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R. Villari [a,*], P. Batistoni [a], J.P. Catalan [d], B. Colling [b], D. Croft [b], U. Fischer [c], D. Flammini [a], N. Fonnesu [a], L. Jones [b], A. Klix [c], B. Kos [g], M. Kłosowski [e], I. Kodeli [g], S. Loreti [a], F. Moro [a], J. Naish [b], B. Obryk [e], L. Packer [b], P. Pereslavtsev [c], R. Pilotti [a], S. Popovichev [b], P. Sauvan [d], I.E. Stamatelatos [f], T. Vasilopoulou [a,g], JET Contributors [1]

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[a] ENEA, Department of Fusion and Nuclear Safety Technology, I-00044 Frascati (Rome) Italy
[b] Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[c] Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Karlsruhe, Germany
[d] Universidad Nacional de Educación a Distancia (UNED), C/Juan del Rosal 12, Madrid, Spain
[e] Institute of Nuclear Physics Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Krakow, Poland
[f] Institute of Nuclear and Radiological Sciences, Energy, Technology and Safety, National Centre for Scientific Research Demokritos, Athens, Greece
[g] Jozef Stefan Institute, Jamova cesta 39, 1000, Ljubljana, Slovenia

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ABSTRACT

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 (DTE2 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 DTE2.

1. Introduction

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 programme [1], several activities are performed within the EUROfusion Consortium in preparation of Streaming and Shutdown dose Rate experiment for the future Deuterium-Tritium (DTE2) campaign, based on the experience gained in previous experiments performed in 2012–2014 [2,3]. During DTE2 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. Decay gamma-ray dose in-vessel measurements will be performed with TLDs. High-sensitive, low activation, spherical ionization chambers will be used to measure the shutdown dose rate in two ex-vessel positions on the side-port of Octant 1 close to the radial neutron camera and in Octant 2 above the ITER-like antenna (ILA). The results of the neutron fluence measurements will be compared with calculations carried-out with MCNP5 and MCNP6 [4] Monte Carlo Codes as well as with ADVANTG [5] hybrid code. 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].

* Corresponding author.
E-mail address: rosaria.villari@enea.it (R. Villari).

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

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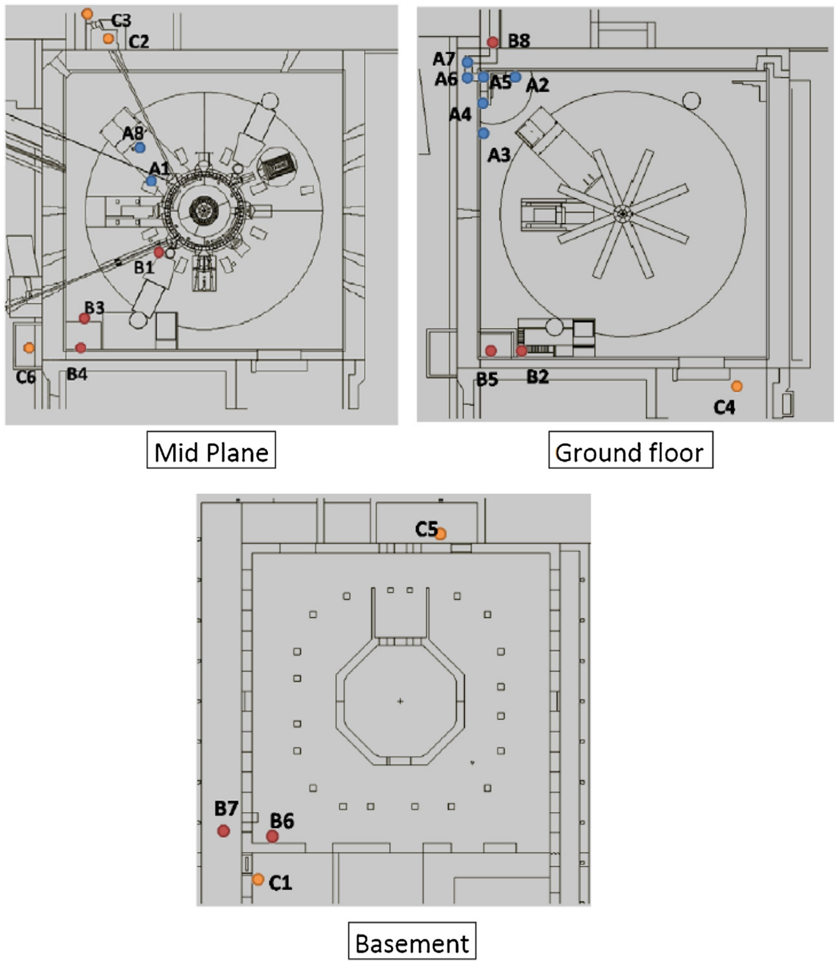

Fig. 1. Overview of positions of the detectors for the 2015 DD neutron streaming experiments. Note that the detectors are at different levels.

In preparation of DTE2 activities, neutron streaming measurements are in progress in the present JET Deuterium–Deuterium (DD) campaign and will be followed by shutdown dose rate measurements. These activities are complemented by the benchmarking of the different neutronic codes with the ongoing (and past) measurements and between the codes themselves.

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 approximately 40 m away from the plasma. New streaming paths in JET biological shield are investigated for 2015 DD campaign and DTE2 in addition to those studied in 2013–2014 DD campaign [2]. The locations are shown in Fig. 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. 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 East-wall (C1) and in the chimney (C5). A1-A7 and B1-B8 refer to the positions already used in previous experiments.

The neutron fluence measurements with TLDs detectors, as in the previous experiment [2,10], are now complemented with activation foils measurements in six positions (A1, A2, A4, B2, B3 and B5) close to the TLDs' assembly for cross-calibration of the two methods [11].

The TLDs assembly is shown in Fig. 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 Institute of Nuclear Physics Polish Academy of Sciences (IFJ) in Poland. The combination of ^{nat}LiF/^{7}LiF detectors allow the distinguishing between neutron/photon components of a radiation field. All TLDs were located in the centre of polyethylene (PE) moderators (ϕ 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). The TLDs types and the current assembly were optimized on the basis of previous experience (2012–2014 DD campaigns [2]). These detectors were calibrated in terms of air kerma and neutron fluence in a thermal neutron field. More details on TLDs production, annealing, readout and calibration are in references [2,10].

The activation foils assembly is shown in Fig. 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, aluminum holders containing Co, Ag, Ta and Ni foils, bare and Cd-covered, were used. The activation reactions Co ^{59}Co(n,γ)^{60}Co, ^{58}Ni(n,p)^{58}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.

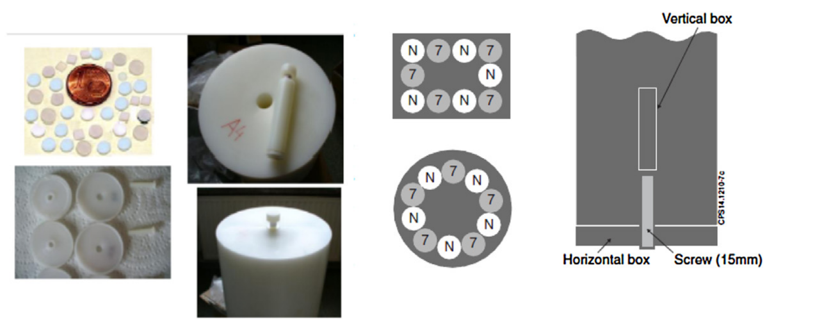

Fig. 2. TLDs assembly in polyethylene moderator and arrangement in circular and rectangular box screwed (N: MCP-N, 7: MCP-7) [10].

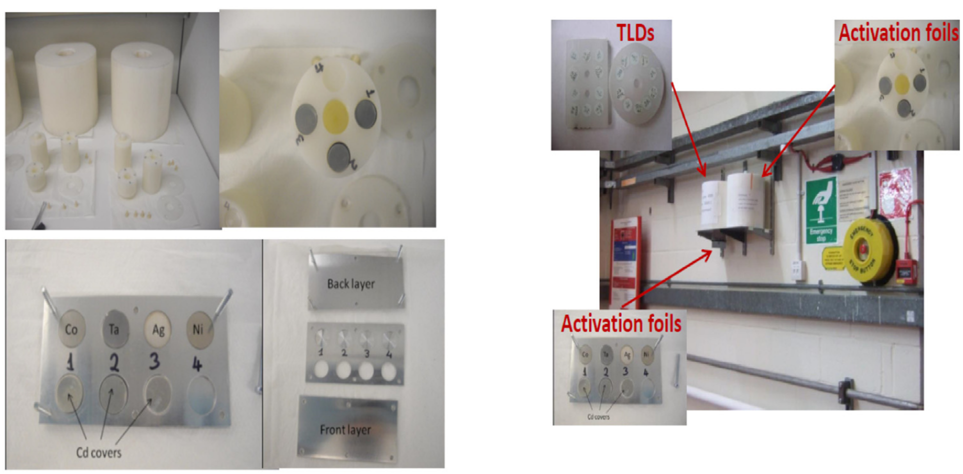

Fig. 3. Activation foils in polyethylene moderator (top-left) and aluminum holder (bottom-left) and assembly of TLDs and Activation foils in position A2 (right) [11].

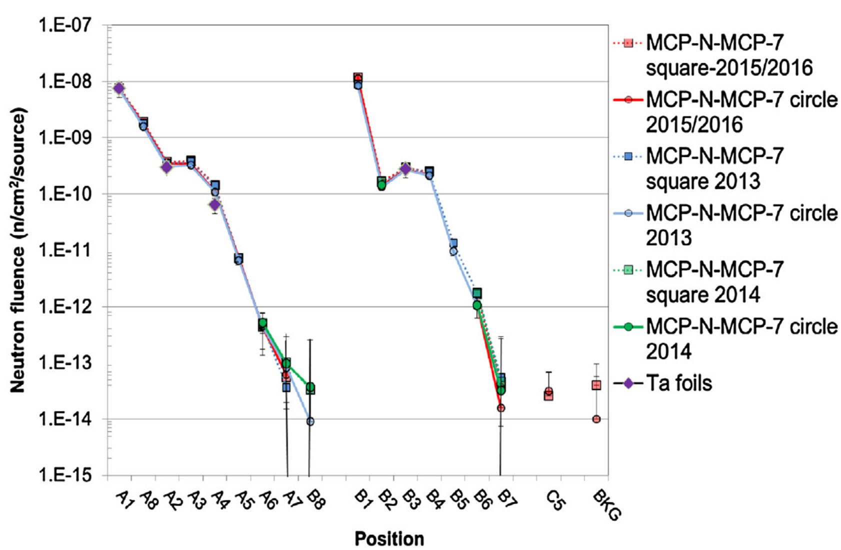

Fig. 4. Neutron fluence measurements with TLDs and Ta foils during 2015–2016 DD experiment, results of previous experiment [2] are also shown.

2.2. 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 National Centre for Scientific Research (NCRS) 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 3.52×10^{18} n during the first irradiation and 2.66×10^{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 Fig. 4. The adopted procedure and assumptions to derive the neutron fluence from the TLDs measured signal are described in [2]. The results are normalised to one source neutron using the neutron yield

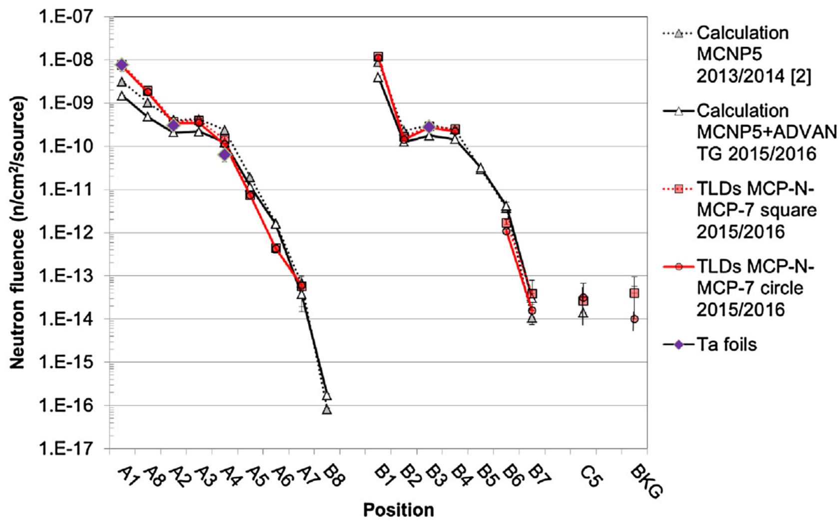

Fig. 5. Calculated and measured neutron fluence with TLDs and Ta foils. Calculations with MCNP5 using weight windows created by ADVANTG and previous calculation from Ref. [2] are both shown.

measured by JET neutron diagnostic systems. Results of previous benchmark [2] are reported as well for comparison. With exception of B1 positions (due to a variation of the surrounding environment), 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 h on 16 processors to generate the weight windows and the MCNP was run for 10,000 CPU min. For comparison, the previous MCNP calculation performed for the 2013–2014 benchmark (see calculation C2 in Ref. [2]) lasted about a week to generate the weight window and about 3 days to generate the results on 64 cores. 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 for previous benchmark [2] and same correction factors were applied to these new measurements.

Results of the new and previous calculations together with the 2015–2016 measurements available today are shown in Fig. 5. The comparison between calculations and measurements confirms the trend observed in the previous experiment [2], i.e. an 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 improper TLDs calibration. The TLDs are presently calibrated in thermal neutron field, hence the calibration factors are suitable at the positions far from the tokamak, because the fast neutrons emitted in the plasma chambers are strongly moderated by surrounding components and in polyethylene cylinder. Actually, this is not true close to the tokamak, because 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 previous and present calculations, it could be also noted that the recent results from MCNP5 combined with ADVANTG are lower than previously observed close to the machine. This discrepancy, still under investigation, might be due to the

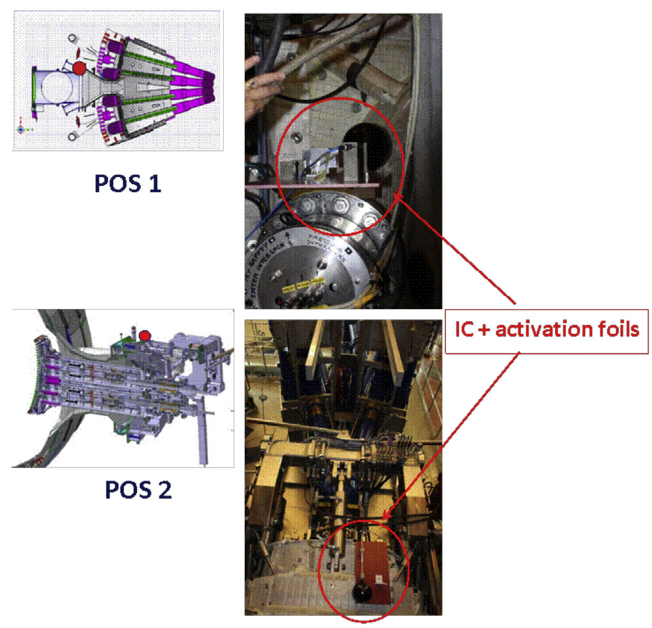

Fig. 6. Installation of the experimental assemblies for DD shutdown dose rate experiment.

parameters used in the forward and adjoint calculations performed by the discrete ordinates solver in ADVANTG requiring a more accurate set-up.

To optimize the set-up of calculation for JET application, JSI is performing an accurate sensitivity analysis of ADVANTG parameters in collaboration with ORNL. The analyses of this 2015 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 selection of detectors and positions, the complete assembly for DTE2 has been defined and optimized as described in [3]. Installation has been completed and

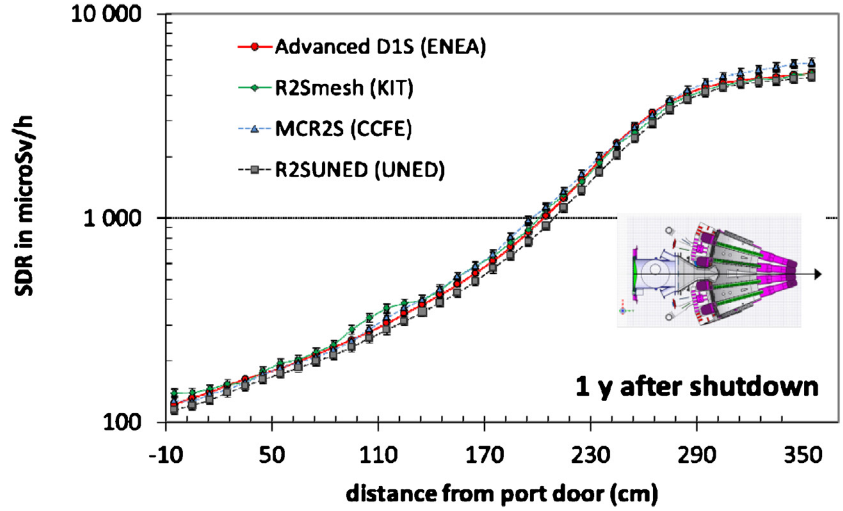

Fig. 7. Shutdown dose rate calculated at 1 year after DTE-2 shutdown along the mid-port of Octant 1 with Advanced D1S, R2Smesh, MCR2S and R2SUNED vs. distance from the port door.

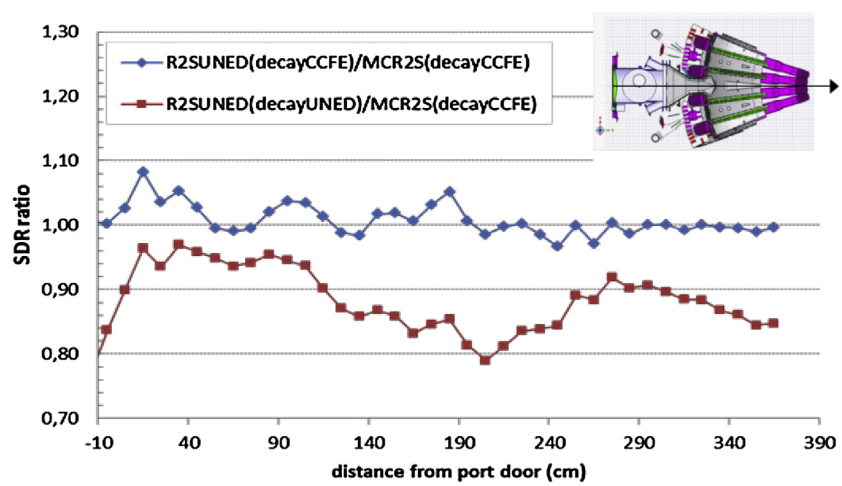

Fig. 8. Comparison between R2SUNED and MCR2S results at 1 year after JET shutdown: R2SUNED calculations using original decay gamma source from UNED and the CCFE one calculated by MCR2S.

ex-vessel measurements will be performed during the shutdown following the end of the present DD campaign.

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 the ILA in Octant 2.

Before the installation at JET, careful calibration and irradiation tests were carried-out in ENEA facilities. The ENEA IC was calibrated at ENEA-INMRI (Istituto Nazionale di Metrologia delle Radiazioni 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. Before the installation at JET, natural background dose measurements were performed in Frascati, Italy, to confirm the temporal stability during long lasting acquisition. 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 [3,12].

The detectors have been fixed at JET on low activation shelves and pressure and temperature close to the ICs will be monitored during measurements. Special low noise cables (100 m long) have been installed to connect the ICs to the electrometers located outside the torus hall and their high voltage power supply; the IC data acquisition will be remotely controlled. A dedicated software has been developed by ENEA for controlling the continuous acquisition during and after plasma shots.

Activation foils assembly in aluminum holder as used in streaming experiment (see Fig. 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 Fig. 6. Gamma-ray spectra from activation decay measurements will be also performed using a portable High-purity Germanium detector at the end of DD operations.

The SDR measurements will start before 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 [3]. 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 Fig. 7). 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 Fig. 8. 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). Different methodology in neutron flux calculations causes also the discrepancy observed for R2Smesh in the zone around 110 cm from the port (Fig. 7).

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 SDR calculation. Fine mesh voxel was increased from $1 \times 1 \times 1$ cm to $15 \times 15 \times 15$ cm and coarse mesh voxel from $6 \times 6 \times 6$ cm to $30 \times 30 \times 30$ cm. The results of this sensitivity study show that the size of the fine mesh voxel affects the final results within ±10% and that it should be not greater than $3 \times 3 \times 3$ 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.

4. Conclusions

Several calculation and experimental activities are in progress to prepare future neutron streaming and SDR benchmark experiments for DTE2 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. Furthermore, besides the code benchmarking, the measurements techniques presented in this work might be also exploited to characterize the radiation field in ITER environment during operations and at the shutdown.

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