EUROFUSION CP(15)06/36

L. Snoj et al.

Neutronic Analysis of JET External Neutron Monitor Response

12th International Symposium on Fusion Nuclear Technology (ISFNT)
Jeju Island, Korea
(14th September 2015 – 18th September 2015)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Neutronic analysis of JET external neutron monitor response

Luka Snoj[a*], Igor Lengar[a], Aljaž Čufar[a], Brian Syme[b], Sergey Popovichev[b], Paola Batistoni[c]
Sean Conroy[d] and JET Contributors[1]

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom
[a]Reactor Physics Division, Jožef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia
[b]Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom
[c]ENEA C. R. Frascati, via E. Fermi 45, 00044 Frascati (Roma), Italy
[d]VR Association, Uppsala University, Department of Physics and Astronomy, PO Box 516, SE-75120 Uppsala, Sweden

The power output of fusion devices is measured in terms of the neutron yield which relate directly to the fusion yield. JET made a transition from Carbon wall to ITER-Like Wall (Beryllium/Tungsten/Carbon) during 2010-11. Absolutely calibrated measurement of the neutron yield by JET neutron monitors was ensured by direct measurements using a calibrated ^{252}Cf neutron source (NS) deployed by the in-vessel remote handling system (RHS) inside the JET vacuum vessel.

Neutronic calculations were required in order to understand the neutron transport from the source in the vacuum vessel to the fission chamber detectors mounted outside the vessel on the transformer limbs of the tokamak. We developed a simplified computational model of JET and the JET RHS in Monte Carlo neutron transport code MCNP and analyzed the paths and structures through which neutrons reach the detectors and the effect of the JET RHS on the neutron monitor response. In addition we performed several sensitivity studies of the effect of substantial massive structures blocking the ports on the external neutron monitor response. As the simplified model provided a qualitative picture of the process only, some calculations were repeated using a more detailed full 3D model of the JET tokamak.

Keywords: *JET, MCNP, Neutron yield, calibration*

1. Introduction

In the JET tokamak neutron monitors such as fission chambers (FC) and activation system are used to measure the absolute fusion power and yield. In order to ensure the accuracy, these systems had to be recalibrated after the transition from the carbon wall to the ITER-like wall during the 2010-2011 shutdown. The calibration was carried out in 2013 when the RHS was used to position the ^{252}Cf neutron source on more than 200 positions inside the vacuum vessel and the response of the neutron monitors (FCs and activation system) to the source on various positions was measured [1, 2]. Main focus of this article are the responses of the three ^{235}U FCs that are located near the transformer limbs outside the vacuum vessel.

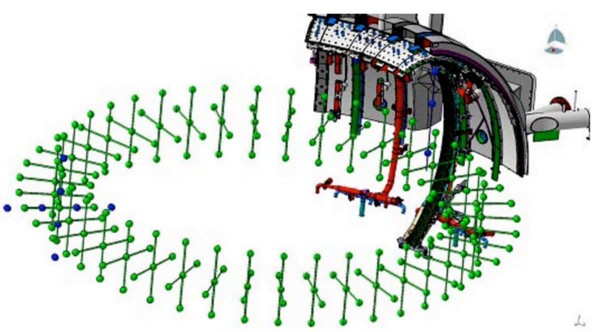

Fig. 1. Draft of in-vessel scan pattern.

There were 40 positions in the toroidal direction around the torus with each position having 5 locations: central (C), located near the plasma center 30 cm above the midplane of the reactor, with 4 additional positions 50 cm from the central position in the upper (U), lower (L), inner (I), and outer (O) directions (see Figure 1).

In preparation and in support of this calibration many analyses using the MCNP [3] particle transport code were carried out. To study the main effects a simplified model of the JET tokamak was developed which is suitable for scoping studies and investigations of the general behavior as it has relatively simple geometry, is easy to use, and has short computation times. A simplified and more symmetrical model is also better suited for investigation of the general behavior and characteristics than a more detailed and device specific model as there is less device specific characteristics. To simulate the calibration experiment more accurately the detailed model of JET was used as the actual machine has a much more complex geometry than found in the simplified model. The more complex geometry includes many asymmetries as the octants of the actual machine are not identical neither on the inside nor on the outside of the vacuum vessel. To ensure the relevancy the detailed model was updated for the comparison of the simulations with the experimental results of the

author's email: luka.snoj@ijs.si

1 See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

calibration. The target accuracy of the absolute calibration of the fission chambers was 10 % which is comparable with accuracies achieved in previous calibrations [1].

2. Analysis using a simplified model

2.1 Simplified MCNP model

For the scoping calculations the simplified MCNP model of the JET tokamak was developed with simplicity and fast calculation time in mind [4]. The only types of surfaces used in the model are planes, cylinders and spheres (Figure 2). The shape of the vertical cross-section was chosen to be rectangular to avoid using toroidal surfaces and to keep down the number of surfaces used in the problem. To ensure the relevancy of the results parameters like mass of the components and their main dimensions were preserved as closely as the simplifications and the availability of the data at the time allowed.

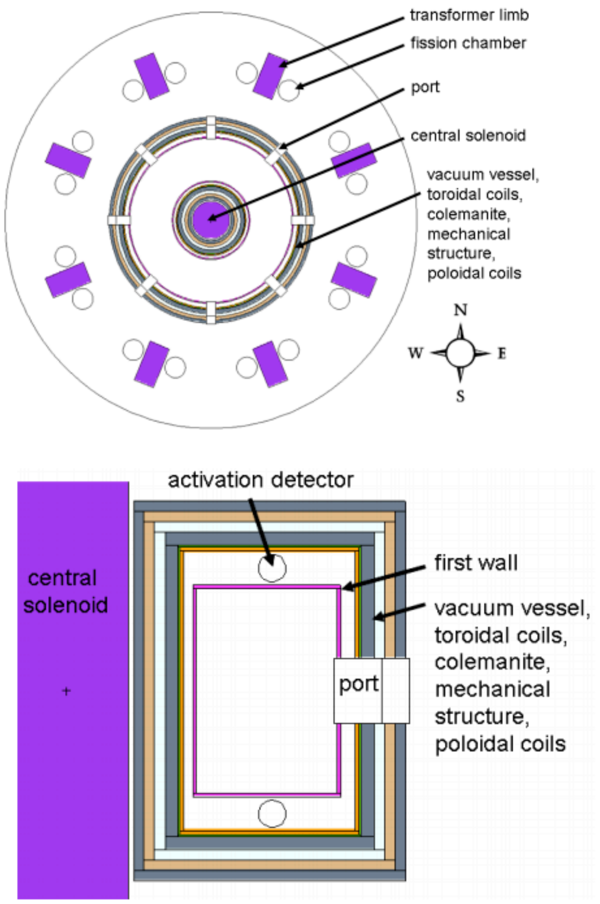

Fig. 2. Horizontal (top) and half of the vertical (bottom) cross section of a simplified MCNP model of JET.

2.2 Room return and port contributions

Effect of the room return on the FC responses was investigated because it was found to represent an important contribution. It was performed using the flagging option of MCNP [3] which allows the detector response caused by the neutrons that have crossed the torus hall wall boundary to be tallied separately. Two major conclusions can be made from the results. Firstly, the room return is higher when the neutron source is positioned in front of one of the ports which is mainly due to the higher probability of escape from the vacuum vessel. Secondly, the relative contribution of the back-scattered neutrons to the total FC response strongly depends on the position of the NS relative to the detector. It ranges from 10 % when the detector is close to the NS to 50 % when detector is on the opposite side of the tokamak from the NS.

Next the relative contribution of neutrons that are coming from each port to the total FC response was studied. Analysis of the contributions of different ports to the detector responses and the effect of massive objects blocking the ports is important since in JET many of the ports are, to different extents, covered or filled by massive objects like diagnostics systems and in case of the calibration experiments the RHS that comes into the reactor through one of its ports. For this analysis, again, the flagging function of MCNP was used to separate the tallies for neutrons crossing different ports. It was determined that 90-95 % of the total neutron detector response comes from neutrons that have left the interior of the machine through the ports. This means that only 5-10 % of the detected neutrons have penetrated the reactor wall. The share of these neutrons is greater for detectors close to the NS as their spectrum is harder. Investigation into the relative importance of the neutrons passing through various ports to the total detector response showed that the largest contribution to the detector response comes through the port that is the closest to the detector and the second largest contribution through the port closest to the NS.

Additionally the effects of massive objects in front of the ports were studied. The calculations showed that the total contribution to the detector responses is affected as predicted by the port contributions analysis. When a massive object is put in front of a port the detector response is decreased for the corresponding port contribution. All of the above findings are thoroughly described in [4].

3. Calculations using a detailed model

3.1 Detailed MCNP model

In order to compare the measured FC responses versus NS position with the calculations a detailed and updated MCNP model of the JET tokamak was used. The geometry of the detailed model is presented in Figure 3. This model includes various asymmetries such as antennae and limiters inside as well as the divertor at the bottom of the vacuum vessel.

After comparing the results of the detailed and simplified models it was confirmed that all major characteristics studied using the simplified model are also present in the detailed model. As expected it was found that the asymmetries of the octants have an important effect on the response of the fission chambers which means that the behavior is much more complex.

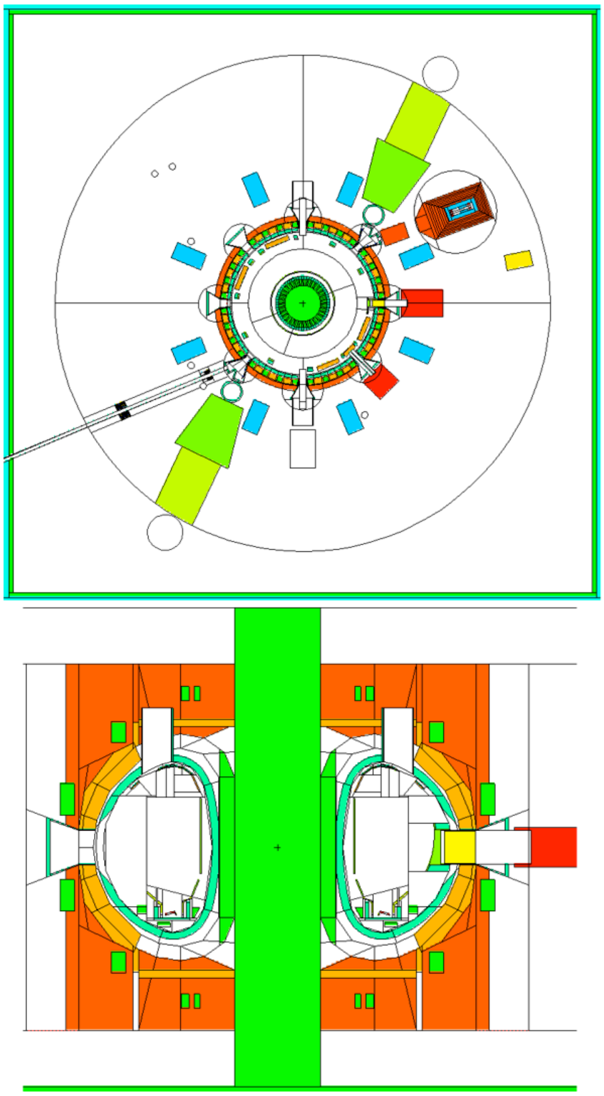

Fig. 3. Horizontal (top) and vertical (bottom) cross section of a detailed MCNP model of JET.

3.2 Model of the RHS

The experimental conditions during the calibration experiments differ from conditions during normal operation, one major difference being the presence of the RHS inside the vacuum vessel. The model or the RHS was developed [5] and is presented in Figures 4 and 5. The RHS is a dexterous, force-reflecting master-slave servo-manipulator that is capable of performing complex tasks inside the vacuum vessel of the tokamak JET [6]. RHS was chosen as a method to position NS on various locations in the tokamak was chosen as this system is already available so its use does not require structural changes to the reactor, it can handle different sources (it is also suitable for the delivery of the DT neutron source during the DT calibration), and is compatible with the conditions inside the reactor. The model is constructed entirely out of cylinders and boxes to keep it simple and a set of programs and scripts was developed to make the transition from the coordinates provided by the RHS team to the MCNP model as quick and effortless as possible. In order to support the calibration experiment, many MCNP input files with RHS on various positions had to be prepared. Source baton, a holder for the capsule of the ^{252}Cf designed to separate the NS from the RHS, was modeled quite closely as the effects of its shape and material composition on the neutron flux and spectra were expected to be substantial. Additionally its accuracy was experimentally confirmed through characterization measurements that are described in [7].

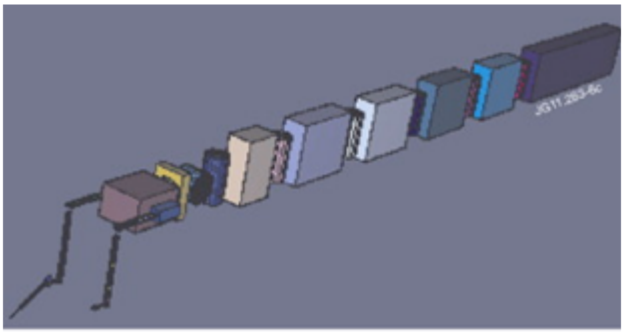

Fig. 4. 3D view of the MCNP model of the RHS in its basic configuration. The color of the structures does not indicate anything, it is just a coloring system of the MCNP Visual Editor.

3.3 RHS correction factors

In order to account for the uncharacteristic conditions during the calibration the correction factor methodology was used. This way an assessment of the detector response in conditions close to the experimental conditions was made. The results of the measurements were multiplied by the correction factors that account for the differences in conditions during the calibration relative to the conditions during other experiments. The correction factor is calculated as the ratio between a simulation of distorted and undistorted neutron detector response, i.e. a detector response for the case of the RHS and other calibration specific objects present in the tokamak divided by the detector response for the case with only the objects present during normal operation are included in the model.

The correction factor $C_{RH}^{i,j,k}$ for the detector i (fission chambers D1, D2 and D3), NS position j (j=1:40) and NS location k (C, U, L, I, O), is defined as:

$$C_{RH}^{i,j,k} = \frac{{}^{i,j,k}_{RH}}{{}^{i,j,k}_{0}}, \quad (1)$$

for undistorted detector response $^{i,j,k}_{0}$ and distorted detector response $^{i,j,k}_{RH}$.

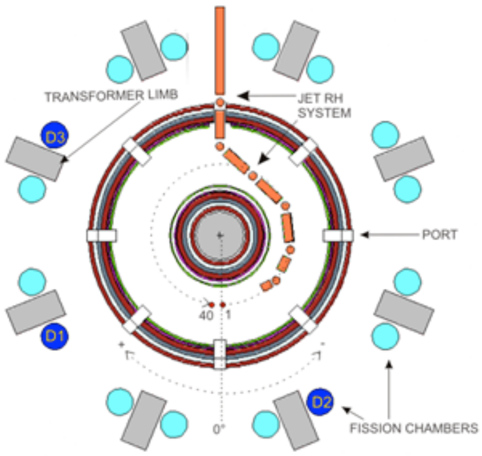

Fig. 5. RHS in a model where the positions of the fission chambers D1, D2 and D3 are shown as well as the definitions of the angles and the position numbering.

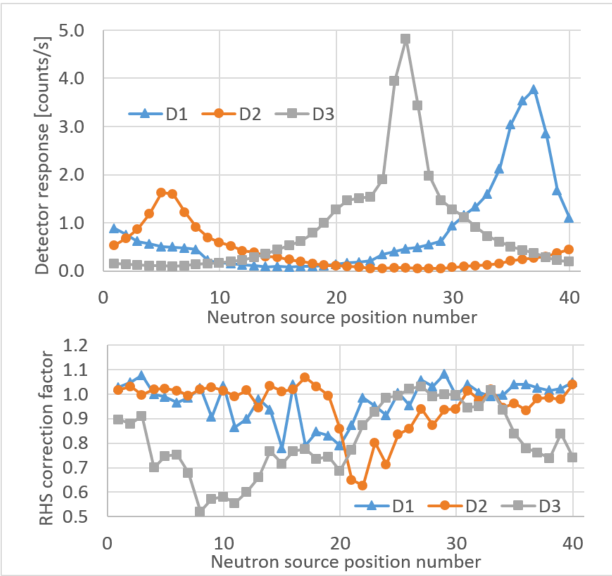

Fig. 6. Response of the fission chambers and RHS correction factors for the NS on central positions.

As seen from Figure 6 the disturbance of the FC response for NS on some positions can be substantial, even up to 50 %. However, large corrections are found in positions for which the absolute response of the detector is very small, therefore their effect on the integral detector response is limited [5].

As the plasma neutron source in the tokamak is of toroidal shape one should obtain the calibration factor for the volumetric neutron source. The calibration measurements, however, were performed in points on rings, presenting a ring shaped neutron source. Therefore in this work we focus only on the ring source. Transition from the ring source to the toroidal plasma neutron source was done later with another correction factor which describes the difference in the detector response to the ring neutron source and the plasma neutron source.

In order to quantify the effect that the RHS has on a detector response for the ring neutron source the ring correction factors were introduced as:

$$C^{i,k}_{RH\ \ IW} = \frac{\bullet_{j=1}^{40} \ {}^{i,j,k}_{RH}}{\bullet_{j=1}^{40} \ {}^{i,j,k}_{0}}. \qquad (2)$$

Values of the central ring correction factors for the detectors D1, D2 and D3 were 1.01, 0.99 and 0.92 respectively which shows that the integral effects of the RHS on the FC responses are relatively small and that, as predicted in the scoping study, the effect are biggest for the fission chamber D3 which is the closest to the port where the RHS enters the tokamak and thus blocks the port.

Additional studies were made where the density of the RHS was varied to assess the sensitivity of the detector response to the uncertainty of the RHS material composition, the effect of the NS holder on the neutron flux [7] etc. were carried out to make sure that the model of RHS is representative of the real system and that with its use in the simulations we produce reliable results.

3.4 Comparison with measurements

At the end the results obtained with the simulations and results of the measurements were compared to ensure the relevancy of the calculations.

Comparison showed reasonably good agreement of the calculated and measured detector responses. There are some unavoidable discrepancies that are the result of the uncertainties in the geometry or material compositions of parts of the JET tokamak. Even though these discrepancies are substantial for some NS positions the overall accuracy of the correction factors, major results of the computational support of the calibration experiment, is expected to be much better than the accuracy of the reproduction of the experimental data. The reason for this is the fact that the correction factors describe the effects of objects like RHS in relative terms and thus many of the uncertainties that are not a result of these objects cancel out. Later comparison of the results of the measurements from the fission chambers and activation system which were calibrated separately confirmed this and confirm that the uncertainty of the calibration is lower than the target value of 10 %.

4. Conclusions

Through the analysis described in the article we gained a good understanding of the most important effects related to the neutron transport from the neutron source in the vacuum vessel to the neutron monitors. We found that a minority of the neutrons hitting the fission chambers penetrate the tokamak wall, whilst most come via the ports. The highest contribution to a fission chamber response comes via the port nearest to a detector and the second highest contribution comes via the port closest to the NS. If the port is blocked by a massive object, the fission chamber response is decreased by up to the contribution of that port. It was observed that the torus hall wall significantly affects the response of each external fission chamber due to back scattering of neutrons. The effect of the JET RHS was studied and quantified for all the locations where the NS was positioned during the calibration experiments. It was found that the effect is the largest when the RHS is blocking the port near the detector or the NS, which is in agreement with the findings obtained by the simplified model. It was found that the simplified model is good enough for scoping studies and to study qualitative behavior of the neutron monitor response. The desirable characteristics of the simplified model are simple use, short computational times and generalness of the results but the relevance of the calculated absolute values can be questionable as there are many local effects caused by the objects that contribute to the asymmetry of the tokamak which the simplified model does not take into account. For the cases in which absolute values are to be calculated, the detailed model is more suitable as all of the most important objects are modelled and so the device specific local behavior is reproduced to a much higher extent.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

This work was supported by the Slovenian Research agency and carried out within the projects no. Z2-4000 (A) Calculations to support neutron monitor calibration - JET fusion reactor example case (postdoctoral research project) and no. J2□5467 Neutron calculations for use with neutron diagnostics - application to the JET fusion reactor.

References

[1] D.B Syme, et al., “Fusion yield measurements on JET and their calibration,” *Nuclear Engineering and Design*, 246, pp.185-190 (2012).

[2] D.B. Syme, et al., “Fusion yield measurements on JET and their calibration,” *Fusion Engineering and Design*, 89, pp.2766-2775 (2014).

[3] X-5 Monte Carlo Team, *MCNP – A General Monte Carlo N-Particle Transport Code, Version 5*, Los Alamos National Laboratory, (2003).

[4] L. Snoj, et al., “Calculations to support JET neutron yield calibration: Contributions to the external neutron monitor responses,” *Nuclear Engineering and Design*, 246, pp.191-197 (2012).

[5] L. Snoj, et al., “Calculations to support JET neutron yield calibration: Modelling of the JET remote handling system,” *Nuclear Engineering and Design*, 261, pp.244-250 (2013).

[6] P. D. Murcutt, et al., “High level integration of remote handling control systems at JET,” *Fusion Engineering and Design*, 86, pp.1911-1914 (2011).

[7] L. Snoj, et al., “Calculations to support JET neutron yield calibration: Neutron Scattering in source holder,” *Fusion Engineering and Design*, **87**, pp.1846-1852 (2012).