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Characterisation of Neutron Generators and Monitoring Detectors for the in-Vessel Calibration of JET

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Abstract

A calibration of the JET neutron detectors was carried out prior to the upcoming deuterium-tritium experimental campaign. Two Compact DT neutron generators (NGs) were purchased for this purpose from VNIIA, Russia. These generators are capable of producing approximately 2×10^8 neutrons/s with a DT fusion energy spectrum. Preceding the in-vessel calibration measurements, these compact generators were tested and fully characterised at the UK's National Physical Laboratory (NPL). In order to support the characterisation measurements, detailed neutronics models were developed of the NGs, monitoring detectors and remote handling (RH) apparatus. Neutron spectra calculated from these models have been used to help determine NPL long counter efficiencies and effective centres, as well as NPL reference iron and aluminium activation foil reaction rates. The neutron emission rate has been measured for both generators as a function of angle using absolutely calibrated long counters and the relative emission rate by monitoring single crystal diamond detectors. The measured anisotropy profile is shown to be reproducible with a detailed NG MCNP model. Consequently, the neutron source routine and the MCNP model of the NGs can be reliably used for the analysis of the in-vessel calibration at JET.

Details of the calculated and measured NG free-field fluence, anisotropy, detector responses and MCNP simulated responses are presented.

Introduction

The proposed 14 MeV neutron budget for JET during the DTE2 operational campaign will be higher than any previous DT campaigns at JET. With this proposed budget, the achievable neutron fluence on the first wall of JET will be up to 10^{20} neutrons/m^2. In order to fully exploit the nominal neutron budget available, and to obtain a full scientific return for the investment into the DT campaign, an accurate calibration of JET neutron detectors and in-vessel activation system, at 14 MeV neutron energy has been performed. [1]

The calibration will also have the objective to benchmark the calibration procedure envisaged at ITER, with an accuracy of better than 10%. In order to achieve this target accuracy, the 14 MeV Neutron Generator (NG) selected as the calibration source has to be precisely characterised, the monitoring detectors calibrated and the computational models validated, prior to the calibration of the JET detectors.

JET is equipped with a multitude of diagnostics; amongst the most critical are the KN1 and KN2 neutron detectors. The KN1 diagnostic consists of three paired 235U/ 238U fission chambers, mounted on the vertical mid-plane of the vessel close to the transformer magnet limbs in Octants 2, 6 and 8. The KN2 diagnostic, the in-vessel activation system, pneumatically delivers capsules containing dosimetry foils to and from 'Irradiation Ends' located inside the torus structure. The primary purpose of the KN2 diagnostic is to provide a reliable cross calibration of the time resolved neutron yield monitors (KN1).

Extensive neutronics analyses are required to determine the calibration coefficients of the JET detectors. These include correction factors relating to:

- The difference in neutron source distributions between the NG calibration source and the JET tokamak D-T plasma
- The deployment of the JET remote handling apparatus, carrying the NG in-vessel; which perturbs the NG neutron flux being measured.

In order to accurately determine these corrections a detailed and validated neutronics model of the NG and mechanical supports is needed.

The work presented here describes the process of deriving a validated NG computational MCNP model to support the in vessel calibration of JET diagnostics.

14 MeV Neutron Generator

Two neutron generators (NG), with deuterated/tritiated titanium targets, were purchased from VNIIA [model Ing-17][2]. These generators are capable of producing approximately $2\text{x}10^8$ neutrons/s, with a 14 MeV neutron spectrum, when operated with a nominal 100kV acceleration voltage and a tube current of 110 μA. The generator is capable of running in a continuous mode for a maximum of 30 minutes at maximum emission rate.

The NG consists of an evacuated glass tube on which a copper disc is welded. The copper disc has a target layer of titanium hydride with deuterium and tritium absorbed in it. The ion beam has a spot size of 5mm, on a target of diameter 15mm. The relative concentration of deuterium and tritium in the target, and also on the filament that produces the ion beam, is nominally stated as 50%/50% by the manufacturers. The accelerating voltage is set by the user.

A pair of CVD diamond monitoring detectors, diamond (#1 and diamond #2), have been attached to the NG in well-defined positions using fixed mechanical supports. These monitoring detectors serve to accurately measure the NG's fluctuating output and provide an accurate, relative, measure of neutron emittance per NG irradiation via the $^{12}\text{C}(\text{n},\alpha)^{9}\text{Be}$ reaction. Monitoring Al, Fe and Nb activation foils are also fixed to the mechanical supports, with a detachable horse-shoe shaped holder, see figure 1. The activated foils, detached from the holder, are measured on a High Purity Germanium (HPGe) detector at the end of the NGs daily use. The HPGe measured gamma rays emitted via the following decay reactions: $^{27}\text{Al}(\text{n,p})^{27}\text{Mg}$, $^{56}\text{Fe}(\text{n,p})^{56}\text{Mn}$, $^{27}\text{Al}(\text{n},\alpha)^{24}\text{Na}$ and $^{93}\text{Nb}(\text{n,2n})^{92\text{m}}\text{Nb}$. These foils function as daily, absolute, yield monitors and when combined with diamond detector data can be used to derive the inter-shot time varying yield of each shot.

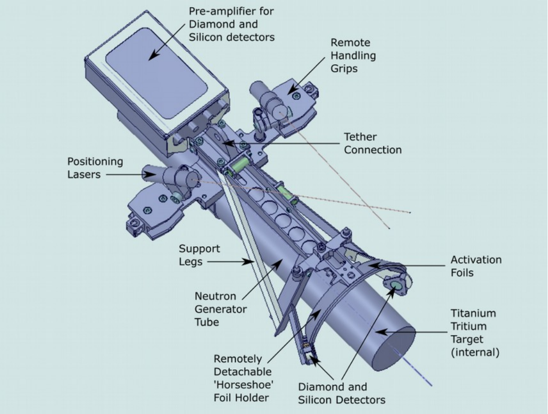

Fig. 1 *Neutron generator, remote handling attachment, foil holders and pre-amp.*

NPL neutron fluence measurements

Characterisation of the D-T generators took place in two campaigns in 2015/16 at the UK's National Physical Laboratory, London.

The DT neutron distribution is characterised by an energy-angle dependence and anisotropy in the neutron emission intensity, due to the reaction kinematics and scattering of the neutrons in the materials of the NG and RH apparatus. Hence, a faithful model is extremely important in simulating the experimental neutron distribution accurately.

Measurements of the neutron fluence as a function of angle, i.e. the anisotropy profile, were carried out using the absolutely calibrated NPL DePangher long counter and Fe/Al activation foils. The relative neutron emission rate was determined using monitoring diamond detectors by collaborating European laboratories. [3,4]

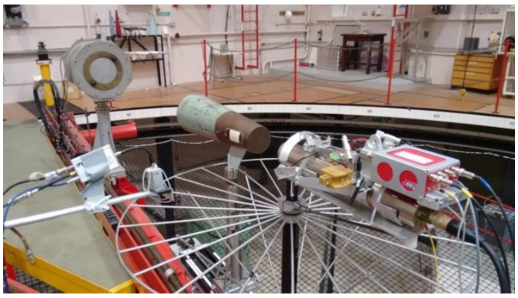

Fig. 2 *NPL lower scatter cell with NG, DePangher long counter and shadow cone.*

The NPL facility has a low scatter cell in which the experimental campaign was carried out (fig. 2).

In order to determine the angular distribution of neutrons emitted by the NGs, a series of measurements, by a well characterised long counter, were carried out at NPL. The LC was positioned at approximately 3m from the NG on a rotatable arm in the NPL low scatter cell. Measurements were carried out every 15 degrees and around features of interest. The NPL De Pangher long counter (LC), is a BF3 tube of 38mm diameter, surrounded by cadmium and polythene moderating material to provide a relatively flat response to neutrons over a large energy range over the energy region from approximately 1 keV to 7 MeV. Above this energy the response decreases monotonically.

It is standard procedure for LC measurements to be carried out with and without a shadow cone. This allows for the determination of the scattered (indirect) component of the measurement relative to the total. A simple subtraction of scattered from total fluence measurements leaves one with the direct component of the fluence. The shadow cone used consisted of 20cm of iron and 30cm of borated wax, where the half-angle subtended by the cone was 4.57 degrees.

There are two important parameters to consider when making fluence measurement with the LC. The detector response of the LC is neither perfectly flat as a function of energy nor is it perfectly efficient. Thus the efficiency has to be known for the energy or spectrum in which it is used. The only way to determine this would be to use a calculated spectrum in MCNP and derive the necessary correction factors for the counter. The effective centre of the detector varies with the energy and spectrum of neutrons being measured. Due to their cylindrical geometry and finite depth, the exact position of the effective centres of long counters is not obvious. The position varies with energy so the effective centre has to be determined for the particular energy spectrum in which it is used. [5].

Early in the campaign, diamond detectors with spectroscopic preamplifiers were used to measure the neutron spectrum at several emission angles, in close proximity to the NG. These measurements show, with good resolution, the mixed beam nature of the NG. [6]

The simulations of the neutron source energy spectrum were performed using the ENEA-JSI source subroutine. This subroutine extends the standard MCNP6 capabilities by additionally simulating neutron production due to more general interactions of beam D/T ions slowing down in the target of the NG and the D/T nuclei present. This subroutine also accounts for atomic and molecular species, in the beam, which result in different effective energies on the target. [7]

The composition of the various ions and molecular species were deduced by comparing with measurements the weighted fits of individually simulated spectra of various ion and molecular species of deuterium and tritium and their beam energies. The deduced species mix, table 1, shows that the largest component of the NGs ion beam is D-T$^+$ ions, forming approximately 80% of the incident ion beam. Simulated spectra, using the ENEA-JSI MCNP custom source routine and the deduced ion beam components, readily reproduce the measured spectrum to a high degree of fidelity. [6]

Ion beam component	Relative abundance in the ion beam (%)
D$^+$	0.63
T$^+$	2.66
D-D$^+$	8.95
T-T$^+$	7.32
D-T$^+$	80.44

Table 1. Beam composition determined from neutron component intensities and assumption of equal D and T concentrations in the target.

Samples of the resulting NG emission spectra are shown in Fig. 3. The high energy D-T peak can be seen to gradually move to lower energies at larger angles, due to the reaction kinematics and scattering of the neutrons passing through longer path lengths in the NG. A quite large proportion of the neutron flux density is observed at lower than the D-T peak energies, in the case of the 0 degree emissions, approximately 25% of the neutrons are of less than 13MeV. These, and calculated spectra at other measured angles, were used by NPL to determine the spectrum averaged efficiency and effective centre of the LCs for all measurement angles.

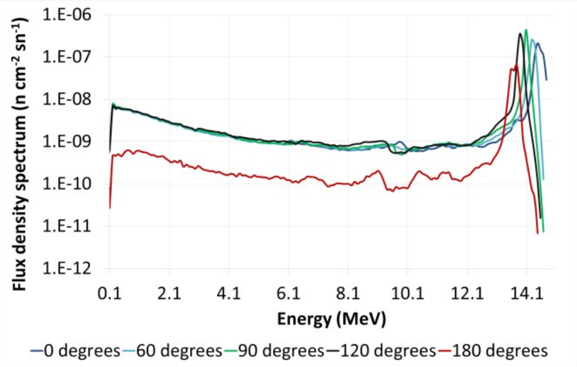

***Fig. 3** NG flux density spectrum at 3m from NG target. [units of neutrons per cm per simulated source neutron]*

The free field fluence at 3m from the NG target was calculated by NPL 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, for imperfect shadowing of the shadow cone and for air out-scatter. Uncertainties in these corrections were added in quadrature with the statistical uncertainties in the direct counts.

Modelling of the NG

A detailed MCNP model of the mechanical support, activation monitoring foils/holder, pre-amplifier, positioning lasers and monitoring detectors has also been developed, based on CAD models (Fig. 4). The CAD models of the NG, RH apparatus and monitoring detectors were simplified using SpaceClaim [8]. Overly detailed minute features, such as screw threads and hexagonal bolt heads, were rounded as well as spline surfaces removed and approximated with conical or spherical surfaces. Overlaps in geometry (interferences) were fixed and the final model was converted to MCNP Constructive Solid Geometry (CSG) form, using SUPERMC [9].

A simple generic MCNP model of the NG tubes has been developed using the manufacturer's technical documentation (fig. 5 (left)). This model showed poor agreement with LC measurements. Thus a more detailed model was developed using X-ray Computed Tomography (XCT) scans of the generator, carried out at NPL. These were performed using a Nikon XT H 225M micro XCT system, with maximum X-ray beam energy of 225 keV (Fig. 2). These scans revealed, in 3D, details that were not evident in the manufacturer's documentation. The manufacturer's information was then used in conjunction with the CT scans to create more comprehensive and detailed CAD models of the NG target, backing and housing (Fig. 4).

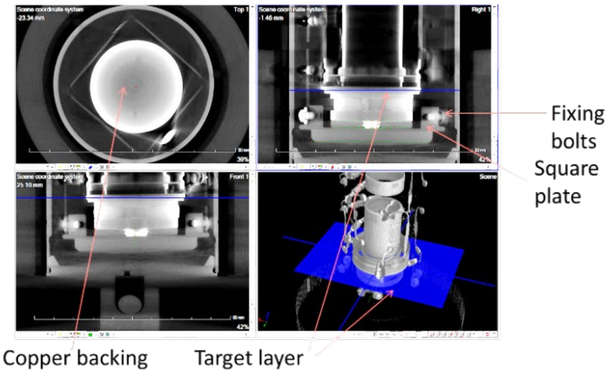

***Fig. 4** CT scans showing accelerator body and target/backing.*

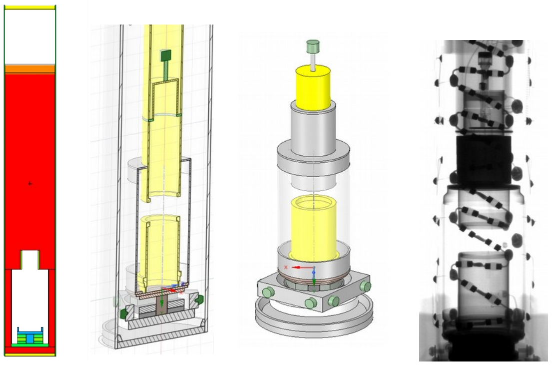

***Fig. 5** Left: generic drawing of NG, centre: detailed CAD model of NG target end. Right: single slice from CT scan showing accelerator body and target/backing.*

Where available, the Fusion Evaluated Nuclear Data Library, FENDL 3.0 [10], was used for neutron transport simulations. The full model (NG with mechanical support and monitoring detectors) is used to accurately simulate the neutron field around the neutron source. The neutron fluence and spectrum have been calculated at the monitoring detectors and the neutron spectra at the LC positions.

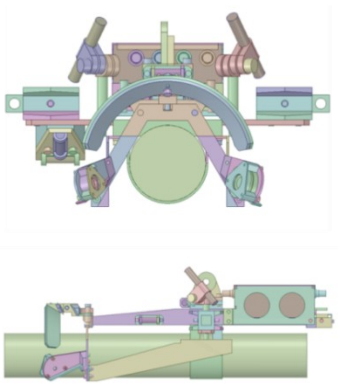

***Fig. 6** MCNP model of NG and of mechanical support, including the monitoring detectors.*

Fig. 7, Shows a comparison of the simulated angular neutron flux intensity, using the generic NG model based on manufacturer's drawing against the detailed NG model based on CT scans. For the simulations, MCNP tally spheres were arranged at 300cm from the NG target at 15 degree intervals and other additional angles of interest near rapidly changing features. MCNP track length estimate of flux (F4) tallies were used to calculate the neutron flux density. Large systematic deviations between the generic model and detailed model, upto 7-10%, can be seen in both forward and backwards directions relative to the NG target.

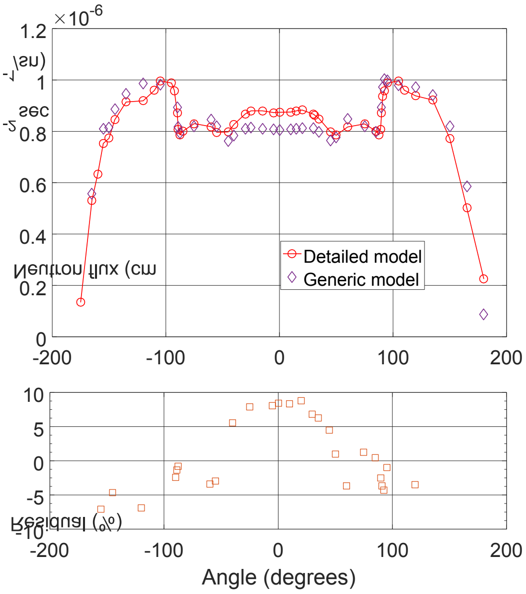

***Fig.** 7 Calculated Neutron flux density using simple generic model and detailed model of NG, at 300 cm from the NG, per simulated source neutron (sn^{-1}). Bottom: plot showing percentage difference between models excluding outliers.*

NPL determined angular yields of the NGs, based on two experimental campaigns using weighted means of multiple measurements, are presented in Fig 8. The fluence is normalised per emission per diamond detector #1 of 1.0×10^7 counts at 3m from the target. Also, plotted alongside the consolidated measurements, are normalised simulation results of the detailed NG model. LC measurement have uncertainties of the order of 5% in all but the backward direction, where due to the inability to carry out a shadow cone measurement, much larger uncertainties were assigned to the estimated scatter correction. The computational results have statistical uncertainties of less than 1% associated with each simulated data point.

Residuals can be seen to be very small, less than 2% on the whole, in both forward and backward directions. Above 165 degrees the difference between measurements and simulations does increase and a large deviation at 180 degrees is observed.

This is readily explained in the simulations by the absence of the large communications and power cable at the back of the NG. This was neither CT scanned nor incorporated into the computational models of the NG. Measured data, at 180 degrees, also has much larger uncertainties associated with it than at other angles. This is due to the inability to incorporate a scatter correction at this angle due to the lack of space behind the NG to correctly position the shadow cone. See reference [3] for details of the measurements and associated uncertainties.

There is a very large fall in measured fluence at these backwards angles, primarily due to the long path lengths of neutrons through the NG body. This results in a much lower fluence (~14%) in the backward direction against that of the same solid angle in the forward direction. Thus, the NG model deviates from the measured fluence only through a small solid angle and low relative fluence, which is factored into the total yield with larger associated uncertainties.

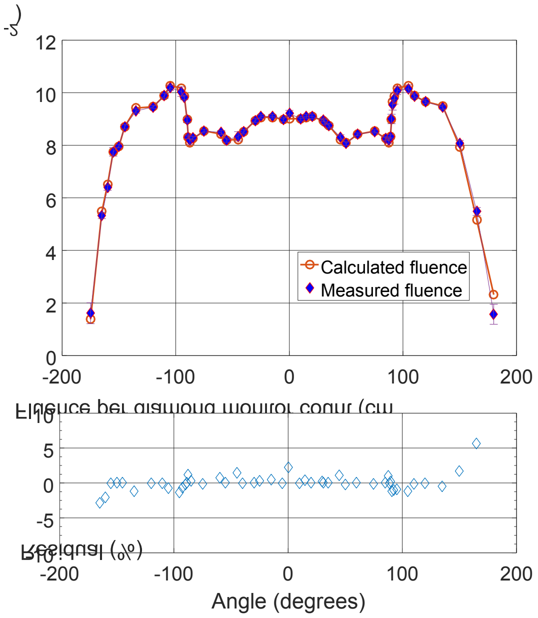

***Fig. 8** Average Measured fluence per diamond monitor count (Dia#1) at 300 cm from the NG neutron-producing target compared to normalised calculated values.*

A supplementary, independent measure, of the neutron output from the NG was carried out by NPL using activation methods. Fe and Al foils were arranged in a circular planar geometry, at ~30cm around the NG, fig. 9. Activated foils were measured using highly efficient gas flow proportional counters, which were used to determine the activities of the foils from the β particles emitted in the decay.

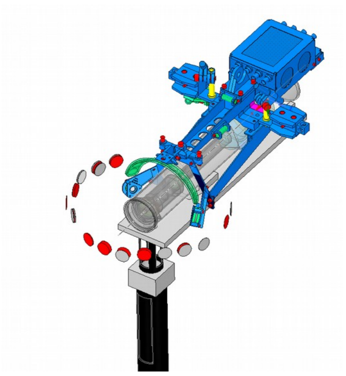

***Fig. 9** Simulated Fe and Al foil arrangement around* NG in planar geometry as measured at NPL.

Weighted averages of multiple measured Fe and Al foil reaction rates normalised to computed reaction rates, shown in fig. 10, show a linear and flat response as a function of angle, i.e. a good agreement between modelled energy/angular distributions and measurements is observed between all the angles measured between -50 to 125 degrees.

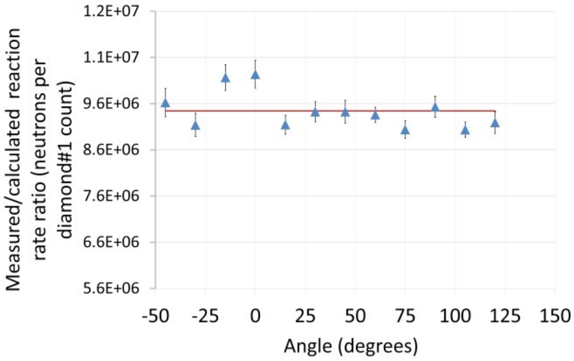

***Fig. 10** Consolidated results of NPL Fe and Al foil activation measurements.*

Total 4π.sr emission rates were derived from each foil using the MCNP calculated reaction rates of (n,p) and (n,α) reactions for the foils in their given measurement geometries. Weighted mean values, normalised to the 2016 campaign, of $2.01(9)\times10^{8}$ and $2.33(9)\times10^{8}$ neutrons/second emitted from the target for NG1 and NG2 respectively. LC measurements of 4π.sr yields for NG1 and NG2 were $2.08(6)\times10^{8}$ and $2.44(7)\times10^{8}$ neutrons/second. Uncertainties in total yield measurements are statetd here within the parenthesis at one sigma confidence on the least significant digit. Both sets of yield measurements show good agreement, within their respective uncertainties. The excellent agreement between simulations, NPL foil measurements - normalised to calculated reaction rates and LC measurements, demonstrates the validity of the modelling work undertaken.

Conclusion

Two 14 MeV neutron generators have been calibrated and characterised during two experimental campaigns at the NPL Neutron Metrology Laboratory, in view of using them for calibrating the JET neutron detectors. In parallel, a detailed MCNP model of the neutron generators has been developed together with a neutron source routine capable of accurately simulating the neutron production from fusion reactions by D and T beams impinging on solid targets containing T and D.

The neutron emission rate has been measured for both generators as a function of angle using an absolutely calibrated long counter, and the relative emission rate by monitoring diamond detectors. The percentage difference in the calculated to measured anisotropy profiles show residuals of less than 2-3%. Except at angles of 165-180 degrees, where the neutron yield falls off sharply. The results of the normalised computed emission rates, with less than 1% statistical uncertainty, and measurements, with less than 5% experimental uncertainty, agree to within their associated uncertainties over a very wide range of angles (0-165 degrees). Anisotropy profiles are identical for both generators and have been shown to be reproducible with the detailed NG MCNP model and custom source routine.

Acknowledgements

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