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Comparison of neutron flux streaming calculations to the 2019-2020 JET Experimental Deuterium-Deuterium Results[1]

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In 2019 JET carried out a very successful Deuterium-Deuterium campaign, referred to as C38, producing a total of 3.75 $\times$ 10^{19} DD neutrons. During this campaign, a series of experiments were implemented to record the neutron fluence at positions close and far from the source and along shielding penetrations. Measurements were performed using LiF thermoluminescence detectors (TLDs) and sets of high purity cobalt, silver and tantalum disc-shaped activation foils, placed inside high-density polyethylene moderators. Both measurements were performed but this paper focuses on the TLD results.

Monte Carlo N-Particle (MCNPv6.1 [1]) code was used by CCFE to calculate the neutron fluence at 22 detector locations in the JET hall. The neutron fluence was calculated for each individual TLD and activation foil as positioned inside the polyethylene moderator, using a detailed JET 360-degree model. These demanding calculations were made computationally feasible due to the employment of AutomateD VAriaNce reducTion Generator (ADVANTG) code developed by ORNL.

The results of the calculations were compared against the experimental results derived from the in terms of neutron fluence and reaction rates, and a satisfactory agreement was observed.

The results of the present work contribute to the verification of ADVANTG software for Monte Carlo simulations of complex geometries, such as those encountered in a tokamak, most particularly at positions far from the plasma source, where no other computation method can provide reliable results. The experiments and calculations will be repeated for the upcoming Tritium-Tritium and Deuterium-Tritium JET campaigns.

1. Introduction

In 2019/2020 JET carried out a successful Deuterium-Deuterium campaign, referred to as C38, producing the highest ever DD neutron yield. During this campaign, a series of experiments were implemented to record the neutron fluence at positions close and far from the plasma source and along shielding penetrations. This work is the continuation of the streaming experiments started in 2012 [2,3]

Measurements were performed using LiF thermoluminescence detectors (TLDs) placed inside high-density polyethylene moderators. A total of 440 detectors were installed in 22 positions (inside the moderaotrs) with positions varying from close to the machine to up to 20 meters away through small penetrations in the concrete biological shield. These positions are displayed in Fig. 1, Fig. 2 and Figure 3.

The aim of this experiment is the validation of the neutronics codes and nuclear data applied in ITER nuclear analyses in a real fusion environment. The neutron fluence calculations performed with MCNP and ADVANTG codes with FENDL3.1d nuclear data libraries are compared to measurements to assess their capability to correctly predict the streaming in the ITER biological shield penetrations up to large distances from the neutron plasma source, in large and complex geometries.

The most recent JET campaign was broken down into 3 separate phases: C38a, C38b and C38c. C38a ran from the 09/06/2019 to 20/12/2019 and produced 3.68 $\times$ 10^{19} neutrons. Some of the detectors were removed at this time as they had received sufficient radiation to perform the measurements. C38b and C38c originally planned to be one campaign but were interrupted due to covid-19. All remaining detectors were removed on 25/03/2020 after the machine had reached 5.18 $\times$

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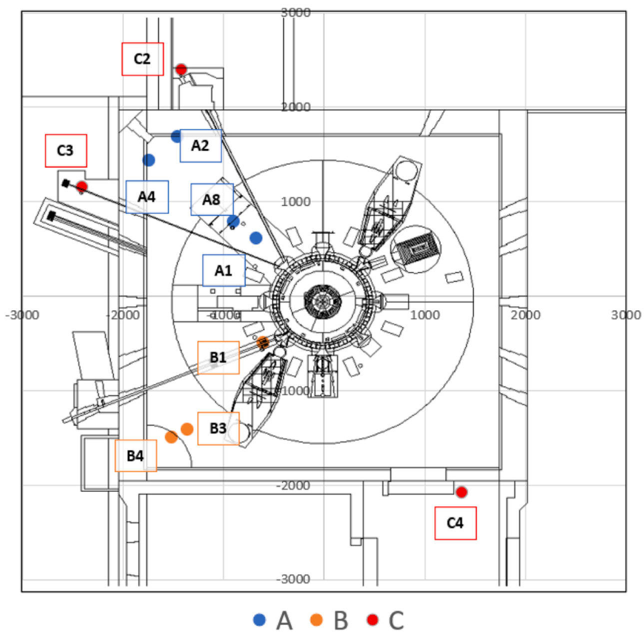

Fig. 1. TLD positions on the z plane around the machine centre illustrated on the MCNP model.

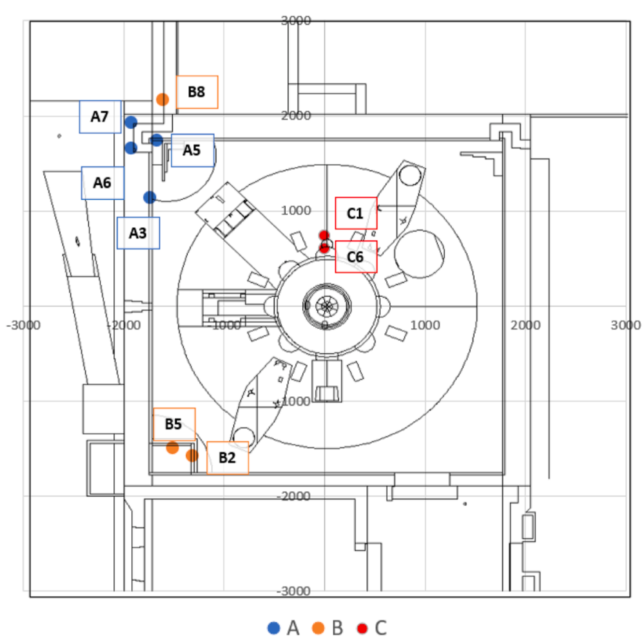

Fig. 2. TLD positions on the ground floor of the torus hall illustrated on the MCNP model.

10^{19} neutrons to perform the remaining measurements. Table 1 lists in full detail when each detector was installed and removed and the total neutron yield of JET during this time period.

2. Methodology

The Monte Carlo N-Particle (MCNPv6.1) code was used by CCFE to calculate the neutron fluence at 22 detector locations in JET hall. The neutron fluence was calculated for each individual TLD positioned inside the polyethylene moderator, using a detailed JET 360-degree model depicted in the figures above. This was done using the reference model MCNP-DD-STRv6D-TLD.

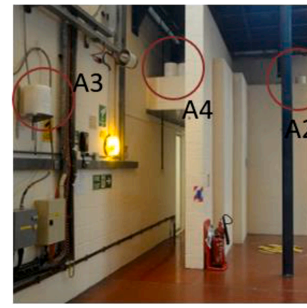

Fig. 3. A2, A3 and A4 experimental location circled with red photographed during installation.

Table 1
List of detector removal dates and neutron yield of JET during their installation.

Dector Name	Instalation Date	Removal Date	Neutron Yield
A1,A8,A2,A3,A4,B1,B2,B3, B4,B5	09/06/2019	20/12/2019	3.68E+19
A5,A6,A7,B8,B6,B7,C2,C3,C5	09/06/2019	25/03/2020	5.18E+19
C6,C7	11/08/2019	20/12/2019	2.82E+19

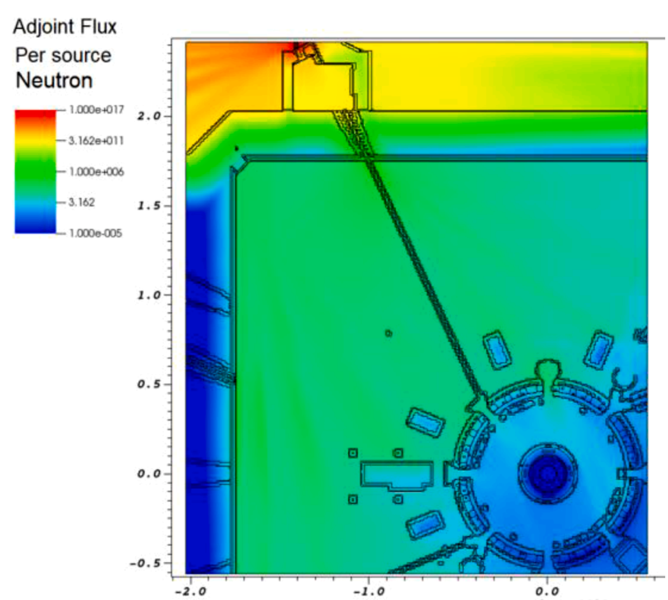

Fig. 4. Adjoint flux calculated using ADVANTG for position C2.

This MCNP model has been in development for over 10 years with many major additions and improvements made in the last 5 years. These improvements include an update to the NBI systems and building models from CAD converted to MCNP using the SuperMC [4]. This model now has over 4400 cells and 10000 surfaces and covers an area over 35 × 35 × 40m.

These demanding calculations were made computationally feasible due to the employment of AutomateD VAriaNce reducTion Generator (ADVANTG) [5] code developed by ORNL. An ADVANTG calculation was run for each detector using the CADIS method. The deterministic code meshes were optimized for each calculation with the mesh resolution being decreased in size round area of interest such as the port openings in the tokamak and the penetration opening in the wall. These meshes went as low as 5 cm in the deterministic calculations to fully resolve the 3-dimensional space.

An example of the adjoint flux (used to derive the window weights)

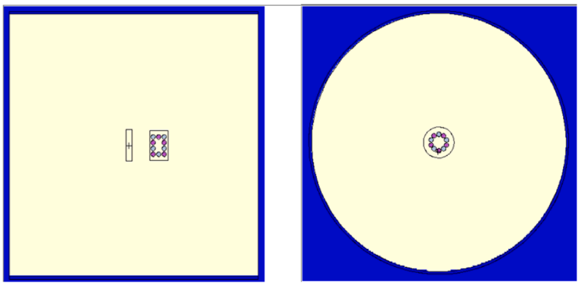

Fig. 5. Detailed MCNP model of the polyethylene cylinders. The TLD horizontal (right) and vertical (left) holders are shown. The cream color represented the polyethylene moderator and the circles in the center are the TLD's.

for position C2 is shown in Fig. 4.

The weight windows from ADVANTG were then used in subsequent MCNP calculations to make the calculations tangible. In the MCNP calculation the neutron flux was calculated in each individual TLD detector inside 25.5 cm diameter polythene moderator as illustrated in Fig. 5. Each moderator contained 20 TLD detectors and the results were summed in MCNP to give 1 result for neutron fluence for each moderator.

Due to the complexity and size of these calculations each of the 22 detectors was ran for an average of 18 days of 64 processors to ensure the statistical error was below 5 % in the TLD cell tallies and at least 8 out of the 10 statistical tests were passed. In these calculations due to the large amount of particle splitting and rouletting it is vital that the majority statistical checks are passed as in previous calculation false convergence has been observed due to heavy splitting of specific paths in penetrations.

3. Results

The results of the MCNP calculations were compared against the experimental results derived from the TLDs (by the Institute of Nuclear Physics Polish Academy of Sciences), in terms of neutron fluence, these results are shown in Fig. 6. Due to the varying JET yields, which the detectors observe during the campaign, the experimental results have been divided by the number of source neutrons to make them easier to compare with MCNP.

This figure shows that five of the experimental position are below or around the measured background level due to being in highly shielded positions. A satisfactory agreement was observed between the calculations and experimental results and shows a similar trend to previous results [2]. The deviation in the calculations from the experimental results increases with distance from the machine. An improvement between calculations and experiment has been achieved during this campaign due to the new calibration of the JET KN1 fission chambers.

The complete set of calculated and experimental results are listed in Table 2 and a plot to highlight the discrepancy in the results is displayed in Figur. The largest deviation is seen at positions A6, B5, B6 and B7. Fig. 7.

The detector B5 is positioned far from the machine in a chimney that leads to the basement of the JET torus hall. B6 and B7 are positioned in the basement. To reach these positions the neutrons scatter and penetrate thought many concrete walls and floor. Previous studies [6] show that the amount of boron and hydrogen in these walls can have up to a factor of 4 effect on the neutron fluence values observed at those positions. There is a large discrepancy for detectors A6 and A7 due to their

Table 2
Comparison of calculated and experimental results. The results are the neutrons per cm^2 per source neutron.

Detector Name	Expeimental Results [n/ cm^2 /source neutron]	MCNP results [n/ cm^2 /source neutron]	C/E
A1	2.98E-09	2.35E-09	0.79
A8	8.64E-10	1.30E-09	1.51
A2	1.60E-10	4.02E-10	2.51
A3	1.80E-10	4.50E-10	2.50
A4	6.03E-11	1.97E-10	3.27
A5	3.36E-12	1.22E-11	3.63
A6	2.10E-13	1.37E-12	6.52
A7	2.79E-14	1.25E-13	4.47
B1	4.62E-09	1.09E-08	2.36
B2	7.00E-11	2.00E-10	2.86
B3	1.22E-10	3.25E-10	2.66
B4	1.03E-10	2.81E-10	2.73
B5	5.88E-12	3.92E-11	6.66
B6	6.15E-13	4.86E-12	7.90
B7	6.77E-15	6.57E-14	9.70
B8	3.04E-15	5.52E-17	0.02
C6	5.85E-10	1.20E-09	2.05
C7	1.08E-09	1.02E-09	0.94
C5	3.22E-15	3.56E-14	11.07
C3	5.46E-15	1.37E-17	0.004
C2	4.65E-15	1.58E-18	0.0003

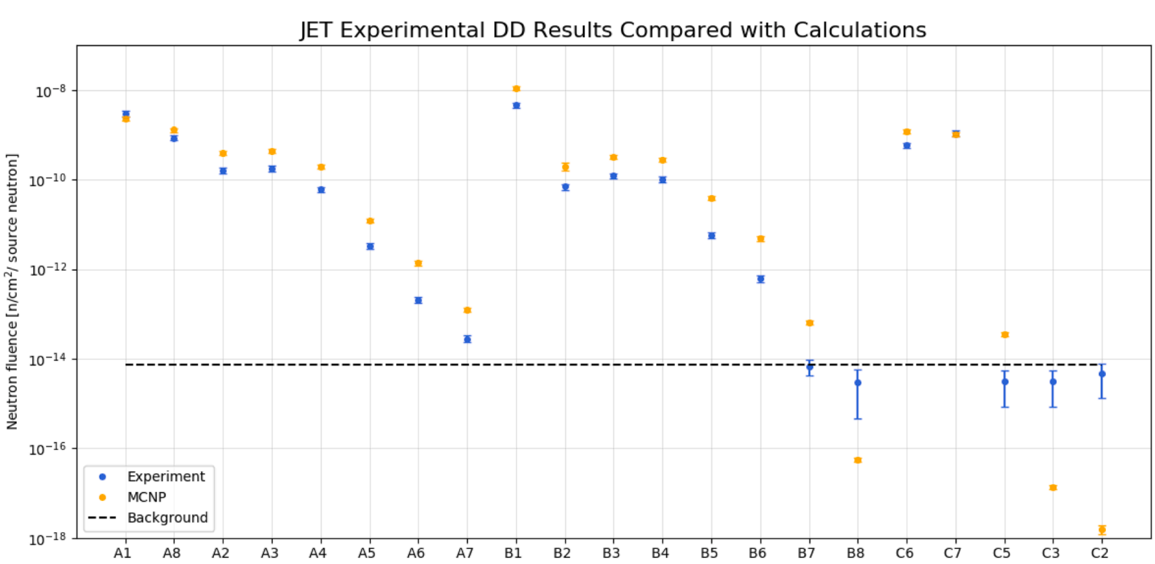

Fig. 6. Comparison of the experimental and calculated neutron flux [per source neutron] for each detector for the 2019-2020 DD campaign.

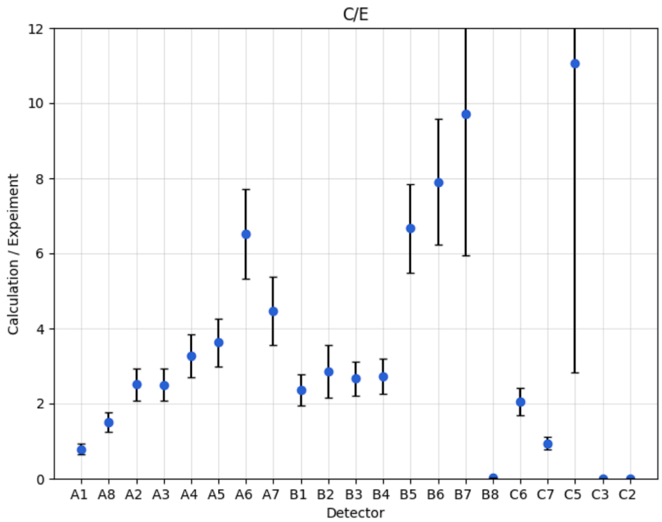

Fig. 7. Calculated results dived by the experimental results to highlight discrepancies.

position far from the torus in the labyrinth.

There are several sources of uncertainties in this complex environment. The main reasons for the discrepancies in the calculations are partly caused by modelling approximations and imprecise material information available for the JET tokamak machine and concrete used in the biological shielding due to the age of the machine. Indeed, the tokamak structural components as well as the large diagnostic, heating systems and all the equipment surrounding the machine are not described in detail in the MCNP model and the material chemical compositions are unknown for some components; such lack of accuracy affects the neutron transport and the calculated quantity. The neutron scattering/absorption occurring in the equipment materials is not therefore completely taken into account and this can explain the overestimation of the neutron fluence, even in B1 and C6. An improvement in C/E comparison with respect to previous results [2] is obtained. This is mainly due to the improved accuracy in calibration of the TLDs assembly and the JET neutron diagnostics and the results can be considered satisfactory when taking in to account the complexity of measurements and simulations in tokamak environment.

4. Conclusion

The neutron fluence has been calculated using MCNP and compared against the experimental results for the JET 2019-2020 DD campaign. The neutron fluence was measured in various positions close to the JET machine, at the Torus Hall walls, outside the biological shield in the SW labyrinth and in the SE chimney down to the Torus Hall basement.

These results show a comparison between experimental and calculated results in the C38 campaign as previous experimental DD campaigns [1] with some improvements due to new methodologies using ADVANTG and the new JET fission chamber and TLDs calibration. The main source of discrepancy is related to the lack of accuracy in geometrical modelling and materials. The results of the benchmark can be considered satisfactory considering the complexity of measurements and simulations in tokamak environment.

These results also contribute to the utilisation and exploitation of ADVANTG software for use with MCNP simulations of complex geometries, such as those encountered in a tokamak, most particularly at positions far from the plasma source, where other computation method an alternative method struggle to provide sufficiently converged results.

The experiments and calculations will be repeated for the upcoming Tritium-Tritium and Deuterium-Tritium JET campaigns.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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