RADNEXT 3rd Annual meeting

JET research for the preparation of fusion power plants

J. Mailloux*, JET contributors and EUROfusion Tokamak Exploitation Team

***UKAEA Head of JET Science**

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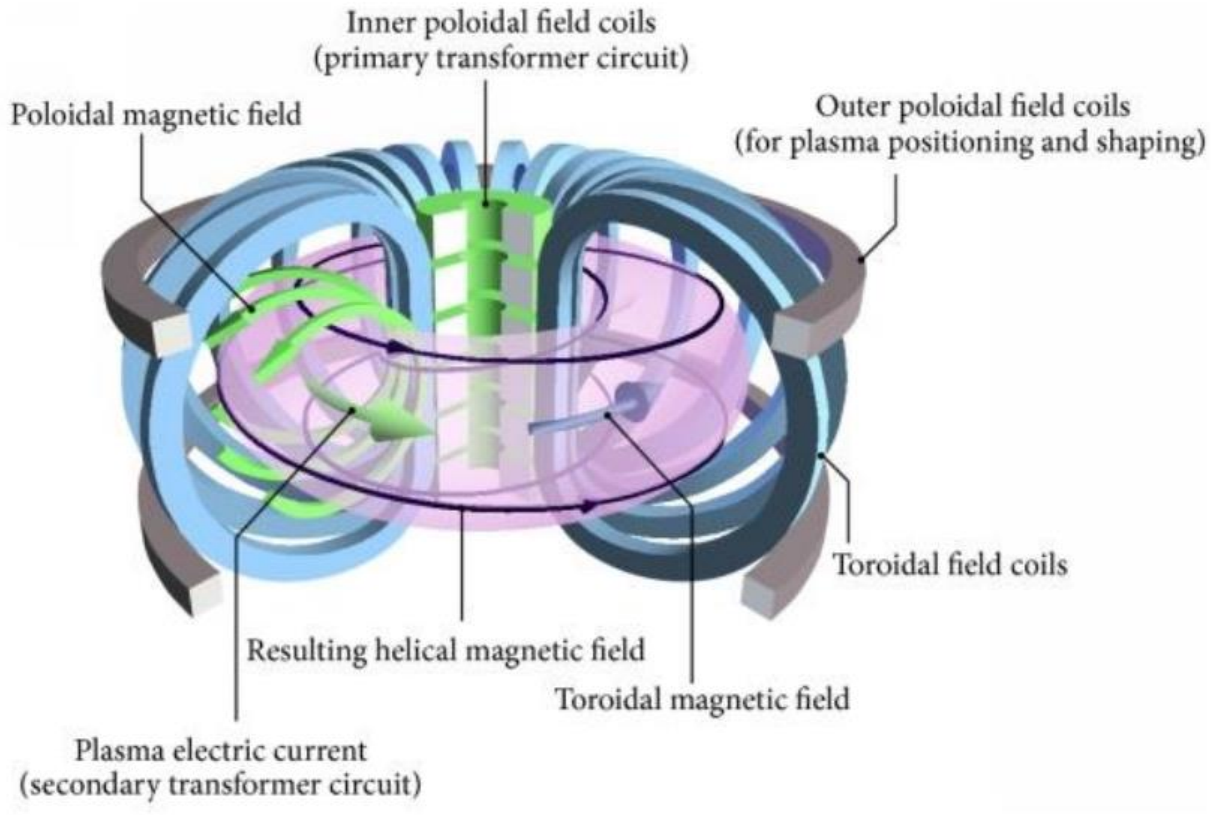
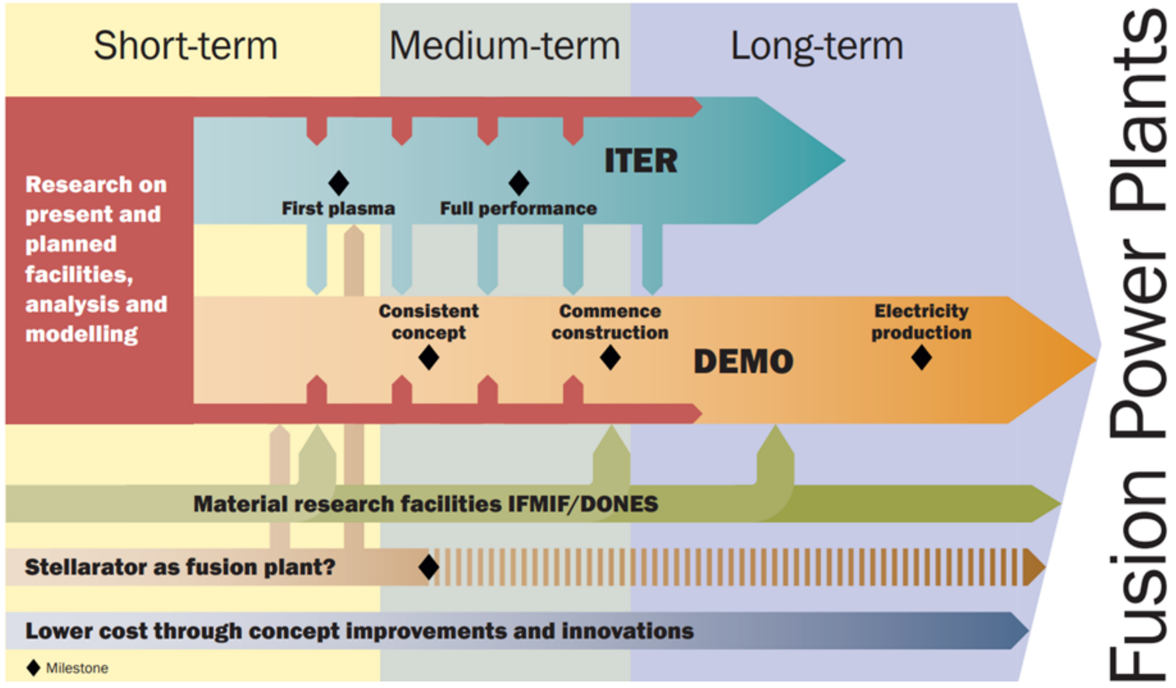
Tokamaks



- Tokamaks use powerful magnetic fields to confine charged particles
- Hot plasma core (~100 million degrees) for optimal D-T reactions but with cool edge compatible with wall
- Complex:
  - Numerous systems and auxiliaries
  - Harsh environment: radiation, temperature gradient, high magnetic field
  - Plasma is non-linear medium
- Decades of results give us confidence we know how to reach conditions required for burning plasmas
- Several challenges remain for commercially viable fusion power plants

Challenges for commercially viable fusion power plants

EUROfusion roadmap



- **Plasma control challenges:**
  - Tolerable first wall heat loads
  - Disruption avoidance and mitigation
  - ELMs suppression
- **Technological challenges:**
  - Tritium breeding blankets
  - Materials and components resilient to ions and neutron fluxes
  - Remote handling

JET helped identify these challenges and directions for solutions

New facilities in place or planned in Europe and elsewhere address these challenges separately (material testing facility, volumetric neutron source, etc) & in an integrated way (ITER, DEMO, STEP, SPARC, BEST)

Culham Campus, Oxfordshire, 2024

Outline

- A short JET history
- Motivation for deuterium-tritium experiments
- Recent results
  - D-T Plasma
  - Neutronics
- Next steps

Joint European Torus: a crucial step towards fusion reactors

JET

Verbatim from 1975:

The essential objective is to obtain and study a plasma in conditions and dimensions approaching those needed in a thermonuclear reactor.

These studies will be aimed at defining the parameters, the size and the working conditions of a tokamak reactor.

The realization of these objectives involves four main areas of work:

- the scaling of plasma behaviour as parameters approach the reactor range;
- the study of plasma-wall interaction in these conditions;
- the study of plasma heating;
- the study of alpha particle production, confinement and consequent plasma heating.

JET ready on time and to budget

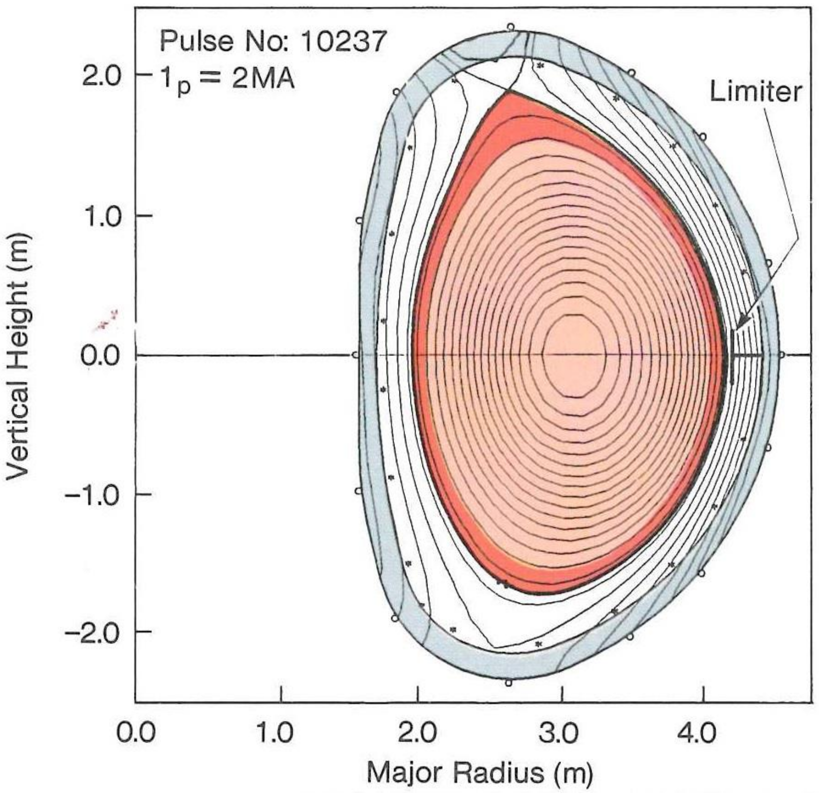
- First discussions for the construction of a big tokamak in Europe started in 1971
- Construction of JET started in 1979
- Final stage of assembly completed in January 1983
- 3MA achieved by the end of 1983

Thanks to the designers' foresight, JET remained relevant for nuclear fusion research for 40 years

JET adapted to address arising science & technology developments: H-mode example

JET was designed for (and started) operation in elongated magnetic limiter configuration

1982 : H-mode (high confinement mode) discovered on Asdex (Germany) ➔ magnetic separatrix a key ingredient - configuration possible in JET ?

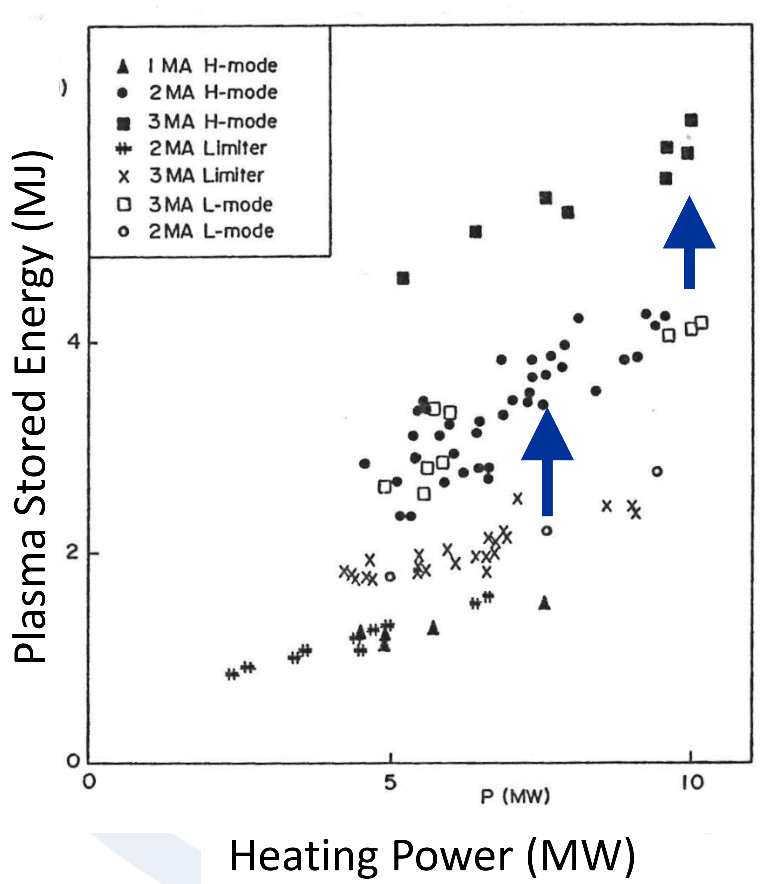


[JET Progress Report 1987]

1986 : first X-point and H-mode studies

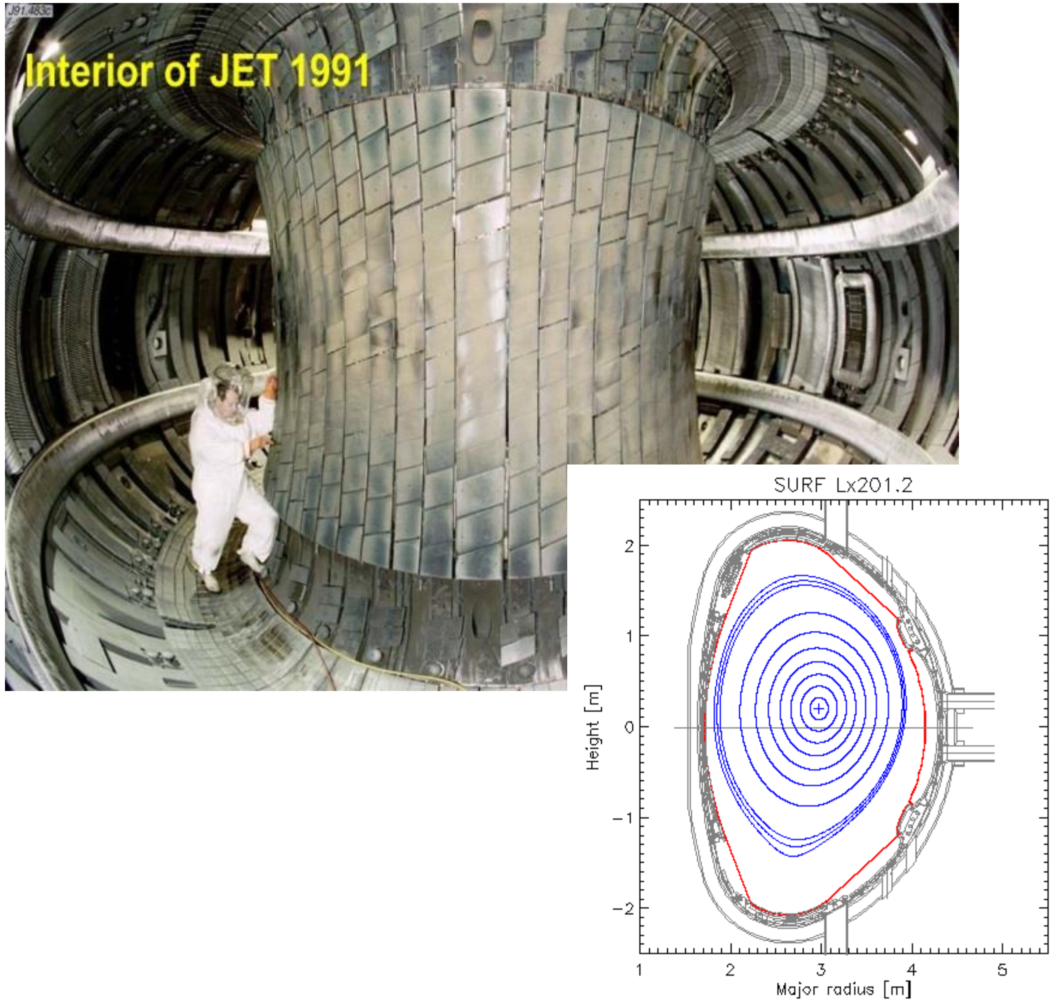
1987 : upgrade of P1 Primary coil (additional amplifier PFX for central pancakes) and improved vertical stabilization

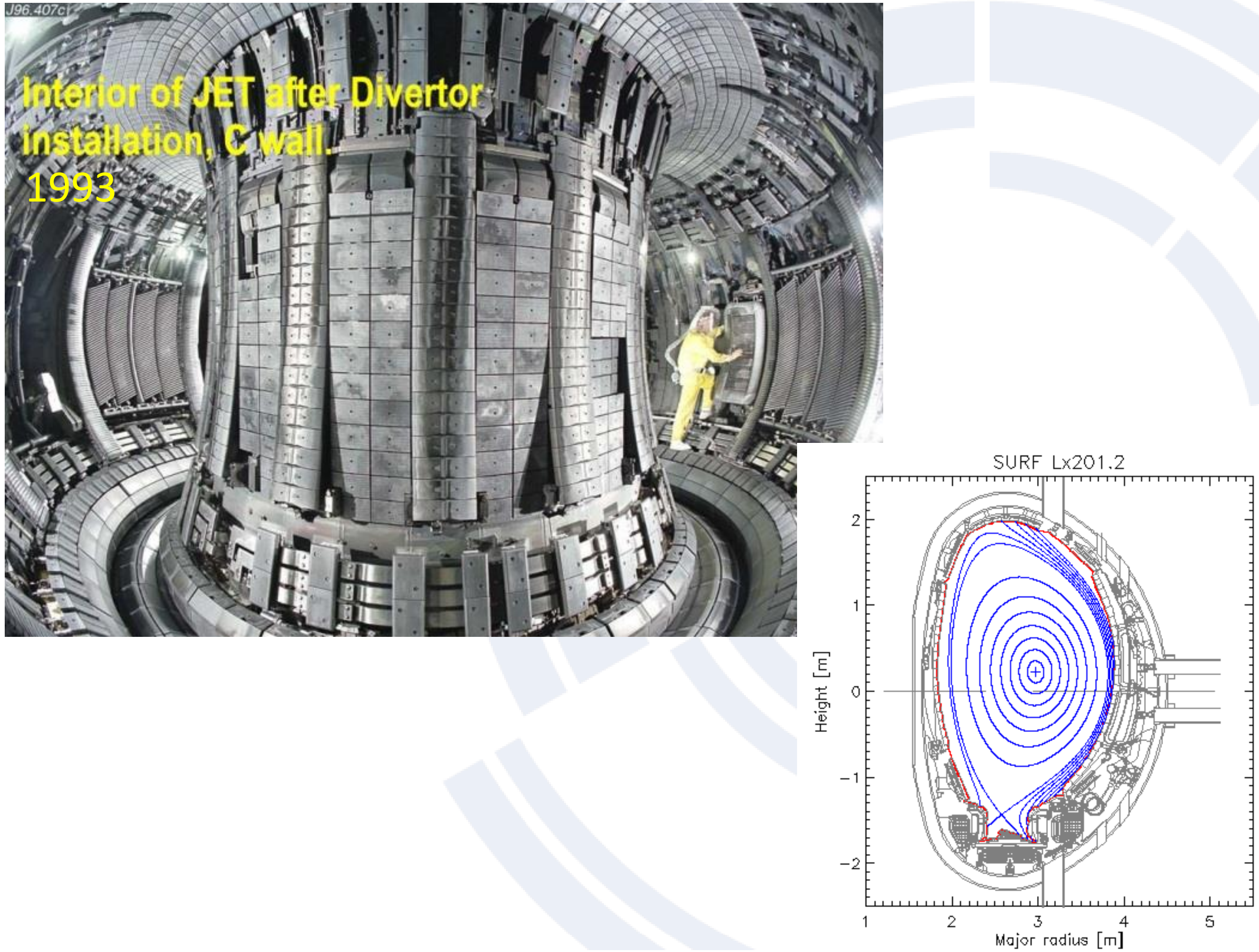
➔ H-mode obtained, doubling the energy confinement time in JET plasmas



[A. Tanga et al 1987 Nucl. Fusion 27 1877]

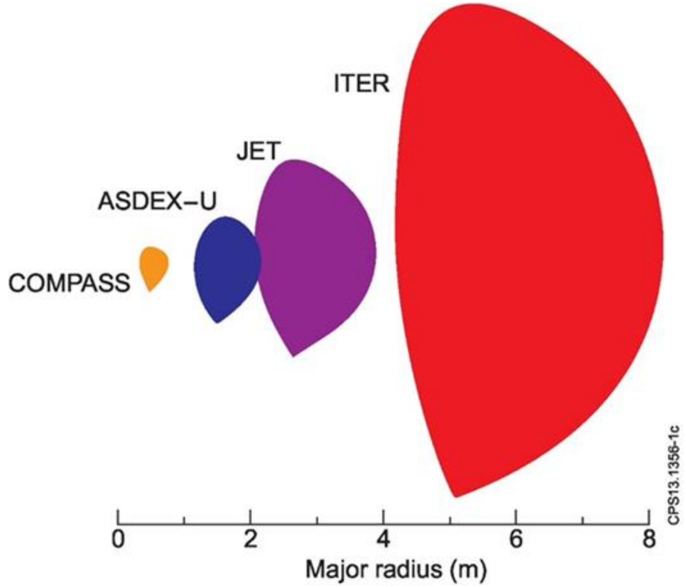
H-mode results motivated addition of divertor (coils, cryo-exhaust & tiles for high heat loads)


Interior of JET 1991


Interior of JET after Divertor installation, C wall.
1993

+ Continuous improvements to heating & fuelling systems, diagnostics, controls, throughout

Summary of JET parameters & capabilities



Major Radius 2.96m
Minor radius 1.25m

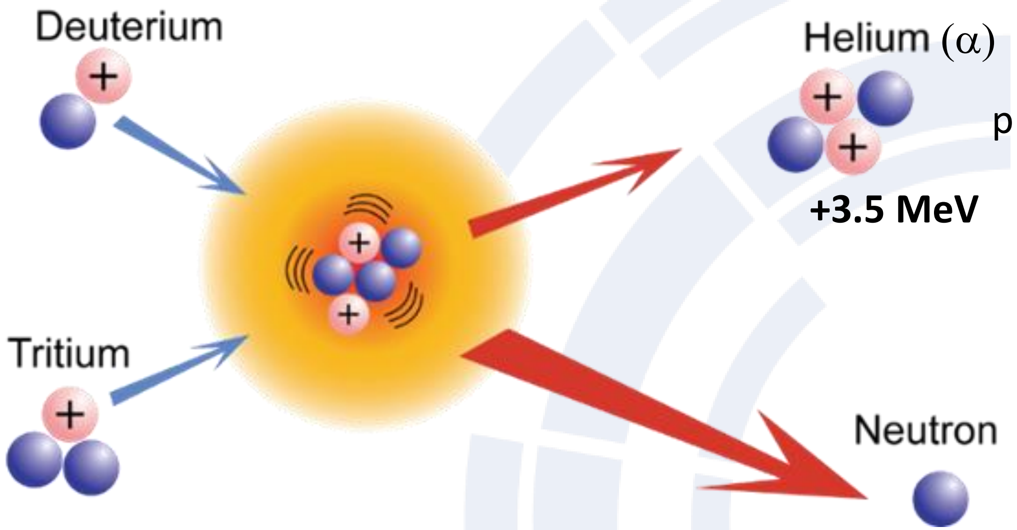
	design	Achieved
Toroidal field	2.8T (3.45T)	**4T**
Plasma Current (D-shape)	3.8MA (4.2MA)	**7MA**
Plasma Current (X-point)		**6MA**
Flat-top pulse length	10s (20s)	**60s**
Main fuel	H / D/ T	H / D / T / **He**
NBI heating	15MW	**34MW**
ICRH heating (25-55MHz)	9MW(12MW)	**22MW**
LHCD (3.45 GHz)		**~7MW**
Combined heating		**~ 37 MW**
Pellet injection		**pacing/fuel**
Disruption Mitigation		**MGI / SPI**
Diagnostics	~ 30	**~ 90**
Maintenance	Remote Handling	

D-T operation: key step to prepare fusion power plants

D-T experiments inform:

- Plasma physics & operation
- First wall & components irradiation and lifetime
- Tritium cycle
- Waste management
- Regulatory aspects

→ **Impacts design and preparation of nuclear power plants operation & decommissioning**



plasma self-heating

+3.5 MeV

Electricity generation

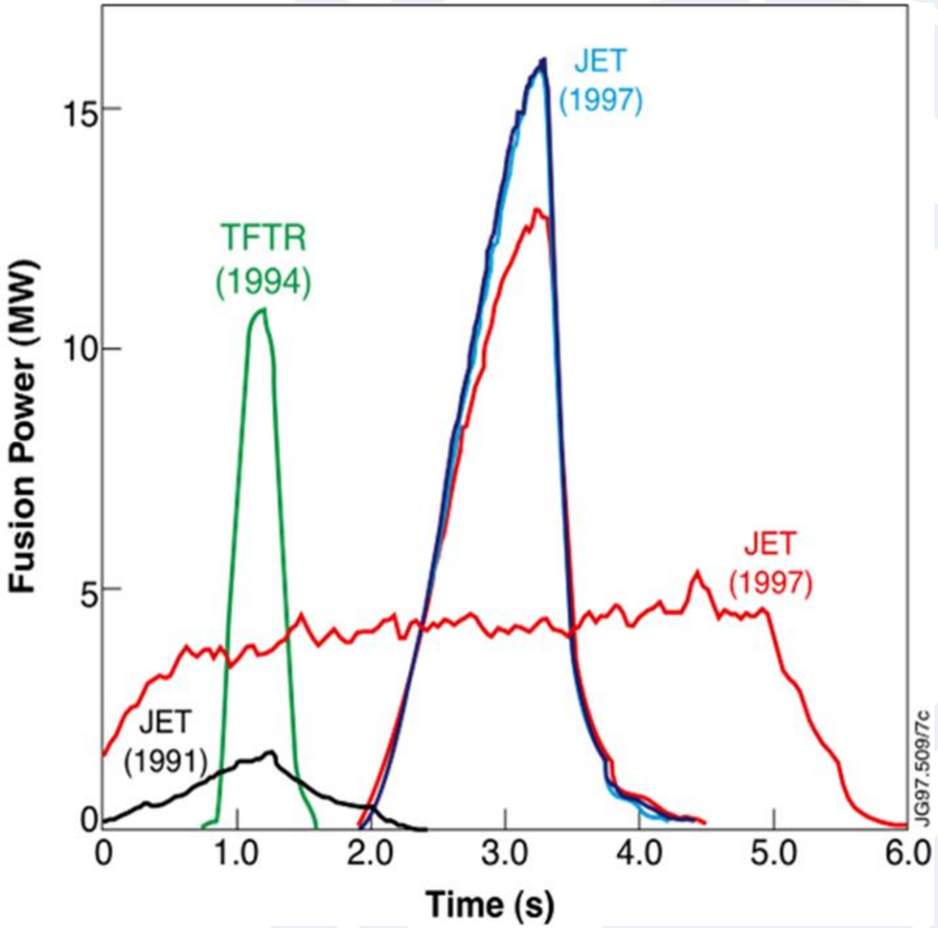
+14 MeV

Only two tokamaks equipped with T-handling capabilities:

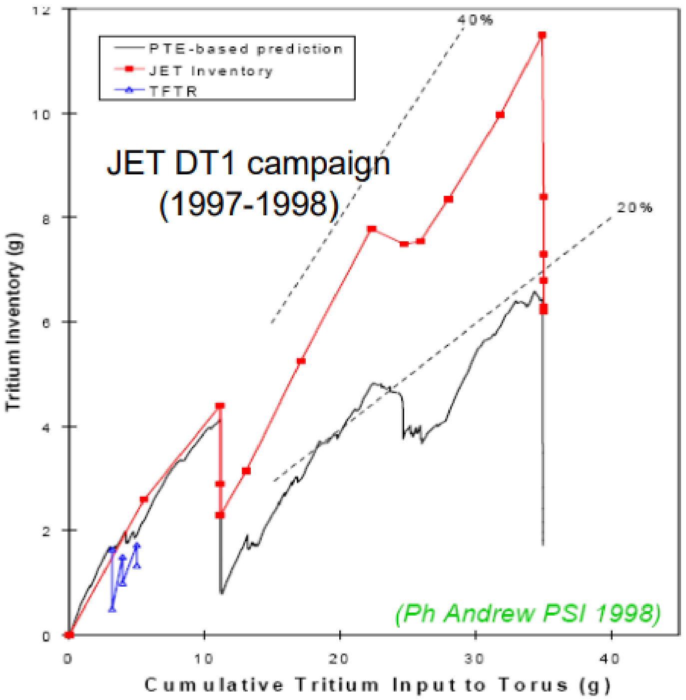
- TFTR (US) closed 1999
- JET (UK) until 2023

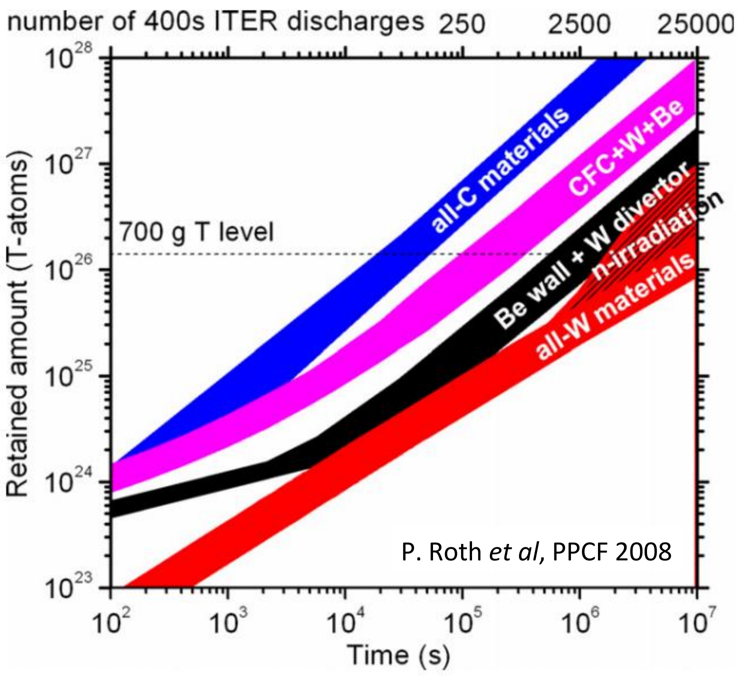
D-T fusion experiments are rare

- Previous D-T experiments:
  - 1991 PTE - JET
  - 1994-96 TFTR (US)
  - 1997 DTE1 on JET
  - (2004 Trace T exp. on JET)
- Demonstrated:
  - D-T Fusion
  - Plasma behaviour affected by use of D-T mixture
  - Clear α-particle effects seen on TFTR, but JET results ambiguous
  - High tritium retention



High tritium retention by CFC wall motivated rethink on first wall materials



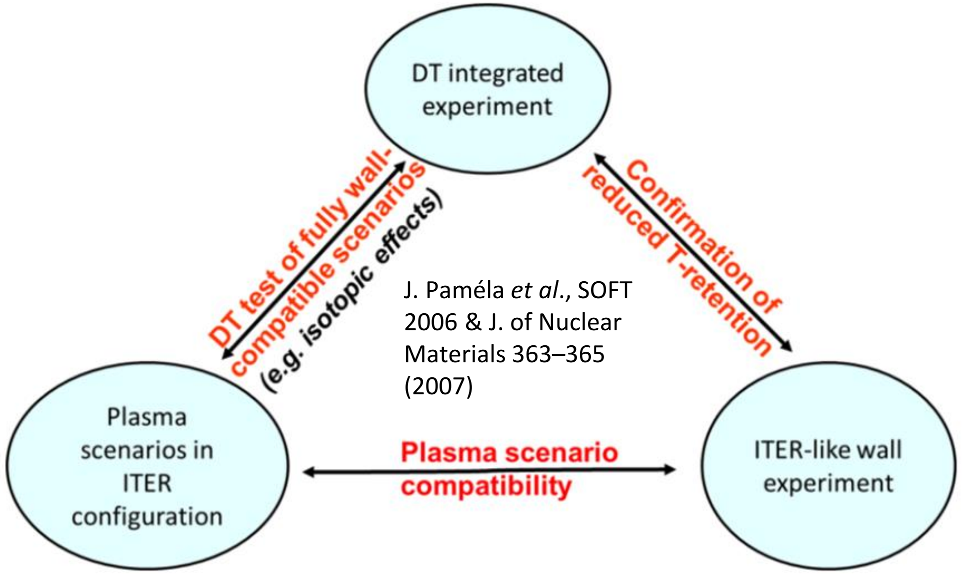


P. Roth *et al*, PPCF 2008

- Long term Tritium inventory limited by safety consideration
- JET ‘Post-mortem’ analysis:
  - T retained in co-deposited layers & flakes
  - 3.7g (out of 35g inventory) in vessel’s remote areas

- Predictions for ITER T inventory motivated use of Be wall & W divertor
  - (note: ITER now proposing all W)
- **Needed demonstration of compatibility with sustained high fusion power**

DTE2: culmination of JET with ITER-like wall project

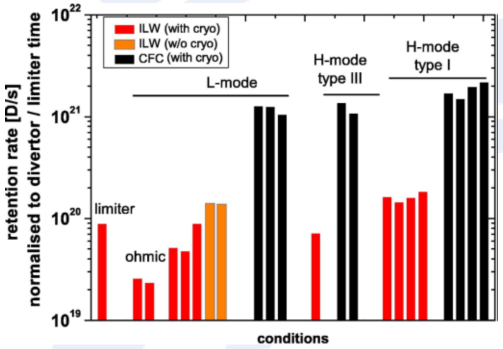


J. Paméla *et al.*, SOFT 2006 & J. of Nuclear Materials 363–365 (2007)

W divertor
& Be walls

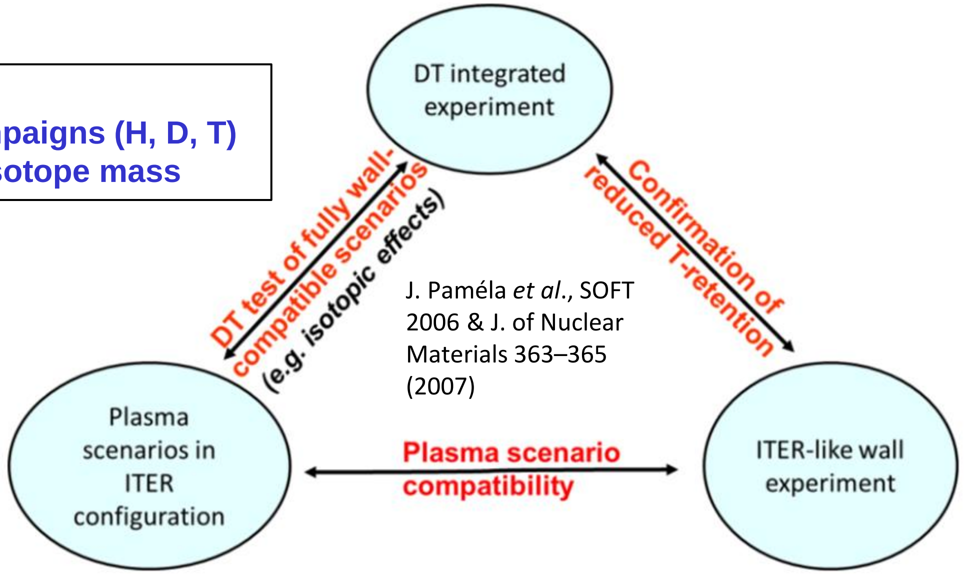
DTE2: culmination of JET with ITER-like wall project

2011-2014 & 2015-2016
Low fuel (D) retention confirmed



DTE2 2021

2016-2021:
Dedicated campaigns (H, D, T) on impact of isotope mass


DT integrated experiment

DT test of fully wall-compatible scenarios (e.g. isotopic effects)

Confirmation of reduced T-retention

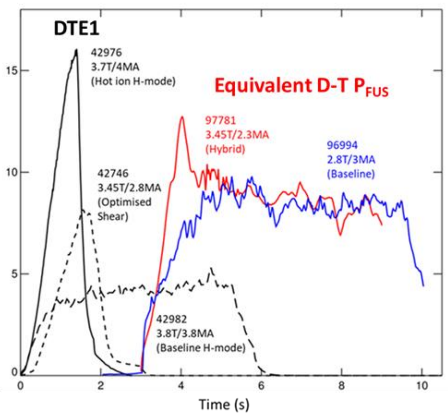
Plasma scenarios in ITER configuration

Plasma scenario compatibility

ITER-like wall experiment

J. Paméla *et al.*, SOFT 2006 & J. of Nuclear Materials 363–365 (2007)

2020 D plasmas

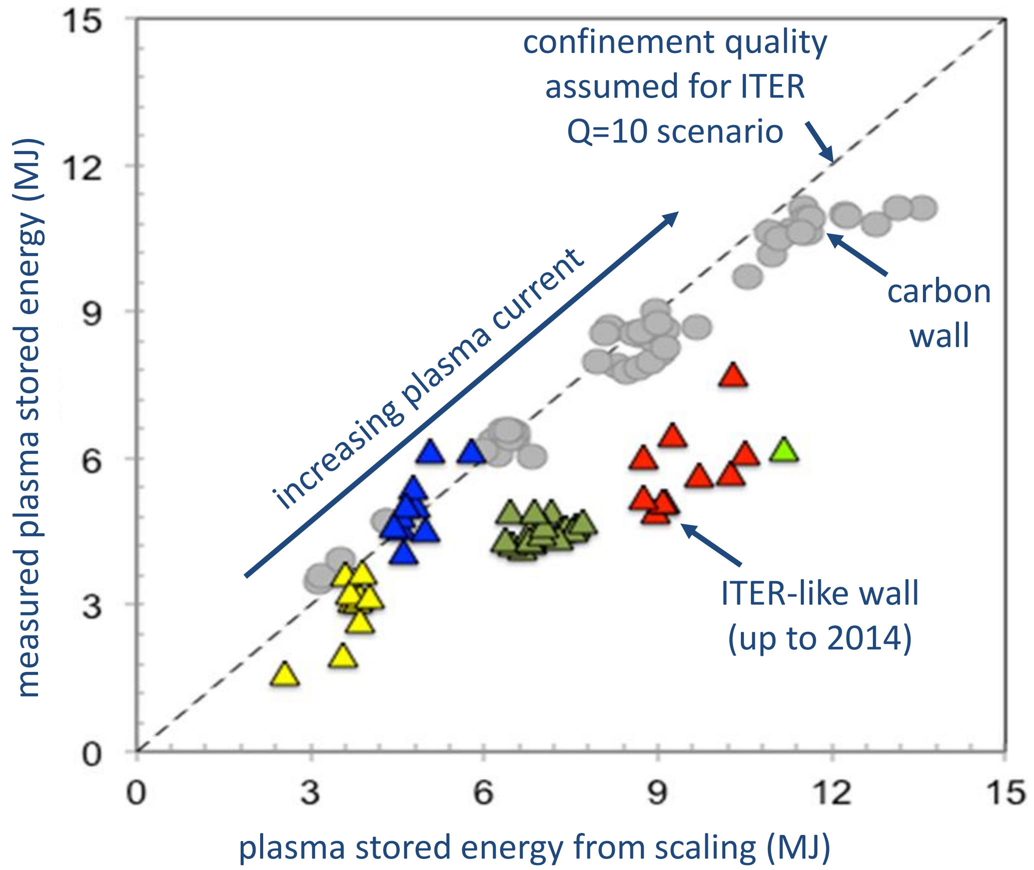


2016-2020:
ILW compatible with high fusion performance (D plasmas)

W divertor
& Be walls

2009-2011: Installation of ILW

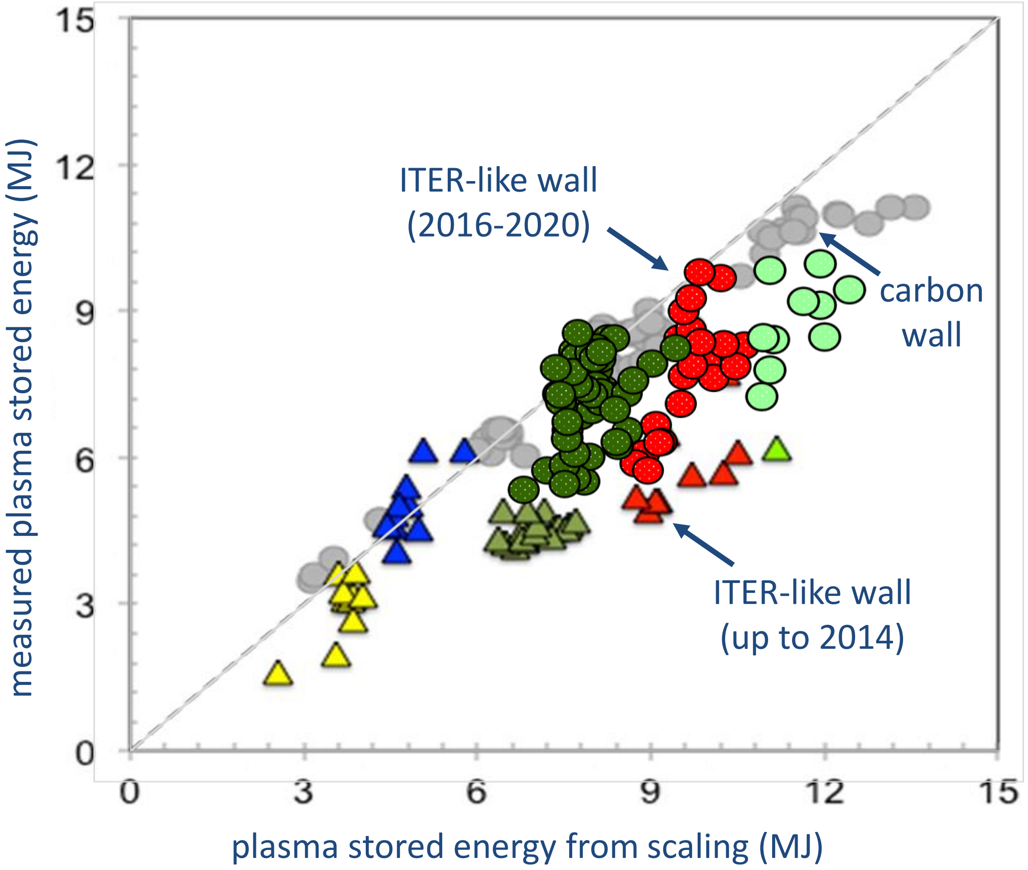
High power plasma operation in JET-ILW challenging



Example: plasma development (with deuterium fuel) to high I_P

- **ILW up to 2014**: Difficult to match plasma performance achieved with carbon wall in early experiments after installation of ILW

High power plasma operation in JET-ILW challenging but possible



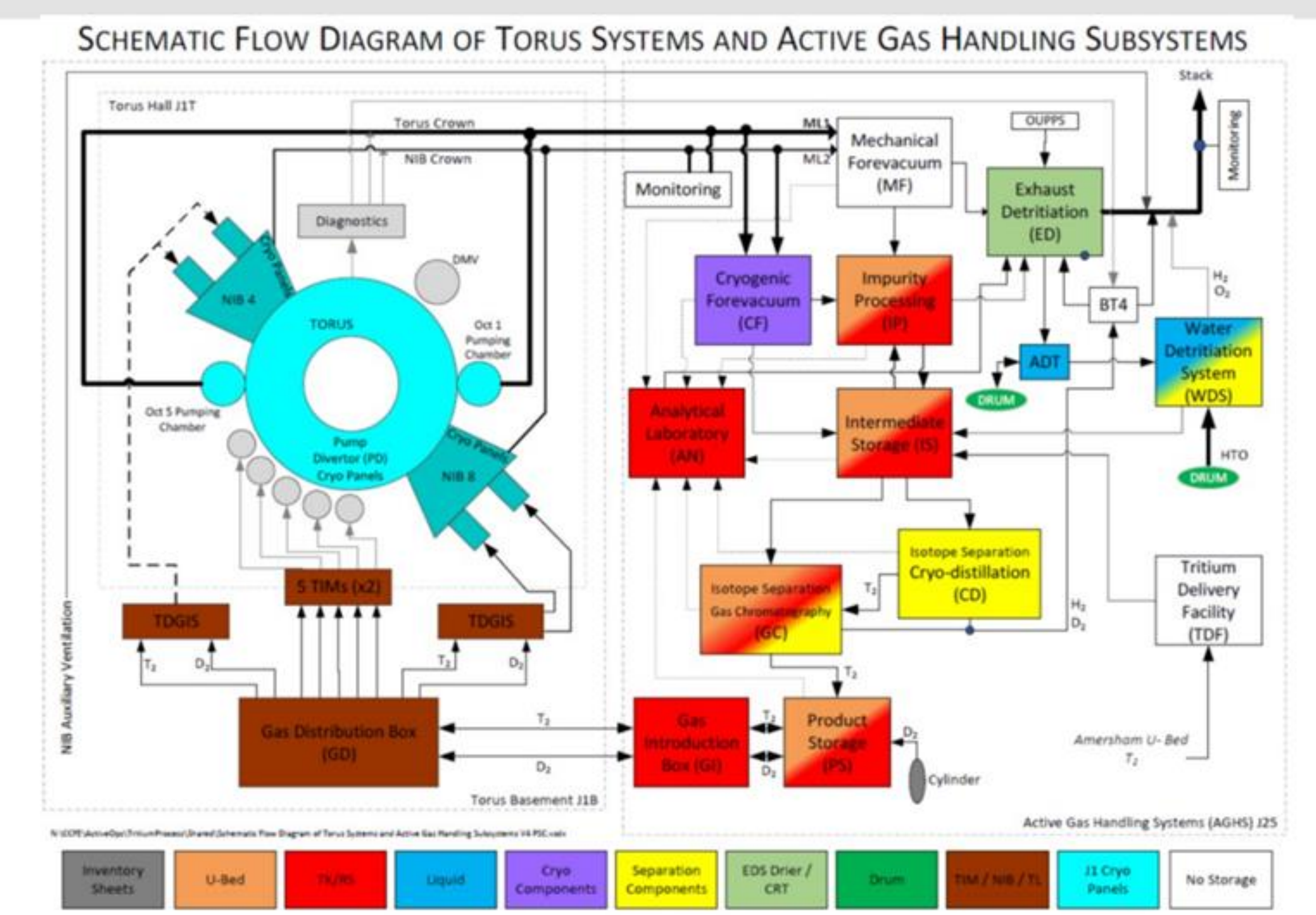
Example: plasma development (with deuterium fuel) to high I_P

- **ILW up to 2014**: Difficult to match plasma performance achieved with carbon wall in early experiments after installation of ILW
- **ILW 2016-2022** confinement recovered at high current, thanks to key plasma techniques:
  - Reduced fuel gas injection rate for increased temperature at plasma edge, improving core energy confinement
  - High frequency frozen fuel pellet injection to pace ELM instabilities, flushing out impurities

This development (and others) demonstrated readiness for DTE2

J. Mailloux et al 2022 Nucl. Fusion 62 042026

Tritium injection and processing systems improved for DTE2



AGHS stores, supplies and recycles T going to and from JET systems

- Only a fraction of the tritium injected (gas and as neutral beam) in a pulse used in D-T reactions
- T recycled from torus exhaust (in batch) and re-used
- Daily tritium budget for experiments limited to 11g

Tritium	Inventory at start	Injected in total during T & D-T campaign	Typically per plasma pulse
DTE1	21g	100g	<0.25g
DTE2	69g	1003g	<2.25g
DTE3		117g	<1.5g

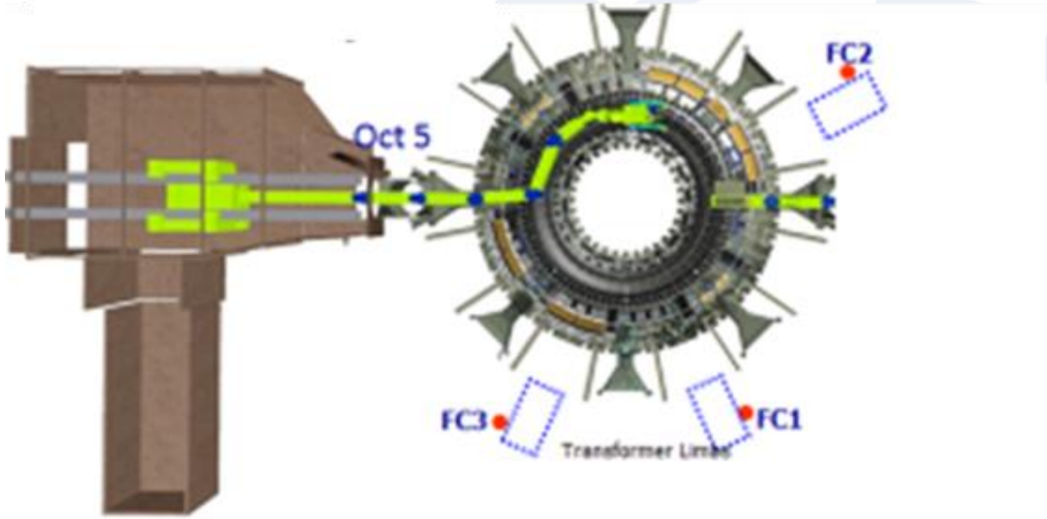
Improved diagnostics and absolute neutron calibration

New and improved diagnostics for:

- ➔ better spatial and temporal edge coverage
- ➔ Improved edge & divertor spectroscopy
- ➔ Better diagnosed fusion relevant quantities, e.g.:
  - Neutron cameras & spectrometers
  - γ-ray tomography
  - Fast Ion Loss Detector (alpha losses)
  - high-resolution sub-divertor residual gas analyser for measuring H, D, T, ^{4}He & ^{3}He

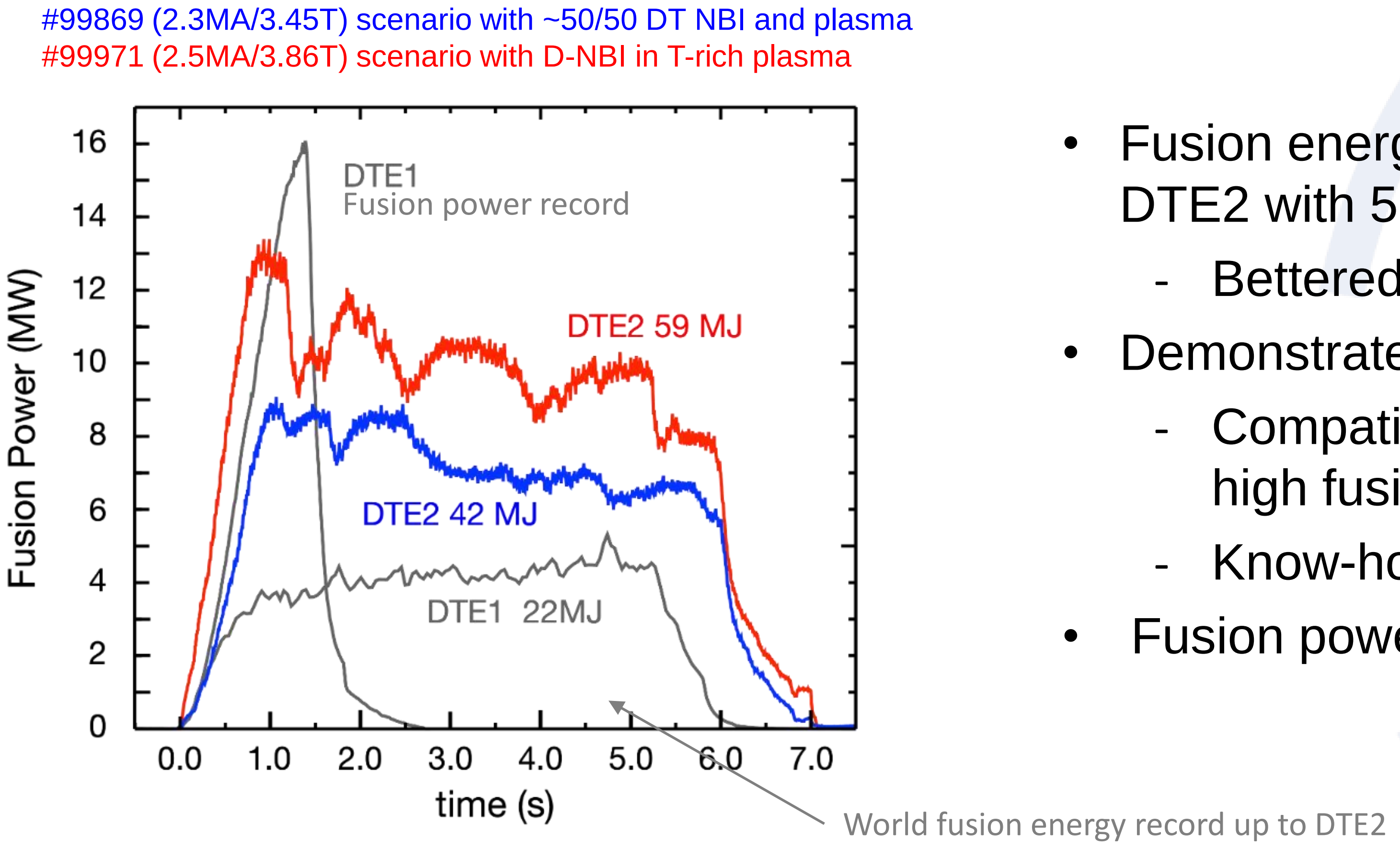
J. Figueiredo et al., IAEA FEC 2018

- Neutron calibration campaign in 2017 with 14MeV neutron generator deployed by remote handling
- Data also used to validate neutronic predictive codes



P. Batistoni *et al* 2018 Nucl. Fusion 58

Fusion energy world record in DTE2

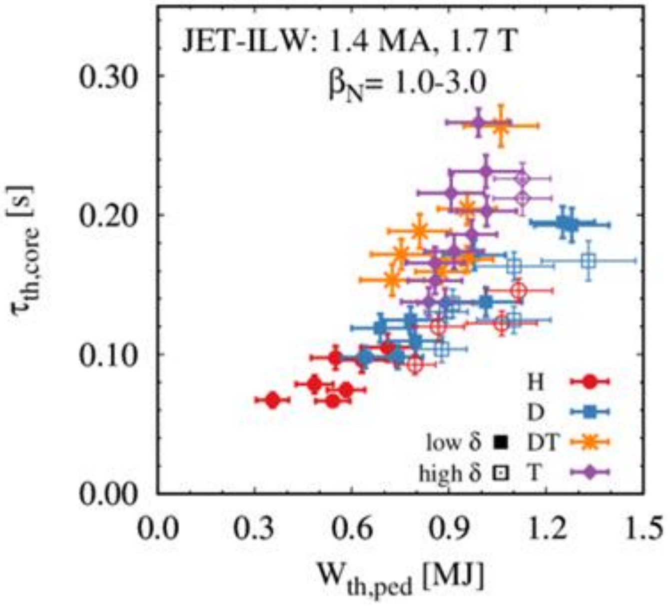


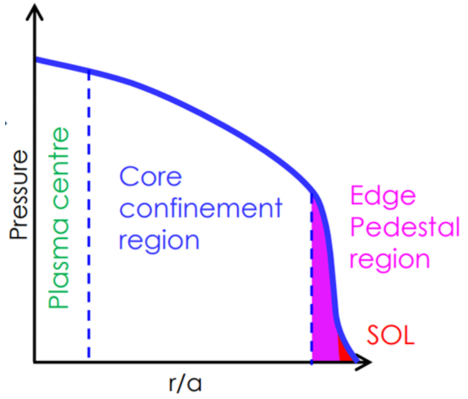
- Fusion energy world record surpassed in DTE2 with 59MJ
  - Bettered in 2023: 69MJ
- Demonstrated:
  - Compatibility of metal wall with sustained high fusion performance
  - Know-how
- Fusion power achieved is in range predicted

C.F. Maggi et al. Nucl. Fusion 2024 https://doi.org/10.1088/1741-4326/ad3e16

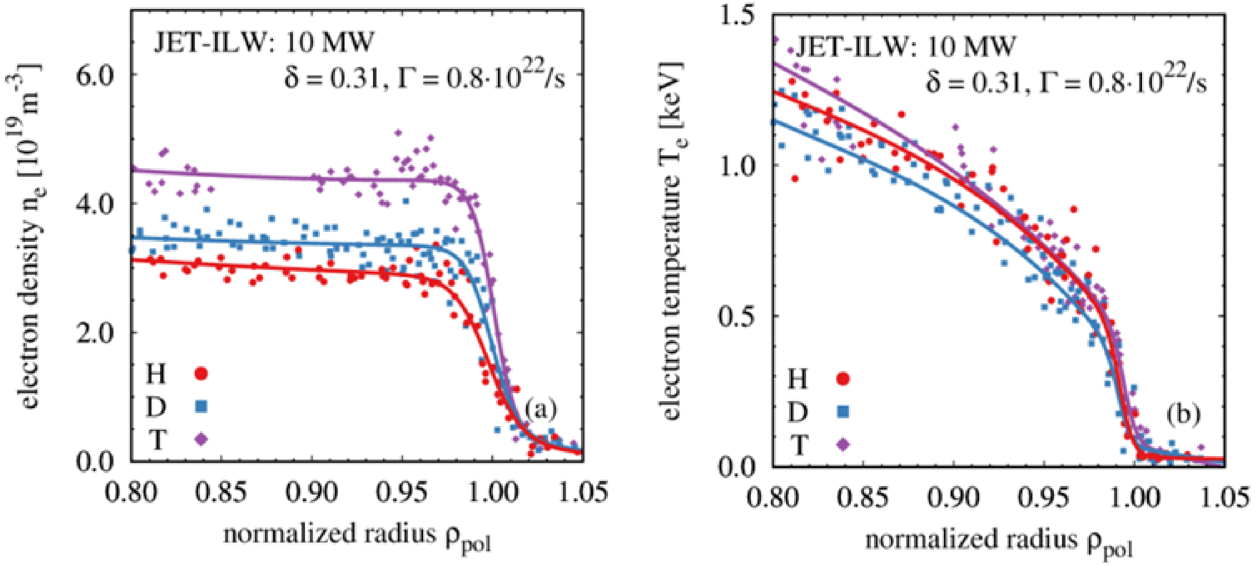
Broad range of experiments performed to understand impact of isotope mass on plasma, for example:

Impact on plasma core





Impact on plasma pedestal



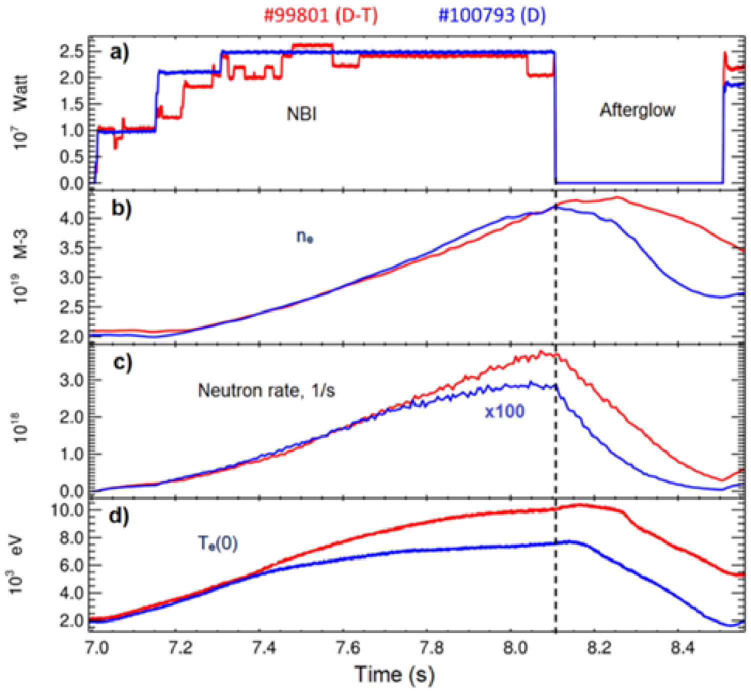
- At matched pedestal: core confinement better in T & D-T plasmas
- Analysis with predictive modelling (not shown here) indicate:
  - main isotope effects correctly included in physics model
  - But electromagnetic effects (fast particles) lead to overestimation → model needs improvement

- At same engineering parameters: pedestal electron density higher at higher fuel mass, for similar electron temperature
- Stability based pedestal model can't reproduce the experimental trends resistive models promising
- Core & pedestal confinement linked → integrated core-edge modelling needed to predict future tokamaks performance

P.A. Schneider et al 2023 Nucl. Fusion 63 112010
L. Frassinetti *et al*., Nuclear Fusion

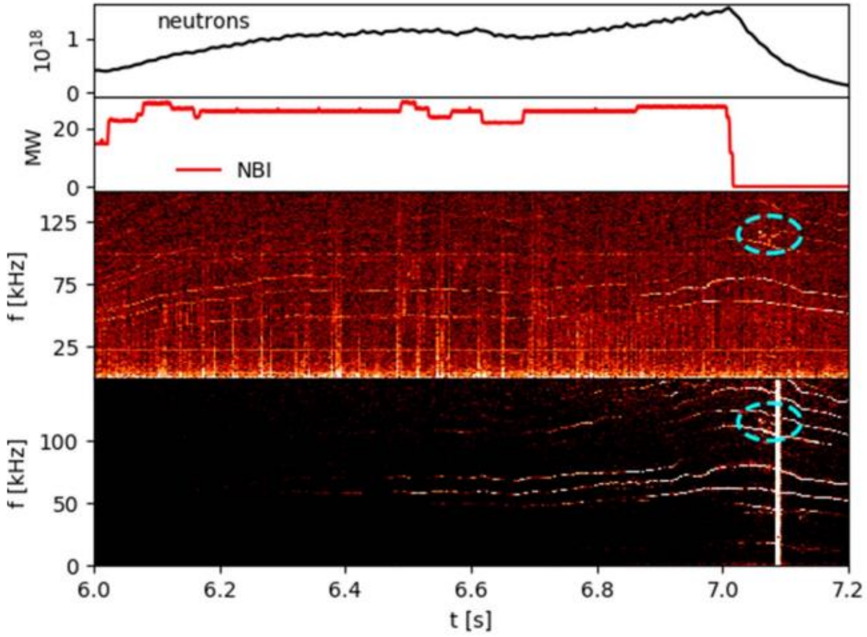
Clear α-particle effects, for example

Direct evidence of plasma heating by α-particles



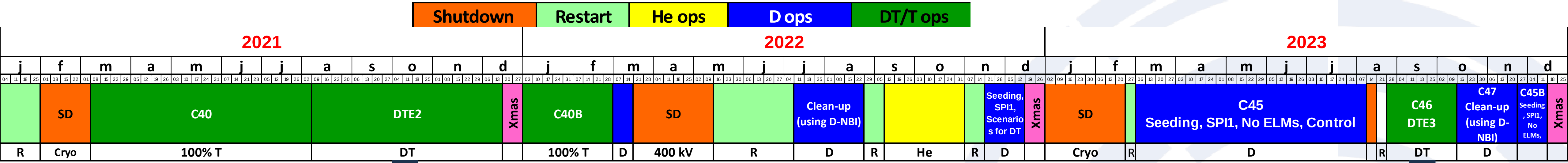
V.G. Kiptily *et al*., PRL 131, 075101 (2023)

Unambiguous observations of α-particles driven modes



M. Fitzgerald *et al.,* 2023 Nucl. Fusion 63 112006

JET D-T campaigns 2021 & 2023



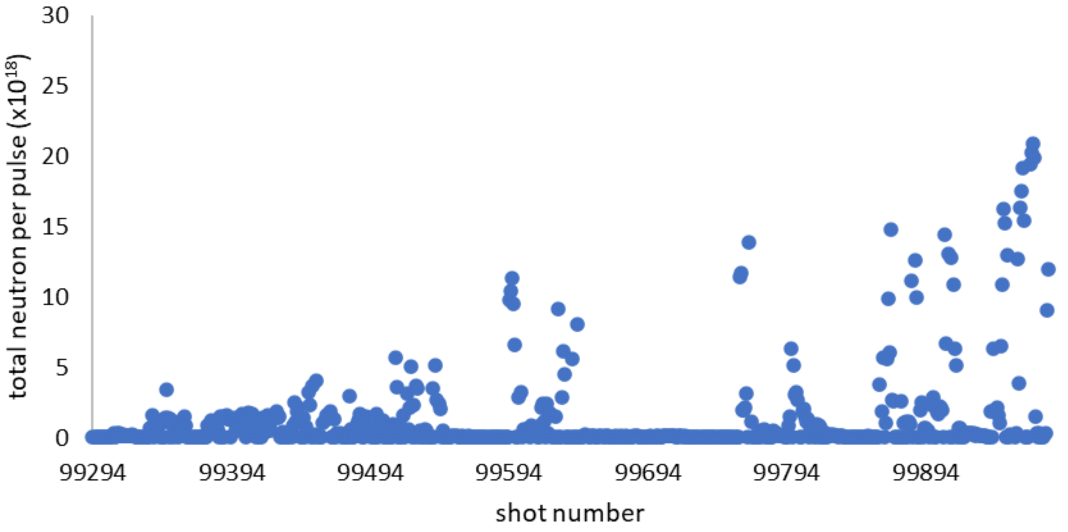
Shutdown | Restart | He ops | D ops | DT/T ops

2021 | 2022 | 2023

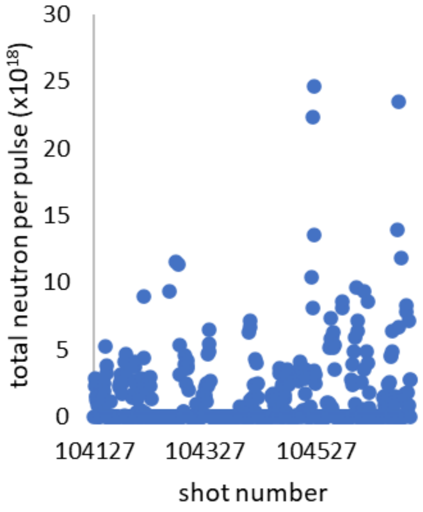
j f m a m j j a s o n d | j f m a m j j a s o n d | j f m a m j j a s o n d

	SD	C40	DTE2	Xmas	C40B		SD		Clean-up (using D-NBI)				Seeding, SPI1, Scenarios for DT	Xmas	SD		C45 Seeding, SPI1, No ELMs, Control			C46 DTE3	C47 Clean-up (using D-NBI)	C45B Seeding, SPI1, No ELMs,	Xmas
R	Cryo	100% T	DT		100% T	D	400 kV	R	D	R	He	R	D		Cryo	R	D		R	DT	D		

DTE2 13 Aug 2021 - 21 Dec 2021
250 experimental plasma shots*
Total neutrons = 8.48x10^{20}
Several technical issues slowed down pace

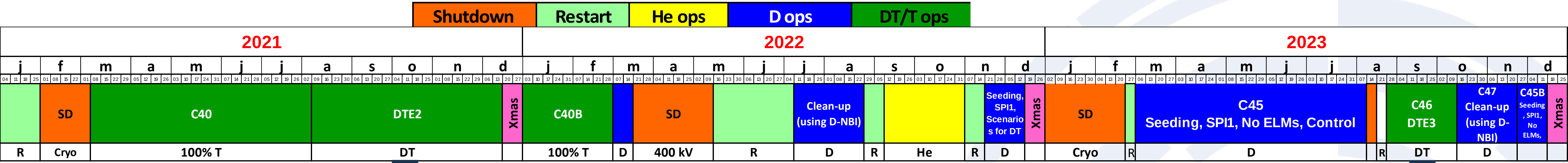


DTE3 30 Aug 2023 – 14 Oct 2023
268 experimental plasma shots*
Total neutrons =7.31x10^{20}
Lessons learnt from DTE2 applied in DTE3



*technically successful, not necessarily useful for the experiment

JET D-T campaigns 2021 & 2023



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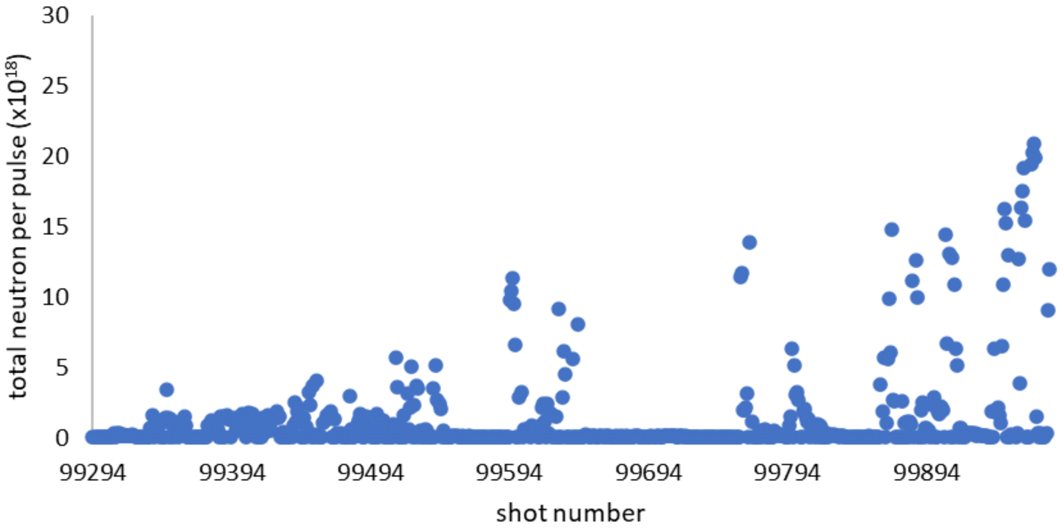
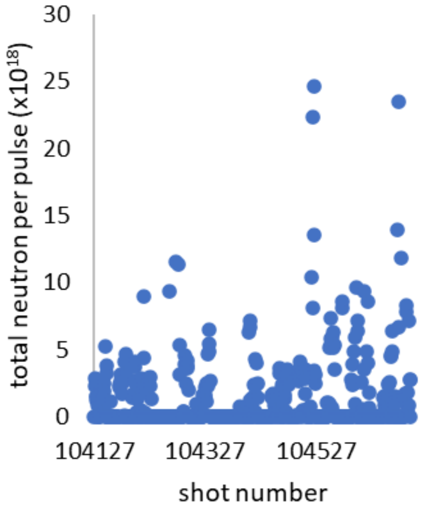


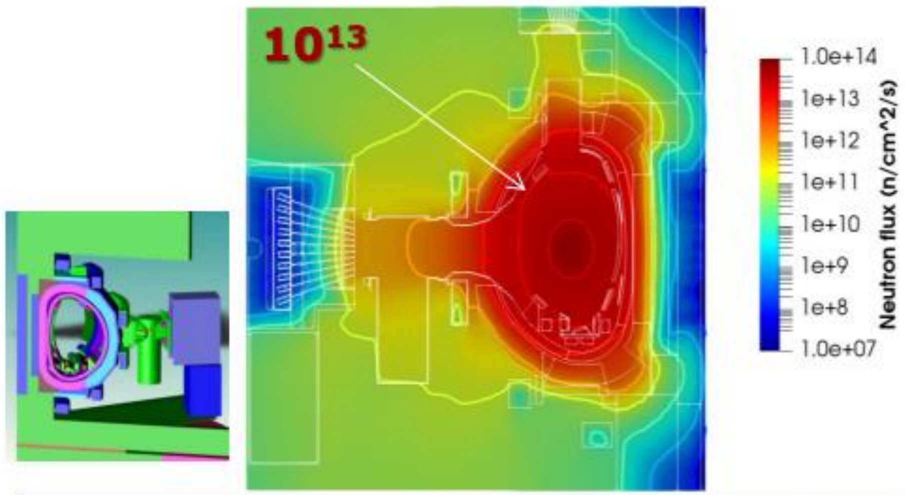
In addition to the plasma programme, DTE2 and DTE3 campaigns included several neutronics experiments



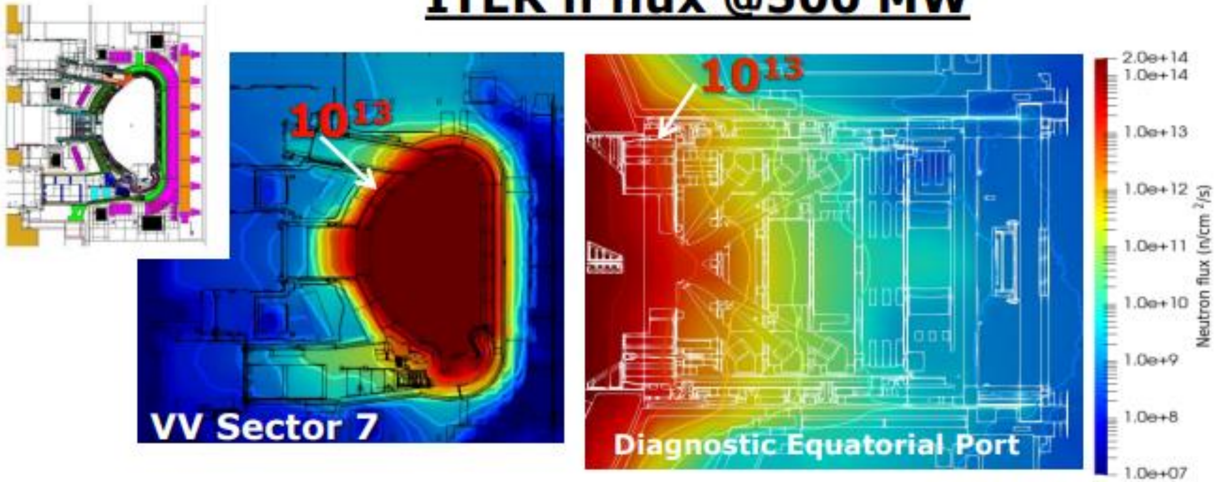
*technically successful, not necessarily useful for the experiment

JET D-T neutron fluence relevant for ITER

JET n flux @ shot 99971 – peak ~4.8x10¹⁸ n/s



ITER n flux @500 MW



ENEA

10^{13} n/cm²/s neutron flux level as in rear ITER blanket- DFW

Cumulated total neutron fluence during DTE2+DTE3 max inboard FW **10^{16} n/cm²**

- **Relevant for some degradation effects**
- **@rear ITER port plugs at the end of ITER life**
- **@middle ITER port plugs- rear blanket @ end of ITER DT-1 (TBD)**

JET DTE relevant for ITER technologies!

JET experience crucial for supporting demonstration

R. Villari, Key technological aspects of recent DT operations at JET, 15th International Symposium on Fusion Technology, 10-15 September 2023, Las Palmas de Gran Canaria, Spain

Wide range of experiments in support of the design and operations of the next step fusion machines

JET

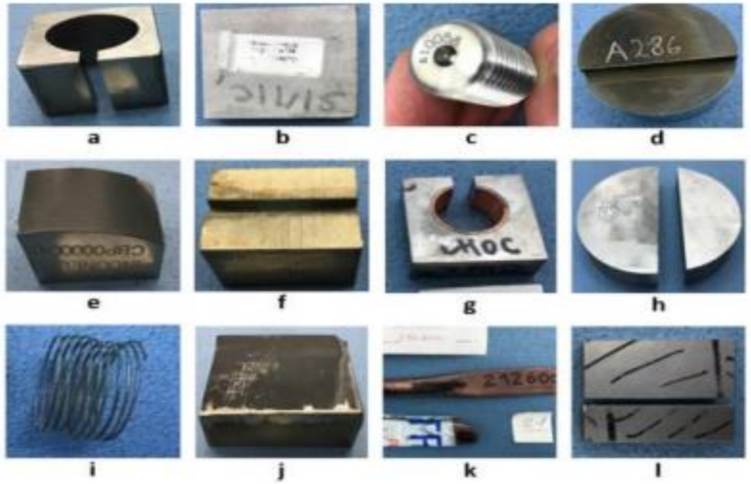
- Activation of ITER materials
- Radiation damage studies
- Test of components:
  - Blanket modules detectors
  - Electronics
  - Magnetic coils
- Water activation experiment
- Benchmarking experiments for:
  - Neutron streaming
  - Shutdown dose rate
- Delayed Be-photoneutrons
- Waste
- Occupational radiation exposure control

These experiments provide:

- Test of computational tools
- Experimental validation
- Measurement techniques development
- Calibration protocols

Activation of ITER materials

- **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



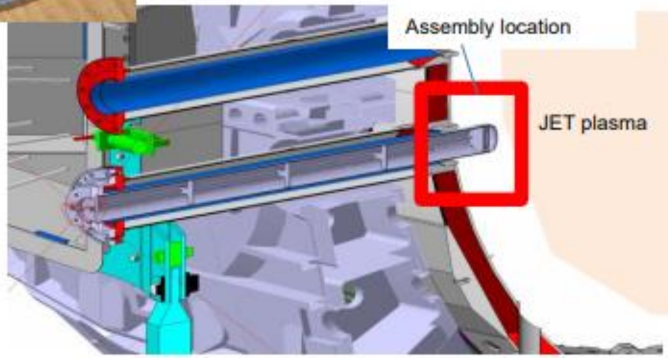
Nb3Sn, SS316L steels from various manufacturers, SS304B, Alloy 660, Be, W, CuCrZr, OF-Cu, XM-19, Al bronze, Nb3Sn, NbTi and EUROFER

L. Packer et al., submitted to Nuclear Fusion

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 **2x10¹³ n/cm²/s**
One order of magnitude less
than ITER FW@500 MW

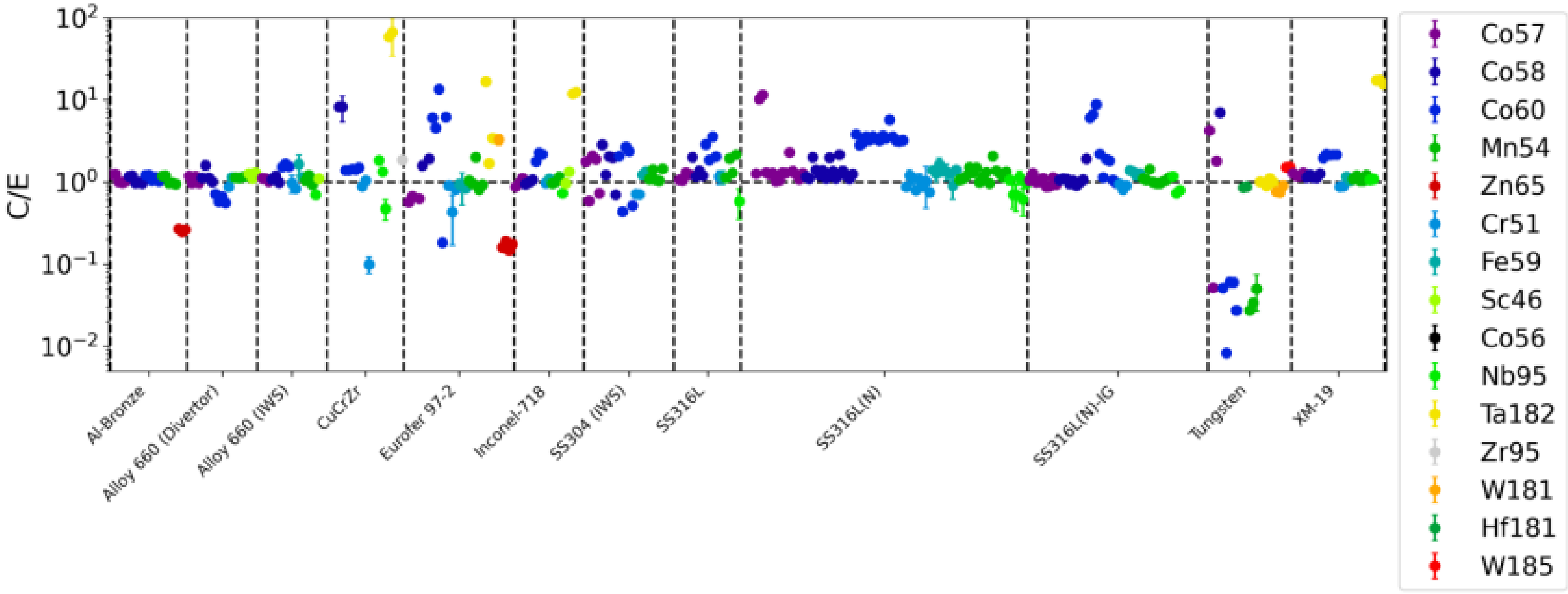
DT N fluence
5x10¹⁵ n/cm²

UK Atomic Energy Authority

IJS

Activation of ITER materials: comparison of prediction vs experiments

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 et al., submitted to Nuclear Fusion

R. Villari, Key technological aspects of recent DT operations at JET, 15th International Symposium on Fusion Technology, 10-15 September 2023, Las Palmas de Gran Canaria, Spain

Neutron single event effects (SEE) experiment on electronics during DTE3

Single Event effects (SEE) induced by neutrons is the one of the major problems in tokamaks.

- One SEE can damage or destroy electronic devices and sensors, corrupt signal in digital/analogue circuits, corrupt data/programs in processors/FPGAs/memories.
- Commercial electronics designed and qualified for natural terrestrial ground-level neutron environment (0.01 n/cm^2/s) → not suitable in tokamaks areas where electronics is installed.
- Radiation-hardening or radiation-qualification, local shielding, relocation or multiple-redundancy → impracticable / not doable for electronics in tokamaks.

Alternative approach: Replace the *qualification of electronics for its neutron environment in the facility* (not doable) by the *qualification of an optimized neutron environment in the facility for general electronics.*

- This alternative approach requires specific methods and models that need to be validated before implementation.

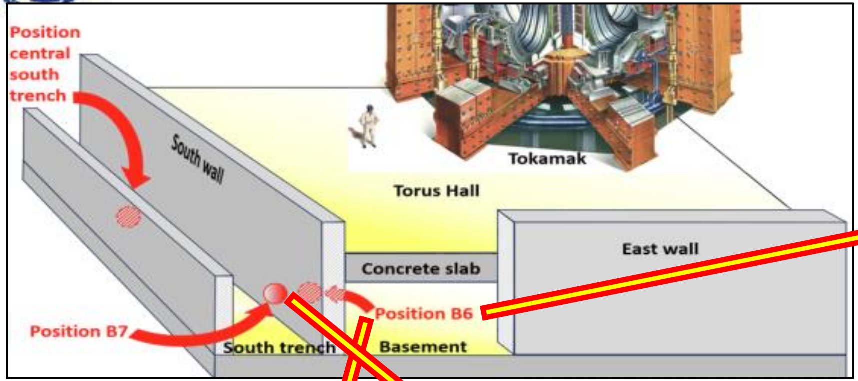
- **Preliminary study** : validation of the method and models

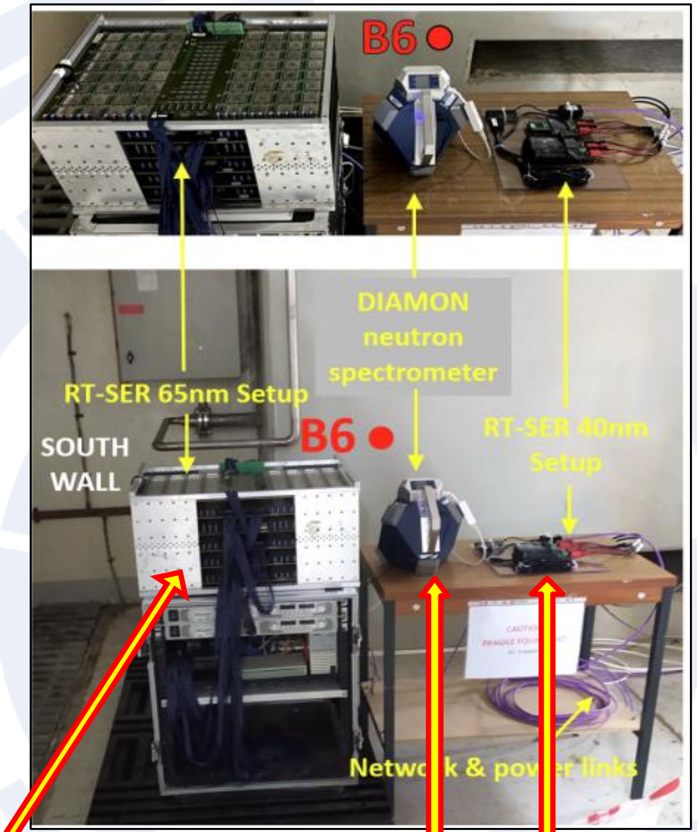
  ⇒ **SEE experiments in tokamaks** : at WEST under D-D plasma neutrons then **at JET under D-T plasma neutrons**

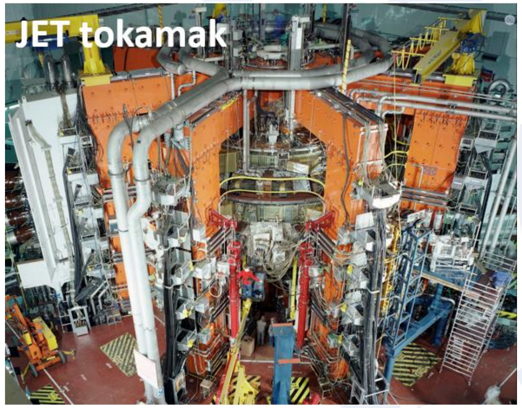
- A detailed study (implementation of the method and models) will follow.

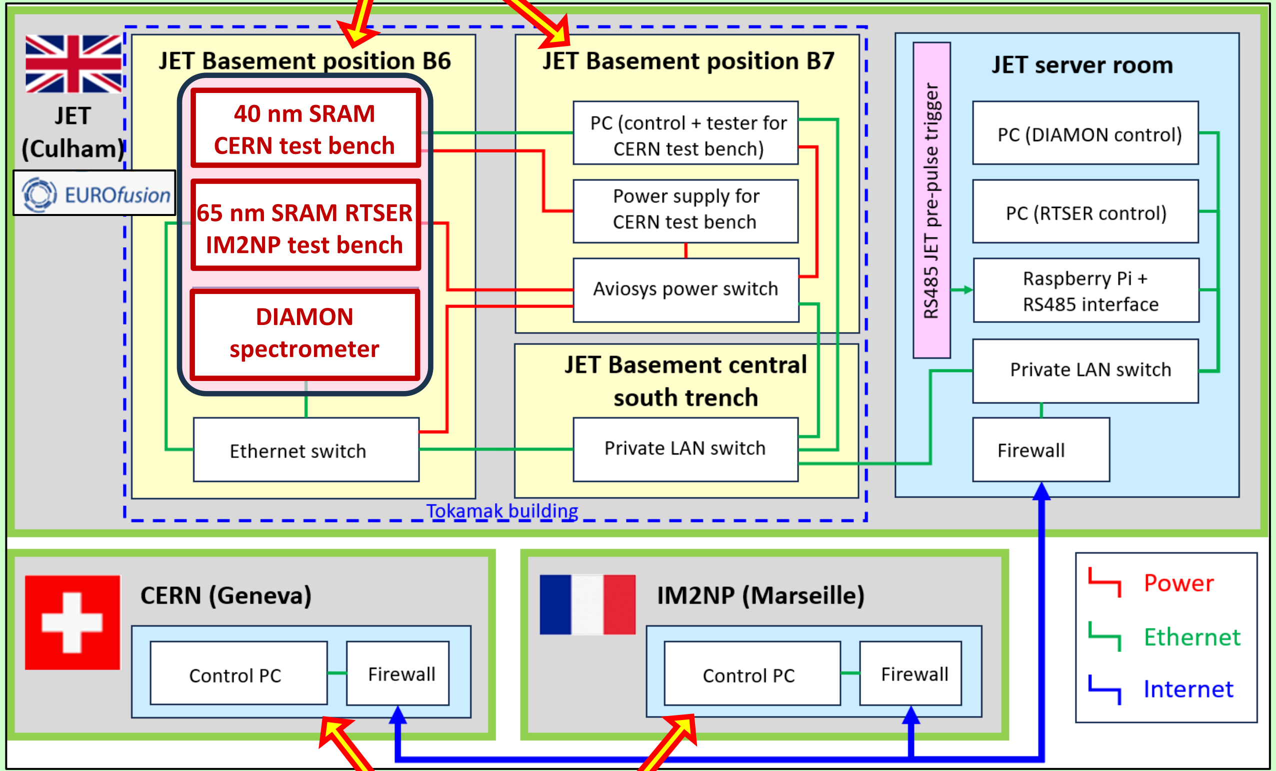
Note: *Particle physics accelerators face the same problem with neutrons having roughly the same energy range. For this reason, this work is carried out jointly by nuclear fusion labs (IRFM, UKAEA) and high energy physics labs (CERN).*

SEE experiment on electronics during DTE3: set-up









JET (Culham)

EUROfusion

Tokamak building

JET Basement position B6

- **40 nm SRAM CERN test bench**
- **65 nm SRAM RTSER IM2NP test bench**
- **DIAMON spectrometer**
- Ethernet switch

JET Basement position B7

- PC (control + tester for CERN test bench)
- Power supply for CERN test bench
- Aviosys power switch

JET Basement central south trench

- Private LAN switch

JET server room

- RS485 JET pre-pulse trigger
- PC (DIAMON control)
- PC (RTSER control)
- Raspberry Pi + RS485 interface
- Private LAN switch
- Firewall

CERN (Geneva)

- Control PC
- Firewall

IM2NP (Marseille)

- Control PC
- Firewall

Power
Ethernet
Internet

Remote control from CERN (CH) and IM2NP (FR)

Real Time Soft Error Rate (RTSER) test bench for SEE measurements, from **IM2NP Institute** (Aix-Marseille University, FR): 384 memory chips (65 nm bulk SRAM, BPSG-free, manufactured by STM), 3.226 Gbits in total.

Portable neutron spectrometer DIAMON from **Raylab** (IT), energy range from thermal to 20 MeV neutrons.

SEE test bench for SEE measurements, from **CERN** (CH): 2 memory chips (40 nm bulk SRAM manufactured by ISSI), 64 Mbits in total.

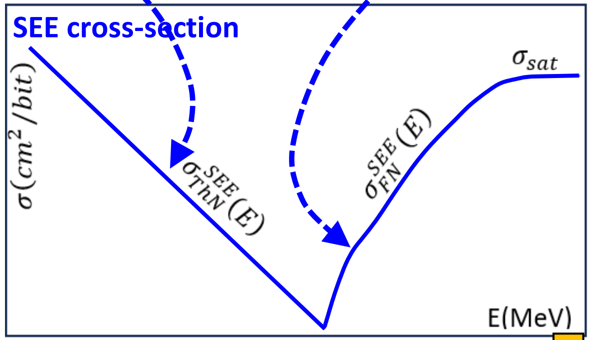
SEE experiment on electronics during DTE3: preliminary results

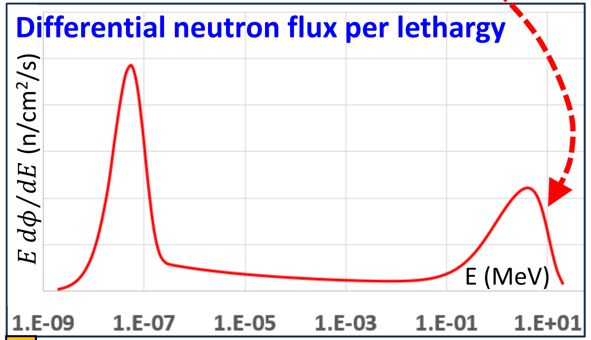
Measured at TENIS facility (ILL, Grenoble, FR)

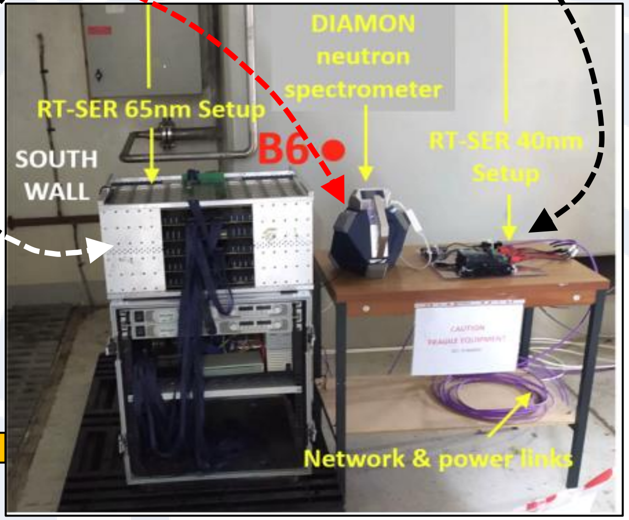
Measured at AMANDE facility (IRSN, Cadarache, FR)

Spectrum measured at test benches location at JET during DTE-3 campaign.

SER measured on test benches at JET during DTE-3 campaign.







SER = Single Event Rate

Predicted SER = $\int \sigma^{SEE}(E) \times \frac{d\phi(E)}{dE}\, dE$

Measured SER

$$\frac{predicted\ SER}{measured\ SER} = 0.85$$

Method + models validated for D-T fusion plasmas [2]

Method + models validated for D-D fusion plasmas [1]

Method + models validated for D-D and D-T tokamaks

Preliminary study complete. Next step: detailed study

[2] M. Dentan et Al., “Real-Time SER Measurements of CMOS bulk 40 nm and 65 nm SRAMs Combined with Neutron Spectroscopy at the JET Tokamak during D-D and D-T Plasma Operation”, to be published in IEEE TNS / Proceedings of NSREC 2024 Conference]

[1] M. Dentan et Al., RADECS 2022 proceedings / IEEE / DOI:10.1109/RADECS55911.2022.10412483

Conclusion

JET’s unique set of capabilities:

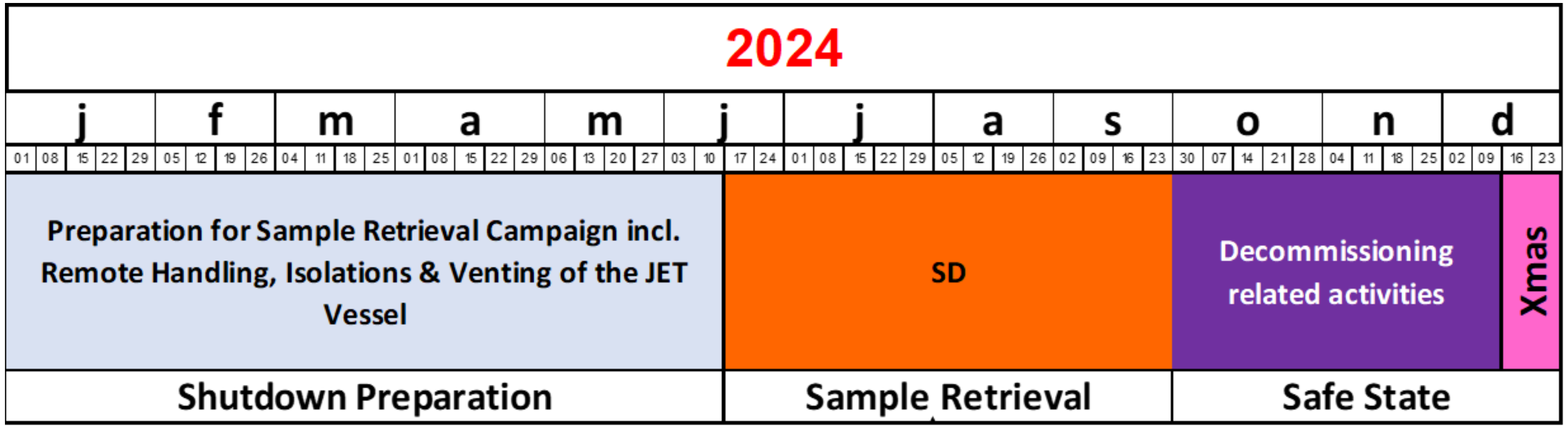
- Tritium handling
- ITER-like wall (ILW): Be wall and W divertor
- size
- High D-D & D-T n fluence

Led to unique results in preparation for fusion power plants, thus fulfilling its original mission

In particular, the recent D-T experiments provided

- Demonstration that metal wall compatible with high fusion power
- Dataset to improve fusion plasma and neutronics predictions

Next for JET: Decommissioning and Repurposing



2024

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01 08 15 22 29 05 12 19 26 04 11 18 25 01 08 15 22 29 06 13 20 27 03 10 17 24 01 08 15 22 29 05 12 19 26 02 09 16 23 30 07 14 21 28 04 11 18 25 02 09 16 23

Preparation for Sample Retrieval Campaign incl. Remote Handling, Isolations & Venting of the JET Vessel

SD

Decommissioning related activities

Xmas

Shutdown Preparation

Sample Retrieval

Safe State

2024 In-vessel campaign supports scientific programme as well as decommissioning:

- Inspections & high resolutions imagery
- Recover dust sample & monitor
- In-vessel diagnostics calibrations
- Laser Induced Breakdown Spectroscopy experiments to test detritiation of components
- Remove tile samples for post-mortem analysis
- Remote inspections to de-risk future JDR activities

Overall decommissioning plan is over 10 years

Will inform fusion power plant decommissioning and waste management