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**NEUTRONICS FOR ITER NUCLEAR PHASE: INSIGHTS AND LESSONS
LEARNT FROM JET DT OPERATION**

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Abstract

The EUROfusion technological exploitation of the JET Deuterium–Tritium (DT) campaigns produced an outstanding experience and amount of nuclear fusion relevant data for guiding ITER and future fusion reactors advancements. Key achievements include the absolute calibration of neutron diagnostics with $\pm 10\%$ accuracy, detailed characterization of

activation in ITER materials, and experimental validation of radiation transport, activation and shutdown dose rate codes. Dedicated studies explored optical fiber degradation under neutron irradiation, tritium breeding predictions and neutron-induced Single Event Effects (SEEs) on electronics, the latter systematically studied for the first time in a tokamak in DT and validating predictive models. The water activation experiments in JET cooling loops produced unique datasets for multiphysics validation and for improving the understanding of complex neutron-induced phenomena. These achievements demonstrate the reliability of codes used for ITER nuclear analysis, improve the knowledge of irradiation effects, and identify codes' artefacts and critical issues affecting prediction accuracy, including materials' chemical compositions and the role of impurities, and the fidelity of neutronics modelling. A large experimental database and irradiated samples have been generated for continued validation and future studies. Together, these outcomes significantly support the preparation of ITER nuclear operation, licensing and safety demonstrations, advance nuclear fusion science and technology, and contribute to mitigating risks linked to the design, operation, and decommissioning of future fusion power plants.

1. INTRODUCTION

The preparation of the ITER nuclear phase presents several challenges that must be timely addressed to successfully accelerate the achievements of the ITER missions. Given the key role of ITER in the European fusion roadmap, a strong and comprehensive R&D program has been established within EUROfusion in support to ITER. In particular, within the Work-Package Preparation of ITER Operations (WP PriO) [1], several activities have been conducted in the frame of the sub-project “Neutronics, Nuclear Waste, and Safety” aimed at improving the knowledge of neutronics, nuclear technology and safety issues, developing and validating nuclear codes, neutronic tools and experimental techniques to reduce the risks to ITER nuclear operations and maintenance activities. The current rebaselining of ITER project [2], with accelerated transition from first plasma to nuclear operation, the change of plasma-facing first wall material from beryllium to tungsten and the stepwise licensing approach, requires new efforts and open novel scientific challenges.

An outstanding and unique amount of nuclear fusion relevant data and experience have been collected from the latest Deuterium-Tritium (DT) campaigns at JET tokamak (DTE2 and DTE3 campaigns performed in 2023), producing 1.57×10^{21} DT neutrons [3-5]. Dedicated measurements and analyses were carried out to characterise the activation of real ITER materials [6] and the degradation of functional materials, to verify the 14 MeV neutron diagnostics calibration, to test detectors for Tritium Blanket Module (TBM) and to assess the Tritium Breeding Ratio (TBR) predictions in Helium Cooled Pebble Bed (HCPB) TBM mock-up [7]. Benchmark experiments on neutron streaming and shutdown dose rate were performed to validate the computational tools and nuclear data used for ITER nuclear analysis and to assess the performance of advanced neutron shields [5, 8]. Unique experiments explored complex phenomena like water activation in JET cooling loops [5] and Single Event Effects (SEE) [10] on electronics during DT plasma operations. For this exploitation, several active and passive detection systems, test assemblies, and samples were located at about 30 locations inside the JET vessel, in the torus hall, and in the basement during the DT campaigns. Main achievements, recent results and lessons learnt for ITER from technological exploitation of JET DT operations are reviewed in this contribution.

2. MAIN ACHIEVEMENTS FROM JET DT EXPERIENCE

2.1. Achievement of 10% accuracy in neutron diagnostics calibration

Demonstrating the accuracy and reliability of fusion power measurements are essential for obtaining approval for tritium operations on ITER and fusion power plant. In 2017, an absolute calibration of JET main neutron diagnostics, fission chambers (for time-resolved neutron yield rate, KN1) and activation foils system (for integral neutron yield, KN2), was successfully performed using a 14 MeV neutron generator deployed inside the vacuum vessel with power supply, detectors and electronics, via the remote handling system. The calibration was successfully validated during plasma operations in DTE2 and DTE3, achieving the $\pm 10\%$ target accuracy required for neutron yield and yield rate measurements in ITER DT operations. This was accomplished through rigorous methodology, advanced modeling, and cross-calibration, providing valuable insights for future neutron diagnostics calibration in ITER. For ITER, the much larger size, higher complexity, and the need to cover a broader neutron emission range (10^{14} – 7.5×10^{20} n/s) imply that the JET procedure cannot be straightforwardly applied. Achieving the necessary accuracy within limited operational time will be challenging, making the selection of calibration positions and scan strategies critical. The fidelity of neutronics models, the reliability of transport codes, and precise detector response functions will be even more important than at JET, since calibration factors will rely heavily on radiation transport simulations. ITER would also require a more powerful neutron generator (10^9 – 10^{10} n/s), with active cooling, advanced remote handling, and an assembly which must be carefully characterized.

To ensure reliability in using neutron generator, the full setup (including neutron generator, detectors, and connections) should be tested on-site in working conditions, and a dedicated bunker for safe deployment and detector calibration would be needed. Robust methods, system redundancies, continuous model verification, and cross-calibration will be necessary to mitigate risks. Although calibration with Cf-252 sources and MCNP-based energy corrections can reduce uncertainties, limited source strength and difficulties in handling the source are serious concerns and the reliability of the approach depends strongly on the quality of the neutronics models.

2.2. Neutron transport and materials activation: characterisation and experimental validation of nuclear codes for design and safety demonstration.

The JET experience has significantly contributed to the development and improvement of neutron and gamma measurement techniques, as well as to the advancement of neutronics codes used for design and safety analyses in fusion reactors. Substantial efforts have been dedicated to the experimental validation of the codes used for ITER and DEMO nuclear analysis, including MCNP5/6 with ADVANTG, TRIPOLI-4©, and, more recently, OpenMC for radiation transport; FISPACT-II for activation, and several MCNP-based approaches – such as Direct 1-step (D1S) and Rigorous 2-step (R2S) – for shutdown dose rate (SDDR) calculations. These validations were achieved through the comparison between calculations and measurements, revealing generally conservative predictions for maintenance conditions and discrepancies primarily related to uncertainties in geometry, material chemical compositions, and code-specific artefacts [5, 6].

2.2.1 Characterisation of the activation of ITER materials

Samples of real ITER materials used in manufacturing the main in-vessel tokamak components were irradiated under 14 MeV neutrons during DTE2 and DTE3 campaigns at JET. The materials considered include SS316L steels from different suppliers, SS304B, Alloy 660, tungsten (W), CuCrZr, XM-19, Al-bronze, Inconel, and EUROFER. The study aims to improve confidence in post-irradiation nuclide predictions and residual radiation fields, which are highly relevant to ITER operations, maintenance, and decommissioning activities. The irradiated samples were analysed across five laboratories using gamma-ray spectrometry, and the results were compiled into a database for comparison with computational predictions. Fig.1 shows the comparison between calculations performed with MCNP6 and FISPACT II and measured activity in ITER materials irradiated during DTE2 in the Long-Term Irradiation Station (LTIS) [6].

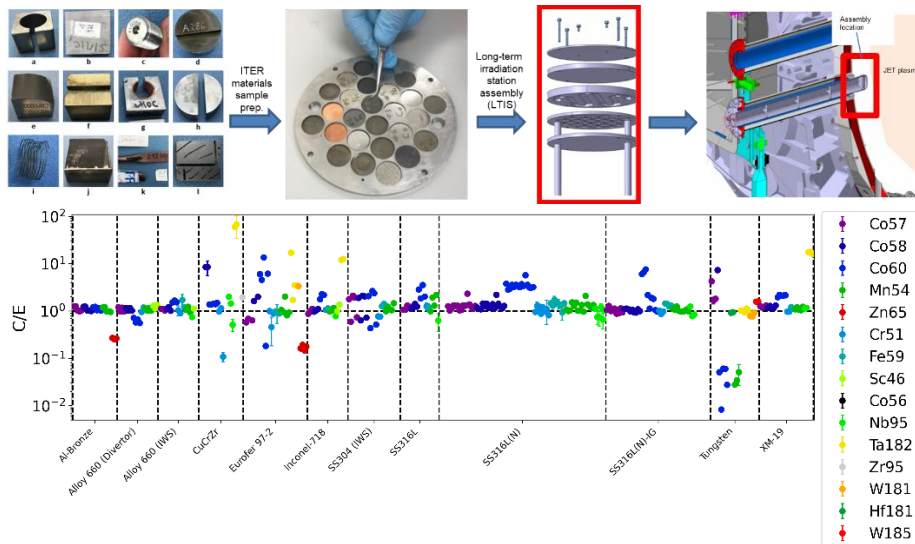


Fig. 1 (a) ITER materials samples preparation and installation in LTIS position. (b) Calculated-to-experimental activity ratios for various isotopes in ITER materials irradiated during the DTE2 campaign [6].

Overall, a good agreement was found between simulations and measurements, although significant overestimations were observed, especially for radionuclides important for maintenance planning. The most pronounced discrepancies were seen in CuCrZr and W monoblock samples. Most isotopes, including ⁴⁶Sc,

^{51}Cr , ^{54}Mn , ^{57}Co , ^{59}Fe , ^{95}Nb , and ^{181}Hf , showed calculated-to-experimental (C/E) ratios close to 1 within 25%. However, significantly elevated C/E values were reported for ^{58}Co , ^{60}Co , and ^{182}Ta in several materials, indicating conservative predictions for key SDDR-relevant isotopes. Conversely, underestimations for ^{60}Co were observed for certain materials, such as EUROFER. Agreement within 25% was achieved for Al-bronze and SS316L(N)-IG. Unexpected findings included the presence of $^{110\text{m}}\text{Ag}$ in CuCrZr and Al-bronze samples, as well as the occurrence of ^{182}Ta in selected steel alloys. In the case of ^{65}Zn , its presence was tracked back to contamination caused by brass deposition from electrical discharge machining (EDM). Consequently, polished samples were used in the DTE3 campaign to mitigate this source of error. Further investigations into discrepancies in elemental and impurity compositions were conducted using a combination of nuclear and analytical techniques. Recent analyses performed on CuCrZr and W samples using both non-destructive methods (ED- and WD-XRF at AGH University of Krakow) and destructive techniques (ICP-MS at NPL) revealed impurity levels that deviated from those reported in the material certificates. These findings partially account for the activation anomalies observed. A subset of samples was also examined at the EC JRC Radionuclide Metrology Laboratory (Geel) using advanced gamma-ray spectrometry. Overall, comparisons between EUROfusion and JRC datasets showed a satisfactory level of consistency, although certain discrepancies remained - especially for ^{60}Co - highlighting the need for further validation using larger datasets and additional inter-laboratory comparisons in future experiments.

Preliminary results from the ongoing analysis of DTE3 samples broadly confirm trends observed in DTE2. In particular, CuCrZr irradiated in DTE3 did not exhibit the presence of Ta-182, which was the dominant contributor to the high C/E ratio (~60) observed in DTE2. Additional radionuclides such as Y-91, Ta-182, and W-185 were identified in several samples, and the measurements with a Compton Suppression System (CSS) revealed further nuclides requiring investigation.

As for short-lived nuclides, W-187 was measured after irradiation of the W monoblock sample in the KN2 6U irradiation-end during a selected DTE3 pulse. The C/E ratio of 2.1 for this case indicates a moderate overestimation of the activity by the FISPACT calculations.

2.2.2 Neutron fluence and shutdown dose rate assessment

In high-performance tokamaks, radiation fields during and after operations are extremely complex. The calculation of the neutron flux and nuclear quantities in ITER and future reactors is challenging in particular in regions far from the plasma because of complicated geometries, narrow shield penetrations, and the use of several materials. Neutron irradiation activates components, producing a gamma field with strong spatial and temporal variations, even at the end of operation. Accurate prediction of the SDDR is therefore essential for safe maintenance, but limited experimental data are available for validation in ITER-relevant conditions. To overcome this, ITER-oriented benchmark experiments at JET have been carried out in the last decades to validate neutron streaming and SDDR predictions. During the JET DTE2 and DTE3 campaigns, neutron fluence was measured with thermoluminescent dosimeters (TLDs) and activation foils placed in more than 20 positions inside and outside the Torus Hall up to 40 m from the plasma. In parallel, spherical ionization chambers monitored real-time SDDR at ex-vessel locations near the radial neutron camera in octant 1 and on the top of ITER-like antenna in octant 2 since 2016. The experimental data were compared with radiation transport simulations performed using MCNP5/6 with ADVANTG, TRIPOLI-4©, and with advanced Monte Carlo-based SDDR tools developed in Europe, the UK, and the US, including D1SUNES, Advanced D1S, R2Smesh, MCR2S, R2S-UNED, ORCS, and the N1S hybrid tool.

The TLDs measurements and calculations of the neutron fluence during the DTE2 neutron streaming experiment are shown in Fig. 2. Except for the most shielded position B8 (at the exit of SW labyrinth), the differences in MCNP results from the various parties are within $\pm 14\%$ and the TRIPOLI-4© results are consistent with MCNP within $\pm 20\%$. The comparison of the neutron fluence results of the simulations in TLDs positions from ORNL, UKAEA and JSI and TLDs experimental data from IFJ shows the ratio of the C/E that varies in the range ~ 0.9 in A1 (on the platform of KT1 spectrometer) to ~ 5 in B5 (on the chimney floor, between ducts). An increase of the overestimation of the calculations with the distance from the machine is observed, showing a similar trend to previous DD and TT campaigns. The experimental configuration of TLDs assembly and models were upgraded for DTE3 and the analysis of last experiment is still ongoing.

Fig. 3 shows the temporal evolution of the shutdown dose rate in Octant 1, close to the mid-horizontal port, during the off-operational period following the last DTE3 shot on 14th October 2023 up to the start of the clean-up campaign (about one week later), and during the shutdown phase at the end of JET lifetime, from 18th December 2023 to the 31st December 2024. The temporal range and dose rate levels are directly relevant for ITER SDDR assessments and support the validation of nuclear codes required for safety

demonstrations. The recent results of calculations with MCNP-based Advanced D1S, D1SUNED, and R2SUNED tools are compared with Ionization Chamber measurements. In general, all codes reproduce the same trend and are within $\pm 20\%$, but systematically overestimate the measured SDDR by about $+20\%$ to $+50\%$. The largest overestimation is observed with R2SUNED, which is partially mitigated when a point-wise rather than a multi-group energy discretisation approach is used. The activation data library (EAF-2007 or TENDL-2017) has a minor effect. The systematic overestimation is attributed to ^{58}Co in Inconel components, which dominate the SDDR at these medium cooling times. At the end of JET life, the discrepancy decreases progressively over time, reaching about 15% (Advanced D1S) after one year from shutdown, when the ^{60}Co contribution becomes dominant. Earlier DD and DTE2 results [5] showed a similar trend over the same cooling ranges, though with excellent agreement at short cooling times dominated by ^{56}Mn . Conversely, in Octant 2 (not shown), a more complex behavior was observed, with larger deviations among the codes, mainly due to R2S artefacts and up to -40% underestimation from D1S-based codes, largely caused by geometrical modeling inaccuracies. Overall, the reliability of the codes to predict SDDR remains within a factor of two. The analysis of DTE3 experiment with other computational tools is still ongoing, as well as the online shutdown dose rate measurements during decommissioning.

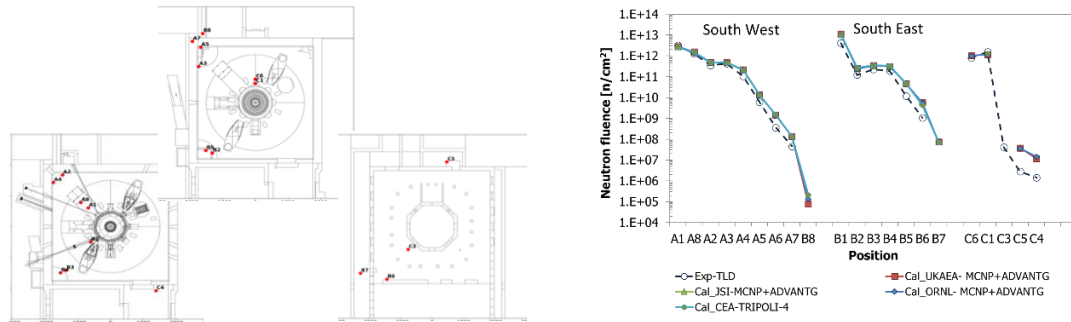


Fig. 2 Neutron fluence measured with TLDs during DTE2 experiment and calculated with MCNP and TRIPOLI-4© (right) at the at positions of TLDs for DT experiments at the JET mid-plane, ground floor and in the basement (left)

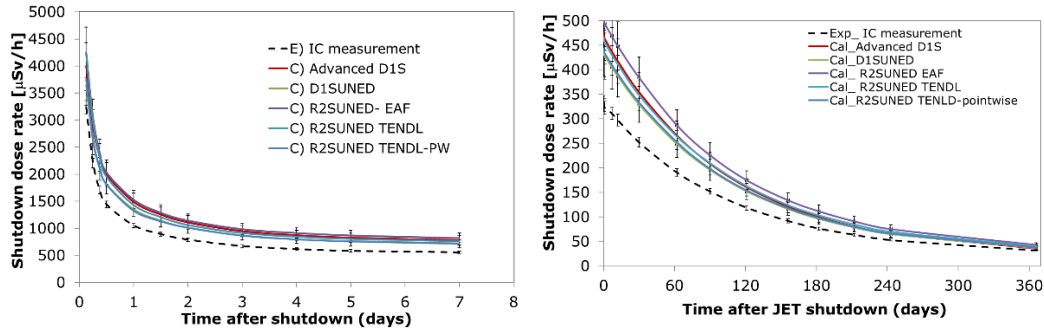


Fig. 3. Shutdown dose rate calculated with AdvancedD1S, D1SUNED and R2SUNED and experimental data in JET Octant 1 at the end of DTE3 operations versus cooling time from the last DTE3 pulse (left) and at the end of end of JET life versus cooling time from the last JET pulse (right).

As for lesson learnt for ITER, over the last years, key factors influencing the accuracy of the simulations have been identified, including the detailed geometric description in neutronics models following machine configuration changes, the correct specifications of chemical impurities in the materials, the reliability of neutron source representation, the representativeness of irradiation scenario and the quality of the nuclear data. All these elements are essential for reliable predictions and contribute to the reduction of the uncertainties.

2.3. Study of degradation of optical transmission in silica optical fiber following DT irradiation

During the TT and DTE2 campaigns, in-situ monitoring was carried out to study the behavior of optical fibers under DT pulses and subsequent recovery phases. Hermetically sealed, metal-coated fused silica fibers were irradiated with neutrons and gammas in the LTIS position. Optical transmission of silica optical fibers degrades under DT irradiation, showing a clear decrease across 200–1200 nm with increasing neutron fluence (up to $\sim 5 \times 10^{15} \text{ cm}^2$) due to radiation-induced defects. Absorption peaks correspond to

defects like oxygen-deficient centers (ODC), self-trapped holes (STH), and non-bridging oxygen hole centers (NBOHC). The study improves the understanding on neutron-induced defects with direct applications to ITER, where silica and optical fibers play a key role in diagnostic systems.

2.4. TBM detectors tests and validation of TBR predictions

Accurate measurement of tritium production in breeding blankets is essential for demonstrating self-sufficiency and controlling tritium inventories in future fusion reactors. ITER Test Blanket Modules (TBMs) will provide the first experimental validation of predictions, but the harsh operational environment poses significant challenges for nuclear instrumentation. JET DT operations offer a unique opportunity to test active and passive detector systems under realistic conditions.

Single Crystal Diamond (SCD) detectors were tested during the DTE2 and DTE3 campaigns. Two of them, one coated with a ^6LiF layer, were installed in the periscope port of octant 3 but suffered malfunctions. Their future retrieval will enable detailed inspections and tests to determine whether the failures were caused by electrical connection issues or by the harsh environmental conditions. A third SCD was installed in a Helium Cooled Pebble Bed (HCPB) TBM mock-up in Octant 8 to benchmark tritium production rate (TPR) calculations. MCNP neutron transport simulations showed an underestimation of the TPR measured in mock-up during DTE2, with a calculation-over-experiment ratio of 0.77, indicating that design calculations of the tritium breeding ratio provide conservative results for the self-sufficiency of fusion reactor employing a HCPB type breeder blanket. At neutron emission rates above 10^{15} n/s, pile-up effects dominated, requiring an upgrade of the measuring chain with a faster amplifier. During DTE3, the system functioned correctly up to 3×10^{17} n/s (neutron flux 3×10^{10} n/cm²/s), but USB data transfer limits caused signal failures at high performance. The amplifier replacement requires in the future a new calibration to determine the tritium production rate.

Experience at JET highlighted key modifications needed for ITER: adapting detectors to much higher neutron fluxes by reducing ^6LiF layer thickness or enrichment, upgrading preamplifiers and data transfer systems, and ensuring thermal and mechanical resistance of cables and connections.

Parallel studies for a Neutron Activation System (NAS) for neutron flux spectrum measurements were performed. Sets of activation foils were irradiated in KN2 irradiation ends, returned via pneumatic transfer, and analysed with HPGe detectors. Several nuclides were identified, though short-lived products proved difficult to capture and initial spectrum unfolding attempts were unsuccessful. The study emphasized the importance of further research on NAS to achieve accurate neutron spectra reconstruction.

2.5. Water activation and understanding complex neutron-induced phenomena.

14 MeV neutrons from plasma operations neutron induce the activation of the water coolants leading to the production of short-lived radionuclides, mainly ^{16}N and ^{17}N . Their radioactive decay produces high-energy gamma rays and delayed neutrons, which can generate significant nuclear loads on sensitive tokamak and plant components. Understanding and accurately predicting these effects is essential for the safety and reliability of ITER, DEMO, and future reactors. Recent advances in multi-physics modelling allow detailed simulations of water activation and induced radiation fields. However, experimental benchmarking remains critical for validating these codes and improving both design strategies and safety assessments. JET has provided the first opportunity to study water activation under in a real tokamak cooling loop in DT. In 2023, two scintillator-based gamma spectrometers, a sodium iodide (NaI(Tl)) and a bismuth germanate (BGO) crystal, were installed in the JET Octant 4 basement as part of the Water Activation (WACT) system was to monitor the gamma emissions from activated water in the Neutral Beam Injector (NBI) duct scraper cooling loop. The detectors were equipped with shielding and collimators, calibrated in situ with gamma sources, and operated using PHOENIX for real-time acquisition and CODAS integration [5]. The installation faced major challenges, including flooding, procurement delays, and deviations from the optimized design that initially envisaged more extensive shielding and additional ionization chamber. Nevertheless, the system was successfully commissioned and the BGO spectrometer provided the first clear observation of high-energy gamma peaks from ^{16}N decay at 6–7 MeV during tokamak DT operations. Signals from more than 1500 shots during the DD, DTE3, and clean-up campaigns, covering neutron yields across five orders of magnitude and pulse durations of up to 60 seconds, were acquired with this system. Compared with DD plasmas (in which water activation is due to 14 MeV neutrons from triton burn-up), DT conditions produced delayed gamma signals over four orders of magnitude stronger, with longer durations and an additional peak attributed to slower water flow in a secondary loop feeding the same pipe. High-performance pulses generated count rates exceeding 10^5 cps, causing pile-up, temporary blackouts, and signals beyond the USB data transfer rate. The NaI spectrometer

was more strongly affected by pile-up, requiring manual acquisition and the use of pile-up rejection algorithms.

Fig. 4 shows the temporal evolution of gamma measurements with the BGO spectrometer together with the neutron yield rate measured from KN1 diagnostic system for both short and long pulses, highlighting the correlation between plasma operations and delayed gamma signals from activated water.

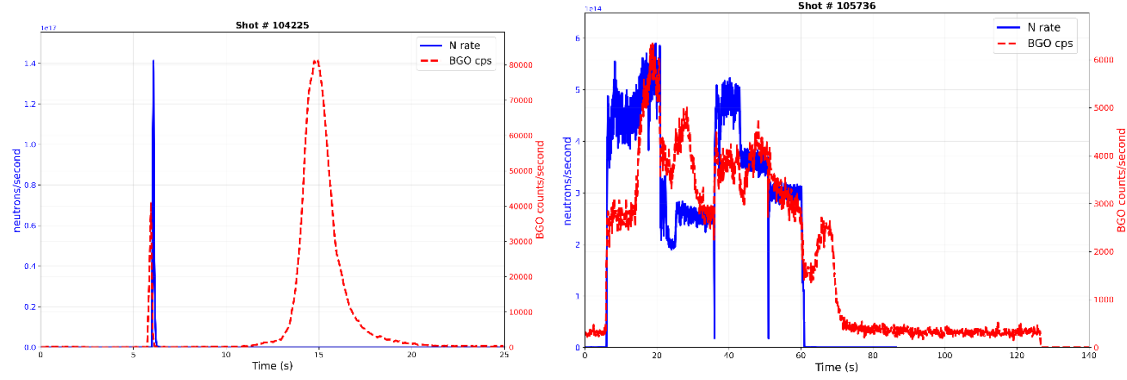


FIG. 3. Total neutron yield rate from KN1 neutron diagnostic (n/s) and gamma count rates (counts/second) in BGO spectrometer of the water activation system versus time (s) from the start of a short pulse #104225 (left) and long pulse # 105736 (right)

Long-pulse DD experiments of up to 60 s provided additional insight into ITER- and DEMO-relevant conditions, showing BGO signals that combined prompt gamma during operation with extended delayed gamma contributions from activated water. These long-duration measurements highlight the importance of accounting for transit times and activation dynamics in reactor cooling circuits, as the loads from water activation will play a significant role during plasma operation.

The resulting dataset represents the first comprehensive measurement of water activation in a tokamak under DT neutron conditions. It provides essential benchmarks for multiphysics simulation tools.

First comparisons with simulations performed with FLUNED showed good agreement at low DT neutron yields, while high-flux conditions revealed the need for advanced analysis methods and, for future system implementation, including improved shielding assembly, the use of faster spectrometers and acquisition system, as well as optical fibers for connections to enhance real-time acquisition.

The unique experiment dataset not only serves for validating advanced computational models but also offers new insights into the correlation between plasma operations, cooling circuit parameters, and the resulting gamma fields fundamental for predicting and mitigating water activation effects in ITER and future machines. Furthermore, significant knowledge has been acquired for the development of complementary neutron diagnostics based on water activation.

2.6. Validation of models and methods for predicting neutron-induced Single Event Effects (SEE) on electronics in tokamaks

Single event effects (SEEs) occur when individual neutrons randomly cause instantaneous malfunctions or failures in electronics. These effects can damage components, corrupt data, and impair the operation of circuits, processors, sensors, and FPGAs. Preliminary studies of neutron-induced SEEs conducted in 2021 in the WEST tokamak [10] provided first validation of methods and models for predicting bit flip rates induced in SRAMs by a tokamak DD plasma neutron environment. The new SEE experiment carried out in 2023 at JET during DTE3 campaign [9] (fig. 4) allowed a final validation of these methods and models, this time in a tokamak in DT.

The experimental setup was installed in the basement (position B6, in figure 2) to investigate neutron-induced single event upsets (SEUs) in SRAM under DT neutron fluxes of about 3×10^5 n/cm²/s, similar to levels expected in ITER port cells. Two test benches were employed: the Real Time Soft Error Rate (RTSER) bench from the University of Marseille, with 384 bulk 65 nm CMOS SRAM circuits (3.2 Gbit total), and the CERN test bench with two 40 nm SRAM circuits from ISSI, one shielded by a 5 mm B₄C layer and the other unshielded. A DIAMON spectrometer provided real-time neutron spectra, complemented by passive activation foils and passive neutron spectrometry (PNS). Results showed single-bit or multi-cell upsets in RTSER, but only single-bit upsets in CERN. Bit-flip rates were 493 bit-

flips/hour/Gbit for RTSER and 2342 bit-flips/hour/Gbit for CERN, corresponding to high reliability degradation factors compared to environmental conditions. B₄C shielding reduced SEUs by more than a factor of 4 but did not restore acceptable reliability, demonstrating the need for improved shielding. As main achievement, the obtained experimental results agreed well with SEU model predictions, with C/E ratios of 0.86 (RTSER) and 1.12 (CERN), confirming the validity of the model and the approach for SEE predictions.



FIG. 4. SEE experiment: test-benches (left and right) and DIAMON neutron spectrometer (center) in JET basement during DTE-3 campaign [10].

3. CONCLUSIONS

The JET DT campaigns have produced unique scientific achievements of direct relevance to ITER and future fusion reactors. They enabled the first successful 14 MeV calibration of neutron diagnostics, advanced understanding of irradiation effects on materials, activation, neutron streaming, shutdown dose rates, tritium production, and single-event effects on electronics, while also refining detectors and nuclear measurement techniques. Extensive benchmarking improved nuclear computational tools, validated Monte Carlo-based codes, and highlighted key reliability issues such as neutronics model fidelity, materials impurities, contamination, and code artefacts. The campaigns produced a large experimental database and irradiated samples for continued study. These outcomes are particularly valuable in the context of the ITER revised plan with two DT phases, providing proven methodologies to reduce risks and uncertainties and supporting nuclear licensing. With JET decommissioning underway, continued international collaboration will ensure that further lessons are acquired, advancing for the design, operation, and decommissioning of ITER and future power plants.

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