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

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In 2019 JET carried out a very successful Deuterium-Deuterium campaign, referred to as C38, producing a total of 3.75×10^{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 that this paper focuses on the TLD results.

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 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 [1] [2]

Measurements were performed using LiF thermoluminescence detectors (TLDs) placed inside high-density polyethylene moderators. A total of 440 detectors were installed in 22 positions (moderators??) 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 Figure 1, Figure 2 and Figure 3.

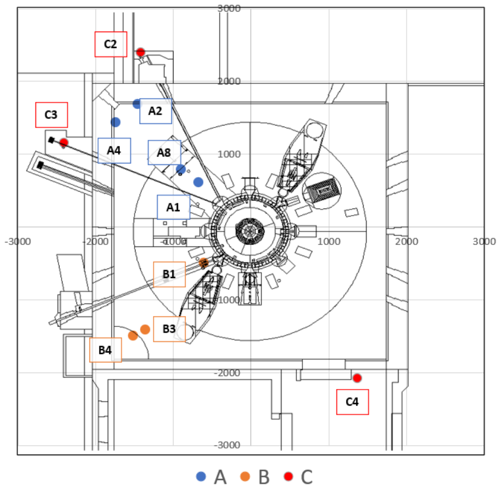

Figure 1. TLD positions on the z plane around the machine centre illustrated on the MCNP model.

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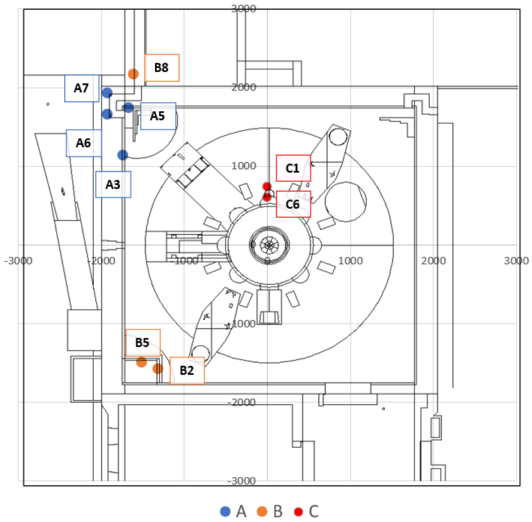

Figure 2.TLD positions on the ground floor of the tours hall illustrated on the MCNP model.

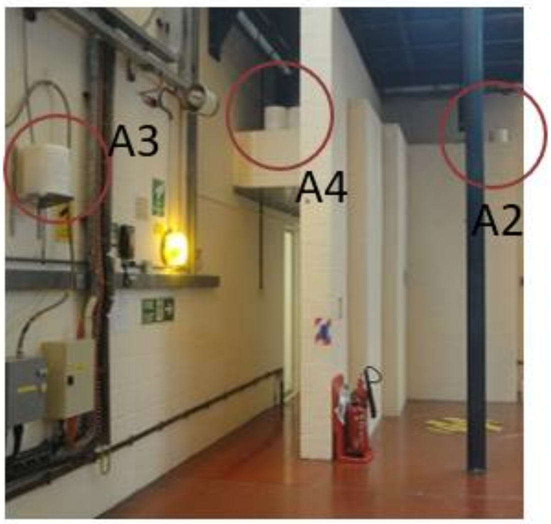

Figure 3. A2, A3 and A4 experimental location circled with red photographed during installation.

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 3.68×10^{19} neutrons. A sub section 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 5.18×10^{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.

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

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.

This MCNP model has been in development for over 10 year 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 using the SuperMC [3]. This model now has over 4400 cells and 10000 surfaces and covers an area over 35x35x40m.

These demanding calculations were made computationally feasible due to the employment of AutomateD VAriaNce reducTion Generator (ADVANTG) [4] 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) for position C2 is shown in Figure 4.

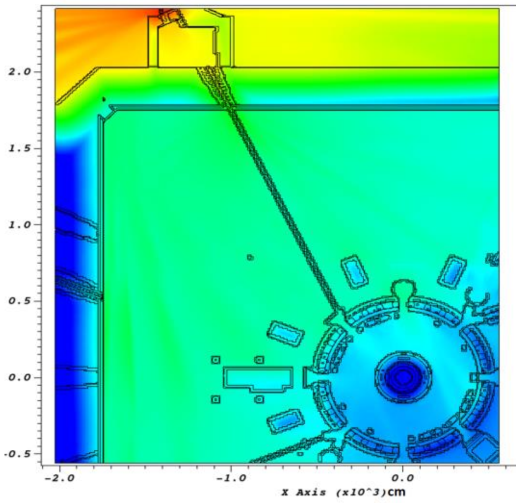

Figure 4: Adjoint flux calculated using ADVANTG for position C2.

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 Figure 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 28316 CPU minutes to ensure the statistical error was below 5 % and at least 8 out of the 10 statistical tests were passed. In these calculations due to the large amount of particle splitting 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.

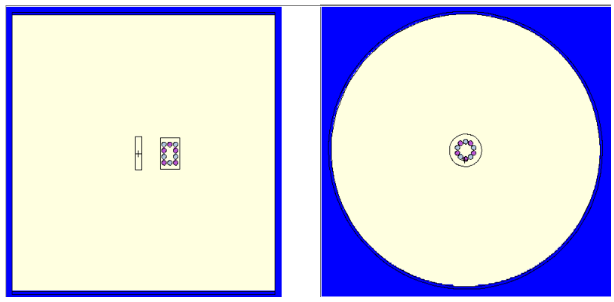

Figure 5. Detailed MCNP model of the polyethylene cylinders. The TLD horizontal (right) and vertical (left) holders are shown.

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 Figure 6. Due to the varying JET yields that each of the detectors observer during the campaign the experimental results have been dived by the number of source neutrons to make them comparable with MCNP

This figure shows that 5 of the experimental position are below or around the measured background level due to being in highly shielding positions. A satisfactory agreement was observed between the calculations and experimental results and shows a similar trend to previous results [1]. The deviation in the calculations from the experimental results increase 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.

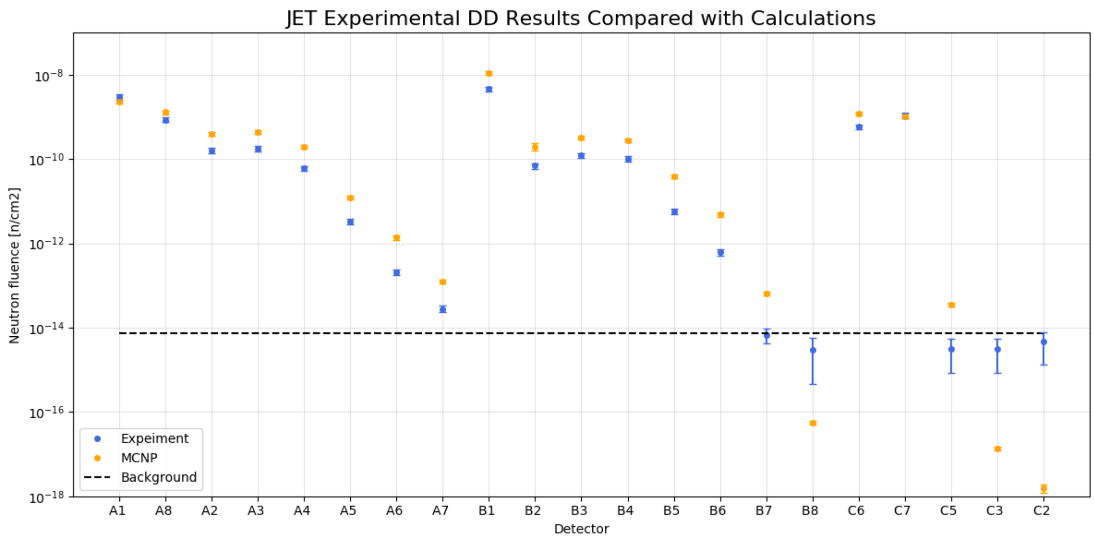

Figure 6. Comparison of the experimental and calculated neutron flux [pe source neutron] for each detector for the 2019-2020 DD campaign.

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

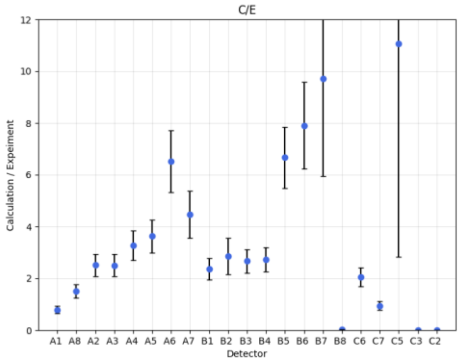

Figure 7. Calculated results dived by the experimental results to highlight discrepancies.

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 [5] 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 position far way in the labyrinth.

It is believed that the discrepancies in the calculations are caused by imprecise material information available for the JET tokamak and building due to the age of the machine, nonetheless this results are excellent when taking in to account the complexity of measurements and calculations.

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 NEUTON]	MCNP RESULTS [N/ CM^2 /SOURCE NEUTON]	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	0.00
C2	4.65E-15	1.58E-18	0.00

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 has been 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 similar comparison between experimental and calculated results as seen during previous experimental campaigns [1] with minor improvements due to new methodologies using ADVANTG and the new JET fission chamber calibration.

These results also contribute to the verification 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 methods struggle to provide sufficiently converged results.

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

Acknowledgments

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