19992	0.00444	7.5015	10.1945
60	151.0	32-39	Al14	394.535	26.420	9600	1.0008	0.18662	0.00041	7.0114	10.0741
75	145.8	17-25	Al78	411.350	26.143	10800	0.9992	0.19294	0.00043	7.5417	9.7857
90	101.8	Test 2 - 2	Al82	413.400	-	2700	1.0010	0.42602	0.00092	16.9932	-
90	149.2	3	Al68	812.865	24.768	1200	1.0000	0.21073	0.00130	7.7978	10.9108
105	141.1	17	Al64	817.591	26.351	1200	1.0000	0.26289	0.00226	10.0632	9.9136
105	147.4	9-14	Al40	395.090	26.536	3600	1.0016	0.23845	0.00038	9.2012	9.9877
120	148.2	68-71	Al76	411.000	26.536	3600	1.0007	0.22579	0.00072	8.6165	9.8747

NG2, November 2015

Angle	Distance (mm)	Shot numbers	Foil ID	Mass, m (mg)	Diamond 0 rate, D/T_{NG} (s ⁻¹)	T_{NG} (s)	F_T	Saturated activity, N_0/m (Bq mg ⁻¹)	$\sigma(N_0/m)$ (Bq mg ⁻¹)	MCNP reaction rate, R ($\times 10^{-10}$ mg ⁻¹)	Neutrons per Dia0 count, Q/D ($\times 10^6$)
-75	148.3	25-29	Al84	411.620	26.551	6000	1.0007	0.18471	0.00058	7.3103	9.5162
0	145.4	25-29	Al82	413.400	26.551	2700	1.0010	0.21204	0.00046	8.1414	9.8092
90	136.9	10-15	Al75	411.000	26.392	7200	1.0004	0.26122	0.00062	9.3189	10.6213
105	150.1	10-15	Al73	411.000	26.392	7200	1.0004	0.21072	0.00052	8.8504	9.0215

NG1, June 2016

Angle	Distance (mm)	Shot numbers	Foil ID	Mass, m (mg)	Diamond 0 rate, D/T_{NG} (s ⁻¹)	T_{NG} (s)	F_T	Saturated activity, N_0/m (Bq mg ⁻¹)	$\sigma(N_0/m)$ (Bq mg ⁻¹)	MCNP reaction rate, R ($\times 10^{-10}$ mg ⁻¹)	Neutrons per Dia0 count, Q/D ($\times 10^6$)
-90	149.4	2-4	Al79	410.950	20.251	2700	0.9989	0.19787	0.00126	7.9056	12.3595
45	153.5	9-12	Al40	395.090	19.176	3600	1.1138	0.13764	0.00171	6.5666	10.9309
90	150.6	9-12	Al78	411.350	19.176	3600	1.1138	0.16717	0.00577	7.7482	11.2512

NG2, June 2016

Angle	Distance (mm)	Shot numbers	Foil ID	Mass, m (mg)	Diamond 0 rate, D/T_{NG} (s ⁻¹)	T_{NG} (s)	F_T	Saturated activity, N_0/m (Bq mg ⁻¹)	$\sigma(N_0/m)$ (Bq mg ⁻¹)	MCNP reaction rate, R ($\times 10^{-10}$ mg ⁻¹)	Neutrons per Dia0 count, Q/D ($\times 10^6$)
-60	146.0	10-14	Al82	413.400	24.723	4500	1.0002	0.19177	0.00054	7.5337	10.2961
0	146.6	26-32	Al28	395.560	23.233	6300	1.0017	0.19653	0.00105	8.0761	10.4742
30	143.5	26-32	Al80	410.640	23.233	6300	1.0017	0.18970	0.00173	8.2963	9.8419
90	148.2	10-14	Al84	411.620	24.723	4500	1.0002	0.19736	0.00055	8.0246	9.9478

11.3 Aluminium foils $^{27}\text{Al}(\text{n,p})^{27}\text{Mg}$ reaction

NG1, November 2015

Angle	Distance (mm)	Shot numbers	Foil ID	Mass, m (mg)	Diamond 0 rate, D/T_{NG} (s^{-1})	T_{NG} (s)	F_T -change these to Mg-27 values	Saturated activity, N_0/m (Bq mg^{-1})	$\sigma(N_0/m)$ (Bq mg^{-1})	MCNP reaction rate, R ($\times 10^{-10} \text{ mg}^{-1}$)	Neutrons per Dia0 count, Q/D ($\times 10^6$)
0	95.8	Test 2 - 1	Al66	816.829	-	1500	1.0921	0.33056	0.00503	12.0823	-
0	151.6	5	Al69	812.955	26.138	1200	1.0015	0.11367	0.00067	4.7762	9.1049
45	143.1	21	Al62	811.223	26.143	1200	1.0026	0.12292	0.00054	4.8730	9.6485
60	151	32-39	Al14	394.535	26.420	9600	1.1730	0.11216	0.00396	4.5656	9.2981
90	149.2	3	Al68	812.865	24.768	1200	1.0005	0.13538	0.00079	5.1329	10.6487
105	141.1	17	Al64	817.591	26.351	1200	1.0000	0.15730	0.00135	6.6522	8.9735
105	147.4	9-14	Al40	395.090	26.536	3600	1.3135	0.15817	0.00416	6.0838	10.0199

NG1, June 2016

Angle	Distance (mm)	Shot numbers	Foil ID	Mass, m (mg)	Diamond 0 rate, D/T_{NG} (s^{-1})	T_{NG} (s)	F_T -change these to Mg-27 values	Saturated activity, N_0/m (Bq mg^{-1})	$\sigma(N_0/m)$ (Bq mg^{-1})	MCNP reaction rate, R ($\times 10^{-10} \text{ mg}^{-1}$)	Neutrons per Dia0 count, Q/D ($\times 10^6$)
0	143.7	2	Al68	812.865	21.227	900.37	0.9997	0.11802	0.00103	5.3964	10.3027
45	153.5	9-12	Al40	395.090	19.176	3600	1.1138	0.08012	0.00100	4.2622	9.8023
90	150.6	9-12	Al78	411.350	19.176	3600	1.1138	0.09051	0.00313	5.0970	9.2600

The $^{27}\text{Al}(\text{n,p})^{27}\text{Mg}$ reaction was not used with NG2 in either campaign.