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

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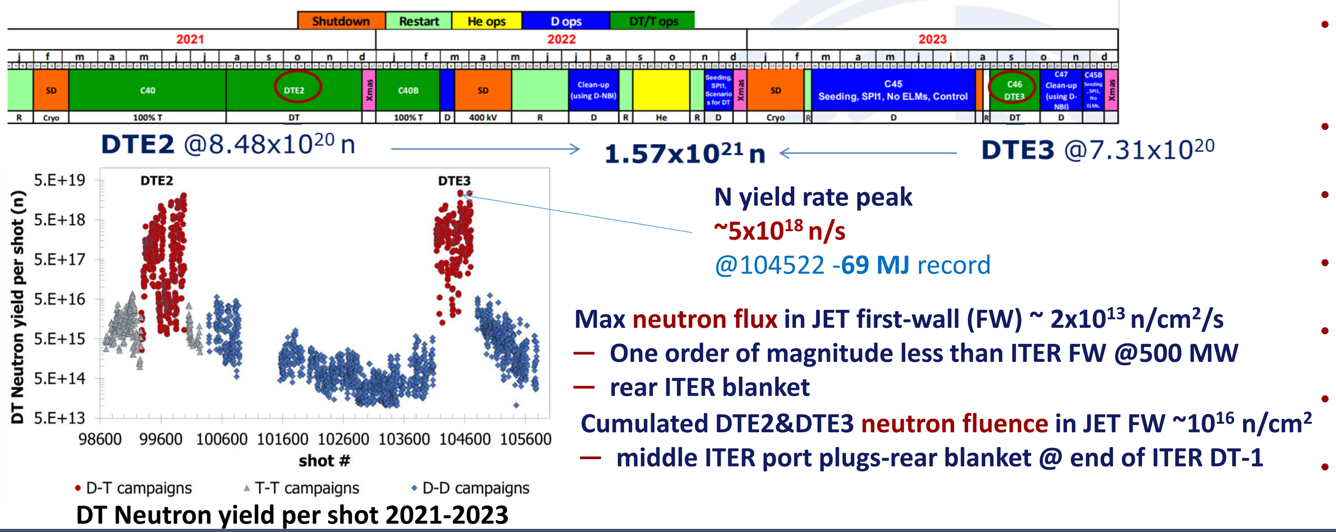
ABSTRACT

The EUROfusion technological exploitation of JET Deuterium–Tritium (DT) campaigns provided unique data and knowledge for advancing ITER and future fusion reactors. Achievements include ±10% neutron diagnostic calibration, ITER material activation studies, validation of radiation transport, activation and shutdown dose rate codes. Research addressed optical fiber degradation and tritium breeding. Water activation phenomena and neutron-induced Single Event Effects on electronics were systematically studied in a tokamak DT environment for the first time. These results validated ITER nuclear analysis codes, improved understanding of irradiation effects and highlighted modeling issues. These outcomes significantly support the preparation of ITER nuclear operation, licensing and safety demonstrations, advance nuclear fusion science and technology and contributes to mitigating risks linked to the design, operation, and decommissioning of future fusion power plants.

INTRODUCTION

- **DT campaigns at JET achieved major progress in fusion energy.**
- **Experiments advanced nuclear technology, safety, and code validation.**
- **JET DT experience provides:**
  - —Unique inputs for ITER nuclear phase and safety demonstrations
  - —Key support for a faster transition from first plasma to nuclear operation under the new ITER re-baselining

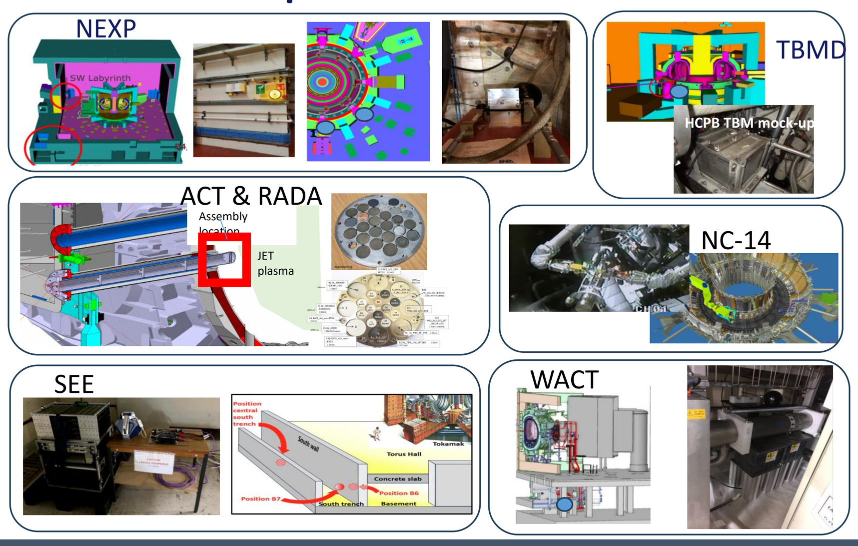
JET DT operations relevant for ITER nuclear phase



DT Neutron yield per shot 2021-2023

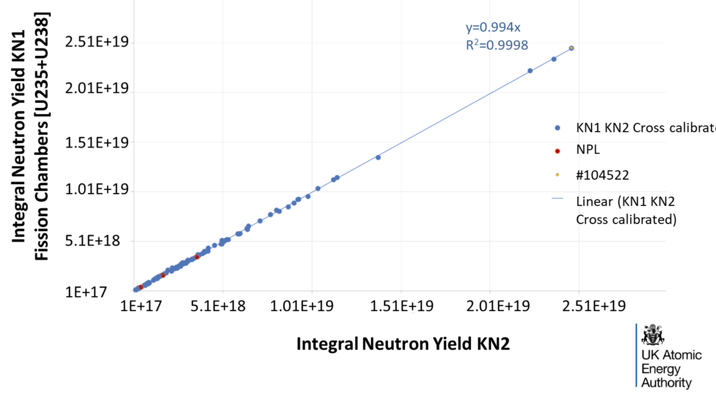
Unique technology-oriented experiments at JET in DT

- **NC-14** Development and validation of methods for **14 MeV neutron diagnostics calibration**
- **ACT Activation** measurements and analysis of ITER materials
- **RADA Damage** study of functional materials
- **NEXP Neutron streaming** and **Shutdown Dose rate** benchmark experiments
- **TBMD** Test of detectors for TBM- validate **Tritium Breeding** predictions
- **WACT** Investigation of **Water Activation** in JET cooling loop
- **SEE** Study of **Single Event Effects** (SEE) induced by neutrons on electronics



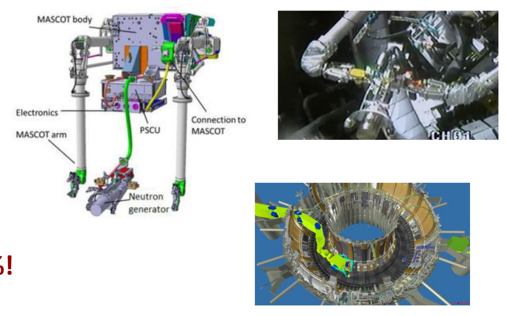
MAIN ACHIEVEMENTS FROM JET DT TECHNOLOGICAL EXPLOITATION

Achievement of 10% accuracy in neutron diagnostics calibration



Correlation of integral neutron yield measurements with KN1 (fission chambers) and KN2 (activation foils)

- ✓ JET Neutron calibration @14 MeV with Neutron Generator (2017) → Total uncertainty **±6%**
- ✓ JET Neutron DT Plasma calibration (2021-2023) → Total uncertainty **±10%!**

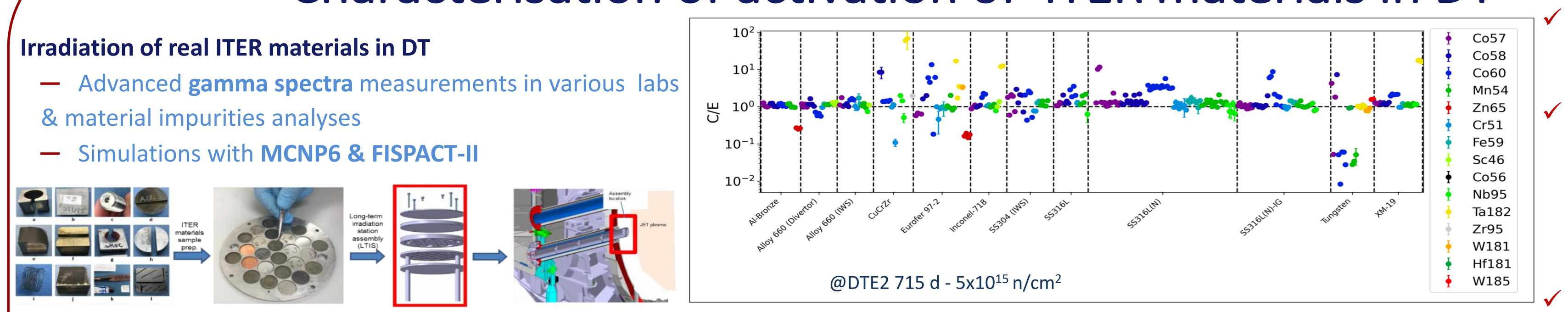


- —Successful operation in vessel of Neutron generator+ Power Supply + detectors + electronics with RH
- —Demonstration & verification of the methodology
- —JET procedure not directly applicable to ITER – several lessons learnt !

Characterisation of activation of ITER materials in DT

Irradiation of real ITER materials in DT

- — Advanced **gamma spectra** measurements in various labs & material impurities analyses
- — Simulations with **MCNP6 & FISPACT-II**



Comparison between Activity predictions MCNP6 + FISPACT II & measurements in ITER materials

- —Demonstrated code reliability
- —Calculated/Experimental (C/E) for nuclides relevant for maintenance generally close or > 1 – **Conservative**
- —**Contamination** (brass) due to manufacturing & cutting techniques
- —**Lack of accuracy in elemental composition in material certificates**
- —Advised more sensitive measurement techniques for **long-lived nuclides**

- Activity of many nuclides generally well predicted **±25%**
- **Overestimation** of ^{58}Co, ^{60}Co and ^{182}Ta in many samples
- **Discrepancies/Anomalies** ^{65}Zn, ^{110m}Ag, ^{56}Co, $^{181/185}$W in various samples with main deviations in **CuCrZr & W**
- **Material impurity analyses** revealed deviations from certificates, explaining some anomalies

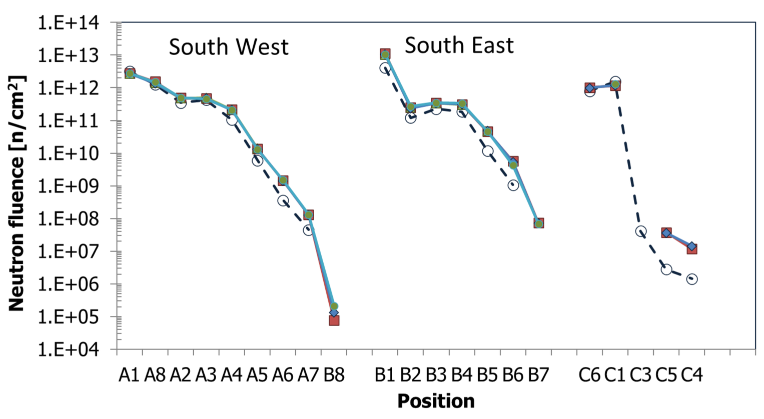
Neutronics benchmark experiments

Neutronics experiments for validating neutronics codes and nuclear data used in ITER nuclear analyses in a real fusion environment in DT

- **On operation:** Neutron fluence
  streaming in penetrations in large/complex volumes
- **Off-operation:** Shutdown dose rate (SDDR)
  in maintenance area

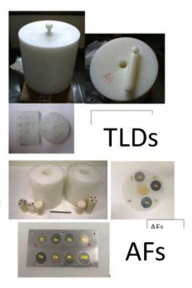
- 23 positions
- >40 m from the plasma
- 8 orders of magnitude variation (10^5 to 10^{13} n/cm²)
- Online SDDR measurements since 2016 (still ongoing)
- SDDR: few μSv/h to tens mSv/h – *ITER relevant range*

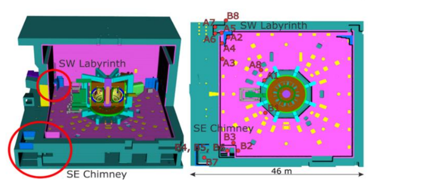
Experimental validation of Neutron streaming and Shutdown Dose Rate predictions in DT

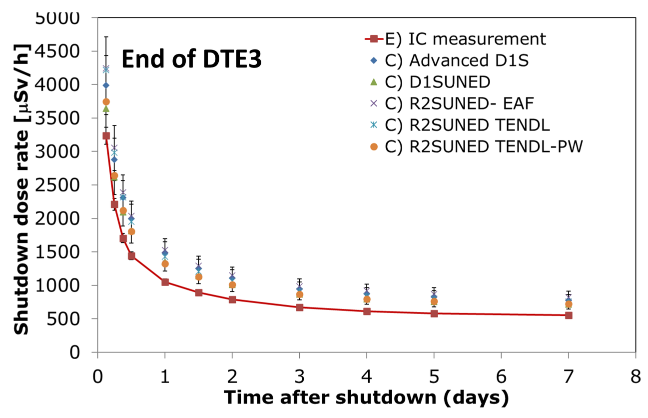


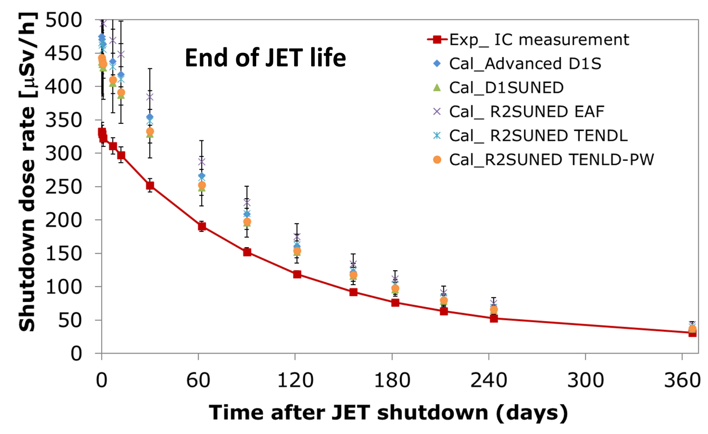
Comparison between Neutron fluence calculations & TLDs measurements for DTE2

- ✓ C/E_{TLD} in the range ~0.9 -10
- ✓ C/C' within **±20%**
- ✓ Increase of the overestimation with the distance from the machine









SDDR calculations & IC measurements at the end of DTE3 and at the end of JET life vs. time in Octant 1

OCTANT 1

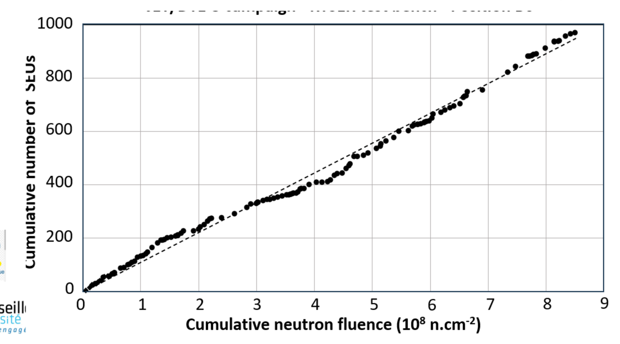
- ✓ **±20%** agreement at short cooling times
- ✓ ^{58}**Co** causes mid-time overestimation.
- ✓ C/E ratio drops from ~**1.5 to ~1.2** within a year after shutdown.
- ✓ Trends differ between octants due to modelling uncertainties & codes artifacts.

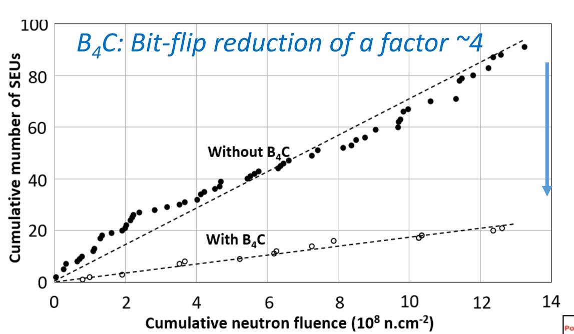
- —Demonstrated reliability of the codes used for nuclear analysis - **Conservative**
- —Modelling & materials uncertainties main responsible for discrepancies

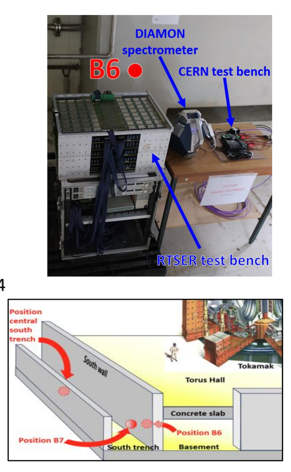
- —Demonstrated reliability of MCNP-based SDDR tools **(C/E within a factor 2)**
- —Identified artifacts and limitations of the computational tools → lead code developments
- —Materials & geometrical modelling inaccuracies are the main responsible for discrepancies

Validation of neutron induced SEE effect on electronics

RTSER = 384 bulk 65 nm CMOS SRAM circuits (3.2 Gbit total) **CERN**= 2x40 nm SRAM circuits (32 Mbit each)



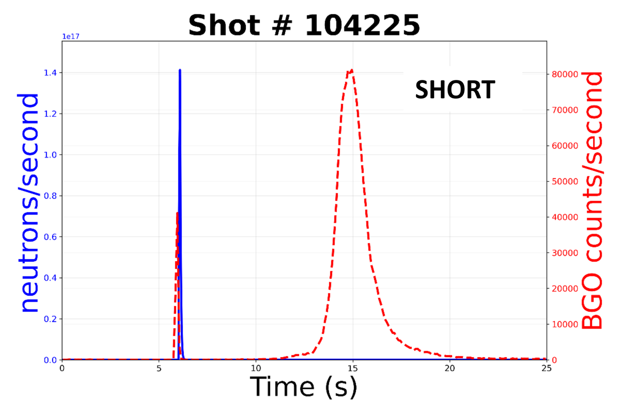


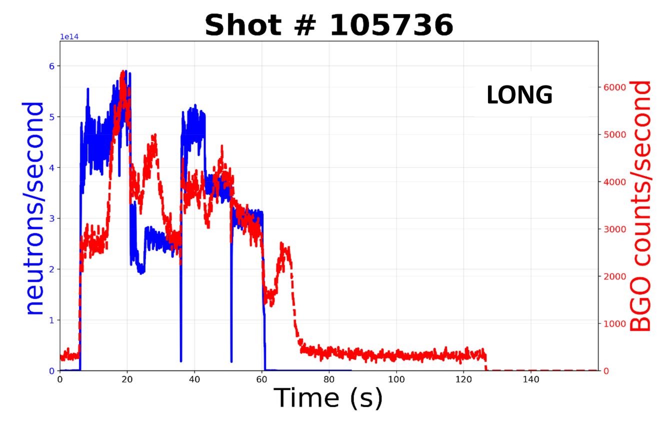


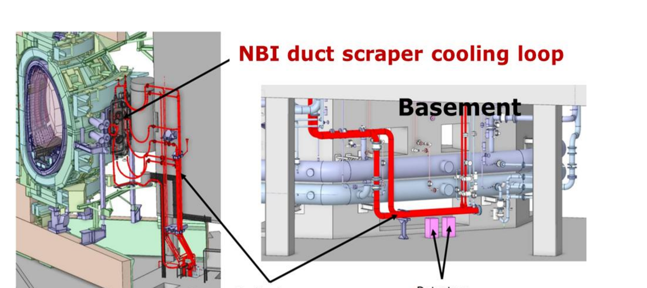
Single Event Upset vs. cumulated neutron fluence in DTE3

- —**Validation of methods & models** for neutron-induced bit-flips prediction
  - — **C/E 0.86 (RTSER) & 1.12 (CERN)**
- —High bit-flip rates and **reliability degradations** compared to environmental conditions
- —**Evident reduction of bit-flips with B_4C shield** → can be further improved

Unique study on Water activation in tokamak in DT







Neutron yield rate from KN1 & Gamma measurements in the basement with WACT system vs. time for short and long pulses

- — First-time insight into **activated water in tokamak** cooling loops
- — Clear **effects of plasma operations** on delayed gamma measurements and water activation
- — Correlation with **plasma operations** and **circuit parameters**
- — Unique dataset for **validating** multiphysics tools
- — Several lessons learnt for water activation- based diagnostics implementation

CONCLUSION

Unique Achievements from JET DT Technological Exploitation

- — Successful **14 MeV calibration** of neutron diagnostics
- — Enhanced **nuclear experimental techniques** and computational tools
- — Validated **ITER nuclear analysis codes** and reliability
- — Advanced **knowledge of neutron irradiation effects**
- — Identified **critical issues** affecting reliability
- — Built a **large database** and collected irradiated samples for future validation

Outstanding experience supporting ITER

Valuable outcomes for ITER re-baseline, providing robust methodologies to reduce risk, uncertainty, and support nuclear licensing

OUTLOOK

- Experience at JET has filled key gaps and provided valuable insight into neutron generation, interactions, and effects during operations and shutdown, offering unique opportunities for learning during decommissioning.
- However, JET showed the following critical limitations for future reactor exploitation:
  - — Structural materials not reactor relevant
  - — No superconductive machine- Short operations
  - — Be first wall
  - — Limited damage/ transmutation
  - — No breeding blanket
  - — Some important phenomena not investigated (e.g. Activated Corrosion Products)
  - — Reactor relevant components/materials not tested (few experiments)

Strategical Priority DT experiments in near future will be critical for advancing fusion reactor development and preserve the knowledge

ACKNOWLEDGEMENTS

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