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DRAFT

ENEA
Italian National Agency for New Technologies, Energy and Sustainable Economic Development

EUROfusion

# Key technological aspects of recent DT operations at JET


Rosaria Villari



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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. to be published in Nuclear Fusion Special Issue: Overview and Summary Papers from the 29th Fusion Energy Conference (London, UK, 16-21 October 2023)*

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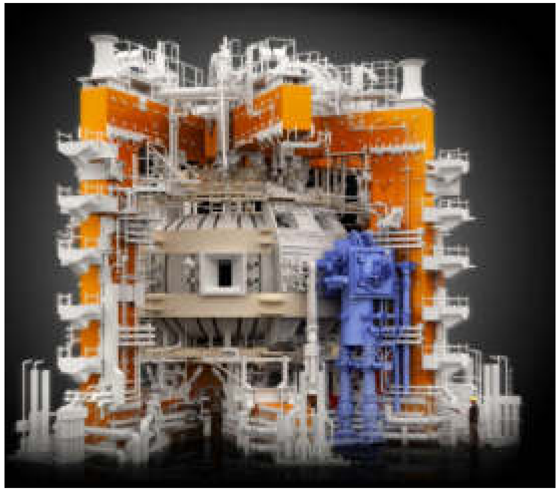
# Introduction

- **A unique high-performance DT campaign, DTE2, was conducted at JET (UK) in 2021, and DTE3 has just started**
- **The EUROfusion technological exploitation of JET DT operations began in 2014 in the frame of WPJET3 program and it is currently ongoing within the WP "Preparation of ITER Operations" (PrIO)**
- **Several technology-oriented experiments and analyses were performed in DT aimed at**
  - **improving the knowledge of nuclear technology and safety**
  - **developing and validating nuclear codes, data and experimental techniques**

**in preparation of ITER nuclear operations**

- **The current revision of ITER project requires new efforts & open novel scientific challenges**



→ *J. Knaster, KN1*

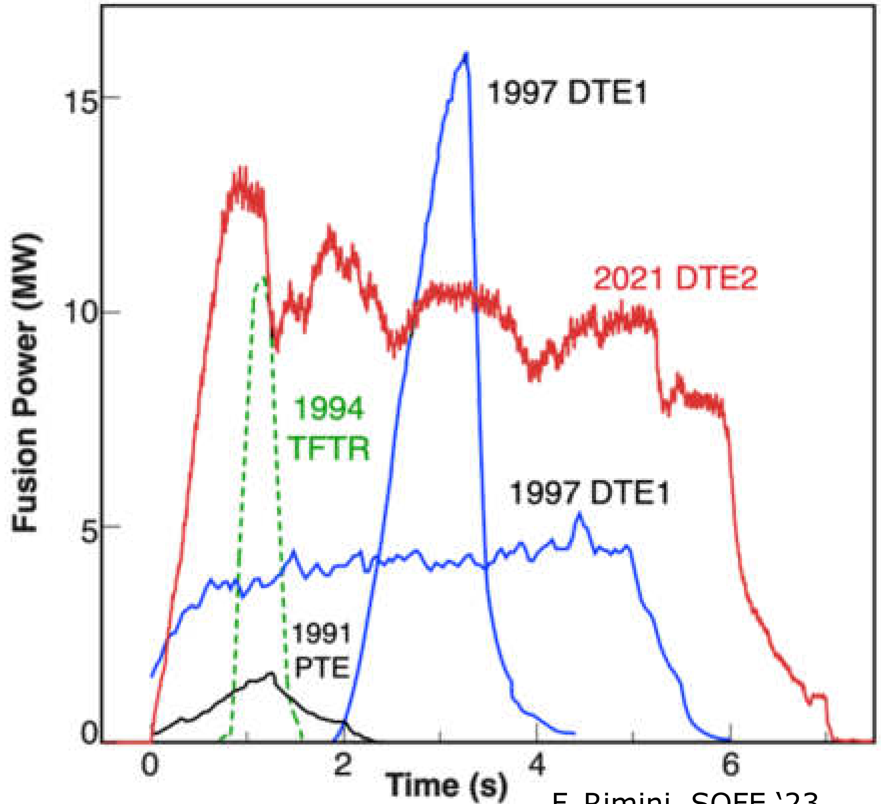
# Deuterium-Tritium operations

**JET was designed to**

- **Demonstrate of D-T operation**
- **Study of D-T plasma physics & technology in fusion reactor relevant conditions**

**Tokamak DT operations only at JET & TFTR**

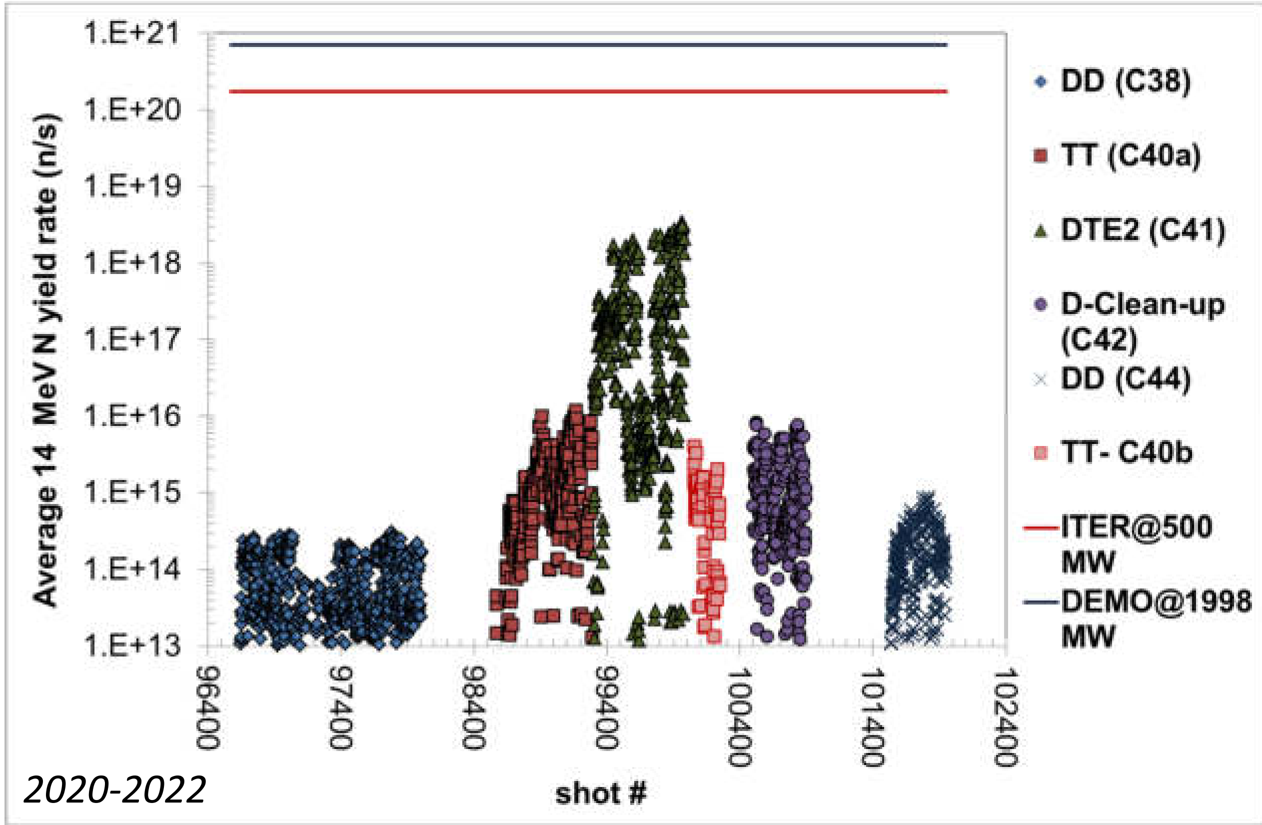
- 1991 JET Preliminary Tritium Experiments (PTE)
- 1994-96 TFTR
- 1997 JET DTE1 in CFC wall- $P_{fus}$ 16.1 MW !
- **2021 JET DTE2 in Be/W wall**
- **2023 JET DTE3- *ongoing***

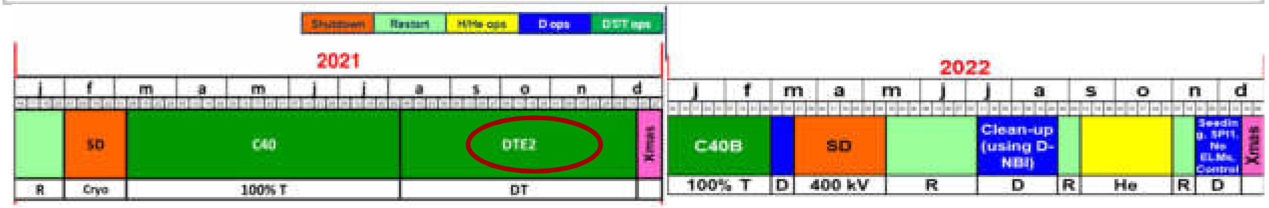



F. Rimini, SOFE ‘23

**Successful JET DTE2 campaign**
DTE2 Record 59 MJ Fusion Energy!
Sustained Pfus 10.3 MW over 5 seconds!

# 14 MeV neutron production at JET 2020-2022




## DD campaigns

DT neutrons generated through T burn-up – typical 1%

## TT campaigns

DT neutrons mainly due to D in chamber – typical 40% - changes over time

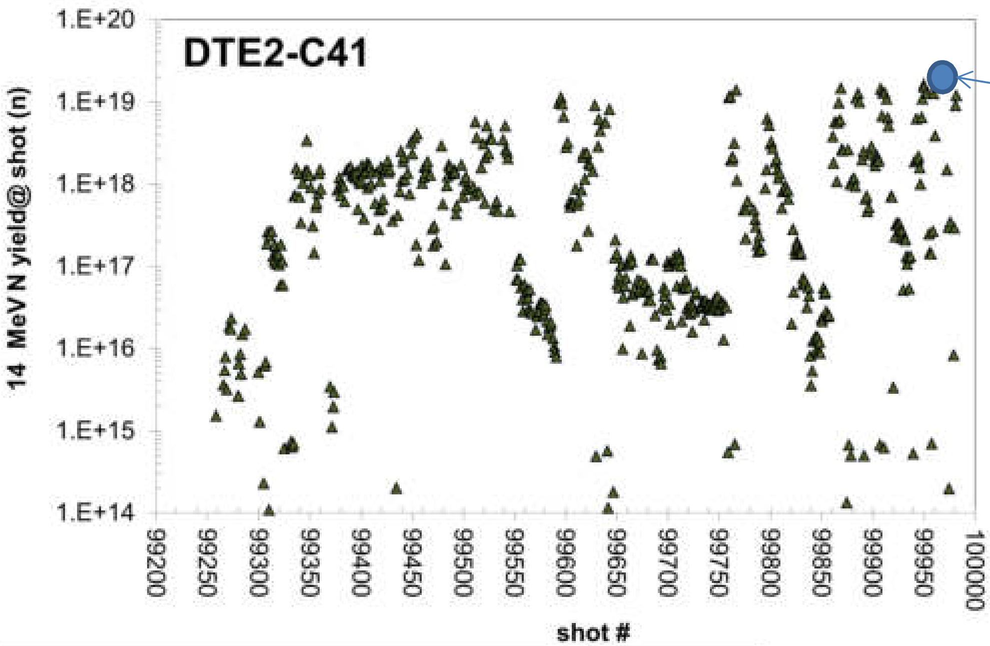
## DTE2 campaign

1 kg of T 240g TIMs + 763g T-NBI @8.48x$10^{20}$ n

Max average 3x$10^{18}$ DT n/s –

**~60 times lower than ITER@500 MW**
**~250 times lower than EU DEMO@1998 MW**

# 14 MeV neutron production during DTE2 .. Top DT performances & DTE3



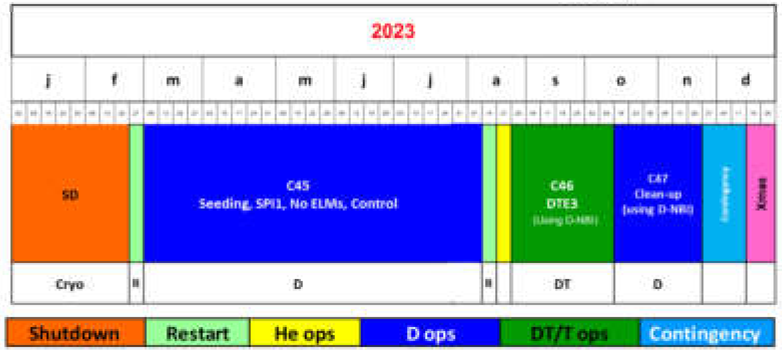

**Top DT shot performance 21-Dec-2021**

**# 99971** (2.5 MA, 3.6 T)
Hybrid in D-NBI in T rich plasma~29MW-NBI+4MW-RF

**14 MeV n/shot 2.09x10$^{19}$**

**N yield rate**

- **Average 3x10$^{18}$ n/s**
- **Peak ~4.8x10$^{18}$ n/s**




J. Mailloux XXX

**DTE3 campaing started on 30 August*!**

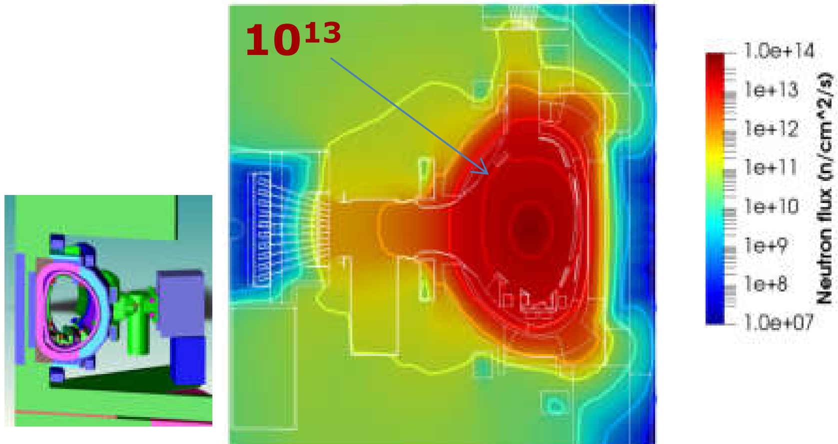
**18 days (36 sessions)**
**<44 bar l/day – T budget**

**D-T neutrons budget for DTE3 + Clean-up: 7x10$^{20}$ n**

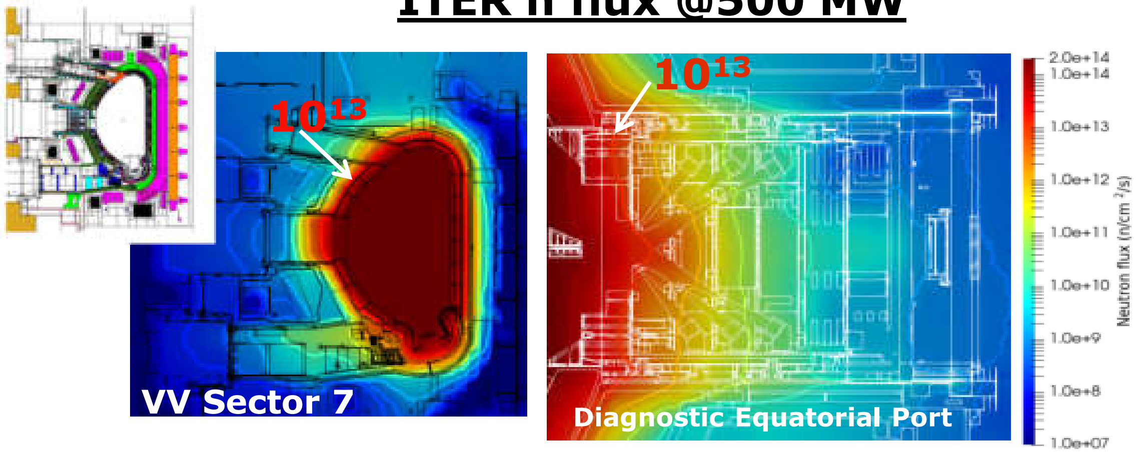
* operator sessions TIM calibration in T, neutrons calibration

# Representativeness of JET DT for ITER

**JET n flux @ shot 99971 – peak ~4.8x10$^{18}$ n/s**




**ITER n flux @500 MW**




**10$^{13}$ n/cm$^2$/s neutron flux level as in rear ITER blanket- DFW**

Cumulated total neutron fluence during DTE2+DTE3 max inboard FW **10$^{16}$ n/cm$^2$**

- **Relevant for some degradation effects**
- **@rear ITER port plugs at the end of ITER life**
- **@middle ITER port plugs- rear blanket at the end of first ITER DT phase**

**JET DTE relevant for ITER technologies!**

**With the new ITER baseline – the JET experience is more significant for supporting demonstration**

# Technological exploitation of JET DT campaign

**DT operations at JET offer a unique opportunity to study in real tokamak environment**

- **Calibration of neutron detectors**
- **Activation and damage of materials & electronics**
- **Tritium breeding & detectors**
- **Validate nuclear codes**
- **Develop advanced techniques**
- **Collect & process nuclear safety data**

**Projects**

- 14 MeV Neutron calibration
- Activation of ITER materials
- Radiation damage studies
- Streaming benchmark exp
- Shutdown dose rate benchmark exp
- Test Blanket Module detectors - TBR
- Water activation exp
- Single Event Effects on electronics
- Occupational Radiation Exposure
- Waste

(14 MeV Neutron calibration through Test Blanket Module detectors - TBR: DD,TT DTE2+ DTE3)

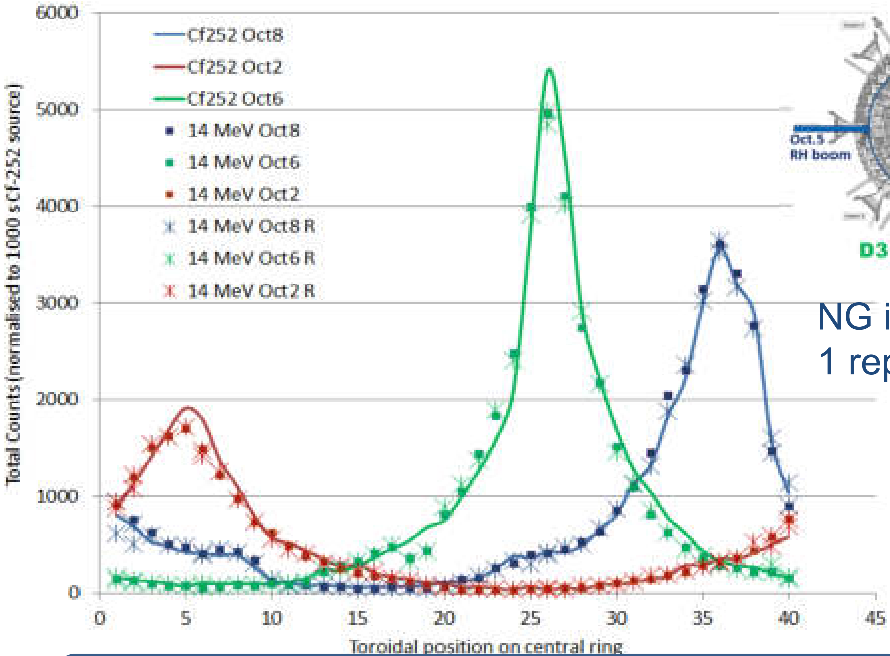
(Water activation exp, Single Event Effects on electronics: DTE3)

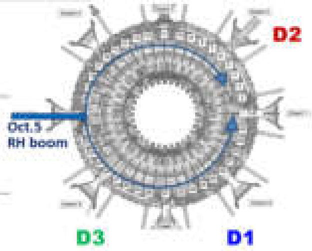
**High relevancy to ITER & DEMO**

# Calibration of JET neutron detectors at 14-MeV neutron energy

**Successfully achieved 14 MeV calibration of JET neutron detectors with Neutron Generator**

## KN1 $^{235}U$ Fission chambers



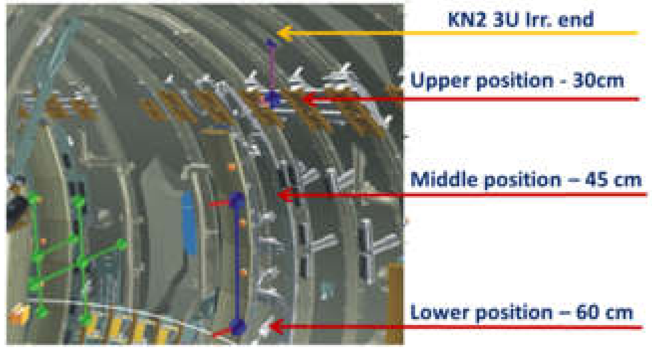




NG in 40 pos
1 repetition (R)

FC Response- consistency NG & $^{252}Cf$

**Total uncertainty ±~6% well within target accuracy ≤ 10%**

## KN2 Activation system



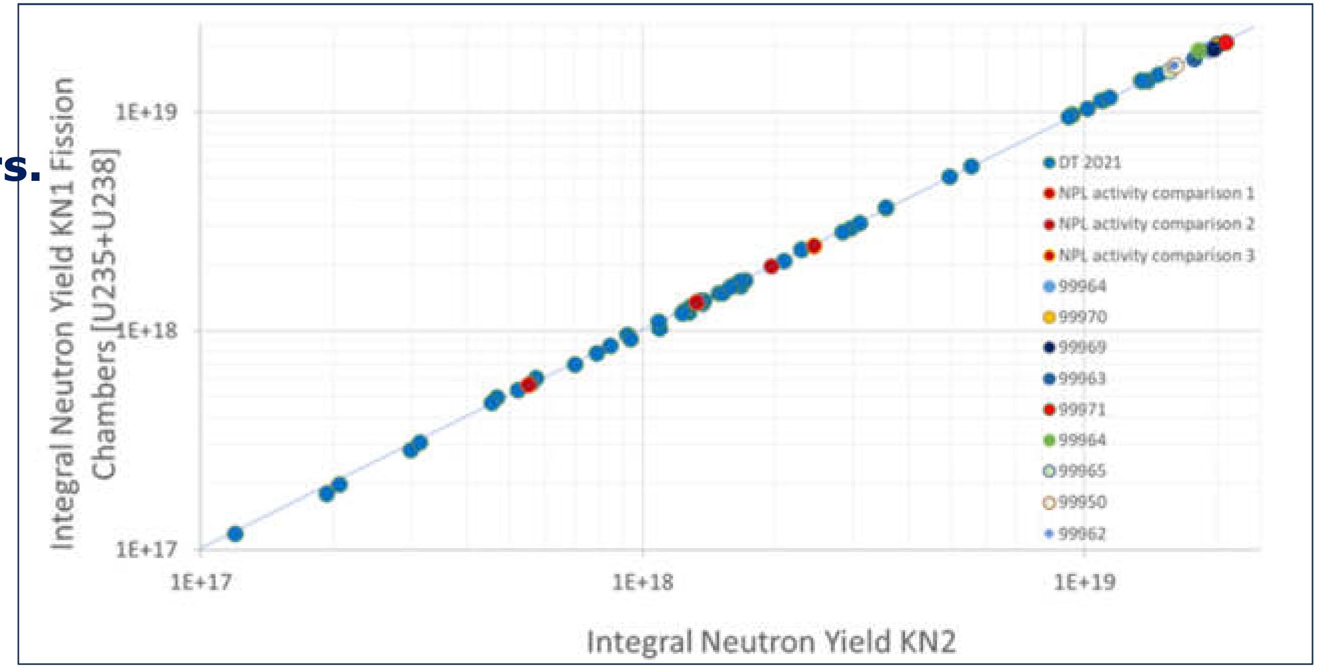

**NG intensity ~2 x10$^{8}$ n/s**

Diamonds & AF monitors
absolute calibration

P. Batistoni *et al.* Nucl. Fusion 58 (2018) 106016

# Successfull verification of 14 MeV neutron calibration

- Many high yield shots measured during DTE2 →rigorous cross calibration of U235&U238 chambers.
- Multiple dosimetry foil measurements -KN2 @shot show excellent agreement.
- Continuous monitoring and cross calibration checks of Fission Chambers and Activation system derived yields.
- Further calibration recently done at the beginning of DTE3




*Z. Ghani, UKAEA*

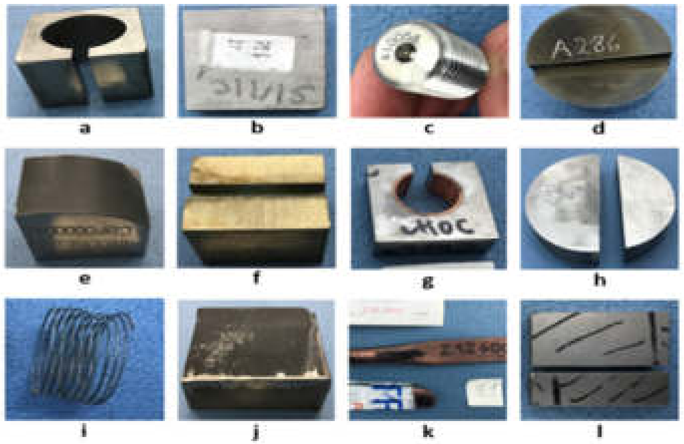
**Total uncertainty within ±10%!**

UK Atomic Energy Authority

- Successful operation in vessel of neutron generator + PS units + detectors + electronics with RH system
- Demonstration & verification of the methodology

# Activation of real ITER material

- **Unique irradiation in tokamak under 14 MeV neutrons of REAL ITER materials used in the manufacturing of the main in-vessel components**
  - Activation measurements of irradiated ITER material samples and dosimetry foils in DT
  - Characterization and data validation for the predictions of ITER materials activation

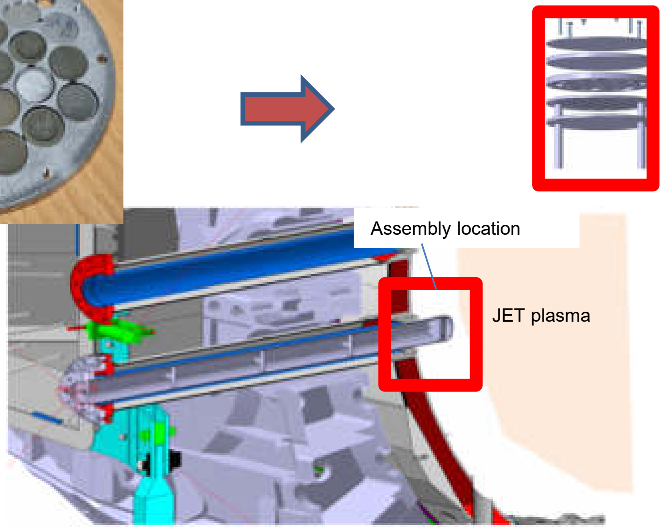



Nb3Sn, SS316L steels from various manufacturers, SS304B, Alloy 660, Be, W, CuCrZr, OF-Cu, XM-19, Al bronze, Nb3Sn, NbTi and EUROFER

27 ITER samples

Long-term irradiation station assembly (LTIS)

715 days of irradiation




L. Packer Nuclear Fusion (2021) 61 116057

DT N flux
up to **$2\times10^{13}$ n/cm²/s**
One order of magnitude less than ITER FW@500 MW

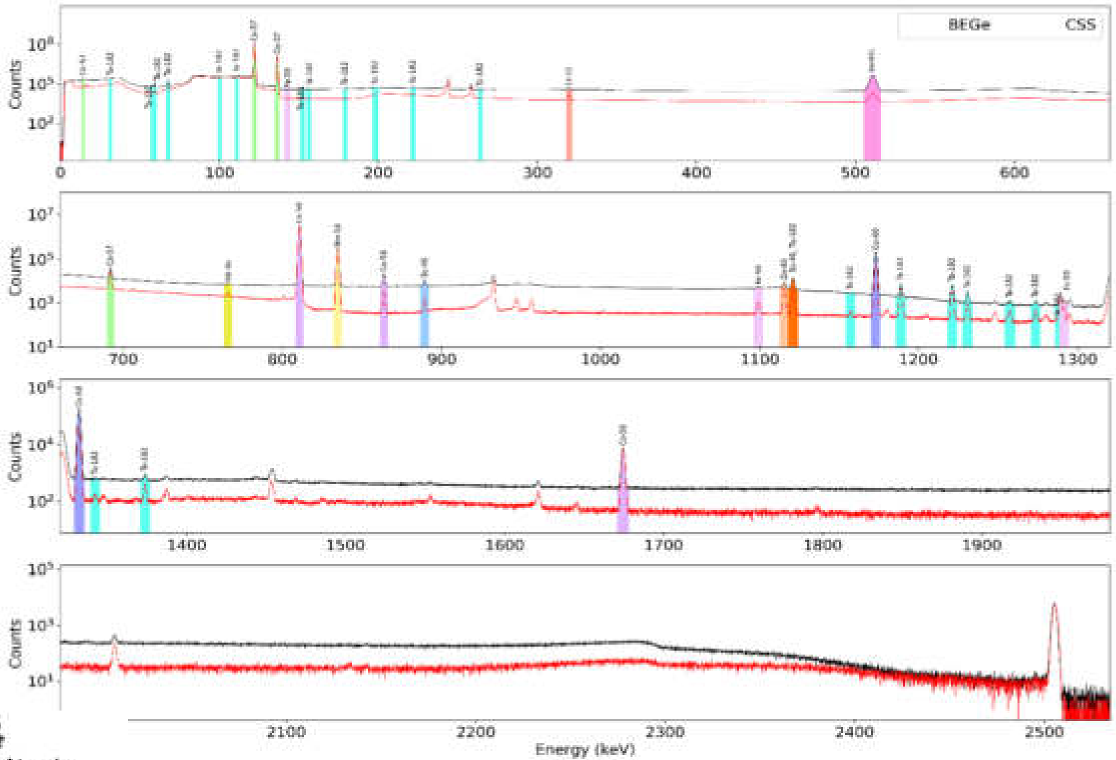
DT N fluence
**$5\times10^{15}$ n/cm²**

→ *L. Packer P5B3*

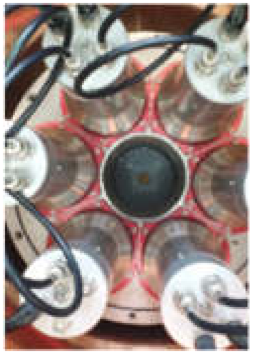
UK Atomic Energy Authority IJS IFPiLM ENEA

# Activation of real ITER material- gamma spectra measurements

- **Irradiated ITER materials were measured using gamma spectrometry techniques to identify and quantify nuclide activities generated through neutron activation.**
- **Measurements performed in various EU labs**




**BEGe detector and Compton Suppression System (CSS)**



- Identified Sc-46, Cr-51, Mn54, Fe-59, Co-57, Co-58, Co-60, Zn-65, Nb-95 and Ta-182 – relevant for maintenance
- CSS reduces the Compton background and improving the signal to background ratio for some nuclides

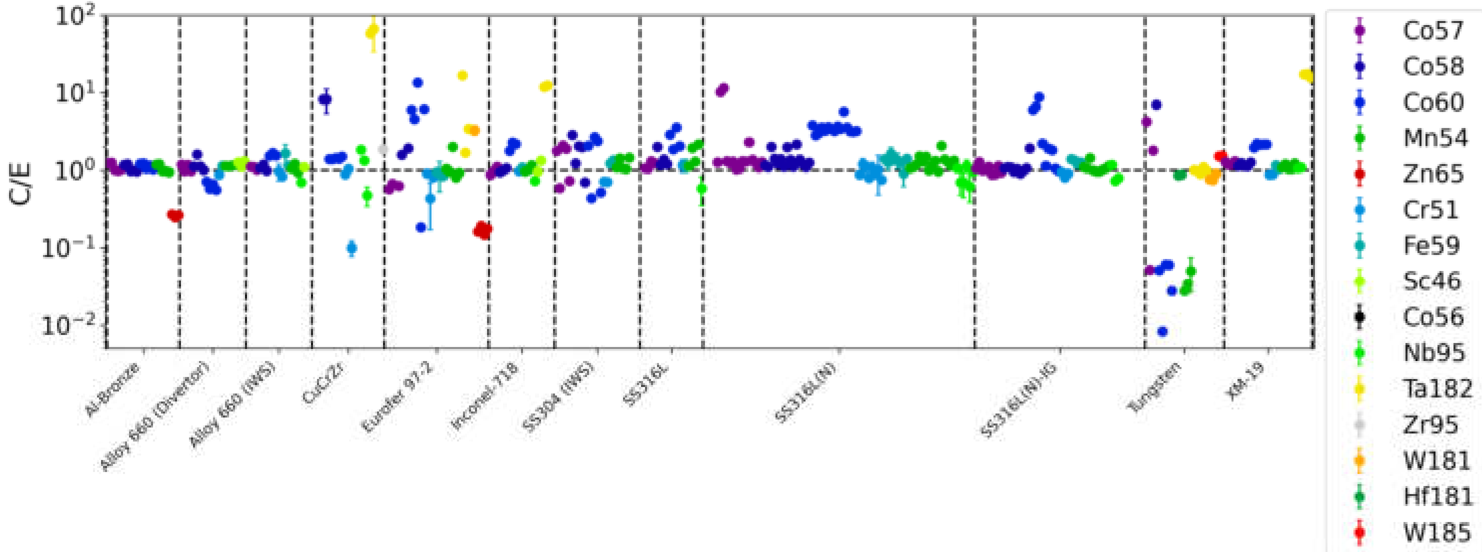
Improved measurements techniques

Inconel-718 ITER#18

UK Atomic Energy Authority

# Activation of real ITER materials: C/E results DTE2 & main achievements

## Comparison between predictions MCNP6 + FISPACT II & measurements




- ✓ Activity of $^{46}$Sc, $^{51}$Cr, $^{54}$Mn, $^{95}$Nb, $^{181}$W and $^{181}$Hf generally well predicted within **±25%**
- ✓ Some overestimation in **$^{60}$Co $\overline{C/E}$ ~2.05** **$^{182}$Ta $\overline{C/E}$ ~9.0** **max ~68.4 CuCrZr**
- ✓ Discrepancies in **$^{65}$Zn, $^{110m}$Ag, $^{58}$Co,** $^{181/185}$**W** in various samples
- ✓ C/E for nuclides relevant for maintenance generally close or > 1 - **Conservative**

- **Demonstrated reliability of MCNP & FISPACT-II with modern nuclear data if accurate and detailed neutronics & materials certificate information are used**
- **Evidenced potential contamination due to manufacturing and cutting techniques**
- **Need for assay of materials compositions & impurities content**

**Polished ITER samples are currently installed for DTE3**

→ *L. Packer P5B3*

# Functional material damage studies- PIE of insulators

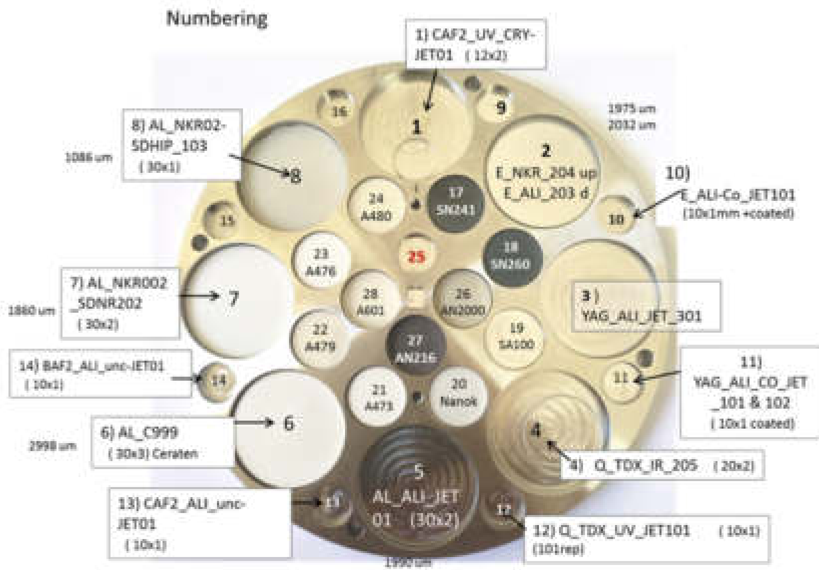
Study of functional materials physical properties degradation during DT to validate simulation predictions of damage induced by fusion neutrons

**Post Irradiation Examination of selected insulators**

- **Set of fusion insulators installed in Sept 2020 in LTIS**
- **Irradiated during TT, DTE2 & ongoing DTE3**

  **Expected cumulated DT N fluence at the end of DTE3 $10^{16}$ n/cm$^2$**

- **Post-irradiation characterization in CIEMAT & DEMOKRITOS labs – expected spring 2024**
  - **Optical:** Optical absorption, Reflectance and photoluminescence
  - **Dielectric:** Loss tangent (kHz to GHz) and thermally stimulated currents.

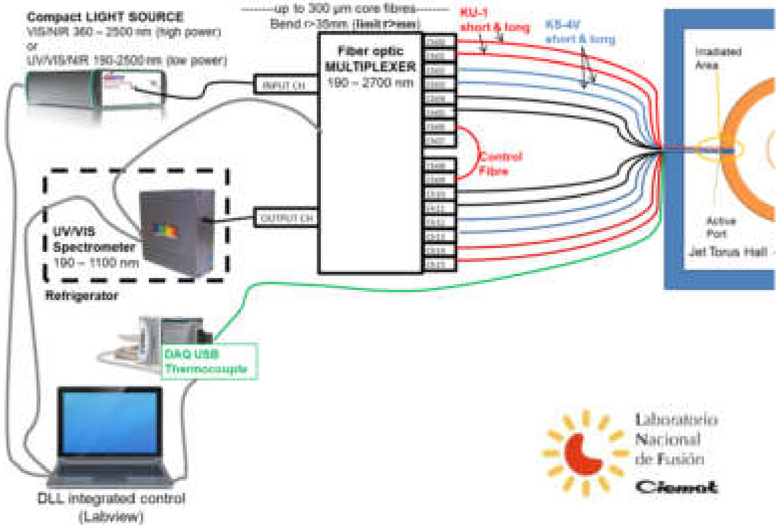


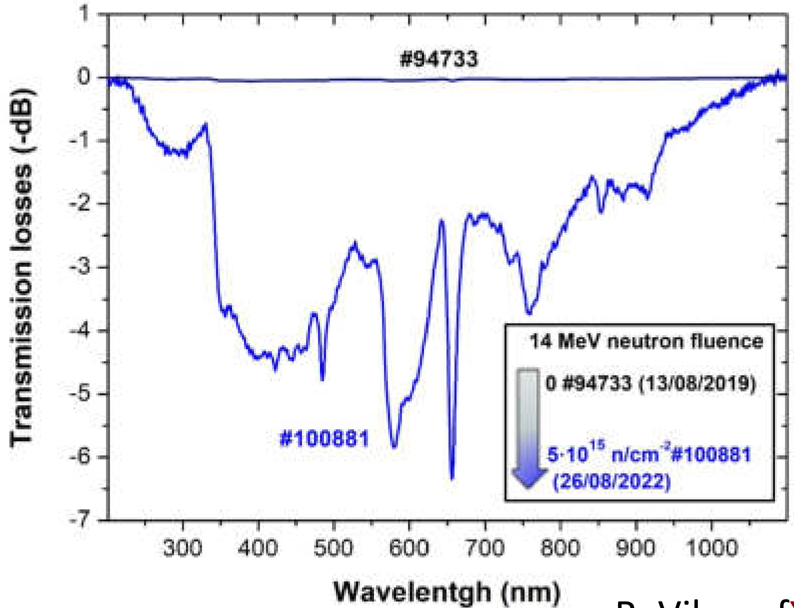

- Oxides ($Al_2O_3$, $SiO_2$, $MgAl_2O_4$, YAG)
- Fluorides ($CaF_2$ ,$BaF_2$)
- Nitrides (AlN, $Si_3N_4$)
- Diamond

Laboratorio Nacional de Fusión Ciemat

# Measurements of degradation of optical fiber transmission

In-situ measurements of optical fibre evolution with accumulating DT pulses and recovery phases



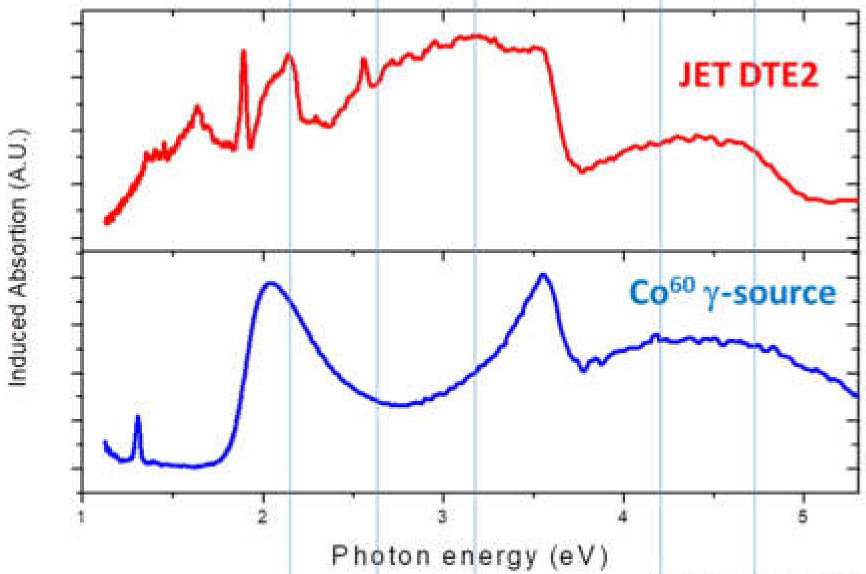

R. Vila, refXXX ?

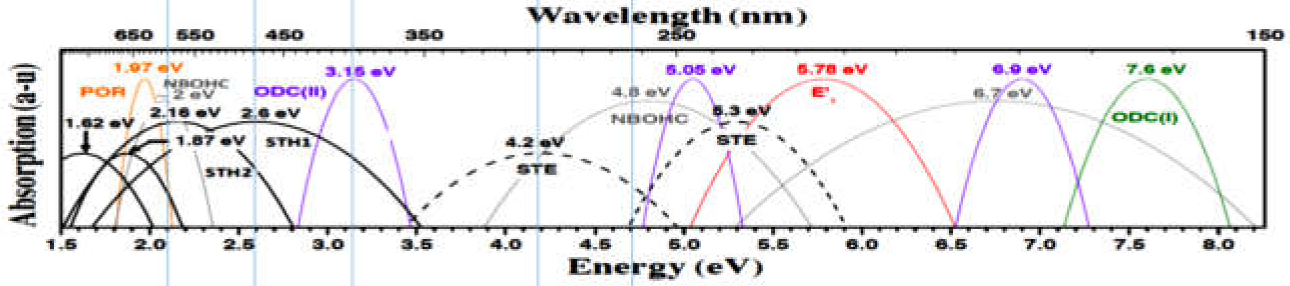
- **Real time testing of optical transmission during TT & DTE2**
- **More than 5000 pulses until Aug 2022 !**

**Observed degradation of the transmission correlated to cumulated dose!**

**In Sept.’22 during the samples retrieval the fiber was broken… no repair/replacement was feasible**

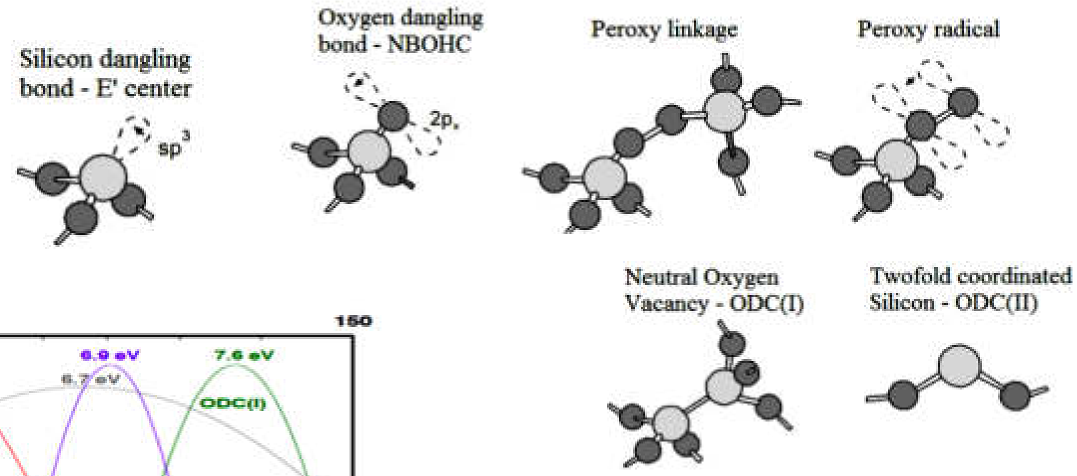
# Effect of neutron and gamma irradiation on optical fiber




**Neutrons are producing ODC, STH's and NBOHC defects.**

**Gamma and neutrons both create self-trapped excitons (STE) that decay into E' and NBOHC**



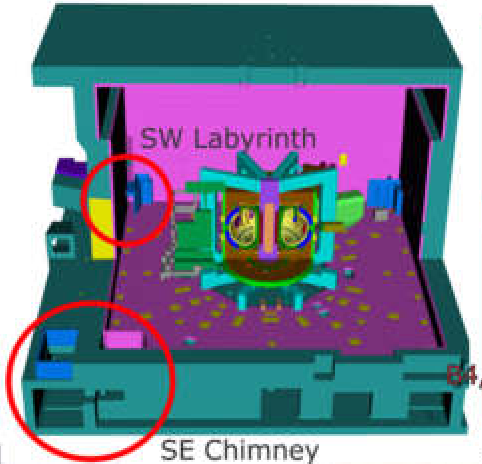

- **Evidenced differences between gamma and neutron induced defects**
- **Unique achievements on transmission characteristics of silica fibres relevant at the initial ITER nuclear stage**

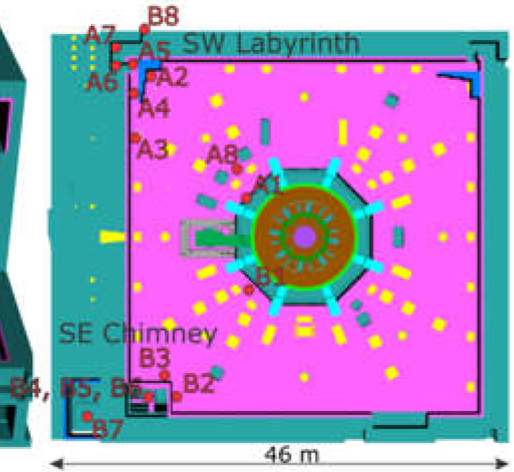
# Neutron Streaming benchmark experiment

**Unique experiment for the validation of ITER-relevant neutronics code in tokamak under DT**

- **Neutron fluence & dose measurements**
  - **Thermoluminescent dosimeters (TLD)**
  - **Activation foils (AF)**
- **Accurate calibration in DD & DT**
- **Calculations**
  - **MCNP5&6 +ADVANTG**
  - **TRIPOLI-4©**
- **Several positions inside the torus hall & labyrinths**

  **22 TLDs & 6 AF**
- **Accurate measurements for quantitative comparison to simulations → Validation**



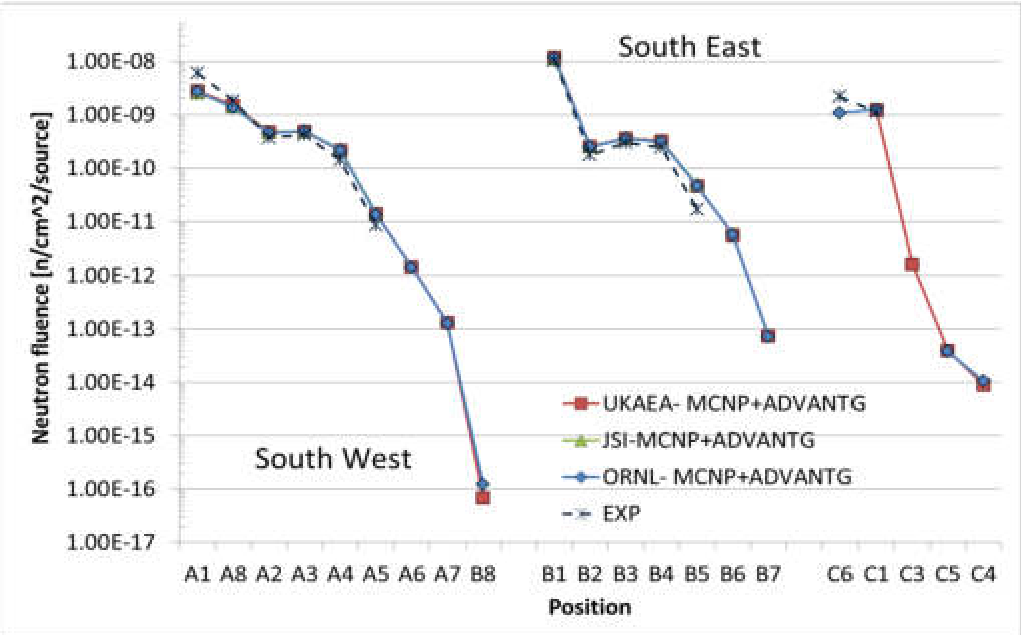


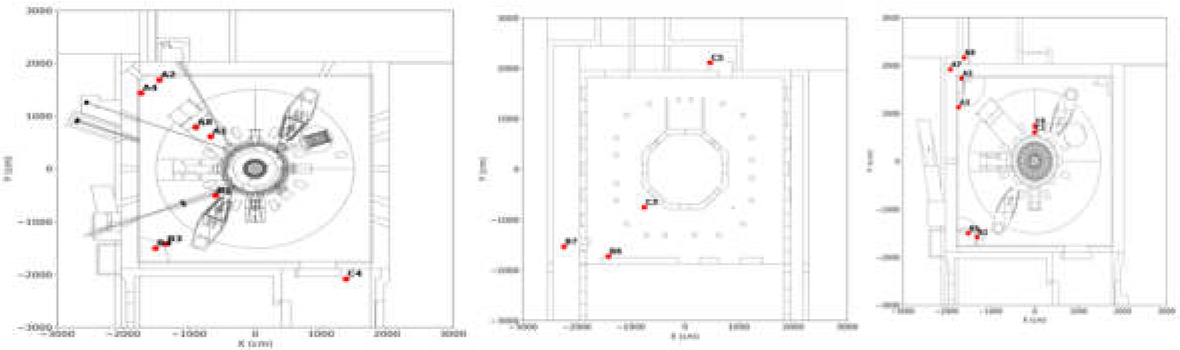
- **>40 m from the plasma**
- **8 orders of magnitude variation**
- **$10^5$ to $10^{13}$ n/cm$^2$ N fluence range in DTE2**

**DTE3: installation of new assemblies**

[Batistoni, NF, 55, 053028 (2015)- Villari, FED,107,171 (2017)- Kos, FED, 147, 111252 (2019)- Naish, FED, 170, 112538 (2021)]

# Preliminary results of TT- 2021 Neutron streaming benchmark experiment



TT (C40A): 8.53x$10^{20}$ N exposure ~240 days

- ✓ **C/E in the range 0.4 (A1)- 2.9 (B5)**
- ✓ Increase of the overestimation with the distance from the machine – same trend as past
- ✓ Improvements compared to past benchmarks thanks to
  - *TLDs calibration*
  - *Updated calibration of JET n diagnostics*
  - *Model & computation methodology upgrade*

*→ I. Lengar P6C2*

- **Implemented robust experimental techniques for neutron fluence measurements**
- **Demonstrated reliability of the codes for nuclear analysis - general conservative predictions**
- **Evidenced the importance of accurate modeling & materials description following machine evolution**

# Shutdown Dose Rate benchmark experiment

**Unique experiments for the validation in DT of the numerical tools used for Shutdown Dose Rate calculations in ITER**

**SDR performed in DD, TT and DT campaigns**

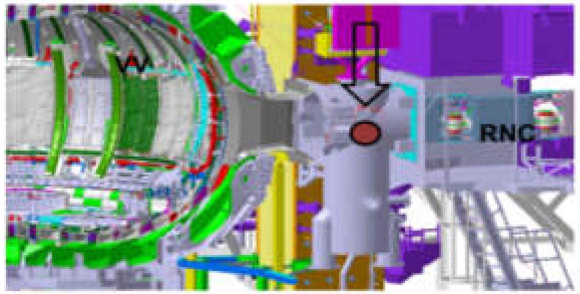
- **2 ex-vessel positions**
  - POS 1: on a lateral horizontal port - OCT1
  - POS 2: on the ITER like-Antenna port- OCT2
- **Detectors & measurements**
  - Neutron fluence with activation foils
  - Shutdown dose rate with spherical ionization chambers (IC)
  - Decay gamma spectra with various spectrometers (DD)
- **Calculations with Rigorous-2 –steps & Direct 1-step codes**
  - Advanced D1S (ENEA)
  - R2Smesh (KIT)
  - MCR2S &N1S (CCFE)
  - R2SUNED & D1SUNED (UNED)
  - ORNL R2S (ORNL)

Ref. ITER tool

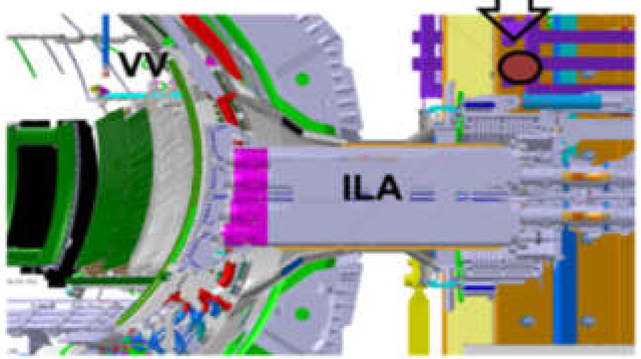
**Validation : C/E comparison & uncertainties**

DTE3 measurements ongoing- New AF assembly

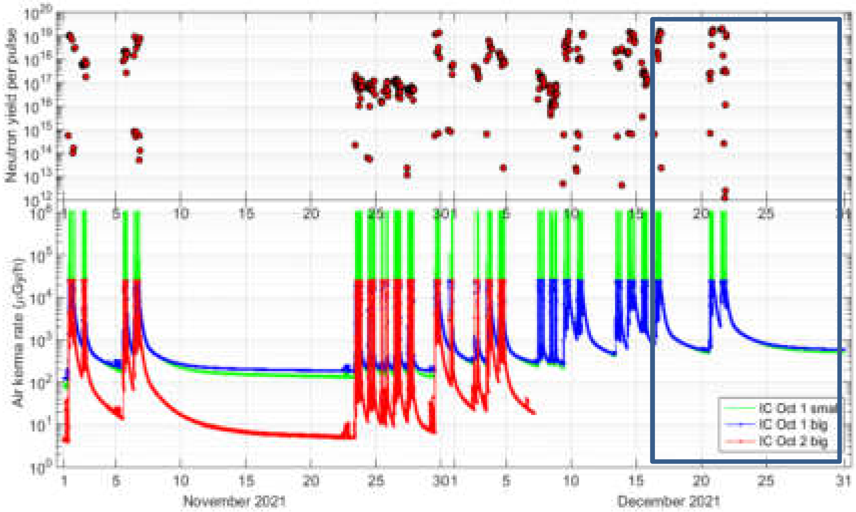
POS 1




POS 2

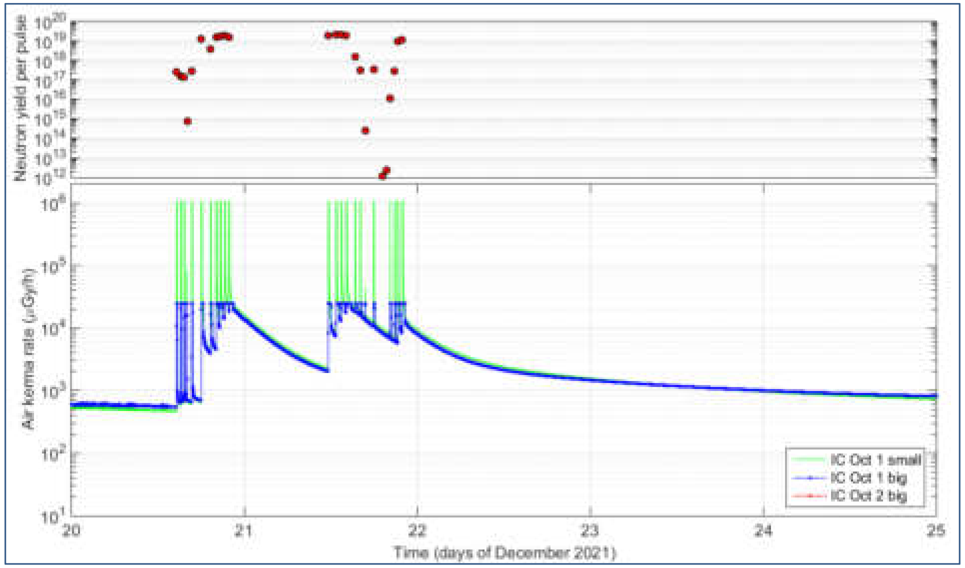


# SDDR Measurements during DTE2




- OCT 1 ~100 µSy/h-20 mSv/h
- OCT 2 ~4µSv/h -~1 mSv/h

- ❖ **Continuos online measurements since 2016**
- ❖ **Full correlation with JET N diagnostics**



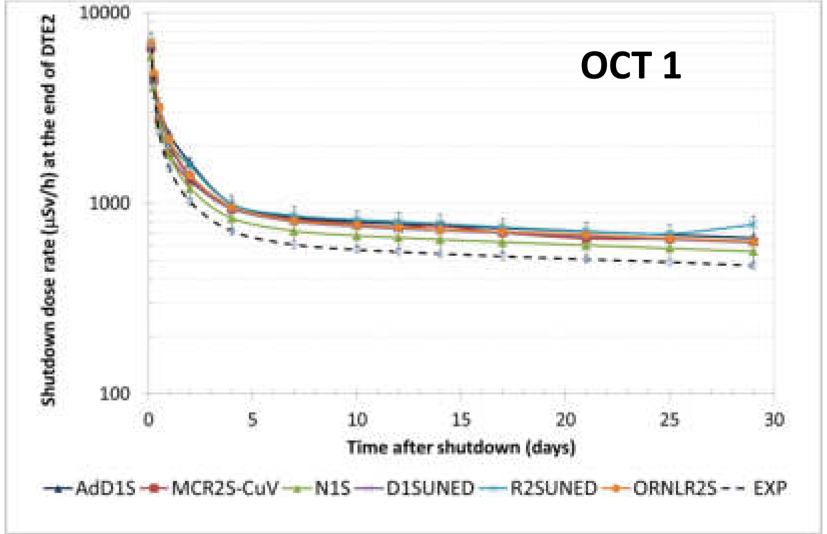

**SDDR ITER requirements**

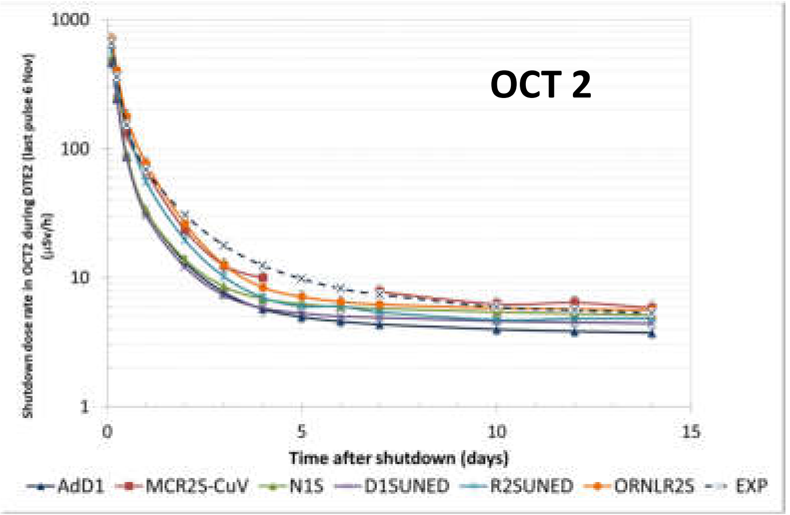
< 100 µSv/h at $10^6$ s after shutdown in Port Interspace

< 10 µSv/h at 1 day after shutdown in Port Cell

- **Implemented robust experimental techniques for online shutdown dose rate measurements correlated with plasma operations**
- **Unique database of shutdown dose rate measurements in tokamak in relevant ITER range**

# Preliminary results DT SDDR benchmark- SDDR C/E




- ✓ **OCT1** optimal agreement at short cooling times (<1d)- overestimation at 1 months + 40%
- ✓ **OCT2** D1S underestimation up to -60% at 2 days of cooling time due to model uncertainties - E discretization artifacts in R2S
- ✓ Better agreement compared to DD due to improved computational models/tools/benchmark analysis methodology & updated JET N calibration

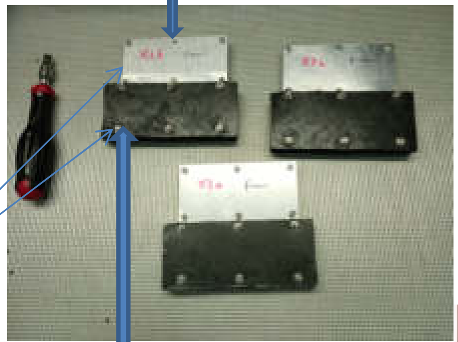
- **Demonstrated reliability of MCNP-based SDDR tools with modern nuclear data library & accurate modeling – geometry/ materials/ machine evolution for SDDR predictions**
- **Identified artifacts and constraints of the computational tools → lead code developments – new features**
- **The accurate knowledge of materials impurity & machine configuration changes play a key role**

More accurate analyses and study of discrepancy in progress

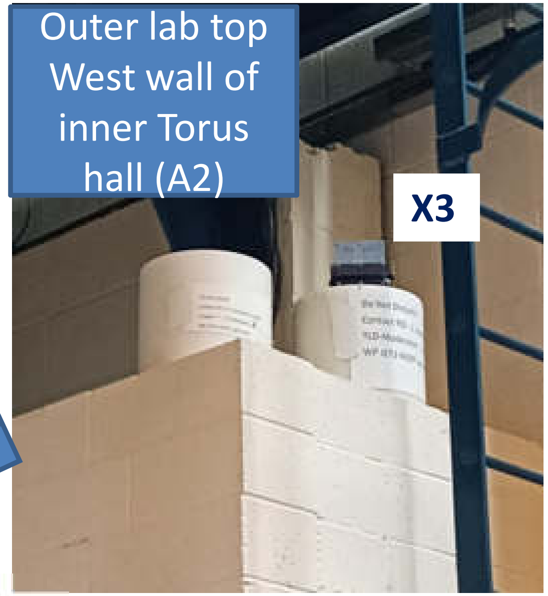
# Neutronics experiments: Tests of B4C flexible shield for DTE3

**Tests with activation foils**

w/o shield



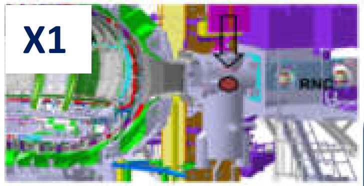
with shield





$B_4C$ 80%$_{wt}$ + Glue 20%
H 1%$_{wt}$
$\rho$ 1.36 g/cm$^3$

https://mirrotron.com/en/products/radiation-shielding





- **Test of shielding performance of flexible Boron shield useful for application in ITER ISS – PC & RPA**

Mirrobor™ used at CERN to protect some electronics

*Kindly procured by CERN*

+ SEE JET test bench

# Test of detectors for TBM & HCPB TBM mock-up experiment

## Test of n/T detectors developed for TBM at JET

- Diamond detectors in vertical port

high temperatures (up to 250 °C), magnetic field (up to 3 T), and high level of fluxes (up to~$10^{13}$ n/s)

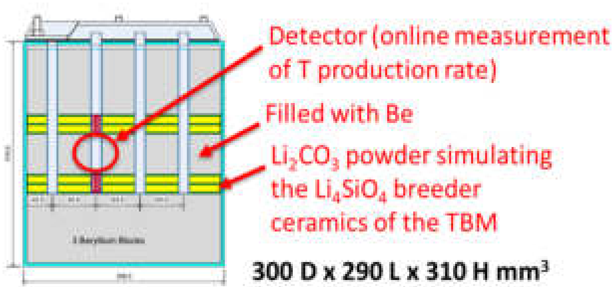
- Activation foil spectrometer system

DTE2 results

☹ **poor repeatability, poor correlation with neutron yield in DT**

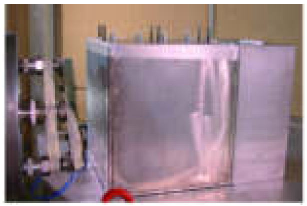
## HCPB TBM Mock-up experiment

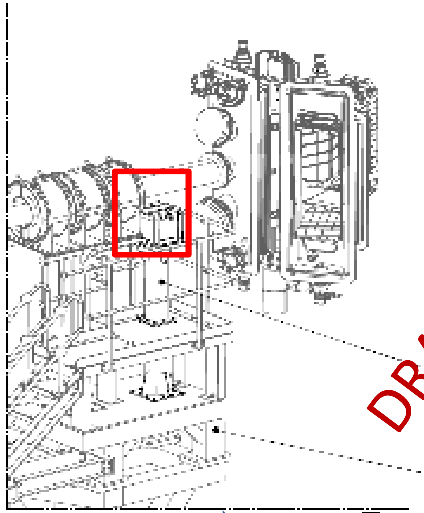
Diamond detector for on line measurement of tritium production rate

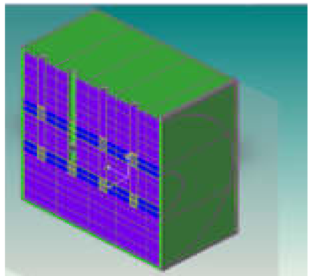



Same mock-up used at FNG for HCPB TBM experiment

[P. Batistoni *et al* 2012 *Nucl. Fusion* 52 083014]







For DT neutron yield rate <$10^{15}$ n/s- **constant detection efficiency** ☺ **>$10^{15}$ n/s saturation**☹

New results?

$C_{MCNP}$/E Tritium production **0.77-0.79**

Underestimation

**Improving in measuring chain for DTE3**

→ *N. Fonnesu P2A4*

# Neutron Single Event Effect (SEE) experiment on electronics during DTE-3

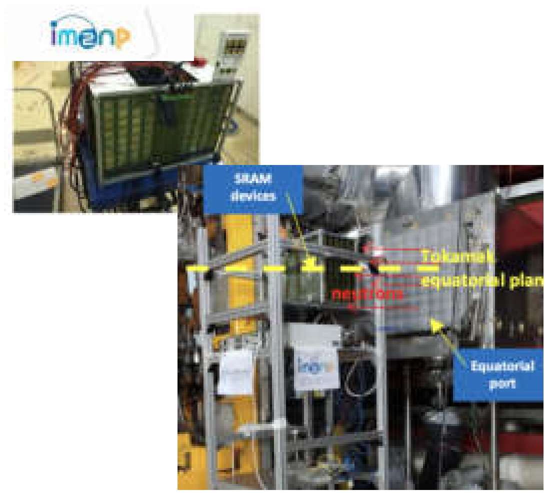
- “**Single event effects“ (SEE)** induced by individual neutrons →damage or destroy electronic devices or sensors, corrupt signals in analogue/digital circuits, corrupt data/programs in memories, etc.
- Commercial electronics - designed and qualified for natural terrestrial ground-level environment N flux ~**0.01 n/cm²/s**→ Impractical in the area where electronics is located
- Radiation-hardening or radiation-qualification, local shielding, relocation and/or multiple redundancy → not applicable for all systems and locations
- **SEE is one of the major problem in modern tokamaks/particles accelerators!**

## SEE experiment at JET

○ **Validation of the prediction of neutron-induced failures in electronic for ITER & modern tokamaks during DTE3**

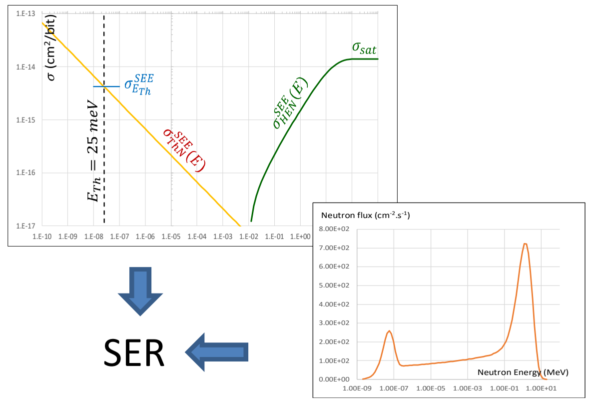
○ **Complement D-D experiment on WEST and experiments at CERN for demonstration of equivalence study**

**Unique systematic study of SEE effects on electronics in tokamak under DT**



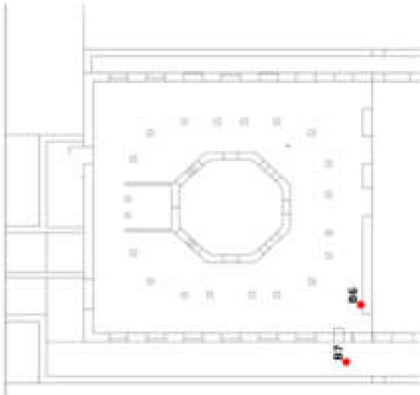

Bit flip SER measurements on RTSER at WEST in DD

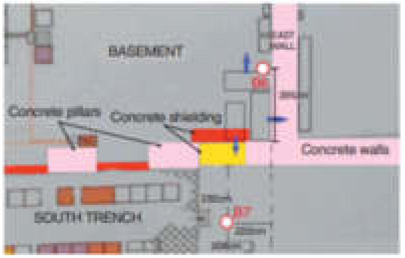
[J.L. Autran, IEEE TNS, ***69***, 501-511, 2022]

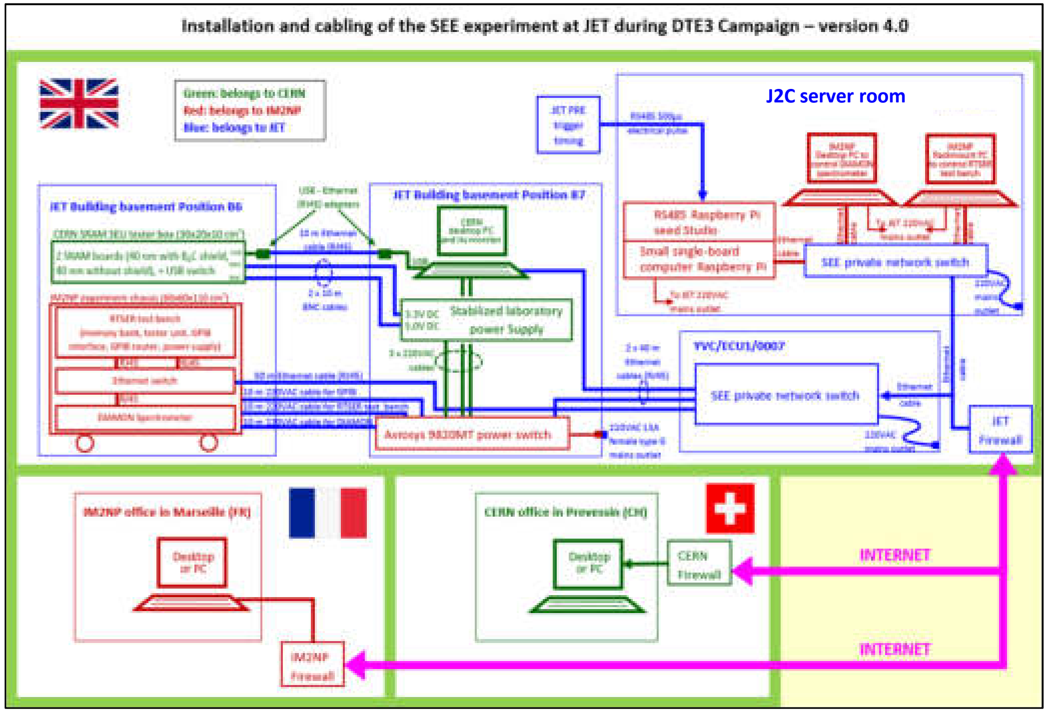


# SEE experiments at JET for validation of the SER prediction method

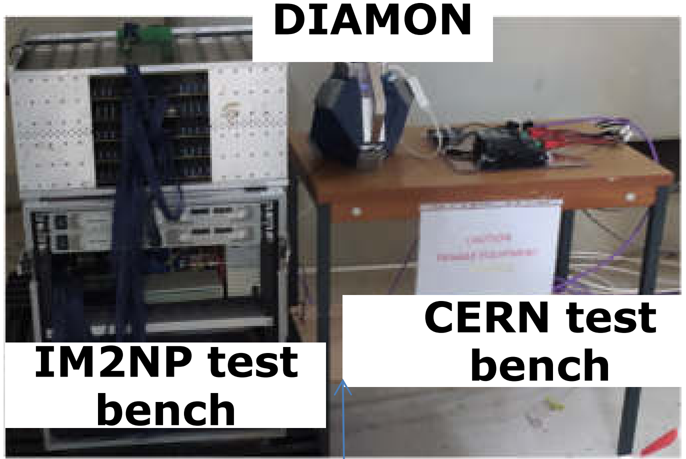
**Installation in JET SE basement – early June '23**






SEE installation in B6




**UKAEA activation foils**

**Real Time Soft Error Rate (RTSER) test bench from IM2NP Institute (Aix-Marseille University)**

384 memory chips (65 nm bulk SRAM, BPSG-free, manufactured by STM)- 3.226 Gbits

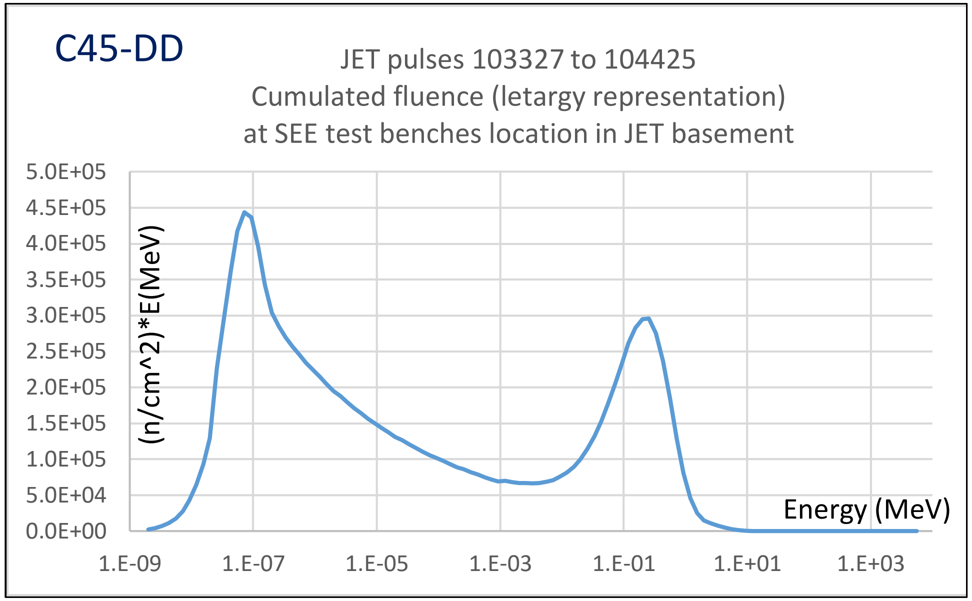
**CERN ISSI test bench**

40 nm SRAM from ISSI – 32 Mbits

**DIAMON – Raylab + Activation foils+ PNS UKAEA**

Neutron spectra

# SEE experiment: first results DD campaign




DIAMON measurements

Cumulative DD neutron fluence 1.3x$10^7$ n/$cm^2$ @77 shots

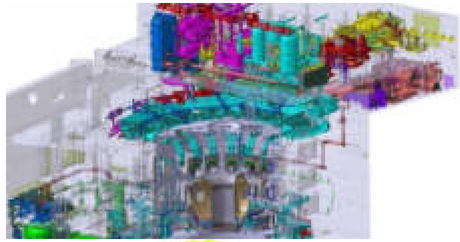
- 8 Single Bit Upset (SBUs) in RTSER test bench (3.2 Gbits STM 65 nm SRAM)
- 1 SBU in CERN test bench (32 Mbits ISSI 40 nm SRAM)

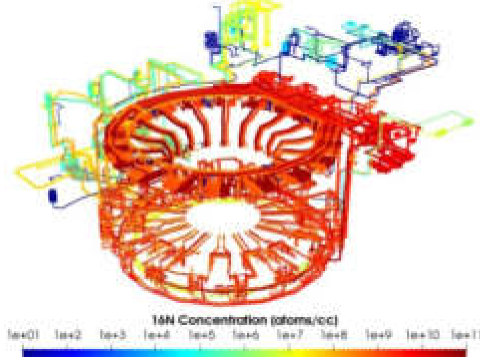
- **The test benches and their remote operation work as expected**
- **Results allow expecting good measurement statistics during the DTE3 campaign**
- **Bit-flips / total fluence in RTSER at JET = consistent with previous WEST DD tests in 2020**
- **Tests ongoing in DTE3!**

# Water neutron induced activation: the fusion challenge

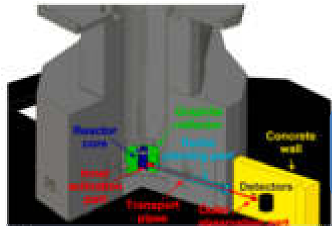
- **Water circulating in cooling pipes is activated by high energy neutrons**
  **${}^{16}O(n,p){}^{16}N$ (E>) & ${}^{17}O(n,p){}^{17}N$ (E> ) reactions**

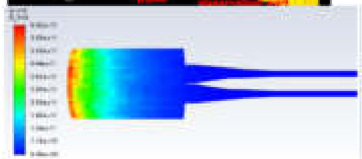
  ${}^{16}N$ $T_{1/2}$ 7.13 s β decay: γ 6.13 MeV (69%) & 7.12 MeV (5%)
  ${}^{17}N$ $T_{1/2}$ 4.173 s β decay: delayed n decay (95%) & γ 871 keV (3.34%)
- **Activated water is transported through the cooling circuits**
- **The decay of ${}^{16}N$, ${}^{17}N$ induces**
  - additional heat load and radiation dose to the machine components
  - significant radiation fields outside the bioshield, critical for sensitive systems
- **The assessment of activated water loads is challenging**
  - use of complex methodologies taking into account exposure, activation, flow velocity and decay for individual water volumes in all different loops
  - Conventional circuit method, Actiflow/Gammaflow (UKAEA), FLUNED (UNED), RSTM (F4E), UniPa DEMO tool (University of Palermo), etc…
- **Experiments essential for computational tools validation**
  - 2019: FNG Water activation experiment under 14 MeV – ITER FW mock-up
  - 2022-2025 Water activation loop at JSI TRIGA fission reactor
  - 2022 First water activation measurements in tokamak at JET post DTE2
  - <u>2023 – ongoing Unique dedicated water activation experiment at JET</u>





*M. D. Pietri, FED, 171, 2021, 112575*



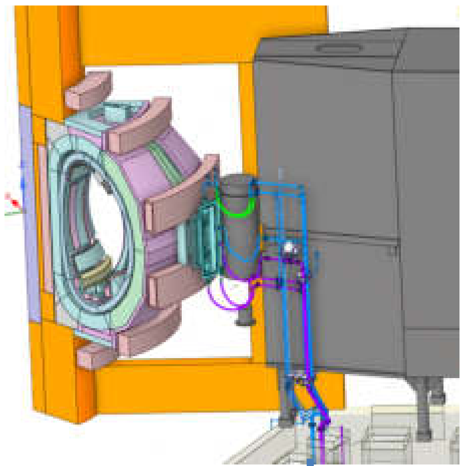


→*R. Pampin P4D3*
→*D. Kotnik PS2113*

# JET water activation experiment during DTE3

**Unique experiment in real tokamak water cooling loop under DT for the validation of water activation predictions in ITER**

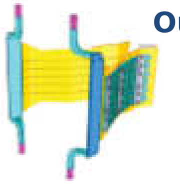
**NBI duct scraper cooling loop Oct 4**

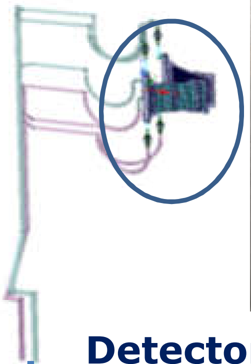


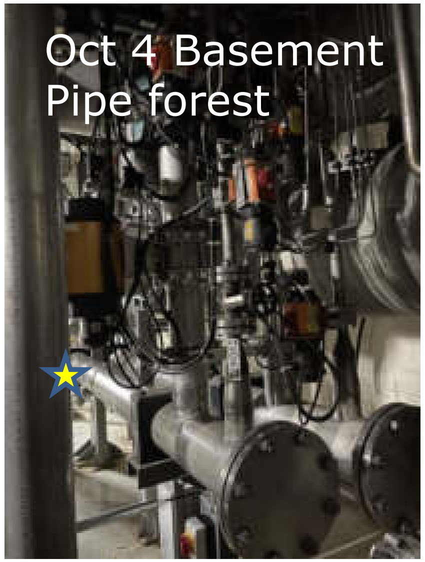
**Basement of octant 4**

**Location of WACT system**

**Outlet horizontal pipe**





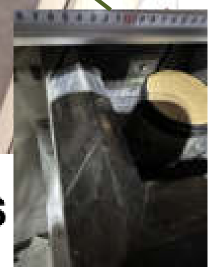




**Detectors**

- Gamma spectrometers: NaI & BGO
- Dose rate: Ionization chamber

**WATER ACTIVATION EXP ASSEMBLY**

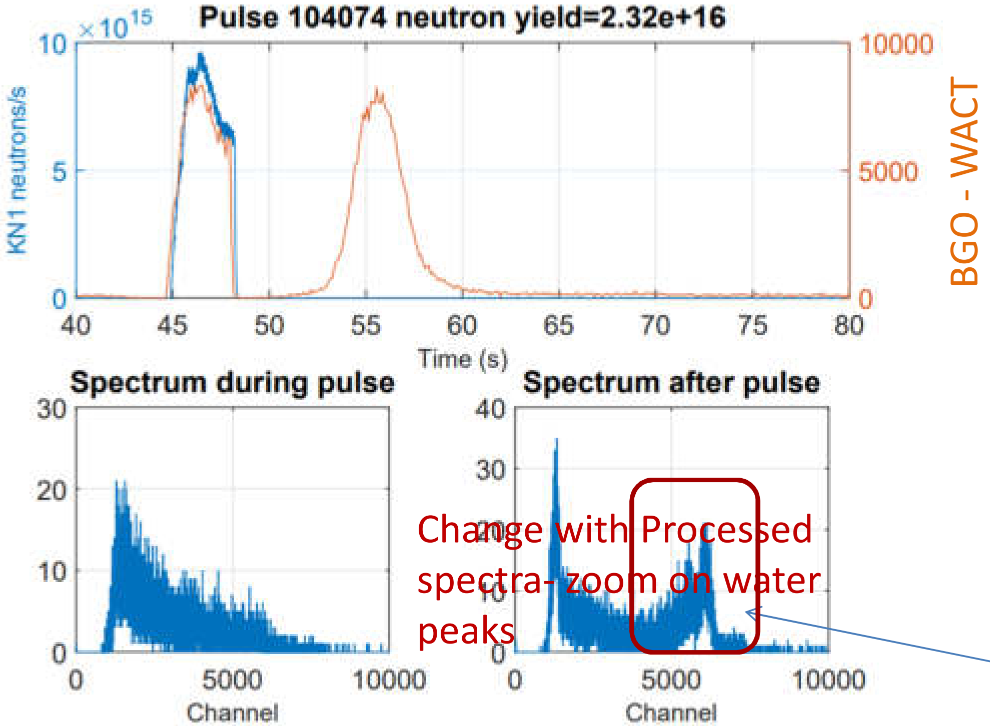
Measurements of $\gamma$ from $^{16}N$ decay

Online acquisition-CODAS

# JET water activation experiment- first measurements!!

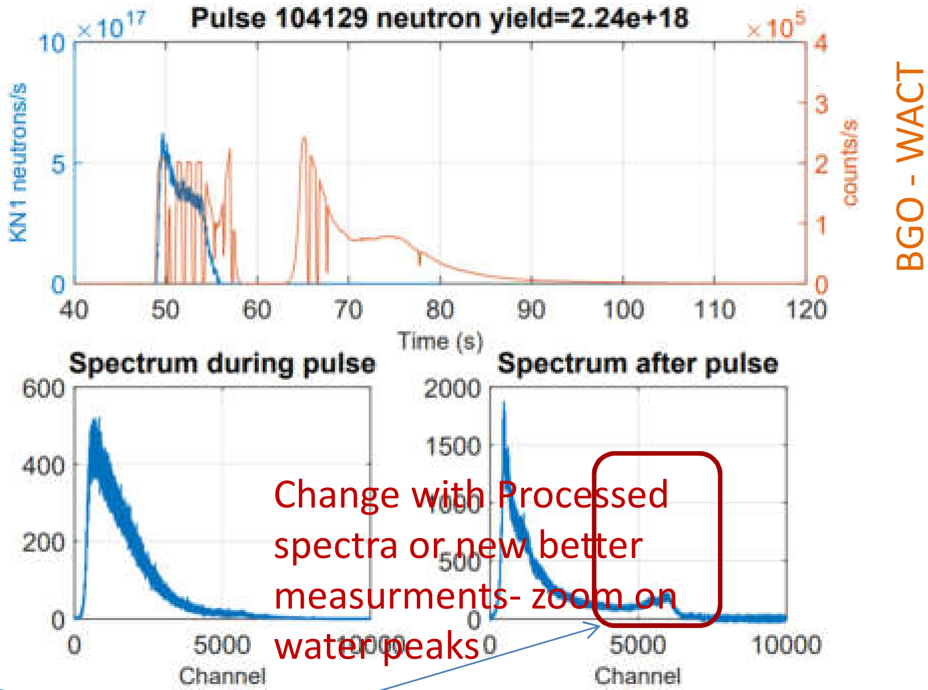
## C45 DD campaign

DT neutrons from T burn-up ~1% total N yield




**Delayed signal due to activated water**

## DTE3 campaign




**Water activation 6&7 MeV peaks!!**

FIRST MEASUREMENTS OF WATER ACTIVATION IN TOKAMAK IN DT!

ENEA IJS UK Atomic Energy Authority

Post-analysis with Actiflow/Gammaflow, RSTM, FLUNED & DEMO tool in 2024

# Conclusions

- **Many scientific achievements relevant for ITER and useful in preparation of DEMO have been obtained so far and a lot of data and results are expected from DTE3!**
- **The unique experience gained through the technological exploitation of JET DT operations has given the opportunity to:**
  - **Implement a successfull method for 14 MeV calibration of neutron diagnostics**
  - **Develop & improve nuclear experimental techniques & computational tools**
    - Gamma and neutron spectroscopy, monitoring & dosimetry
    - T monitors
    - Optical and dielectric characterization
    - Nuclear waste characterization
    - Radiation transport, materials and water activation, shutdown dose rate computational tools
  - **Demonstrate the reliability of the codes used for ITER nuclear analysis**
    Neutron transport, activation and shutdown dose rate assessment - validation
  - **Improve the knowledge on the effects of neutron irradiation**
    Damage, activation, streaming, shutdown dose rate, SEE on electronics, tritium production Neutron transport, activation and shutdown dose rate assessment
  - **Identify critical issues affecting reliability**
    - Calibration
    - Neutronics models & nuclear data
    - Materials chemical compositions- impurities /contamination
    - Operational conditions – scenarios and machine evolution
    - Bugs & artifacts
  - **Produce huge database & collected irradiated samples to be used for many further future studies/validation**
- **The cumulated DT fluence level at JET is now more significant for radiation conditions of ITER first licensing phase & results from JET DD campaigns are also relevant**
- **Thanks to the acquired experience, the implementation of a technological exploitation of DT operations with dedicated experiment in early DT phase in ITER could be feasible and extremely valuable for supporting demonstration in view of the second step licensing and for DEMO**

**Thank you!**

**Questions/Comments?**