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Neutronics benchmark experiments are conducted at JET in the frame of WPJET3 NEXP within EUROfusion Consortium for validating the neutronics codes and tools used in ITER nuclear analyses to predict quantities such as the neutron flux along streaming paths and dose rates at the shutdown due to activated components. The preparation of neutron streaming and shutdown dose rate experiments for the future Deuterium-Tritium operations (DTE-2 campaign) are in progress. This paper summarizes the status of measurements and analyses in progress in the current Deuterium-Deuterium (DD) campaign and the efforts in preparation for DTE-2.

Keywords: JET, neutronics, DTE2, shutdown dose rate, streaming, benchmark

1. Introduction

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

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Neutronics benchmark experiments are conducted at JET for validating the neutronics codes and tools used in ITER nuclear analyses to predict quantities such as the neutron flux along streaming paths and dose rates at the shutdown due to activated components. In particular, in the frame of subproject NEXP of JET-3 program [1], several activities are performed within EUROfusion Consortium devoted to the preparation of neutronics experiments for the future Deuterium-Tritium operations (DTE2 campaign). During plasma operations, neutron fluence and dose measurements will be performed using thermoluminescent dosimeters (TLDs) and activation foils located in several positions inside and outside the Torus Hall. At the shutdown, decay gamma dose rates will be measured using passive and active dosimeters installed inside and outside JET vessel. Decay gamma dose in-vessel measurements will be performed with TLDs and high-sensitive, low activation, spherical ionization chambers will be used to measure the dose rate versus time after irradiation in two ex-vessel positions on the side-port of Octant 1 close to radial neutron camera and in Octant 2 on the top of ITER-like antenna (ILA). The results of the neutron fluence measurements will be compared with three-dimensional calculations carried-out with MCNP5 and MCNP6 [2] Monte Carlo Codes as well as with ADVANTG [3] hybrid code. The results of previous streaming and shutdown dose rate experiments performed in 2012-2014 are reported in ref. [4,5]. Shutdown dose rate measurements will be used to validate recent versions of European tools used in ITER three-dimensional analyses: MCNP-based Rigorous-Two Steps, R2Smesh [6], MCR2S [7], and R2SUNED [8], and a Direct-One Step tool, Advanced D1S [9],.

Measurements and analyses are in progress in the current Deuterium-Deuterium (DD) operations. In this paper the status-of-art and preliminary results of the neutronics experiments in DD campaign in preparation for DTE2 are presented.

2. Streaming experiment

2.1 Experimental assembly

In the *Neutron Streaming Experiment*, neutron fluence and dose measurements during operations are performed in several positions inside and outside the Torus Hall (TH) up to about 40 meters far from the plasma. New streaming paths in JET biological shield are investigated for 2015 DD campaign and DTE2in addition to those studied in 2013-2014 DD campaign [4]. The positions are shown in figure 1. Thermo-luminescent dosimeters (TLDs) were located inside the Torus Hall and along its penetrations in South West (SW) labyrinth, South East (SE) chimney and at basement level. A1-A7 and B1-B8 refer to the positions already used in previous experiments. The six new positions are at the Torus Hall level outside the main entrance door (C4), outside the X-ray spectroscopy bunker (C2 and C3), on the South wall chimney (C6), and at the Basement level outside the Eest-wall (C1) and in the chimney (C5).

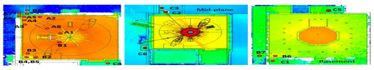

Fig. 1 Overview of positions of 2015 DD neutron streaming experiments. Note that the detectors are at different levels.

The neutron fluence measurements with TLDs detectors, as in the previous experiment [4,10], are now complemented with activation foils measurements in six positions (A1, A2, A4, B2, B3 and B5, with reference to figure 1) close to TLDs' assembly for cross-calibration of the two methods [11].

The TLDs assembly is shown in figure 2. Highly sensitive ^{nat}LiF : Mg,Cu,P (MCP-N) and ^{7}LiF: Mg,Cu,P (MCP-7) TLDs detectors were manufactured and annealed at the IFJ in Poland. The pairs of ^{nat}LiF/^{7}LiF detectors allow the distinguishing between neutron/non-neutron components of a radiation field. All TLDs were located in the centre of polyethylene (PE) moderators (∅ 250 mm, height 255 mm), with MCP-7 and MCP-N arranged within two PE containers, one in horizontal (circular) and the other in vertical orientation (rectangular). This assembly was optimized on the basis of previous experience (2012-2014 DD campaigns [4]). These were calibrated in terms of air kerma and neutron fluence in thermal neutron field. More details on TLDs production, annealing, readout and calibration are in references [4,10].

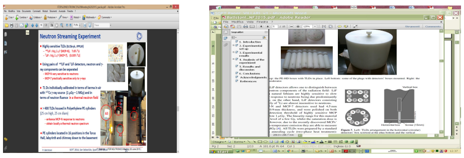

Fig. 2 TLDs assembly in polyethylene moderator and arrangement in circular and rectangular box screwed (N: MCP-N, 7: MCP-7) [10].

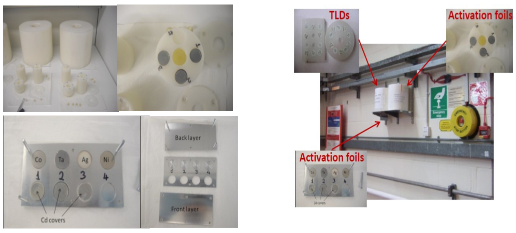

Fig. 3 Activation foils in polyethylene moderator (top-left) and aluminum holder (bottom-left) and assembly of TLDs and Activation foils in position A2 (right) [11].

The activation foils assembly is shown in figure 3 [11]. In each polyethylene moderator Co, Ag and Ta foils bare and Cd-covered (to discriminate between thermal and epithermal neutrons) were positioned. In addition, in order to measure fast neutrons, aluminium holders containing Co, Ag, Ta and Ni foils, bare and Cd-covered, were used. The activation reactions Co ${}^{59}\mathrm{Co}(n,\gamma){}^{60}\mathrm{Co}$, ${}^{58}\mathrm{Ni}(n,p){}^{58}\mathrm{Co}$,

^{109}Ag(n,γ) ^{110m}Ag and ^{181}Ta(n,γ) ^{182}Ta were selected on the basis on accurate transport and activation pre-analysis.

2.1 2015 DD streaming benchmark experiment

All TLDs (apart those from C6 installed on 6th January 2016), and activation foils were installed on 7th November 2015 and retrieved on 11th February 2016 due to unexpected interruption of JET operations. All activation foils and TLDs in positions A1-A4, B2, B3, and B5 were then sent back for readout to NCSR in Greece and IFJ in Poland, respectively. The remaining TLDs were re-installed on the 20th of March (except C4 installed on the 24th of March) and removed on 25th April 2016. The total neutron yield was 3.52 x10^{18} n during the first irradiation and 2.66x10^{18} n in the second period. The irradiated detectors were then sent back to Poland.

The results of measurements in terms of neutron fluence per source neutron at the available positions are shown in figure 4. Results of previous benchmark [4] are reported as well for comparison. With exception of B1 positions, the new TLDs results are perfectly consistent with previous measurements providing confidence in the reliability of the used technique. The measurements with Ta foils are in agreement with TLDs results within the experimental error [11].

At the same time, 3-D calculations were performed by CCFE using MCNP5 with weight windows calculated using ADVANTG code on a 360° JET model describing the tokamak, torus hall wall and penetrations. ADVANTG took approximately 4 hours on 16 processors to generate the weight windows and the MCNP was run for 10000 CPU minutes. The previous MCNP calculation performed for the 2013-2014 benchmark (see calculation C2 in ref. [5]) lasted about a week to generate the weight window and about 3 days to generate the results on 64 cores. Therefore, using ADVANTG code a sensible improvement of the performances with a great reduction of the computational time was achieved. Neutron fluence at the detectors positions was calculated using mesh tally in both cases. The attenuation due to polyethylene moderation was calculated in a separate simulation [4] and correction factors were applied. Results of the new and previous calculations, and the 2015-2016 measurements available today are shown in figure 5.

The comparison between calculations and measurements confirm the trend observed in the previous experiment [4], i.e. underestimation of neutron fluence in the positions close to the machine and a good agreement within the experimental uncertainty at large distances. The underestimation in the position close to the tokamak could be due to the unsuitability of calibration of TLDs in thermal neutron field. Actually, close to the tokamak, the neutron field inside the PE cylinder is not fully thermalized and the detectors are exposed to a significant fast neutrons component. In order to properly take into account the real irradiation conditions at JET, TLDs will be calibrated at 2.5 MeV and 14 MeV neutrons at the Frascati Neutron Generator (FNG) and proper calibration factors will be considered. By comparing the new and previous calculations, it could be also noted that the recent results with MCNP5 and ADVANTG are lower than previously in the positions close to the machine. This discrepancy, still under investigation, might be due to the parameters used in the forward and adjoint calculations performed by the discrete ordinates solver in ADVANTG requiring a more accurate set-up.

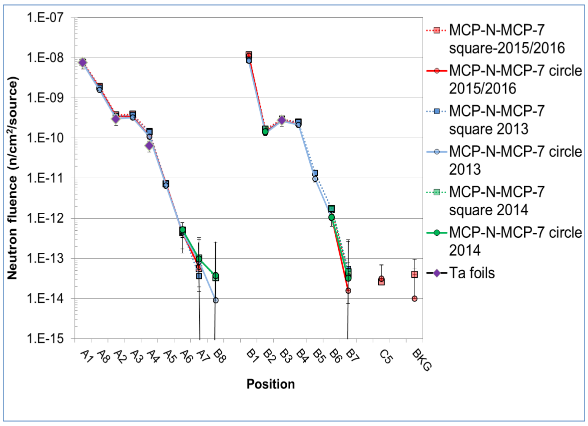

Fig. 4. Neutron fluence measurements with TLDs and Ta foils during 2015-2016 DD experiment, results of previous experiment [4] are also shown.

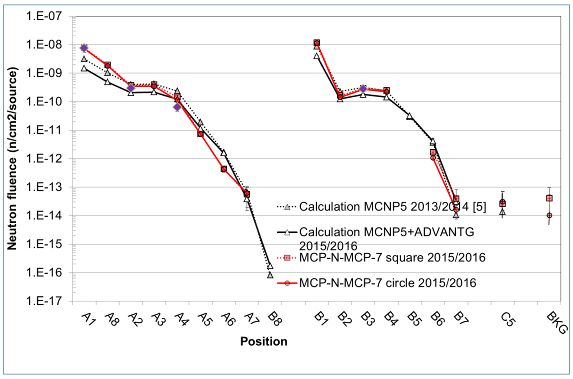

Fig. 5. Calculated and measured neutron fluence. Calculations with MCNP5 using weight windows created by ADVANTG and previous calculation from ref. [4] are both shown.

To optimize the set-up of for JET application, JSI is performing an accurate sensitivity analysis of ADVANTG parameters in collaboration with ORNL, and new analyses will be performed. The analyses of the experiment will be re-assessed after proper dosimeter calibration and computational optimization.

3. Shutdown dose rate experiment

3.1 Experimental assembly and tests

Several activities were also performed for the preparation of the *Shutdown dose rate experiment.* The complete detectors assembly for DTE2 has been designed and described in ref. [5]. Ex-vessel measurements will be performed during next DD shutdown and the installation has been completed. Two spherical air-vented ionization chambers (ICs), procured by ENEA and KIT, have been located at the side port of Octant 1 (as in 2012-2013 experiment [5]) and on the top of ITER-like antenna (ILA) in Octant 2. The detectors have been fixed on low activation shelves and pressure and temperature close to the ICs will be monitored during measurements. Low noise special cables (100 m long) have been installed to connect the ICs to the electrometers located outside the torus hall and the high voltage; the acquisition of the chambers will be remotely controlled. A dedicated software has been developed by ENEA for the real-time acquisition during off-operational periods. Activation foils assembly in aluminum holder as used in streaming experiment (see figure 3) have been located close to the ICs and will be used to perform neutron fluence measurements. The experimental assembly installed in position 1 (Octant 1) and 2 (Octant 2) is shown in figure 6. Decay gamma spectra measurements will be also performed using a portable High-purity Germanium detector at the end of DD operations.

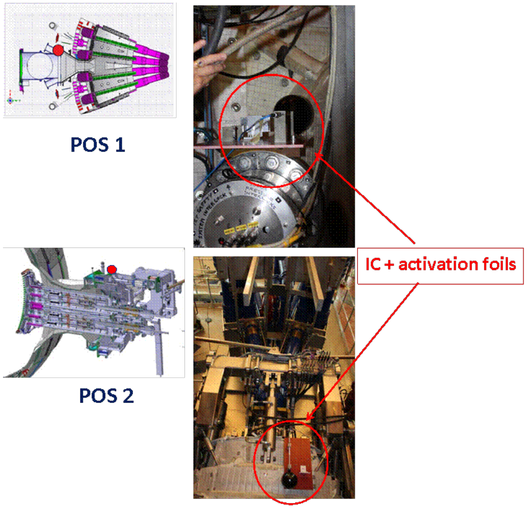

Fig. 6. Installation of the experimental assemblies for DD shutdown dose rate experiment

The ENEA IC was calibrated at ENEA-INMRI (Istituto Nazionale di Metrologia delle Radazioni Ionizzanti) from 30 keV to 1.3 MeV and KIT IC was cross-calibrated with ENEA IC at the gamma calibration laboratory of ENEA-INMRI under ^{137}Cs gamma sources. A very low systematic difference of about 0.5 % in the measurement of the collected charge was observed, with an average charge ratio KIT/ ENEA of 1.005.

Natural background dose measurements were performed in Frascati, Italy, to confirm the stability. Tests were also performed at FNG under 14 MeV neutron irradiation to verify the capability of the system to perform on-line decay gamma dose rate measurements and to check for neutron-induced self-activation of the detectors. The tests were successful and confirmed the high stability of the systems to measure background level and to follow gamma dose decay at the end of irradiation as well as negligible activation of the detectors [5,12]. The SDR measurements will start within the end of 2016.

3.2 SDR calculations: discrepancy and sensitivity studies

As far as the calculation part is concerned, many efforts were devoted to understand the discrepancies among the Advanced D1S (ENEA), MCR2S (CCFE), R2SUNED (UNED) and R2Smesh (KIT) codes observed in previous benchmark [5]. In particular, using the same neutron and gamma meshes in R2S codes, same nuclear data and tally specifications, the recent simulations resulted in a sensible reduction of the differences observed in past benchmark with a general agreement within ±20% for mid-port calculations in Octant 1 at the end of DTE-2 (see figure 7, top). At 1 year from shutdown the MCR2S (CCFE) results are generally higher, while R2SUNED (UNED) gives results generally lower than the other codes. R2SUNED shows the same trend as Advanced D1S. Comparison of decay gamma source results and spectra at various positions and furthermore simulations using the same decay source in common decay format by CCFE and UNED were performed. R2SUNED and MCR2S code provide the same results when the decay gamma source calculated by the other code is used, as shown in figure 7. Hence the observed differences between R2S codes can be due to the different method used to evaluate the neutron flux (cell-under-voxel in R2SUNED and voxel-averaged in MCR2S).

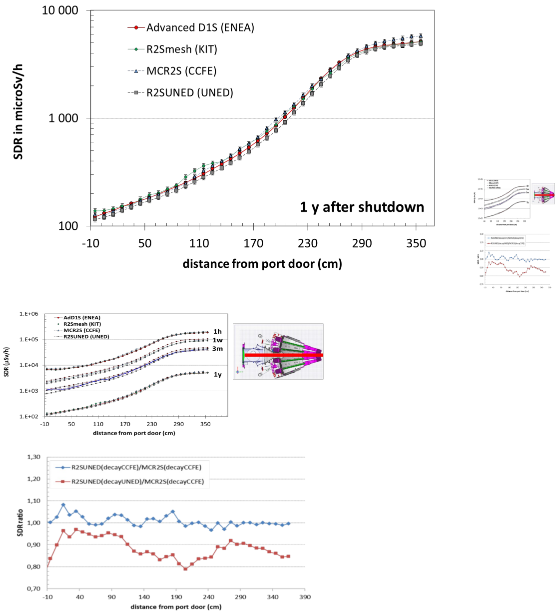

Fig. 7. Shutdown dose rate calculated at 1 year after DTE-2 shutdown along the mid-port of Octant 1 with Advanced D1S, R2Smesh, MCR2S and R2SUNED vs. distance from the port door (top); comparison between R2SUNED and MCR2S

results: R2SUNED calculations using original decay gamma source from UNED and the CCFE one calculated by MCR2S (bottom).

Furthermore, KIT performed a sensitivity study to evaluate the impact of mesh size voxel on SDR assessment with R2Smesh code and to optimize mesh dimensions. The voxel size of the coarse and fine meshes used in R2Smesh approach for neutron spectra and neutron flux calculation respectively, were varied to evaluate the effect on mid-port calculation. Fine mesh voxel was increased from 1x1x1cm to 15x15x15 cm and coarse mesh voxel from 6x6x6 cm to 30x30x30 cm. The results of this sensitivity study show that the size of the fine mesh voxel affects the final results within ±10% and it should be not greater than 3 cm. Conversely, the size of the coarse mesh voxel does not affect significantly the final results and it can be about10 times larger compared to the fine mesh one.

The calculations following DD shutdown including the application of last version of MCR2S code using unstructured mesh capability of MCNP6 will be performed in 2017.

3. Conclusions

Several calculation and experimental activities are in progress to prepare future neutron streaming and SDR benchmark experiments for DTE-2 to validate neutronics codes and tools used in ITER. DD experiments are well progressing and major efforts are devoted to reduce the experimental and computational uncertainties through careful detectors' calibration and optimization of measurements techniques as well as to improve the neutronics codes and modeling accuracy.

Acknowledgments

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