Calculations to Support JET Neutron Yield Calibration: Effects of the Neutron Generator Anisotropy

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ABSTRACT

The calibration of JET’s main neutron detectors, fission chambers and activation system, is based on the measurements of the detector response to a calibration neutron source placed in multiple positions inside the vacuum vessel. The main requirement for the calibration neutron source are well known source characteristics, such as the source intensity and neutron emission energy spectrum as well as its anisotropy. Good knowledge and understanding of these parameters is essential if the JET’s neutron detectors are to be calibrated with the target accuracy of 10 %. These neutron source characteristics are obtained through a combination of Monte Carlo simulations and characterisation measurements performed at a neutronics laboratory.

For the calibration of JET’s neutron detectors to neutrons with the energy of 14 MeV, a compact accelerator based DT neutron generator will be used as a calibration source. Such a generator is inherently anisotropic while additional anisotropy is introduced as a result of the materials surrounding the area where neutrons are produced. Small changes in the position or orientation of the source, when positioned inside the tokamak, can lead to a significant change of the detector responses depending on the relative position of the generator and the detector. This influences the accuracy of the calibration process. The investigation of the effects of uncertainties in the generator’s position and orientation on the fission chambers response are presented.

1 INTRODUCTION

At JET, neutron detectors, mainly fission chambers and activation detectors, are used as a neutron emission and neutron yield monitors, respectively. Neutron yield of DD and DT plasmas is linearly proportional to the number of fusion reactions and by that to the energy released from the plasma in the tokamak. Typically, the target uncertainty of the absolute neutron yield measurement calibration is 10 % [1]. The calibration of neutron detectors is achieved through a combination of measured detector responses to a neutron source in many positions inside the tokamak and calculations that take into account the differences between the calibration and operation reactor configuration. Monte

[1]See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia
Carlo simulations are an important tool both in the preparatory phase to the experimental in-situ calibration and in the analysis of the measurements after the calibration campaign. They are useful to both understand the difficulties and possible sources of the uncertainties before starting with the calibration experiment and to take into account uncharacteristic conditions during the calibration experiments such as changes in the reactor’s geometry and differences in neutron source characteristics (calibration source vs plasma source).

It was decided that a compact accelerator based DT neutron generator (NG) would be used as a calibration neutron source in the upcoming calibration of JET’s fission chambers and activation system to DT neutrons. The use of such a neutron source introduced many challenges that need to be addressed. Some of the problematic aspects of the use of NG as a calibration source are:

- Neutron emission can be time dependent.
- NG is an anisotropic neutron source both in terms of neutron emission intensity and in terms of neutron spectra.
- NG’s construction introduces additional anisotropy to the neutron emission intensity in some directions (further discussed in subsection 2.2). Moreover the uncertainty in the NG’s material composition and geometry translates into uncertainty in the neutron emission and spectrum.

The first point was addressed by attaching so-called "monitoring detectors" to the NG tube. This way, time dependence of the neutron emission can be monitored and all changes in the neutron emission taken into account. The second and to an extent the third point were addressed by the measurements performed to thoroughly characterise the chosen NG as a neutron source in two characterisation campaigns at the National Physical Laboratory (UK) [2]. The target accuracy of the neutron emission characterisation is 5% in order to make the 10% uncertainty of the calibration possible. However, the characterisation of the NG is only one part of the solution. In order to understand the effects that the source anisotropy has on the neutron detector responses and on the uncertainty of the obtained calibration factors, many sets of simulations where NG was put into a complex geometry of a tokamak were performed.

In this paper the analysis performed using a simplified model of the tokamak JET [3] is presented. The simplified model was used to gain qualitative insight into the problem with a relatively small number of simulations. This has been possible because the model is highly symmetrical and the number of simulations can be reduced by using the model’s symmetry.

2 MODELS USED

The MCNP6 version 1.0 Monte Carlo code [4] and data from FENDL 3.0 nuclear data library [5] were used for all simulations presented in this paper.

2.1 A simplified model of the tokamak JET

A relatively simple, highly symmetrical MCNP model of the tokamak was used. All major dimensions and material compositions used in the model were based on the JET tokamak. The model was constructed with simplicity and ease of use in mind while the results proved to be meaningful to JET as a result of linear dimensions and masses being based on those of JET [3]. Detector tallies in this model are located all around the tokamak, in 16 positions, and not just in the three positions where in reality the JET’s fission chambers are located. This way, a single simulation, where the NG
is put on a single position, can be used to determine the detector response for 16 different relative positions between the detector and the NG. To estimate the detector responses, the response function of the JET’s fission chambers was used [6].

![Figure 1: A simple MCNP model of the JET tokamak. The tokamak in the model is surrounded by the reactor hall wall not included in the figure.](image)

### 2.2 The model of the neutron generator

The NG was modelled based on the relatively simple sketch of its interior provided by the suppliers [2, 7]. Preliminary results of the characterisation measurements indicate that the anisotropy predicted by the model is within reasonable limits therefore the model should be reasonably representative of the NG to be used in this analysis.

![Figure 2: The MCNP model of the neutron generator (left) and the anisotropy in the neutron emission (right) as a result of the anisotropy of the DT reaction and from the model of the NG.](image)

The neutron source used in the simulations was in the form of the source definition card (SDEF) based on the simulations performed using the ENEA-JSI source subroutine [8]. The source definition was based on a simulation of an accelerator based system where deuterium ions accelerated to 100 keV are impinging on the tritiated target. The NG’s position in our calculations is defined by a position of the target while its orientation is defined by the direction of the ion beam.
Calculations show that the anisotropy in the neutron emission from the NG is dominated by the material composition and the geometry of the NG while the anisotropy of the DT reaction in the laboratory frame of reference contributes significantly to the neutron spectrum anisotropy \[2,7\].

2.3 Source positions

The symmetric properties of the model were taken advantage of in order to reduce the number of necessary simulations. The neutron generator was only positioned in positions inside one octant (45°) of the tokamak while the rest of the positions were obtained from tally values for other detector positions. For reference positions, the NG orientation inside the tokamak was always tangential to the magnetic axis.

A scenario where the neutron source positioned every 9° (40 neutron source positions in total) is describing a ring source with a radius of 300 cm located 30 cm above the tokamak’s midplane was investigated. This scenario is based on the experimental scenario that will be used for the calibration of JET’s fission chambers.

3 SIMULATIONS

Multiple sets of calculations were performed. To divide a complex problem into simpler ones an isotropic neutron source was used in some calculations and the model of the NG in others. The calculations performed:

- Isotropic neutron sources at 13.1 MeV, 13.6 MeV, 14.1 MeV, 14.6 MeV and 15.1 MeV to investigate the sensitivity of the system to the energy of neutrons.

- The NG oriented in toroidal direction facing clockwise and anticlockwise.

- The isotropic 14.1 MeV neutron source and the NG oriented in toroidal direction with position moved in different directions (vertically, radially and tangentially) to investigate the sensitivity to the NG position.

- The NG orientation was varied to investigate the sensitivity to the NG orientation.

The changes of the detector response to different neutron sources in each of the positions \(R_{ij}\) for detector \(i\) and neutron source position \(j\) were investigated as well as changes in the sum of the detector responses for a ring of positions defined as:

\[
R_i = \sum_j R_{ij}. \tag{1}
\]

In all cases the relative changes in the detector responses \((\Delta r)\) relative to the reference value \((R_{\text{ref}})\) are presented:

\[
\Delta r = \frac{R}{R_{\text{ref}}} - 1. \tag{2}
\]

In simulations where the NG was used the results were normalised per DT neutron released from the generator’s target in contrast to normalization to values per neutron emitted from the NG itself. Due to neutron absorption and multiplication in the NG geometry, these two normalisations produce somewhat different results. Additionally, a scenario where the NG is facing in one direction for half of the positions (clockwise) and in the other (anticlockwise) for the second half was assumed as a reference scenario. This is, again, based on the way the JET remote handling system is planned to position the NG in the JET’s vacuum vessel.
3.1 Sensitivity to neutron energy

The calculations were performed with an isotropic source that emits neutrons at 14.1 MeV, the energy of neutrons released in DT fusion reaction. The results using this neutron source were taken as reference values for the assessment of the sensitivity of fission chambers to the energy of emitted neutrons. Additional simulations using isotropic neutron sources with energies 13.1 MeV, 13.6 MeV, 14.6 MeV and 15.1 MeV were performed. The understanding of the sensitivity to changes in the energy is important as neutrons emitted from the the NG in different directions relative to the direction of its ion beam have different energies ranging approximately from 13.4 MeV to 14.7 MeV.

The results of these simulations, presented in Figure 3, indicate that differences in the energy of the neutrons of the order of 1 MeV in fact introduce a significant change to the calculated detector response calculations. This means that the accurate modelling of the anisotropy in the energy of neutrons emitted from the NG is important. The trend follows a general rule of materials being more transparent to faster neutrons compared to slower neutrons.

![Figure 3: Relative changes in responses of the fission chambers to the ring neutron sources at different energies. The ring of 14.1 MeV neutron sources is taken as a reference neutron source.](image)

3.2 Sensitivity to NG position and orientation

In the JET calibration experiment, the NG will be put in positions inside the tokamak via the remote handling system (RHS) [9]. To reduce the complexity of the problem, the model of the RHS was not used in the analysis presented in this paper. The RHS was not designed for the task of positioning of objects to predefined absolute coordinates within the JET’s vacuum vessel with high accuracy. It was designed to get close to the object it needs to manipulate, grab the object and then move it relative to other reactor components with great precision via master-slave feedback to the operator. Due to this feature the uncertainty of the NG position is expected to be of the order of 2 cm. To get some information about the effects of the anisotropy in NG’s neutron emission the sensitivity of the detector responses to the uncertainties in the NG’s position and orientation were investigated. To somewhat reduce the required CPU time, the sensitivities were only determined at the NG position where this effect was expected to be the most pronounced – the position directly in front of the port (NG at 0°). This position alone contributes around 9% to the total detector response $R_i$. In fact,
previous analyses showed that 90% of the detector response is due to neutrons leaving the vacuum vessel through ports [3].

To assess the sensitivity of the detector responses to the uncertainty of the NG position, the NG was put in positions 2 cm and 5 cm away from its reference position while the orientation stayed the same. Changes in the NG position were done in the vertical (up and down), radial (larger and smaller radius of the source positions) and tangential (forward and backward in the direction of the ion beam) direction. Relative changes were compared to the relative changes calculated using an isotropic 14.1 MeV neutron source in the same positions.

Figure 4: Relative changes in the detector response due to changes in the NG position. The reference neutron source position is at 0° and the detector is located at 14° according to Figure 1.

The graphs in Figure 4 show that for the tested NG position the largest uncertainty comes from the uncertainty in the radius of the circular path that the NG is following. The uncertainties in other two directions have significantly lower effect.

Furthermore, the sensitivity of the detector responses to the uncertainty of the NG orientation was assessed. The orientation of the NG was changed while its position, meaning the position of the centre of the tritiated target, stayed fixed in the reference position. For the assessment of the sensitivity to the orientation of the NG, the changes of 1°, 2° and 5° in vertical and horizontal directions were used. These angles correspond to the uncertainties in the position of one end of the NG compared to the other one of approximately 0.8 cm, 1.6 cm and 4 cm respectively. For the variation of the angle in the vertical direction the angle was defined as positive when the direction of the ion beam was facing upwards. The positive angles in terms of the horizontal angle were angles facing outward compared to the toroidal direction which is tangential to the circle where all of the source positions are located.

Figure 5 indicates that the detector responses seem to be rather insensitive to the orientation of the neutron generator. A notable exception are the detectors that are positioned in the direction behind the NG where the anisotropy of the neutron emission is large due to the geometry of the NG. However, the results of for those detector positions are not the most representative of the calibration experiments due to a lack of RHS that will always be located behind the NG during the calibration experiments.
Figure 5: Relative changes in detector response due to changes in the NG orientation. The neutron source is positioned at 0° and the detector is located at 14° according to Figure 1.

4 CONCLUSIONS

The use of a compact accelerator based DT neutron generator as a calibration source introduces some challenges to the calibration process. The time dependence of its neutron emission can be taken into account by attaching monitoring detectors to it while the effects of the NG’s anisotropy in terms of the neutron emission and energy of emitted neutrons must be well understood in order to reduce the uncertainties in the calibration factors. To reduce these uncertainties, the NG has to be characterised while the computational studies can help in understanding of expected behaviour. The sensitivity study presented in this paper provides some insight into the uncertainties due to the uncertainties in NG positions. It highlights stronger sensitivities that should be paid attention to during the preparation to the calibration process. The sensitivities to neutron energy, uncertainties in position of the neutron generator and in its orientation were investigated and it was found that:

- The energy of neutrons emitted from the generator can significantly influence the calculated detector response. This suggests that the mono-energetic approximation for the neutron source is not a sufficiently accurate description of the neutron emission from the NG.

- The basic shapes of the sensitivity profiles to the uncertainties in the NG position seem to follow the profiles of the isotropic neutrons source. This indicates that in many cases the geometry and the dimensions of the ports have the most important effect on the detector response.

- As expected, the anisotropy of the source somewhat complicates the sensitivity profiles – profiles can be far from linear.

- Results suggest that for 2 cm uncertainty in the NG position an uncertainty of up to 2 % can be expected for each of the NG positions with the highest sensitivity to the uncertainty in the radius of the circle describing source positions. Larger uncertainties in position, however, can lead to significantly larger uncertainties, especially in a case of the uncertainty in the radius in the circle of the source position (Figure 4).

- Sensitivity to the uncertainty in the orientation of the NG seems to be limited. The largest effects can be attributed to the NG’s geometry as the emission falls significantly in the backward
direction. In JET’s calibration scenario this effect should be smaller due to the RHS following the NG and thus blocking neutrons that are emitted into a backward direction.

It is difficult to determine the total uncertainty of the calibration factor based on the presented results only. However, these analyses indicate that it should be possible to keep the total effect of the uncertainties in NG positions below 5% if the accuracy in positions remain $\approx 2$ cm, like in previous calibration, and there are no significant biases in NG positioning. To further investigate these effects, a sensitivity study in a more detailed model will be carried out for the positions where the NG is planned to be positioned. The modelling of the shape of ports as well as the size and position of the detector are important so a model that describes the JET as closely as possible will be used.

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