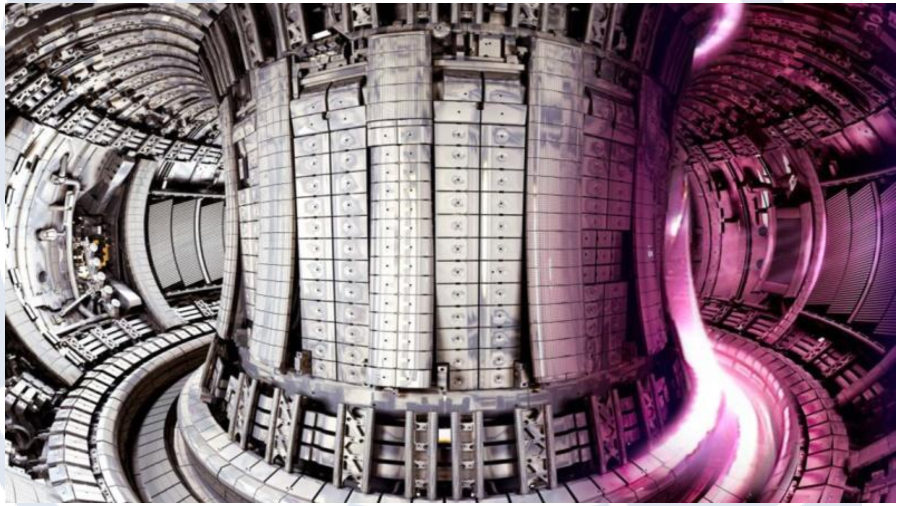
30th IAEA Fusion Energy Conference (FEC 2025)

FEC2025

Neutronics for ITER nuclear phase: insights and lessons learnt from JET DT operation



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JET

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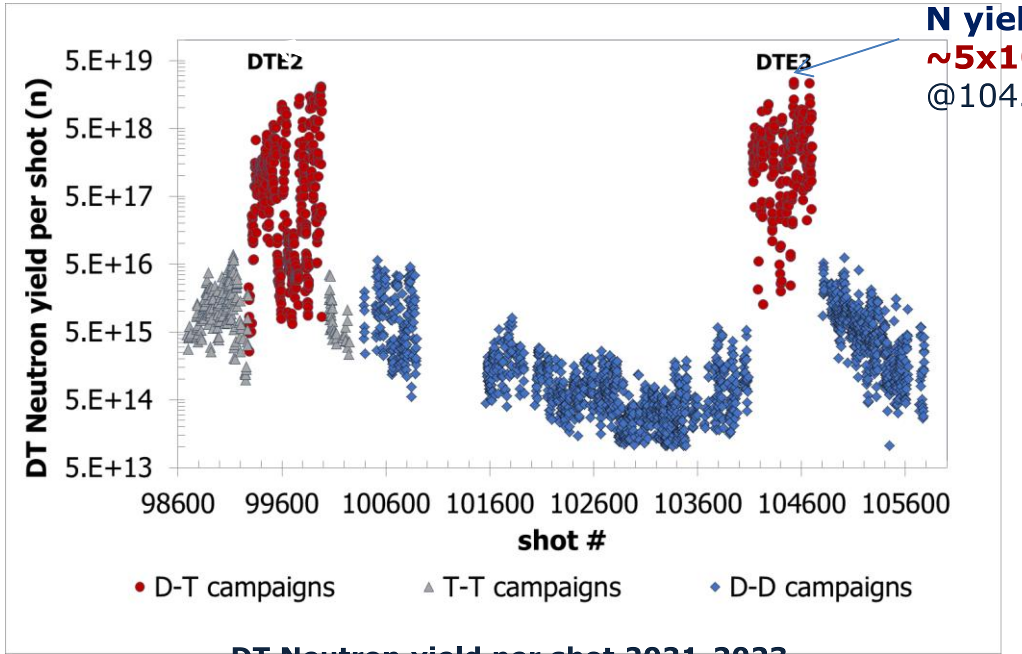
Huge neutrons production during DT campaigns at JET

Unique Deuterium–Tritium (DT) campaigns at JET performed in 2021 & 2023

DTE2 @8.48x10^{20} n → **1.57x10^{21} n** ← **DTE3** @7.31x10^{20}



DT Neutron yield per shot 2021-2023

N yield rate peak
~5x10^{18} n/s
@104522 **-69 MJ** record

Max neutron flux in JET FW 2x10^{13} n/cm^2/s
- **One order of magnitude less than ITER FW @500 MW**
- **rear ITER blanket**

Max cumulated DTE2&DTE3 neutron fluence in JET FW 10^{16} n/cm^2
- **middle ITER port plugs-rear blanket @ end of ITER DT-1**

JET Shutdown dose rate ex-vessel from few μS/h to tens mSv/h
- **same level as in several ITER maintenance areas**

JET DT Operations relevant for ITER Nuclear phase

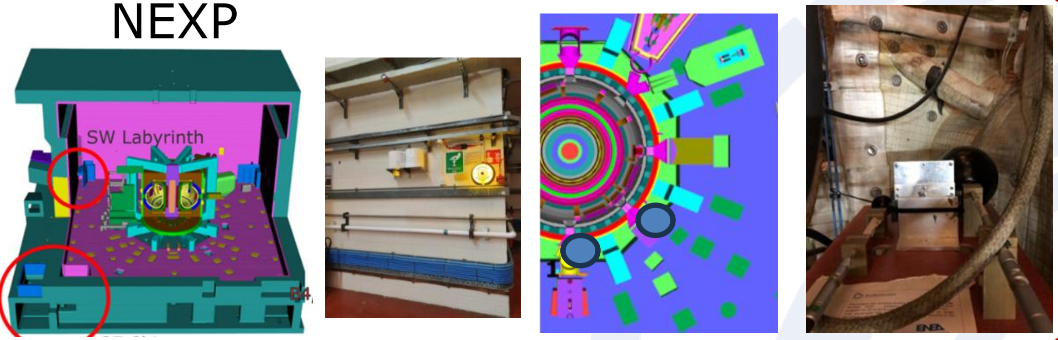
Unique technology-oriented experiments at JET in DT in support of preparation of ITER Nuclear operations

EUROfusion WP PrIO

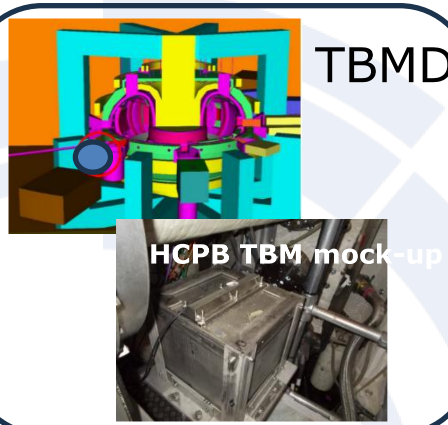
- **NC-14** Development and validation of methods for **14 MeV neutron diagnostics calibration**
- **ACT Activation** measurements and analysis of ITER materials
- **RADA Damage** study of functional materials
- **NEXP Neutron streaming** and **Shutdown Dose rate** benchmark experiments
- **TBMD** Test 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

[R. Villari, FED 217 (2025) 115133] [X. Litaudon, NF 64 (2024) 112006]

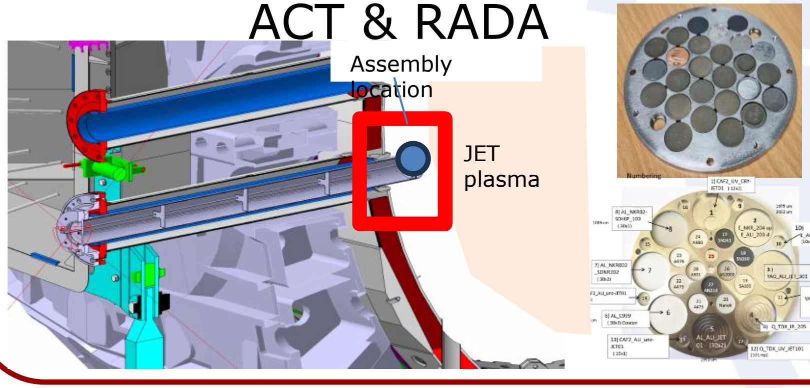
NEXP



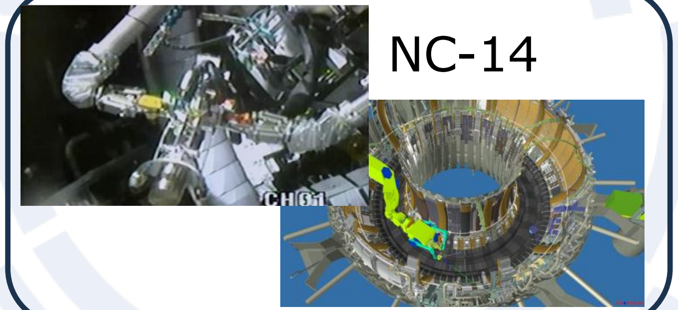
TBMD



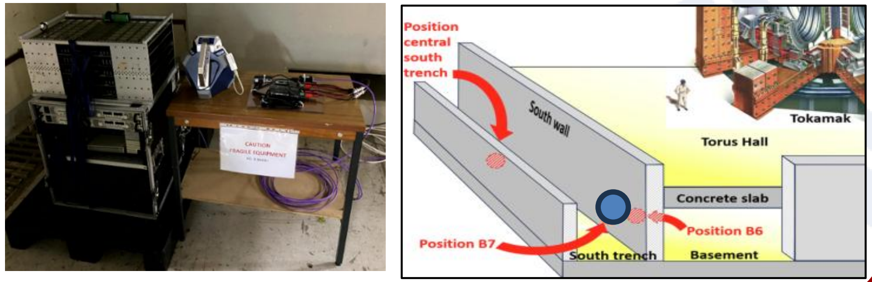
ACT & RADA



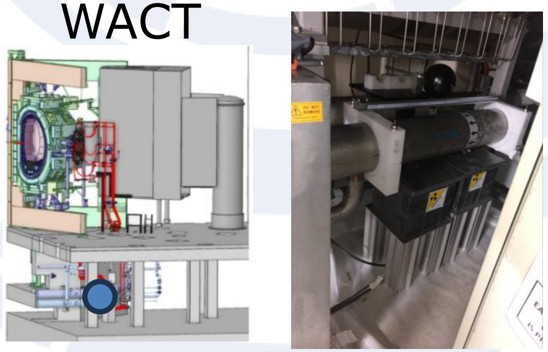
NC-14



SEE



WACT



Neutronics benchmark experiments

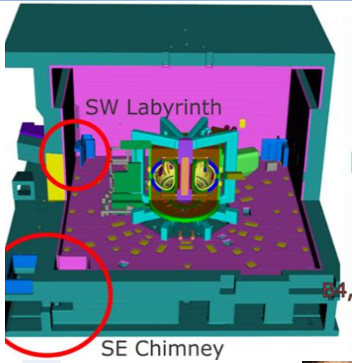
Neutronics experiments for validating neutronics codes and nuclear data used in ITER nuclear analyses in a real fusion environment in DT

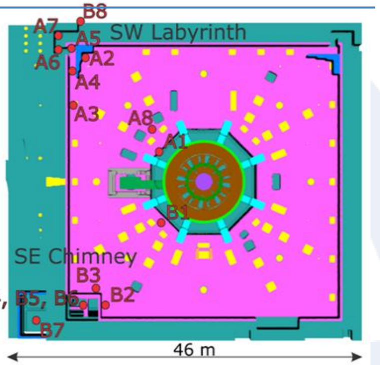
- **On operation: Neutron fluence** streaming in penetrations in large /complex volumes
- **Off-operation: Shutdown dose rate (SDDR)** in maintenance area

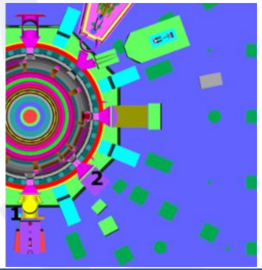
- **23 positions**
- **>40 m from the plasma**
- **8 orders of magnitude variation (10^5 to 10^{13} n/cm^2)**
- **Online SDDR measurements since 2016 (still ongoing)**
- **SDDR: few μSv/h to tens mSv/h – *ITER relevant range***

TLDs

AFs



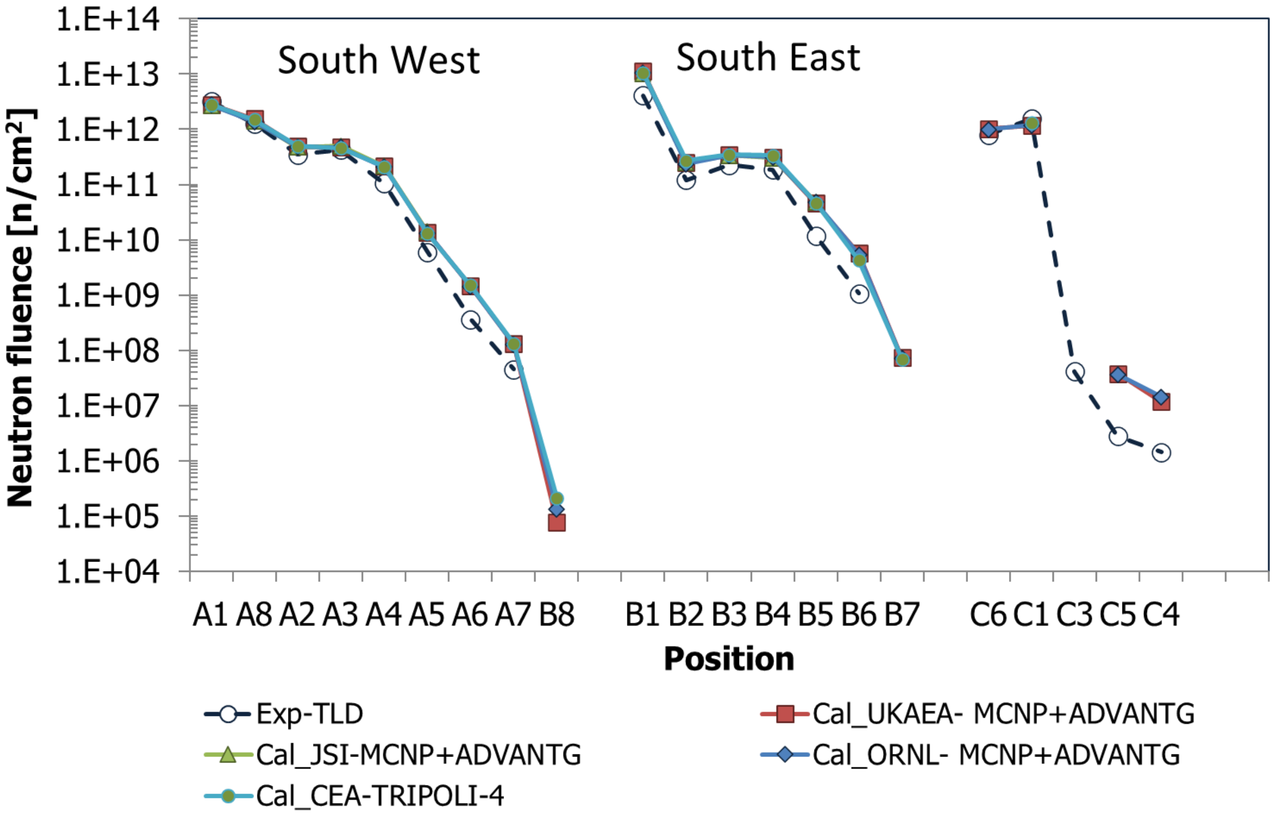




Accurate measurements for quantitative comparison to simulations → Validation

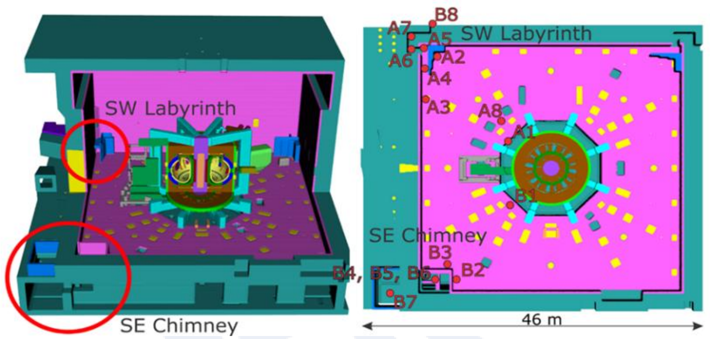
- **Neutron streaming – Rad transport MCNP, ADVANTG, TRIPOLI-4® & OPENMC**
- **SDDR - Rad transport+ Activation:** *MCNP based* **Advanced D1S, D1SUNED, MCR2S, R2SUNED,R2Smesh, ORNL-R2S, N1S** *Other codes based* **OpenMC and TRIPOLI-4© R2S & D1S** *(ongoing)*

Neutron streaming benchmark experiment results in DT for validation of neutron transport codes



DTE2 @ 8.5x10^{20} n

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



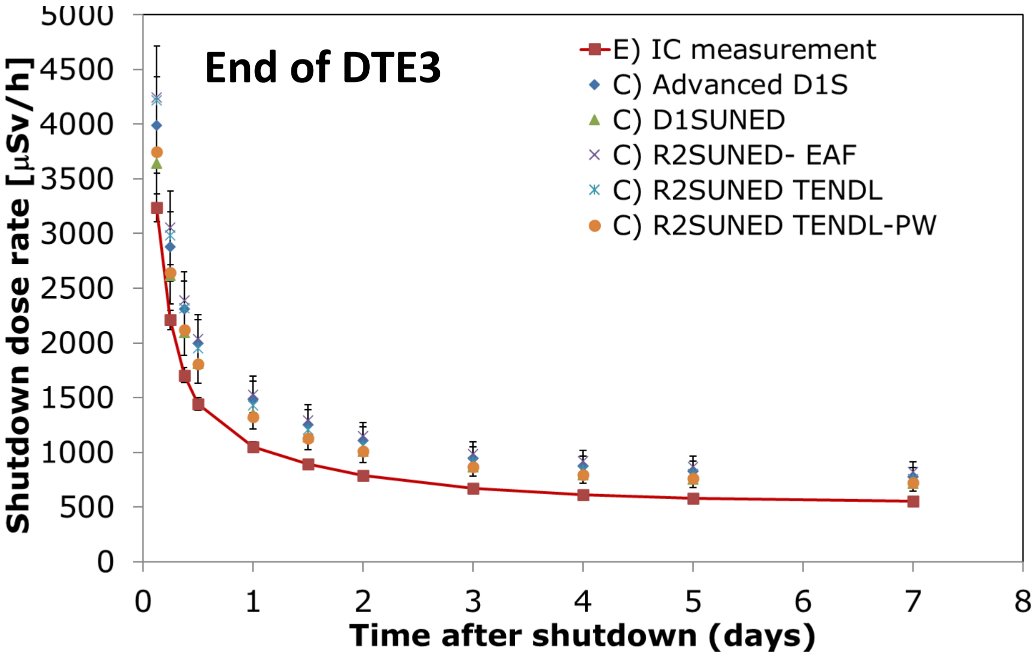
Comparison between Neutron fluence calculations & TLDs measurements for DTE2

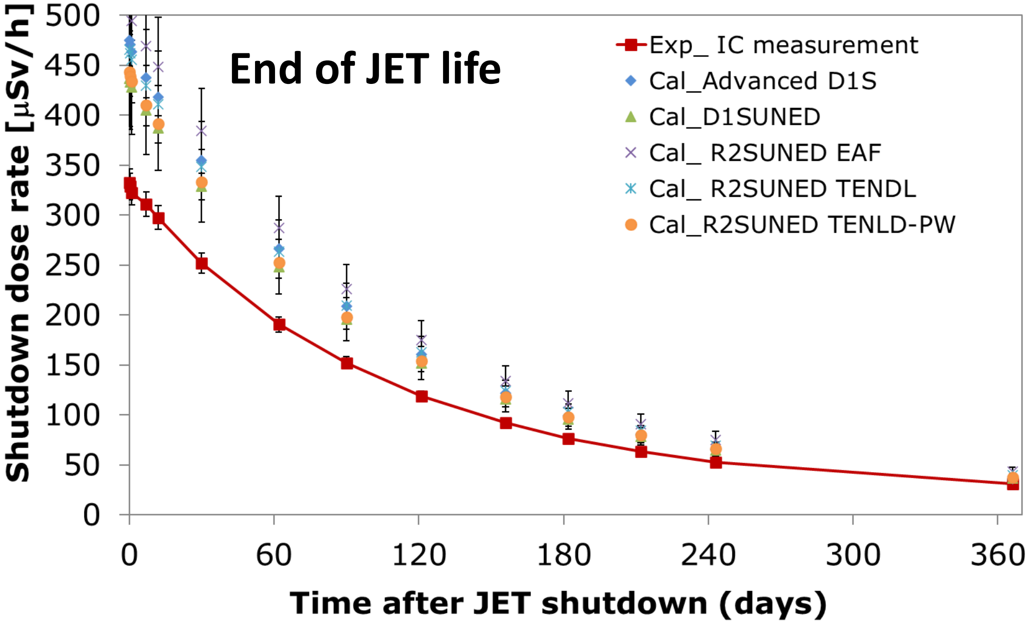
ENEA UK Atomic Energy Authority IFJ IJS Oak Ridge National Laboratory cea

— **Demonstrated reliability of the codes used for nuclear analysis - conservative**

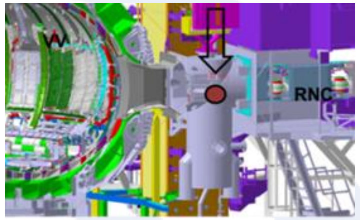
— **Modelling & materials uncertainties main responsible for observed discrepancies**

Experimental validation of Shutdown Dose Rate predictions in DT





OCTANT 1

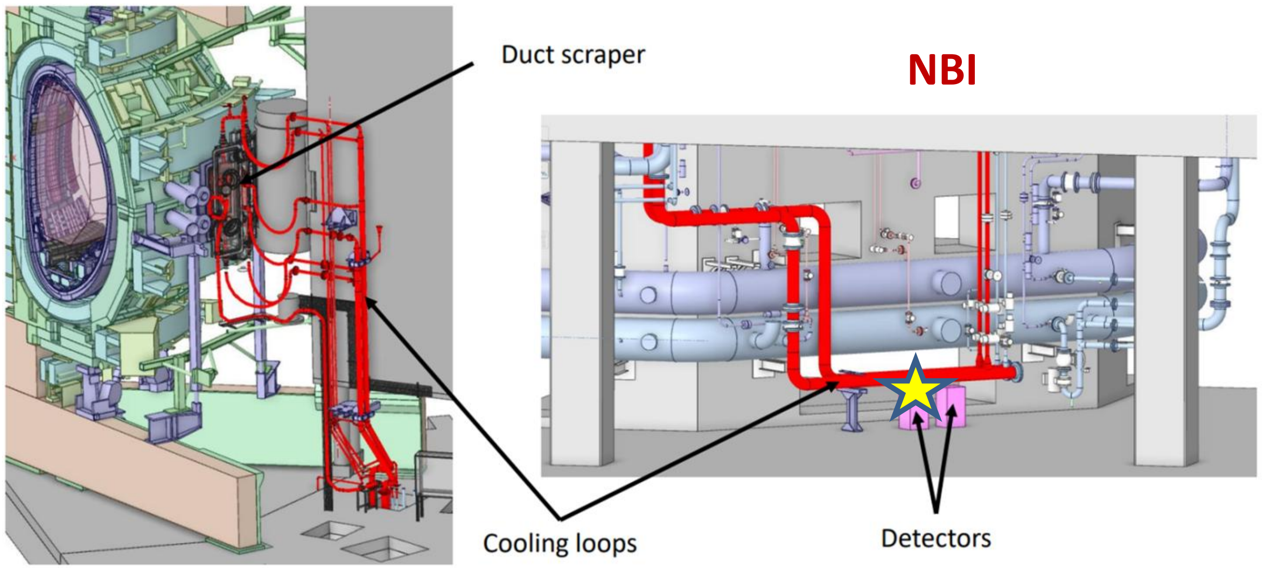


SDDR calculations & IC measurements at the end of DTE3 and at the end of JET life vs. time in Octant 1

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

Unique Water activation experiment in real tokamak cooling loop under DT

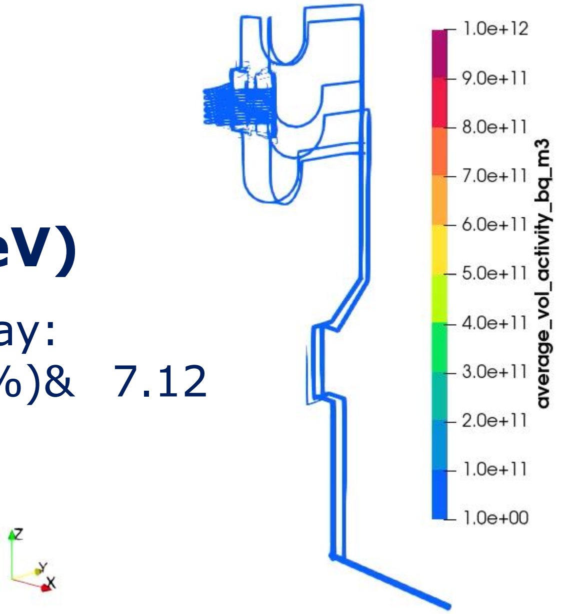
NBI duct scraper cooling loop



Basement

$^{16}O(n,p)^{16}N$ (E_n>10.5 MeV)

$T_{1/2}$ 7.13 s β decay:
γ 6.13 MeV (69%)& 7.12 MeV (5%)

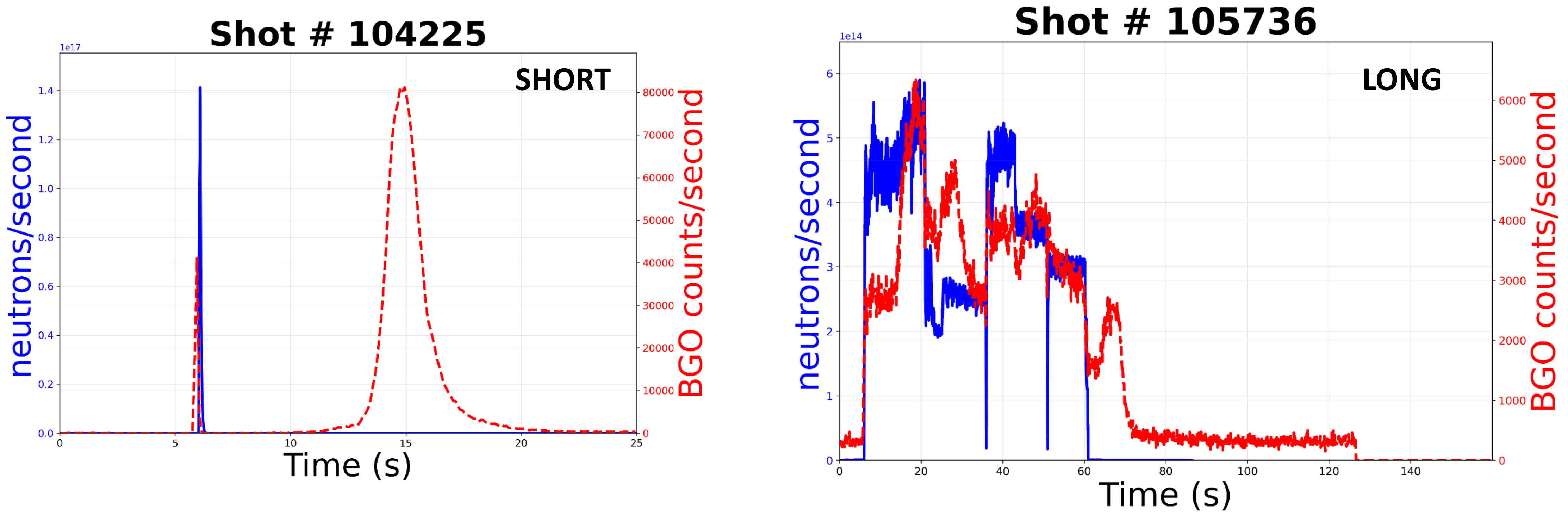


[M. De Pietri]

FLUNED simulation of ^{16}N activity along NBI-duct scraper cooling loop vs. time

Installation of water activation system for measurements of γ from ^{16}N decay in JET basement during DD & DT campaigns

Unique Water activation measurements in tokamak in DT



Neutron yield rate (KN1) & Gamma measurements with WACT vs. time

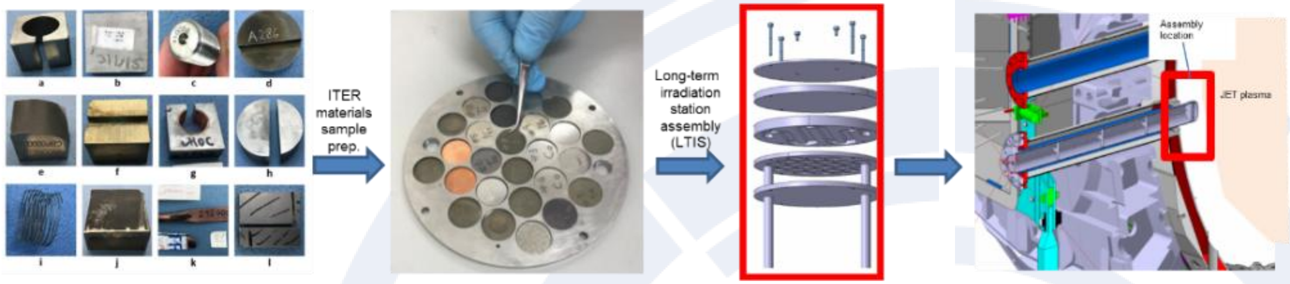
[R. Villari, FED 217 (2025) 115133.]

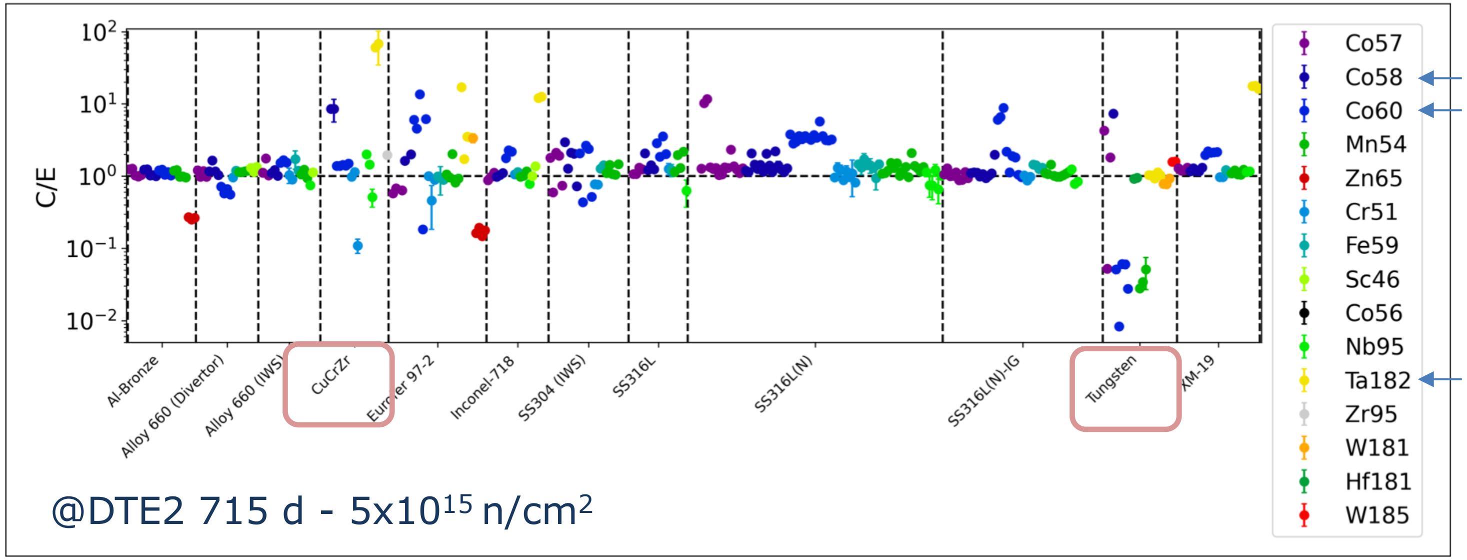
- First-time insight into **activated water in tokamak** cooling loops
- Correlation with **plasma operations** and **circuit parameters**
- Unique dataset for **validating** multiphysics tools
- Several lessons learnt for water activation- based **diagnostics** implementation

Characterisation of activation of ITER materials in DT

Activation measurements and analysis of ITER materials

- **Irradiation of real ITER materials in DT**
- Advanced **gamma spectra** measurements in various labs & material impurities analyses
- Simulations with **MCNP6 & FISPACT-II**





[L. Packer, Nuc. Fus., 64, 2024, 10]

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

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

UK Atomic Energy Authority

IJS

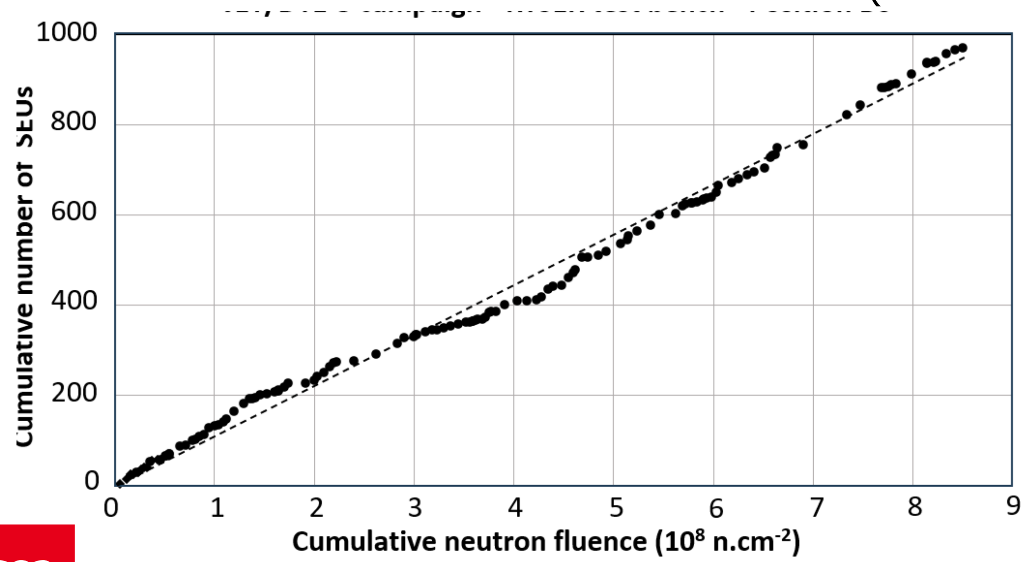
IFPiLM

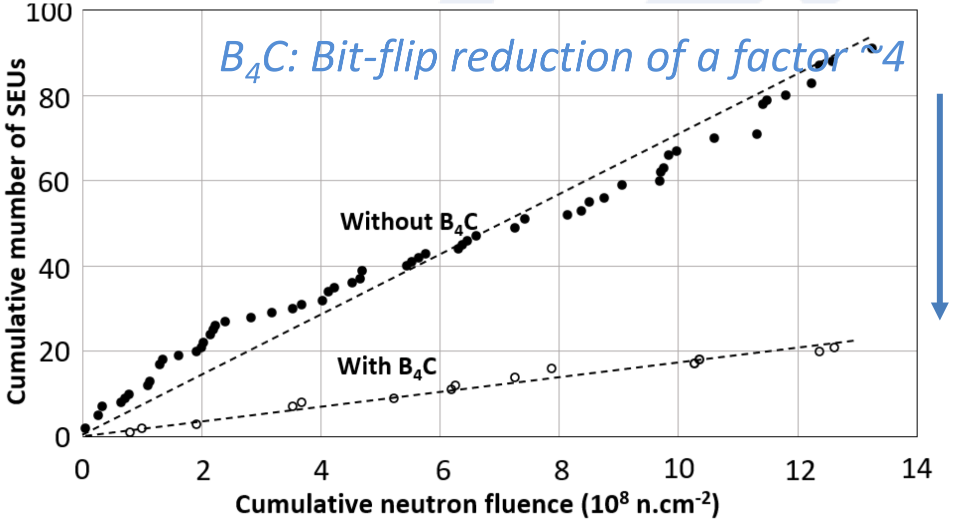
ENEA

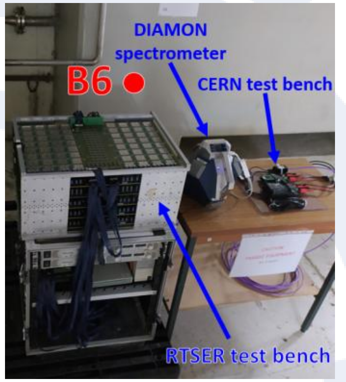
Validation of neutron induced SEE effect on electronics

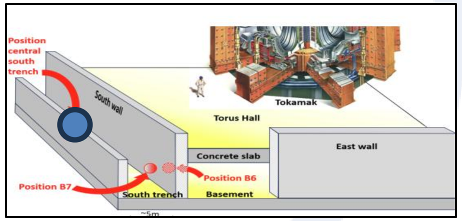
Single Event Effects (SEEs): Random neutron interactions causing instant electronic malfunctions, data corruption, or damage → dedicated SEE experiment in JET basement during DT operations

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

[M. Dentan, IEEE TNS, 72 (2025) 1486]

C/E 0.86 (RTSER) & 1.12 (CERN)

– **Validation of methods & models** for neutron-induced bit-flips prediction

– High bit-flip rates and **reliability degradations** compared to environmental conditions

– **Evident reduction of bit-flips with B_4C shield** → can be further improved

Conclusions & Outlook

JET DT Technological Exploitation –Unique Achievements

- 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

- **Unique inputs for ITER nuclear phase and safety demonstrations**

Limitations for Fusion reactors development

- Non–reactor-relevant structural materials & few tests
- No superconducting magnet; short operations
- Limited damage and transmutation
- No breeding blanket (except TBM mock-up)
- Some phenomena not investigated (e.g.ACP)

Strategic Priority

Further fusion-reactor relevant neutronics experiments in near future will be critical for advancing fusion reactor development and preserve the knowledge

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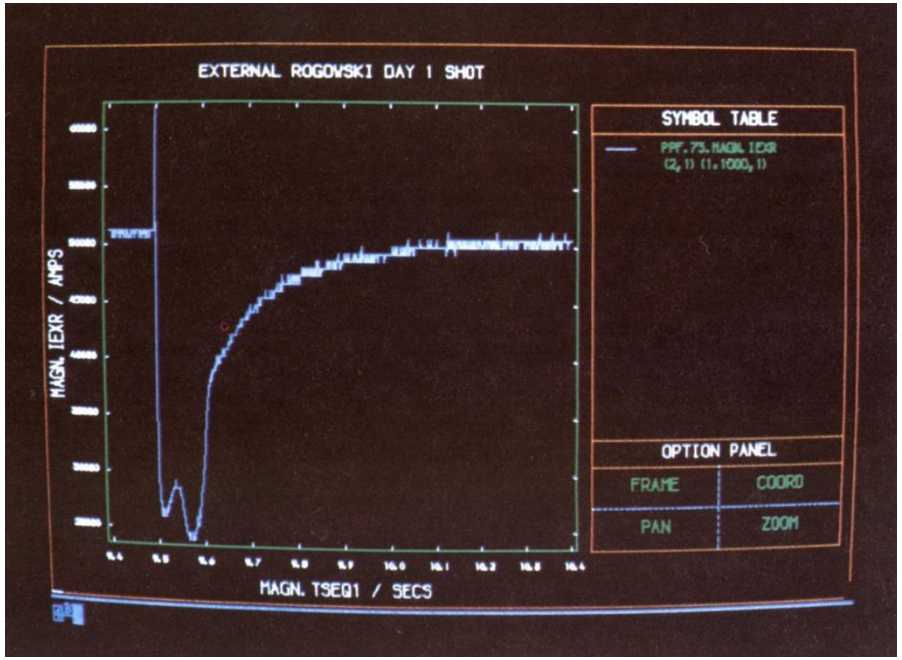
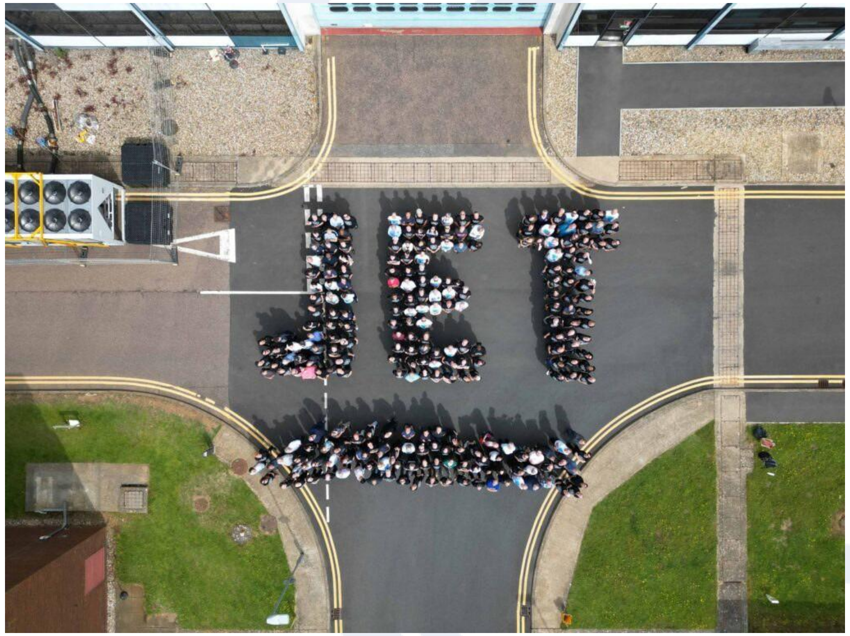
* See the author list of "Overview of T and D-T results in JET with ITER-like wall" by CF Maggi et al. 2024 Nucl. Fusion 64 112012

Thank you!
Questions/Comments?



JET First Shot 25 June 1983

Credit: UKAEA



JET 40th anniversary 25 June 2023

After 40 years of operation, JET concluded its activities in December 2023, providing the scientific community with an invaluable wealth of knowledge for advancing nuclear fusion research