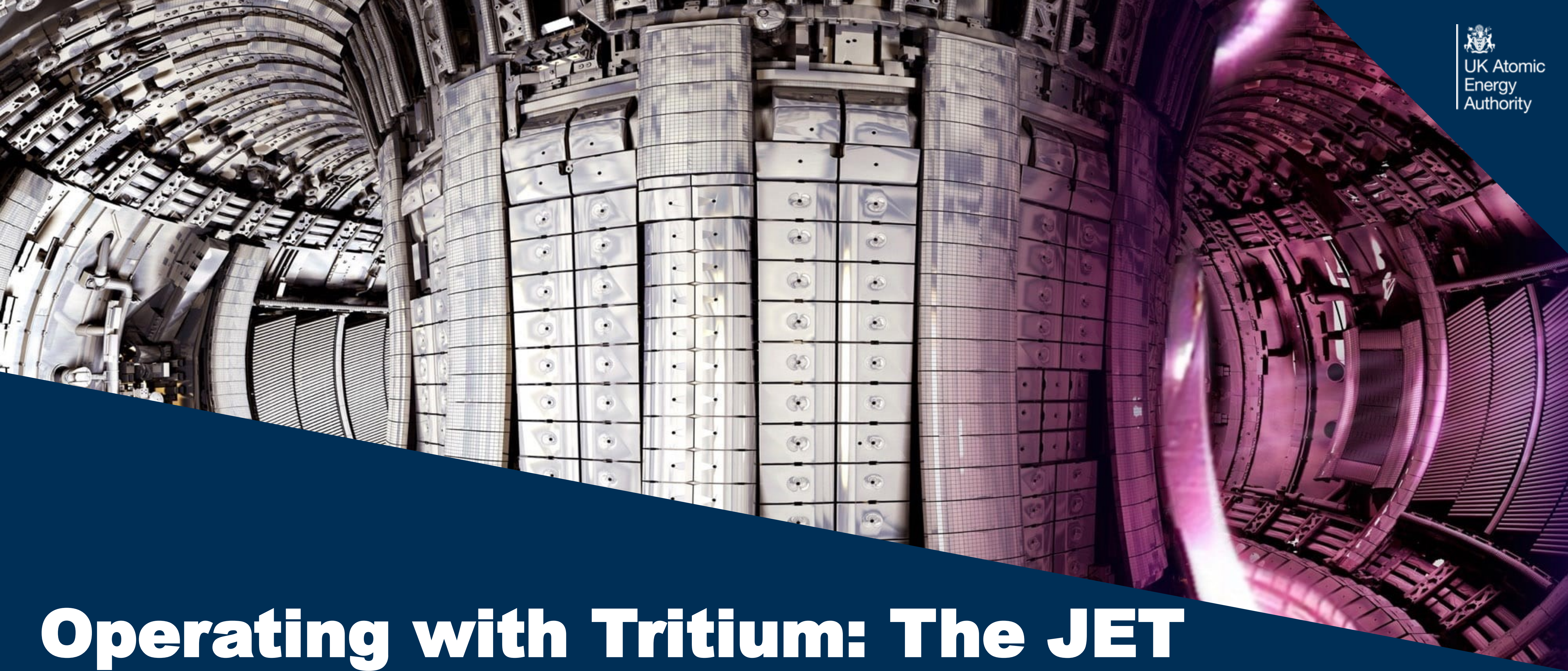


UK Atomic Energy Authority

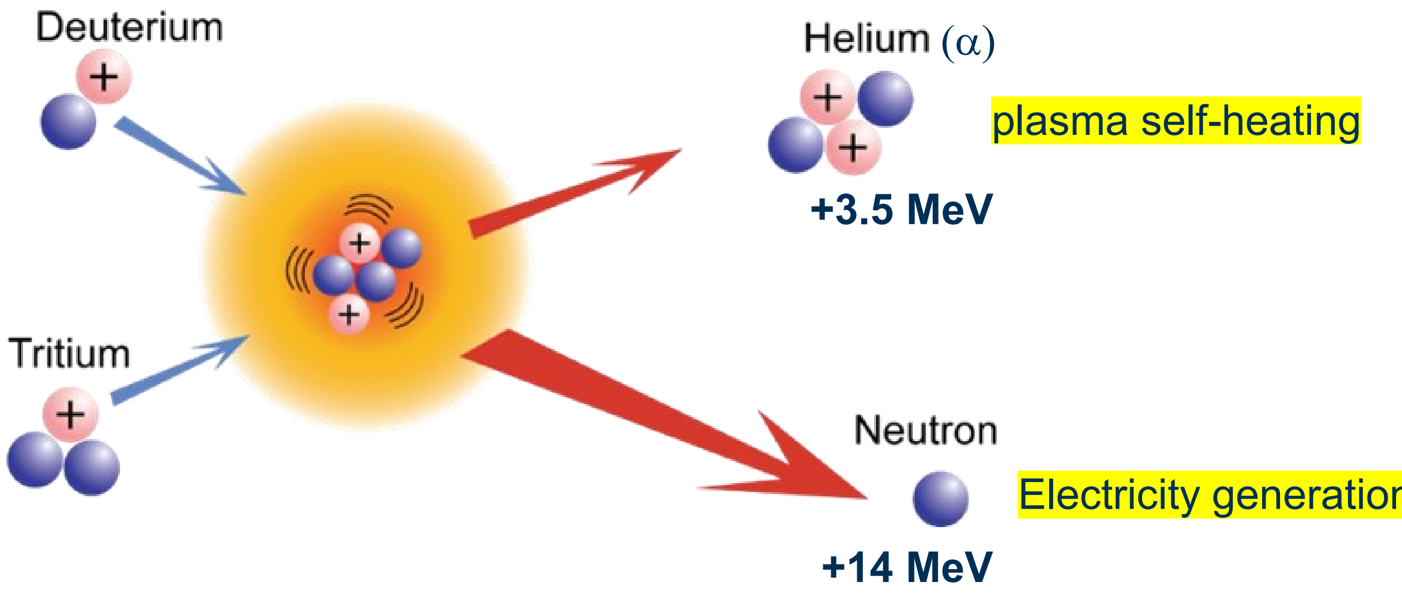
# Operating with Tritium: The JET Experience

**Damian King– JET Operations Manager**

# Outline

- History of JET DT operation & Rationale
- Tritium Plant
- Operational challenges
- Lessons learnt
- DTE3
- Scientific Results

# 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**

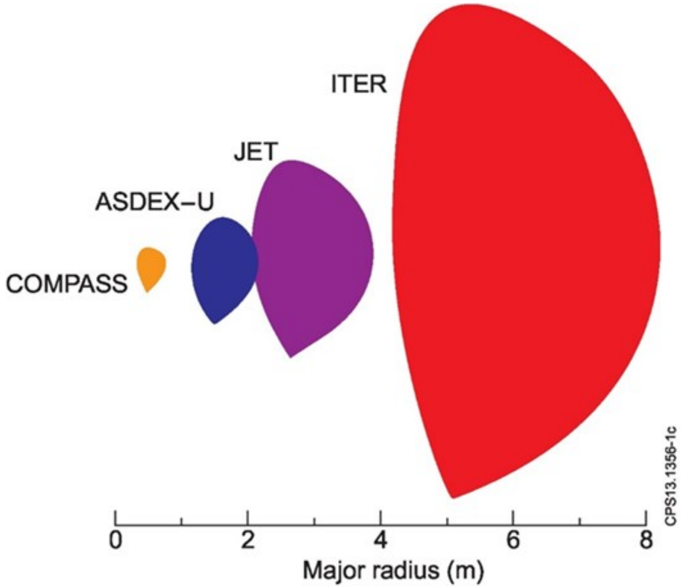
So far only two magnetic fusion devices (both tokamaks) operated with tritium & D-T:

- TFTR (US) closed 1999
- JET (UK/EU) closed 2023

# JET 1983-2023

JET

## **JET's mission** as defined in 1975: **prepare fusion reactors**




JET Major radius 2.96m
Minor radius 1.25m

## Good engineering margins & continuous upgrades kept JET at forefront of fusion research during its 40 years

| | 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 | |

# JET Lifetime, Major Upgrades and Tritium Operation

JOINT EUROPEAN TORUS JET

Assembly, maintenance, commissioning, operation and scientific exploitation carried out by the **JET Joint Undertaking** under the supervision of JET Scientific Council.

EFDA JET, EUROfusion – Scientific exploitation and machine upgrades

UK Atomic Energy Authority – Personnel safety, machine maintenance, upgrades, commissioning and operation

European Commission

**Start of JET operations**
**First plasma**

**Divertor,**
**In-vessel coils**
**In-vessel cryopump**

**Metal wall (Be/W)**
**Wall protection**
**NBI power upgrade**

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1980** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | **1990** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | **2000** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | **2010** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | **2020** | 1 | 2 | 3 | 4 |

**First DT experiment (PTE)**

**DT experiment (DTE1)**

**Trace tritium experiment (TTE)**

**100% tritium and DTE2 experiments**

**DTE3 experiments**

**6 years** **6 years** **18 years** **2 years**

# 1997 D-T experiments (DTE1) results and motivation for the new D-T experiments

# D-T fusion experiments are rare

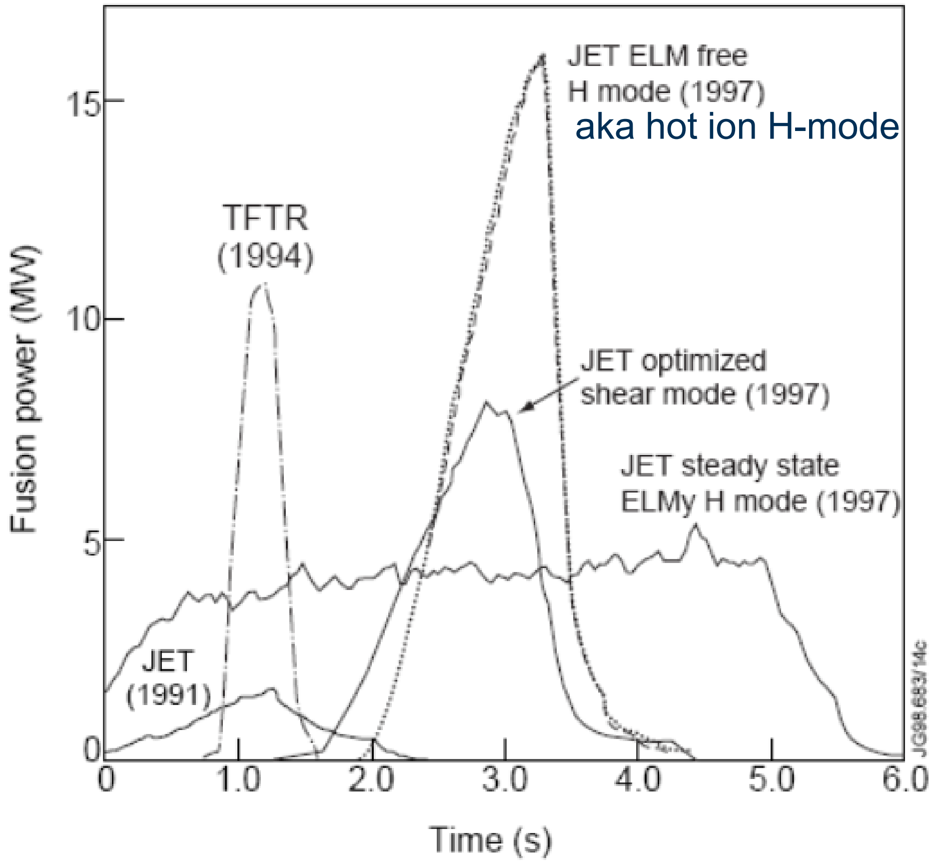
Previous D-T experiments:

- -1991 PTE - JET
- -1994-96 TFTR (US)
- -1997 DTE1 on JET
- -(2003 Trace T exp. on JET)

DTE1: world record fusion

16MW peak D-T power but with transient plasma scenarios

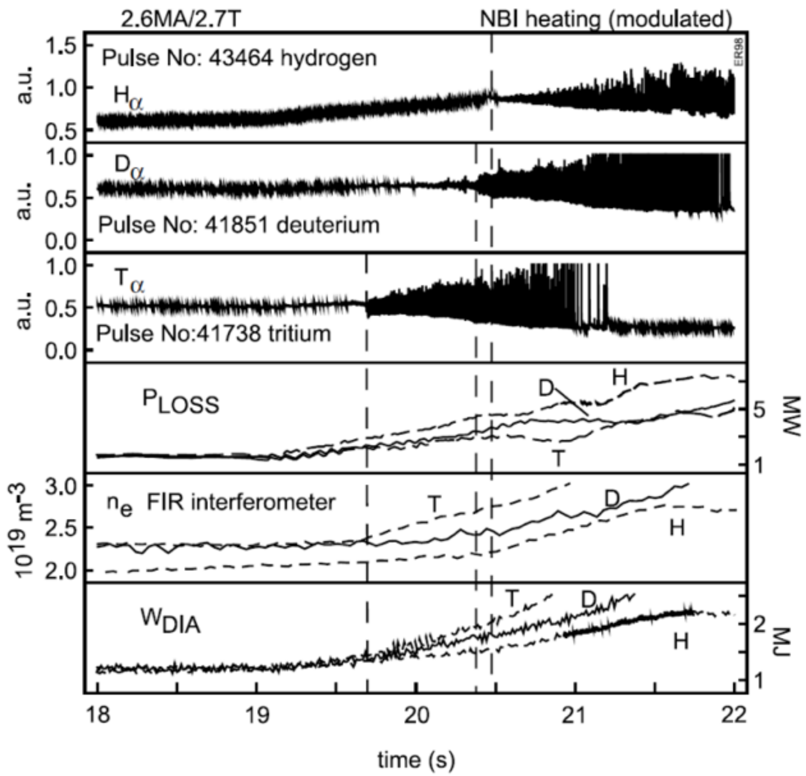
22MJ D-T energy with sustained ELMy H-mode



# Clear impact of isotope mass

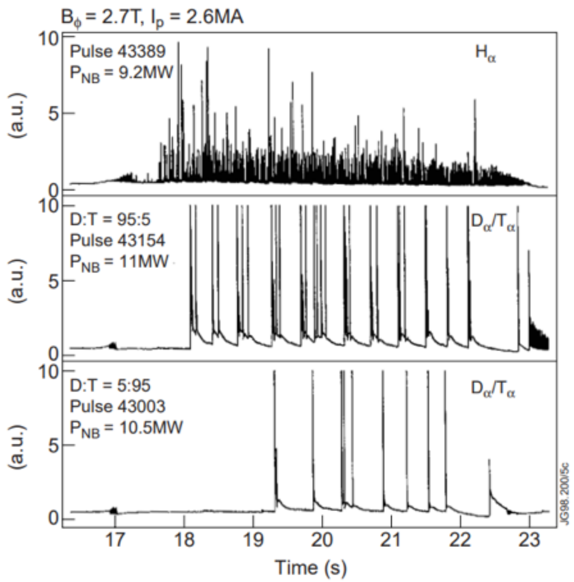
Isotope mass impacts plasma behaviour, e.g.:

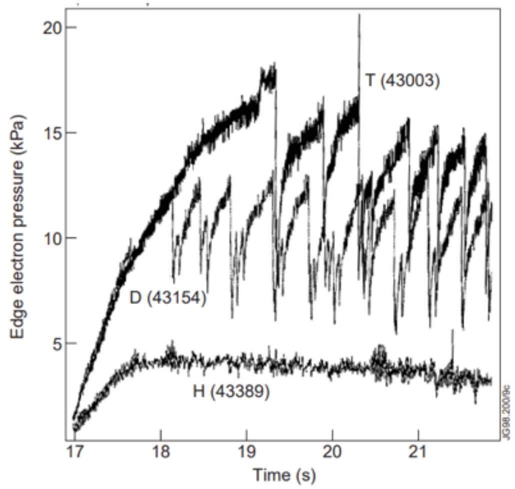
- -L-H threshold
- -Edge pressure & ELM frequency
- -Confinement
- -Detachment




E. Righi *et al*, Nuclear Fusion, 39, 309 (1999)

Saibene G et al. 1999 Nucl. Fusion 39, 1133 [2]




V.P. Bhatnagar *et al.*, Nuclear Fusion, 39, 353 (1999)

Interpretation limited by diagnostic capabilities, e.g. spatial and time resolution of $n_e$ & $T_e$ profile insufficient for detailed pedestal understanding

# Isotope mass impacted high fusion power scenario

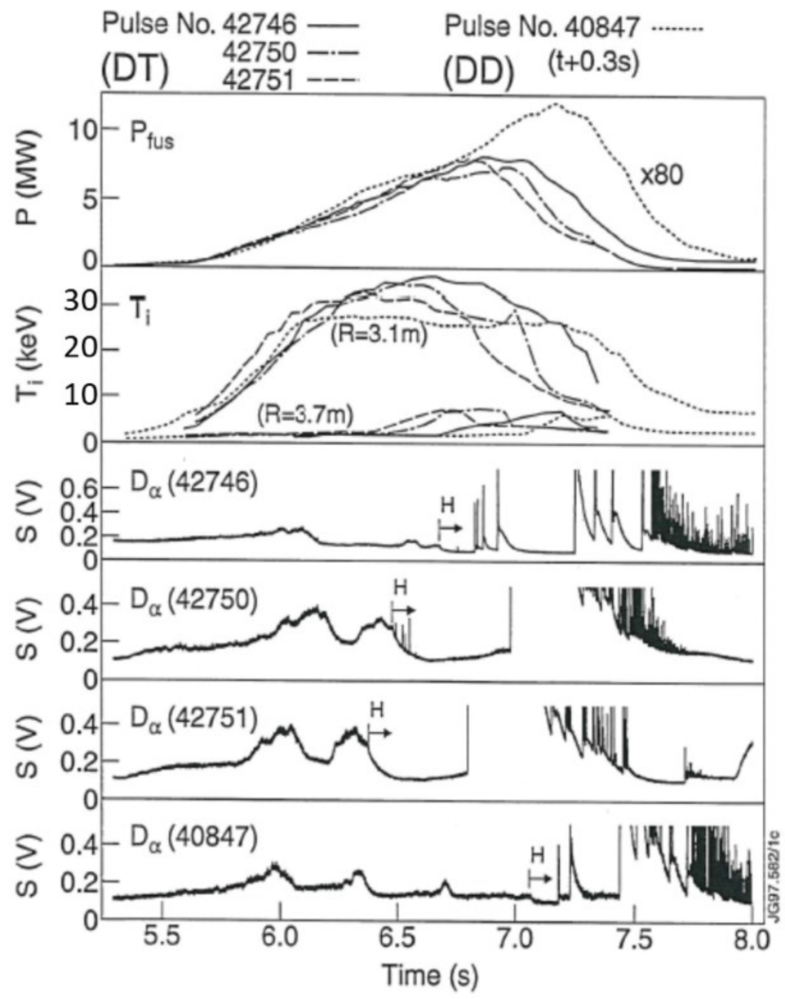
JET ‘Optimised shear’ scenario
(based on DIII-D and TFTR ITB plasmas*)
developed in D in lead-up to DTE1:

- -flat q-profile with $q_{min}$ = 1-2
- -Low electron density ($n_e$)
- -ELM-free plasma

Lower $P_{L-H}$ & different q-profile in D-T prevented ITB & surprised the team

Re-optimisation (NBI & ICRF start time and waveform, gas injection) started but limited by available time, only $P_{D-T}$ = 7MW reached

High C-wall fuel retention impacted capabilities to reach highest tritium ratio



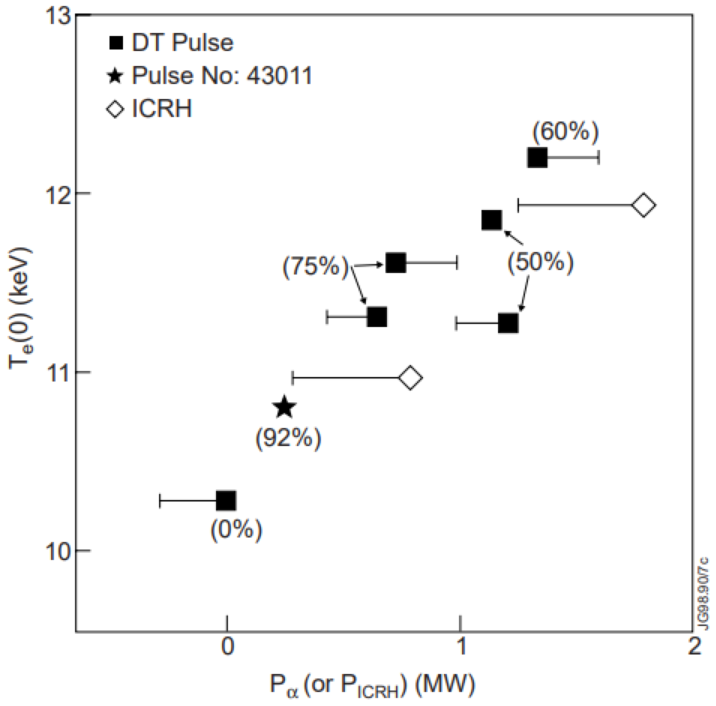

See for example C. Gormezano et al., PRL 80 (1998) 5544

*DIII-D: FM Levington et al., PRL 75 (1995) 4417;  TFTR: EJ Straight et al., PRL 75 (1995) 4421

# Alpha particle effects in DTE1

Clear $\alpha$-driven instabilities observed in TFTR but JET DTE1 results ambiguous due to the presence of ICRF fast ions

$\alpha$ heating observed in TFTR, & in JET DTE1 with scan in D/T ratio – but difficult to disentangle from isotope effects on confinement

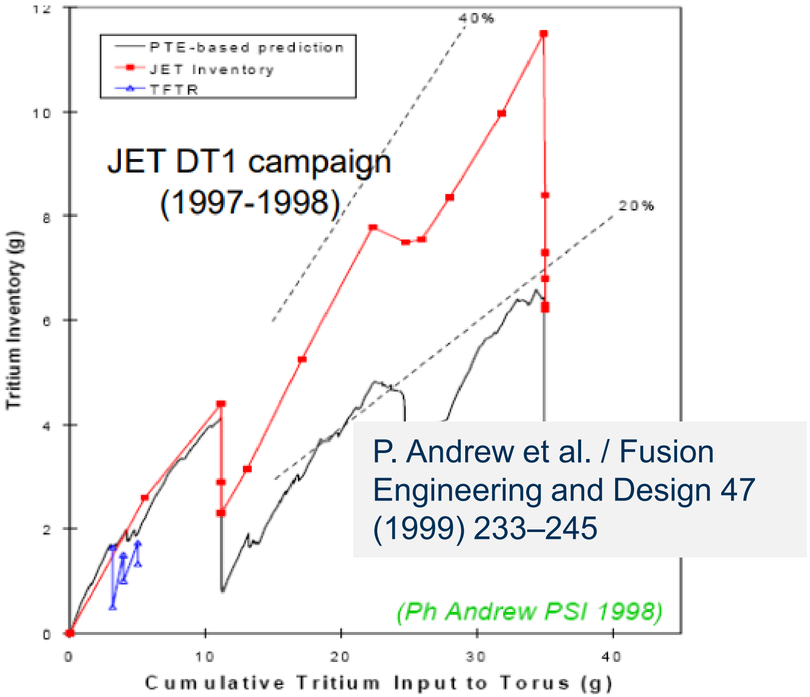


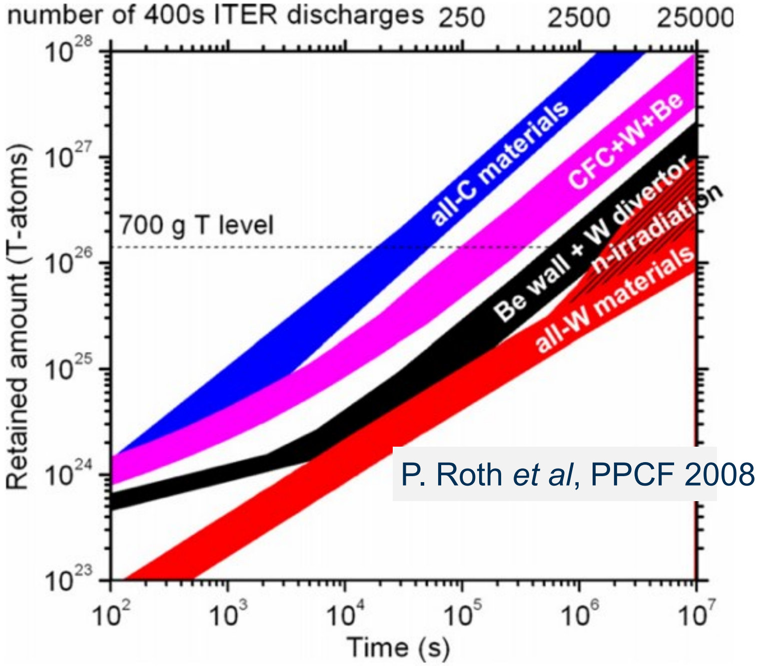

3.4T/3.8MA. D-T pulse have NBI=10MW

Number in bracket is $n_T/(n_{T+}n_D)$

PR Thomas *et al.*, PRL 80 (1998) 5548

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




High T retention undesirable:

- Expensive fuel
- Long term T inventory limited by safety consideration

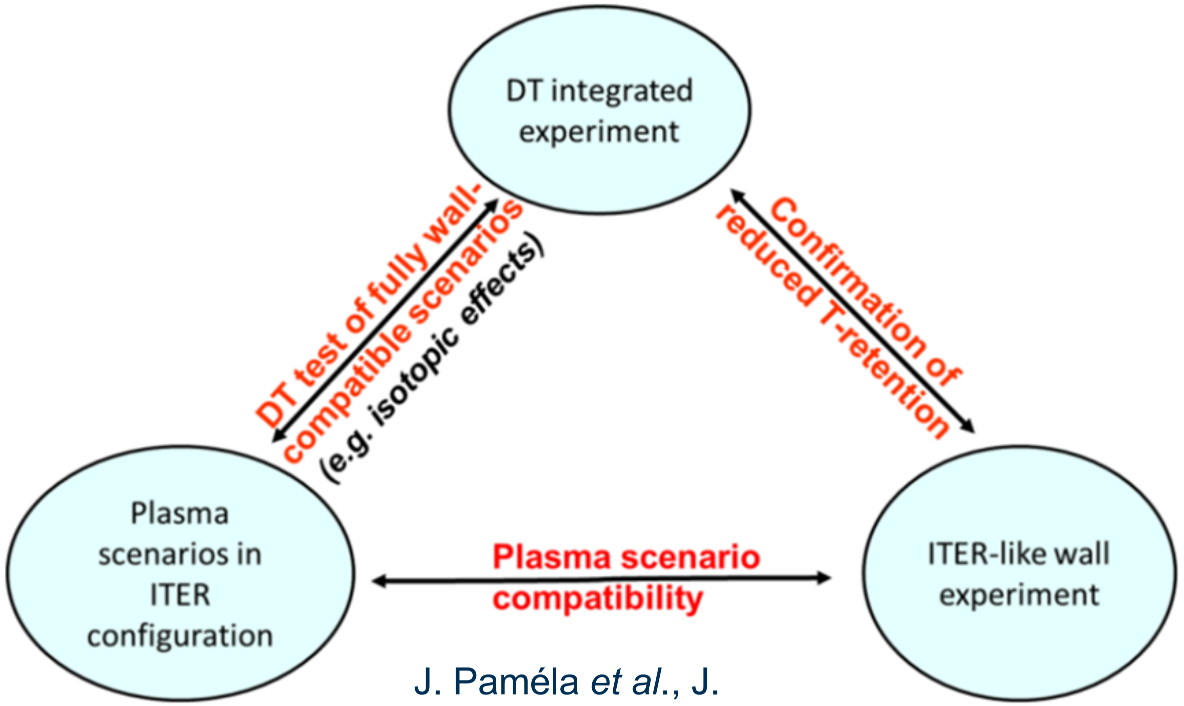
JET 'Post-mortem' analysis:

- -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 → **JET with metal wall, with demonstration in D-T**

# D-T experiments with JET-ILW

- JET-ILW project key part of Europe's support to ITER
- Main goals:
  - Confirm reduced fuel retention
  - Assess compatibility of W with ITER relevant scenarios
  - Demonstrate D-T integrated operation
  + Give new generation of scientists, operators and engineers D-T operations experience

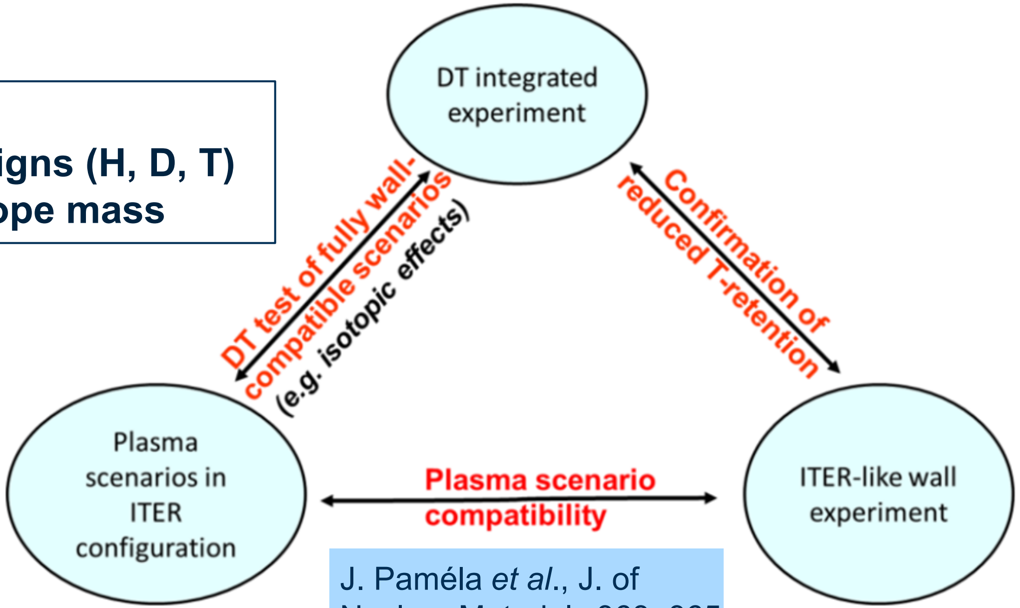



J. Paméla *et al.*, J. Nucl. Mater. 363–365 (2007)

# DTE2: Culmination of JET Operation with ITER-like Wall

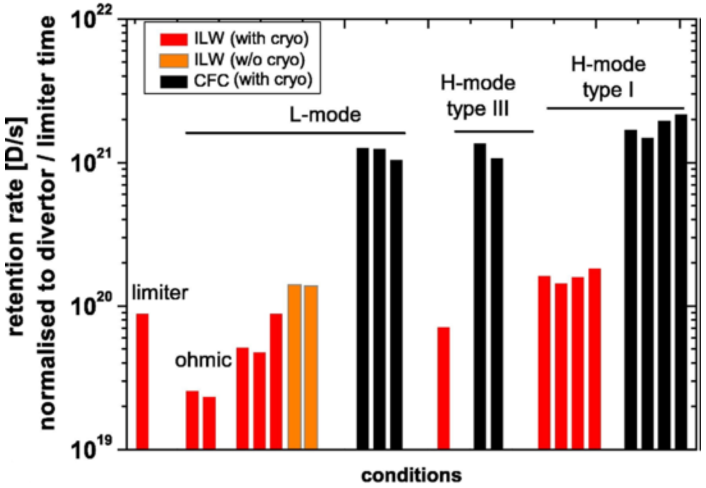
**2021: DTE2**

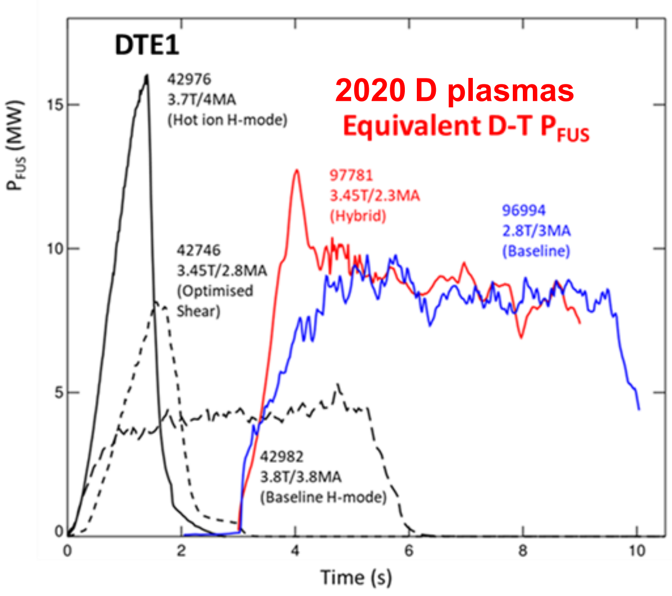
**2016-2021:**
**Dedicated campaigns (H, D, T) on impact of isotope mass**




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

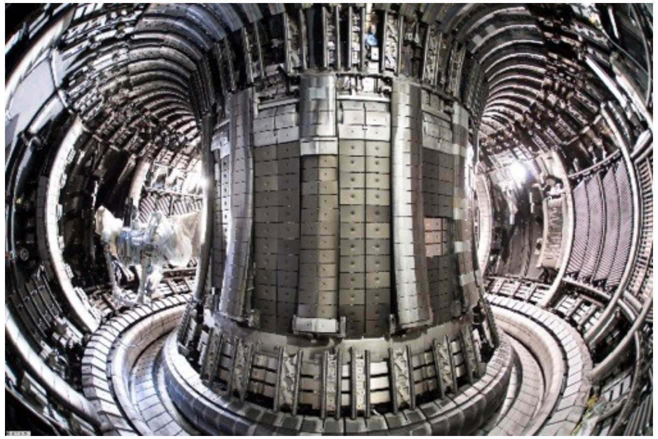
**2011-2014 & 2015-2016:**
**Low fuel (D) retention confirmed**



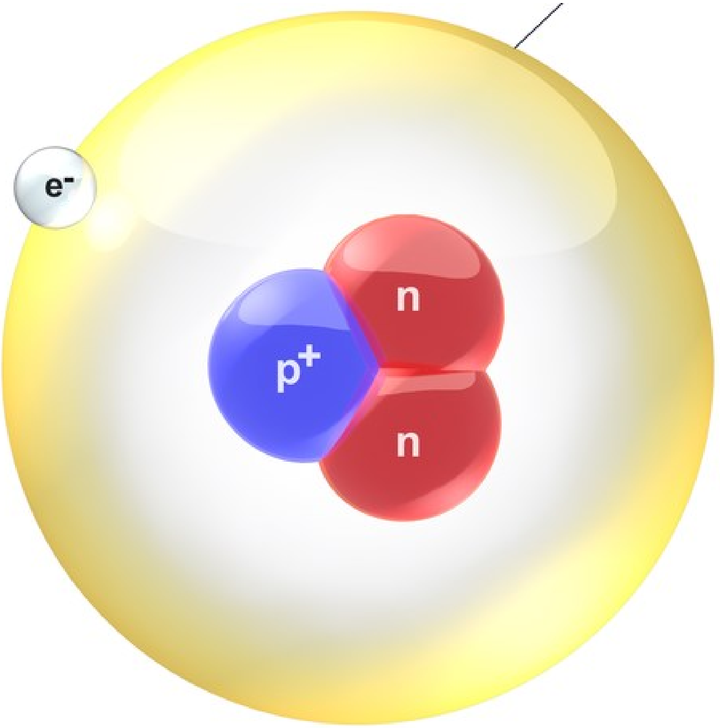




**2016-2020:**
**ILW compatible with high fusion performance (D plasmas)**

**2009-2011: Installation of ILW (W divertor & Be walls)**



# Tritium Plant

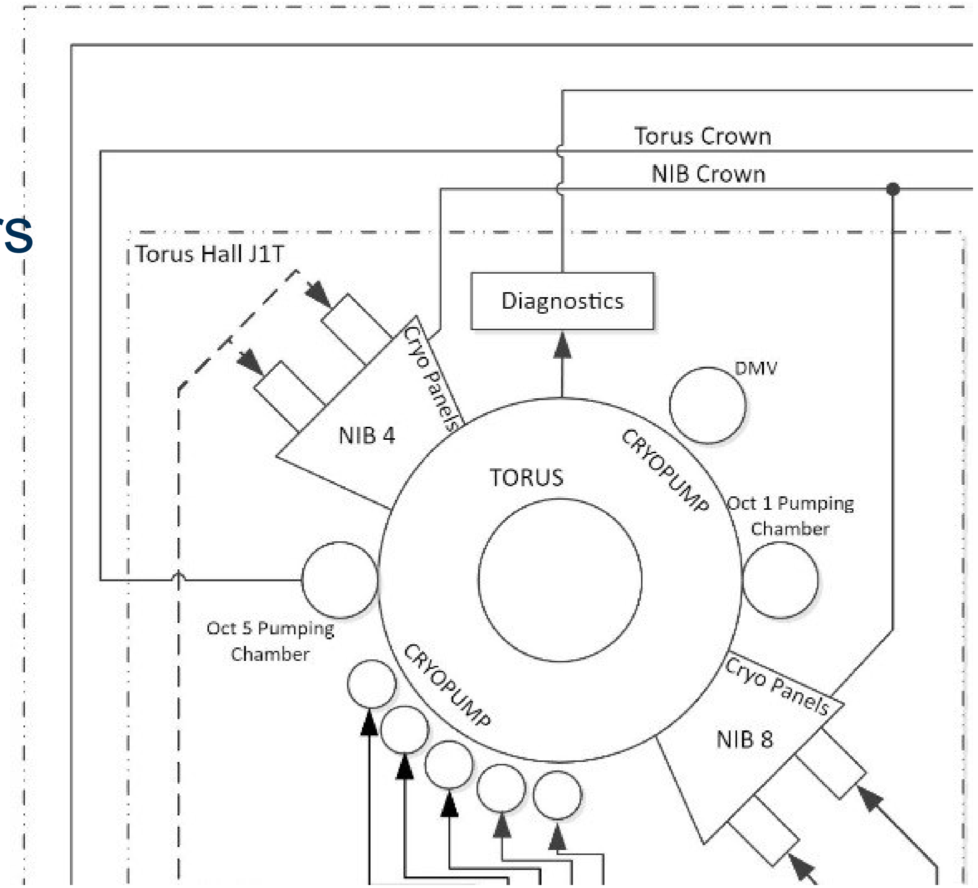


# Standard Gas Handling System

- The fuel cycle on JET for deuterium operations is relatively simple, however tritium needs more!

Neutral Beam Injectors

Pumping systems




Neutral Beam Injectors

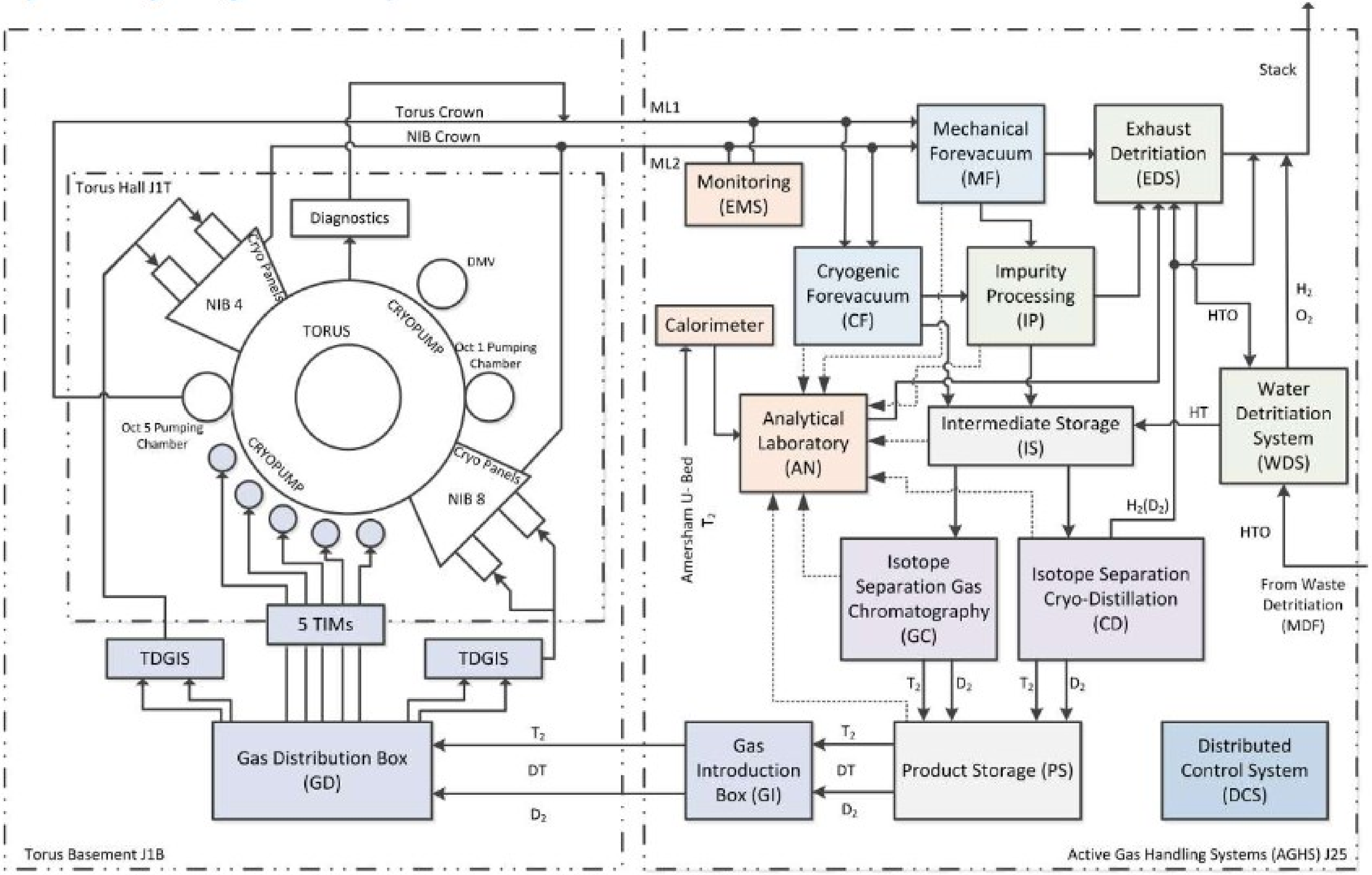
Gas introduction modules (GIMs)

# AGHS Purpose

The AGHS was constructed to feed, process and recycle tritium. The AGHS is located in a separate building connected with the Torus via gas transfer and pumping lines. The main processing steps of the gases in the AGHS are:

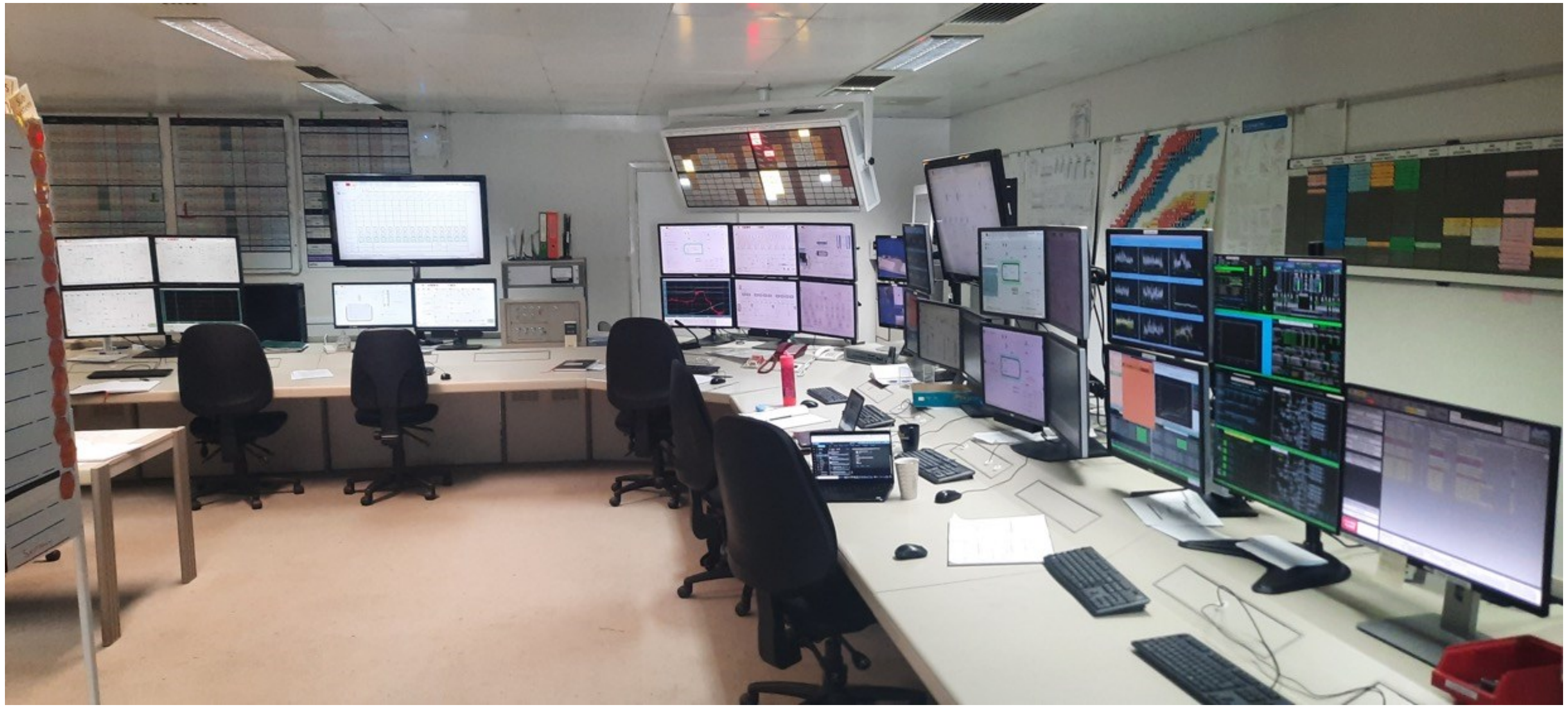
- Feed tritium and deuterium to clients in J1;
- Pump exhaust and regeneration gas loads from the Torus and NBI systems;
- Separate impurities from hydrogen isotope mixtures;
- Recover tritium from tritiated impurities;
- Isotopically separate hydrogen isotope mixtures into pure tritium, deuterium and hydrogen; the former two for recycling to the torus and NIB systems and the latter for discharge into the environment;
- Store pure deuterium and tritium in uranium beds for further re-use;
- Re-supply deuterium and tritium to the Torus and NIB systems.

# Active Gas Handling Subsystems

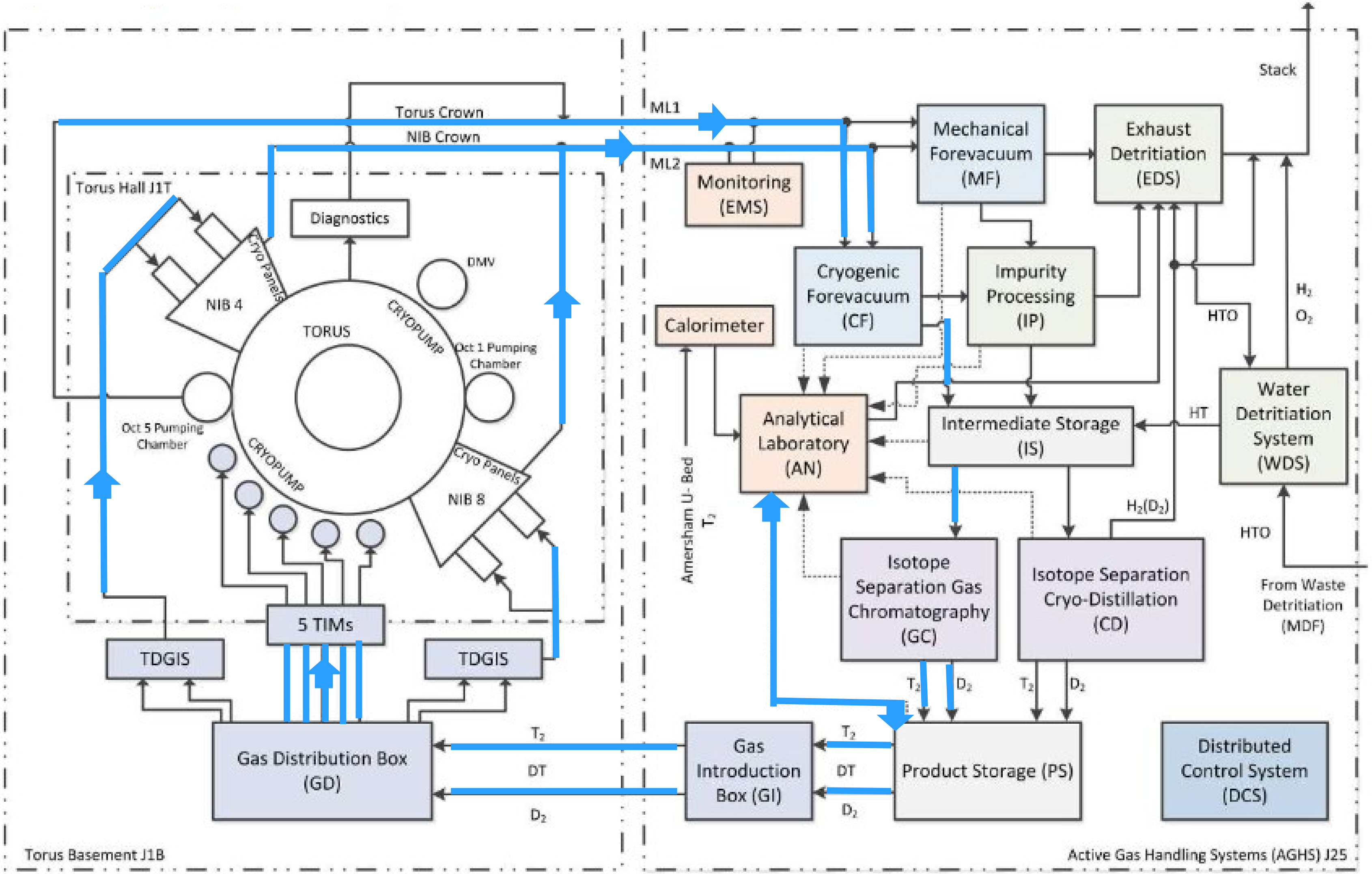


# AGHS control room – DT Ops shifts

- 4 Shift Teams in 12h shift rota
- Shift handover @ 06:45 & 18:45.
- Shift Appointments: Operations Engineer (shift Leader), Plant Supervisor, Control Room Duty Officer,
- Shift cover depends on level of operations (2-4 members + AN tech).
- AGHS Local Rules and Operation Instructions



# AGHS DT ops fuel cycle overview




Supply tritium and deuterium to Torus vessel and NIB's, recover and process tritiated gas from the Torus PD and NIB's cryo panels.

At the start of the ops day AGHS confirms the $T_2$ inventory with EiC and EiC confirms the TIM's filling requirement.

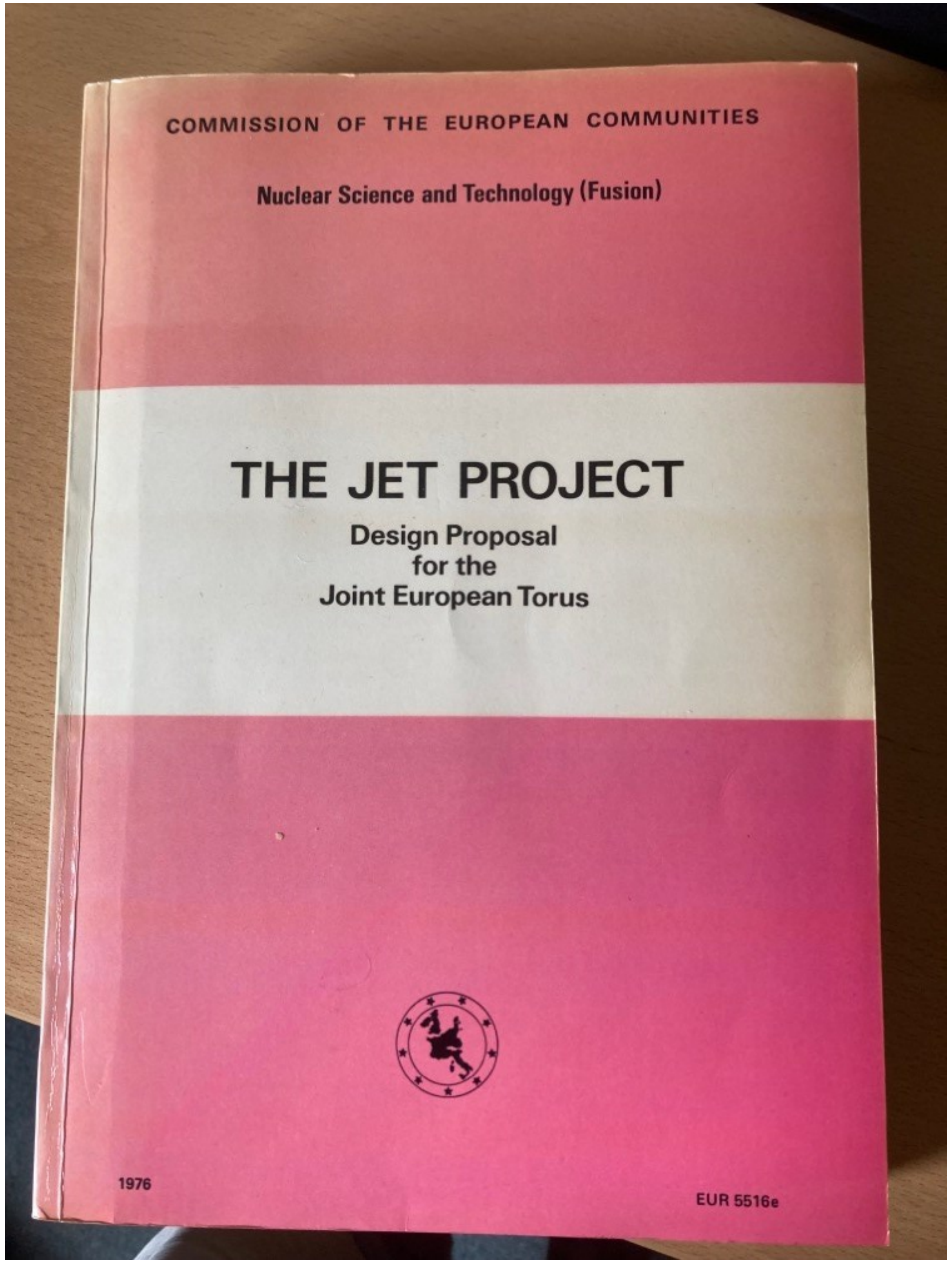
Depending on the ops plan at the end of the ops day, AGHS pulls back the $T_2$ from TIM's and NIB 4 and confirmation email is sent out.

# Communication between JET control room and AGHS control room is crucial

- ✓ Fills of the NBI tritium system communicated from NBI to AGHS, or EIC to AGHS depending on operation mode, NBI & EIC must also communicate
- ✓ Fill of the TIMs: EIC <-> AGHS at request of SL
- ✓ Evacuation of TIMs: EIC <-> AGHS
- ✓ Regenerations planned by JET operations manager and communicated by EIC & Shift Tech

- ✓ Every change must be clearly communicated (change of pumping status, gas being sent to AGHS…)
- ✓ Gas evacuation and inventory recovery, Shift Tech via phone and confirmation email.
- ✓ Various regular safety checks, Shift Tech via phone.
- ✓ All unexpected alarms communicated and appropriate emergency response
- ✓ LHe dewar fill

# Preparations



# Preparation and Decision

- Preparations for DTE2 experiment started ~2010.
- The progress was reviewed in 2015 by the JET DT Readiness Ad Hoc Group and EURO*fusion* Science and Technology Advisory Committee.
- A set of 19 Key Performance Indicators (KPIs) was agreed by the EURO*fusion* General Assembly as prerequisite for making final decision to carry out 100%T and DTE2 experiment.

| | | |
|---|---|---|
| **Fusion Performance** | 1 | Achieve NBI power of 32 MW (averaged over 3s in 20 highest NBI power pulses) |
| | 2 | Achieve ICRH power of 6 MW (averaged over 3s in 20 highest ICRH power pulses with NBI power >10 MW) |
| | 3 | Achieve neutron rate of $5\times10^{16}$ $s^{-1}$ (averaged over 5s in 20 highest neutron rate pulses) |
| **D-T Prediction** | 4 | Update equivalent DT fusion yield after every deuterium campaign |
| **Alpha Physics** | 5 | Demonstrate deuterium discharges with equivalent DT conditions expected to reveal alpha particle effects |
| **Isotope Physics** | 6 | Complete hydrogen campaign, including reference pulses for later use in T and DT campaign |
| | 7 | Complete deuterium reference pulses for later use in T and DT campaigns |
| **Reference Pulses** | 8 | Complete list of all pulses to be repeated in tritium campaign (for performance, modelling, alpha and isotope physics |

| | | |
|---|---|---|
| **Diagnostics** | 9 | Produce high fraction (0.8) of validated ion temperature profiles for high neutron rate pulses (KPI 3) |
| | 10 | Produce validated ion temperature profiles for all pulses within the list of pulses to be repeated in tritium (KPI 8) |
| | 11 | Carry out measurement of TAE damping in an X-point plasma |
| | 12 | Maximise resolvable toroidal mode number (target n=12) |
| | 13 | Complete14MeV neutron calibration using neutron generator |
| | 14 | Demonstrate reliable operation with two DT compatible camera views (wide angle and divertor) |
| **Technical Preparations** | 15 | Carry out successful DT rehearsals |
| | 16 | Adopt DT Safety Case |
| | 17 | Demonstrate reliable operation of tritium introduction modules |
| | 18 | Demonstrate safe deuterium plasma operation with limited first wall protection (WALLS and DT compatible cameras only) |
| | 19 | Complete tritium gas delivery |

- By the end of 2015, the start of JET tritium operation was envisaged in early 2018.

# Preparation - Programme

- Note that amongst these KPIs there was a reference to high neutron rate performance in many plasmas
- This represents the scenario development in two possible scenarios for DT over a number of years
- Integration of the physics and the operations of JET
- A significant proportion of JET time (>50% in some periods) dedicated to this including some enabling physics experiments
- See various publications from JET-ILW period, Nuclear Fusion special issue in particular

| | | |
|---|---|---|
| **Fusion Performance** | 1 | Achieve NBI power of 32 MW (averaged over 3s in 20 highest NBI power pulses) |
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**"Achieve neutron rate of $5x10^{16}s^{-1}$ (averaged over 5s in 20 highest neutron pulses"**

# Preparation - Programme

| | | |
|---|---|---|
| **Fusion Performance** | **1** | Achieve NBI power of 32 MW (averaged over 3s in 20 highest NBI power pulses) |
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| **Reference Pulses** | **8** | Complete list of all pulses to be repeated in tritium campaign (for performance, modelling, alpha and isotope physics |

***For a successful tritium campaign clear plans and goals are necessary, it requires an intense focus on agreed topics***

**"Achieve neutron rate of $5\text{x}10^{16}s^{-1}$ (averaged over 5s in 20 highest neutron pulses"**

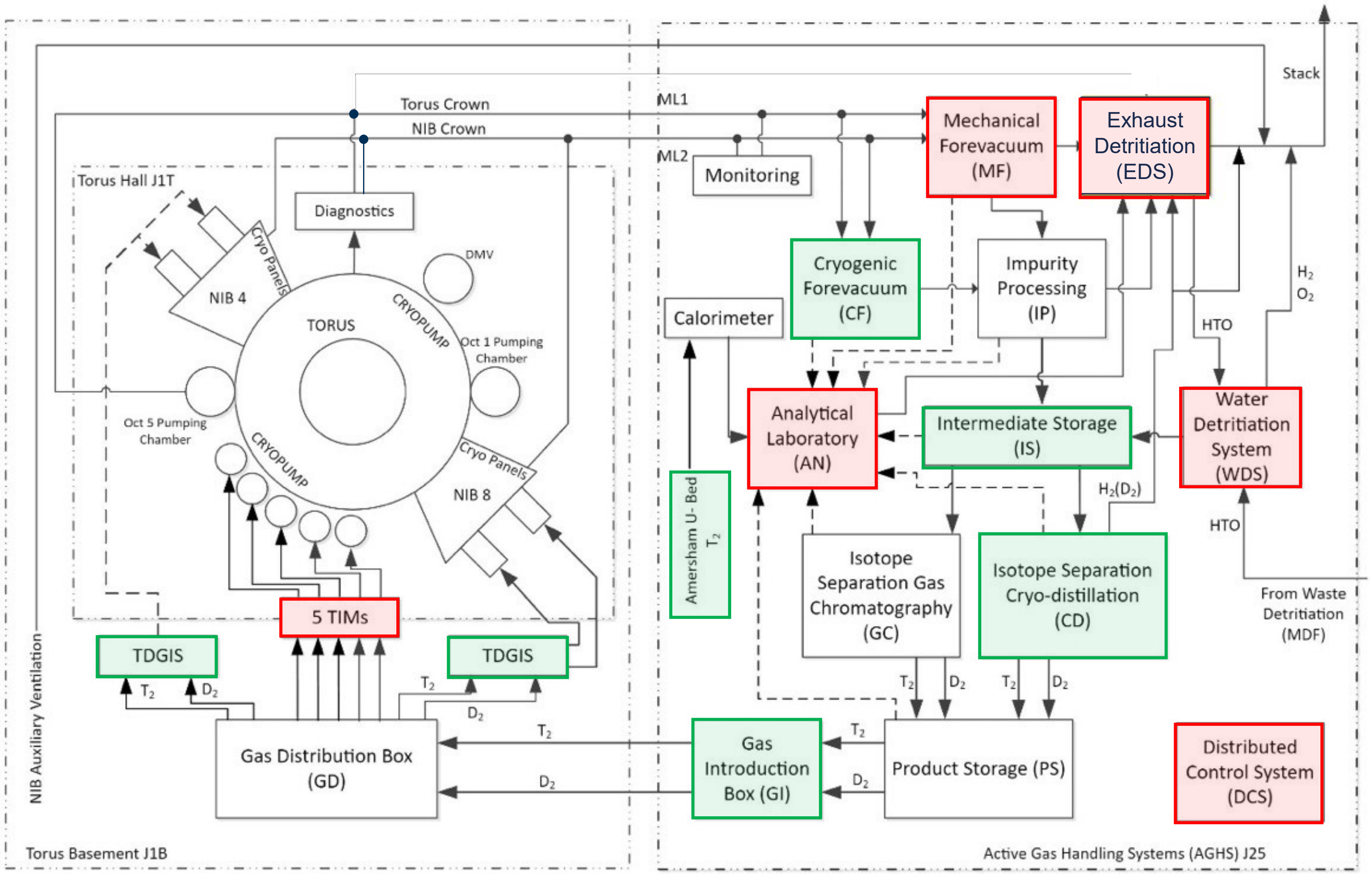
# Preparations for DTE2

- **Upgrade of the Active Gas Handling System (AGHS)** and repair of the Exhaust Detritiation System (EDS)
- Tritium gas injection – 5 Tritium Gas Introduction Modules (TIMs) were designed and installed to supply tritium to the torus vessel
- **DT Compatible Plasma Viewing System**
- **14MeV Neutron Diagnostics Calibration**
- New/Upgraded diagnostic
- DTE2 Safety Case
- **DT Training and Rehearsals**
- Higher neutral beam power and both beamlines in tritium to allow pure tritium campaign
- **Plasma Development**

Divertor TIM

# Upgrade of the Active Gas Handling System

- JET Active Gas Handling System (AGHS) is responsible for the storage, distribution, recovery, analysis and processing of tritium gas and deuterium/tritium mixtures.




## New components:

- Exhaust detritiation system
- Mechanical forevacuum
- Analytical laboratory
- Water detritiation system
- Control system
- Tritium introduction modules (TIMs)

## Extensive upgrades:

- Amersham uranium beds
- Cryogenic forevacuum
- Intermediate storage
- Cryo-distillation
- Gas introduction box
- NBI tritium and deuterium modules (TDGIS)

# DTE2 Safety Case

Production of the new JET DT Safety Case started in 2011, i.e., ~15 years after 1997 DT campaign on JET
– New team required to deliver a safety case suitable for tritium operations.

- Key challenges included:
  - Development of **additional fault sequences** (tritium handling and high neutron dose)
  - Development of **expanded key interlock system** (beyond main operational areas)
  - **Substantiation of engineered safety measures** (particularly older safety equipment)
  - Review and update of **operating instructions**
  - Review and update to our **emergency response arrangements**
  - Development of a **"mode switching" safety case** (switching between 100% D, 100% T and DT operation)

- Provisional DTE2 Safety Case was completed by 2014 and final DTE2 Safety Case was implemented in August 2020.


*Tritium Dispersion modelling data from JET accident conditions using ADMS 5 by CERC*

# DT Training and Rehearsals

Most of the JET operational staff did not have tritium operational experience prior to DTE2.

**Extensive mandatory training** was carried out for all operational staff, with additional training for NBI and AGHS staff.

**DT rehearsals** were carried out in 2015/16 and 2020 for a period of few weeks to exercise operational tasks and procedures envisaged during 100%T and DTE2 experiments while operating machine in deuterium

Staff training aspects
Technical aspects
Plasma operations aspects
NBI characterised with appropriate gas feed

Many lessons learnt during DT rehearsals were subsequently implemented during 100%T and DTE2 experiments.

During **non-active phase** before DT, there was extensive work in preparation

- **Torus gas injection using TIMs** operated in deuterium.
- Development of **exact plasma references in deuterium** (current/field/density/heating power) to be used during 100%T and DTE2 experiments.

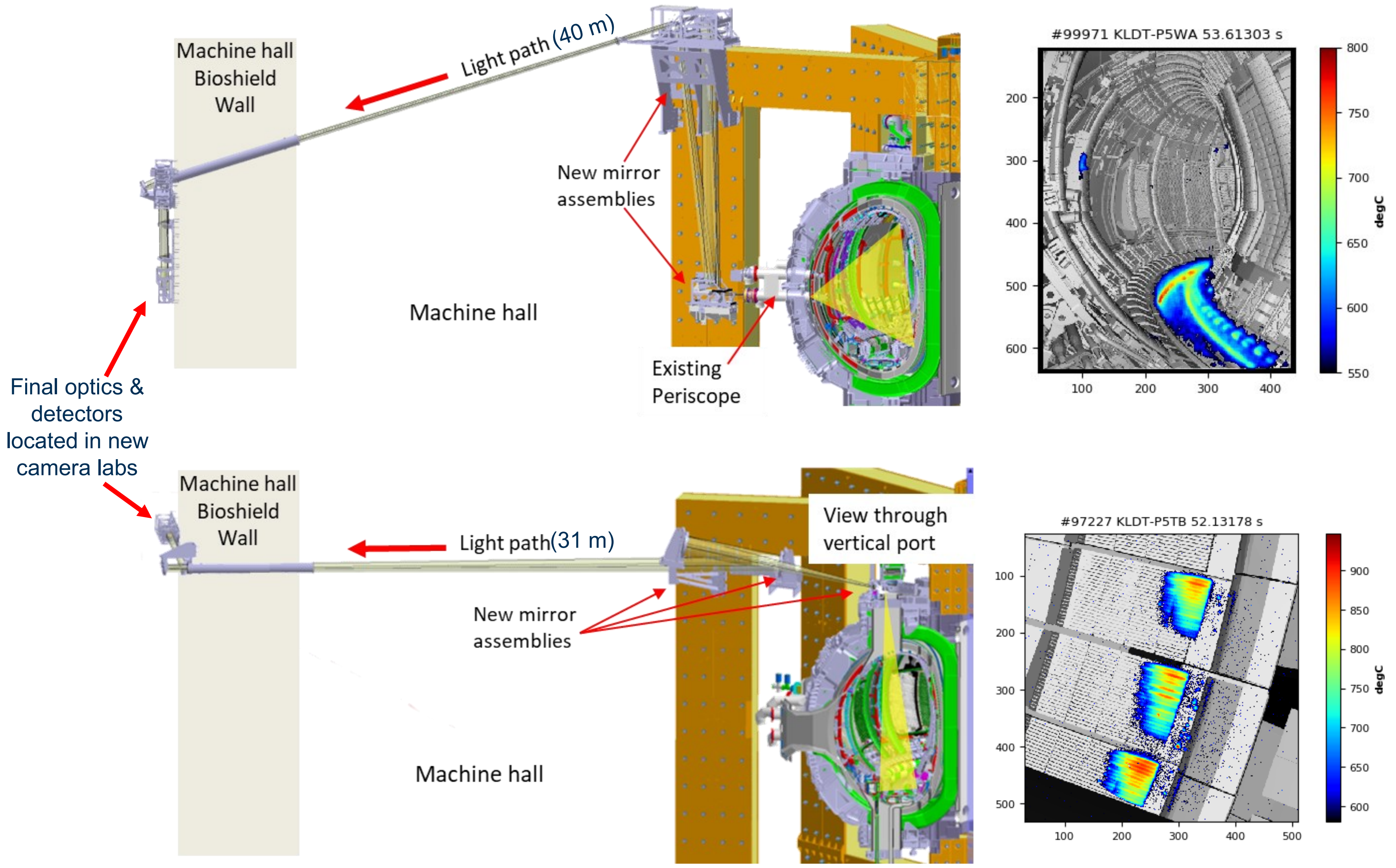
# DT Compatible Plasma Viewing System

JET has ~30 cameras sharing 9 imaging views, but none were radiation tolerant before DTE2

- Cameras were relocated outside biological shield

Balboa, I, et al. Plasma Phys. Control. Fusion, 65 094002, 2023

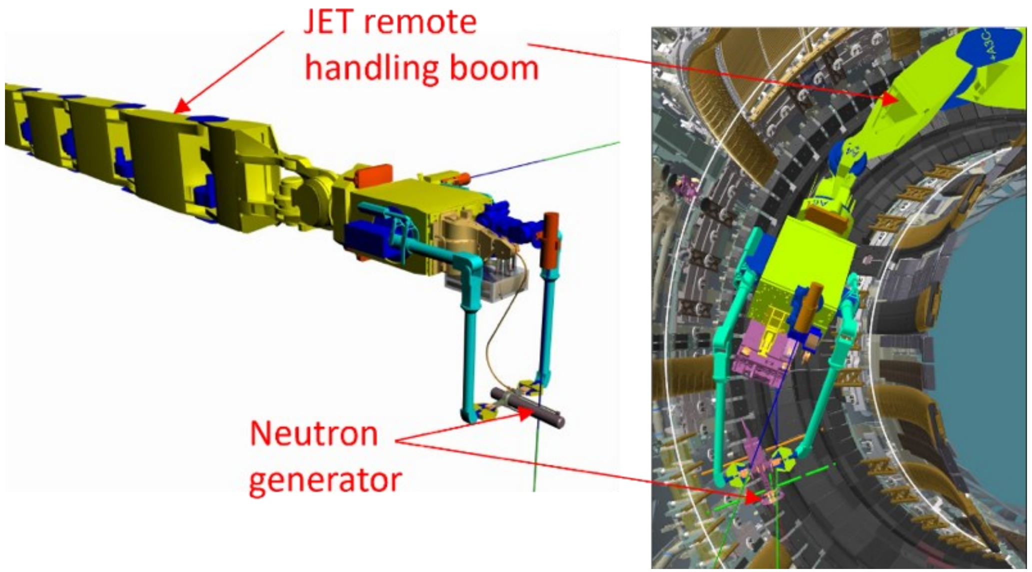
Balboa, I, et al. Plasma Phys. Control. Fusion, 65 064005, 2023



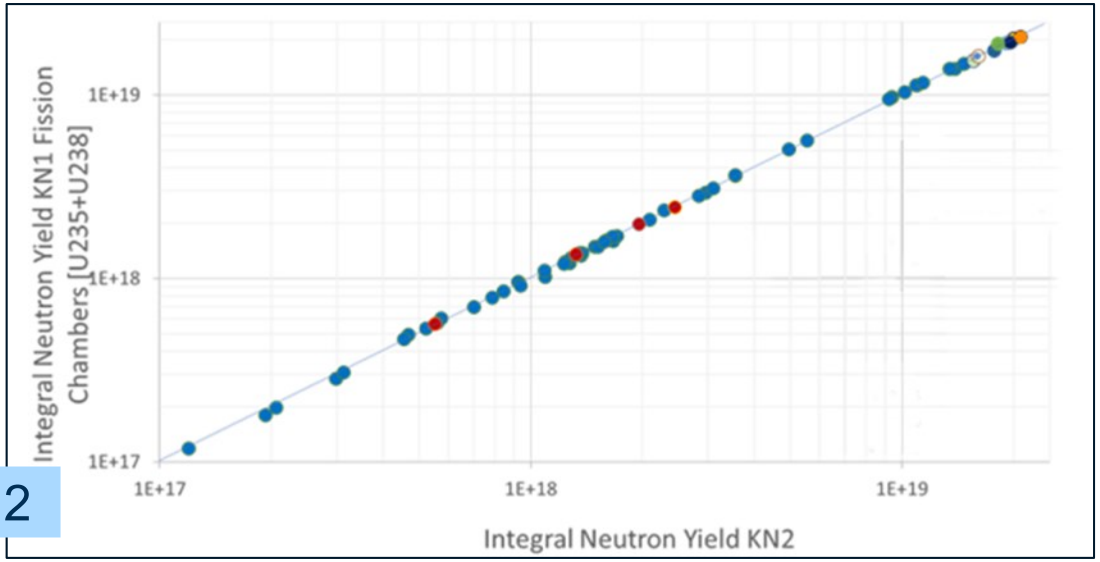
# 14MeV Neutron Diagnostics Calibration

**Accurate measurements of 14 MeV neutron yields** are essential for DT experiments

Thorough calibration of JET neutron diagnostics was the important tasks in preparation for the DTE2 experiment:




- Multi-stage process involving remote handling before campaign and plasma calibrations
- Excellent consistency between diagnostics during DTE2 gave high confidence in calibration (uncertainties <10%)
- Method developed on JET to be used on ITER




P. Batistoni *et al*. 2018 Nuclear Fusion **58** 026012
Z Ghani in preparation

# Other Diagnostics

**Significant increase in JET diagnostic capabilities** relative to DTE1:

To improve coverage of plasma pedestal/edge

To improve understanding of the effect of metallic wall on plasma core/edge/SOL behaviour

**New / upgraded diagnostics for DTE2 experiment**:

TAE antenna (alpha instabilities)

Neutron camera and spectrometer

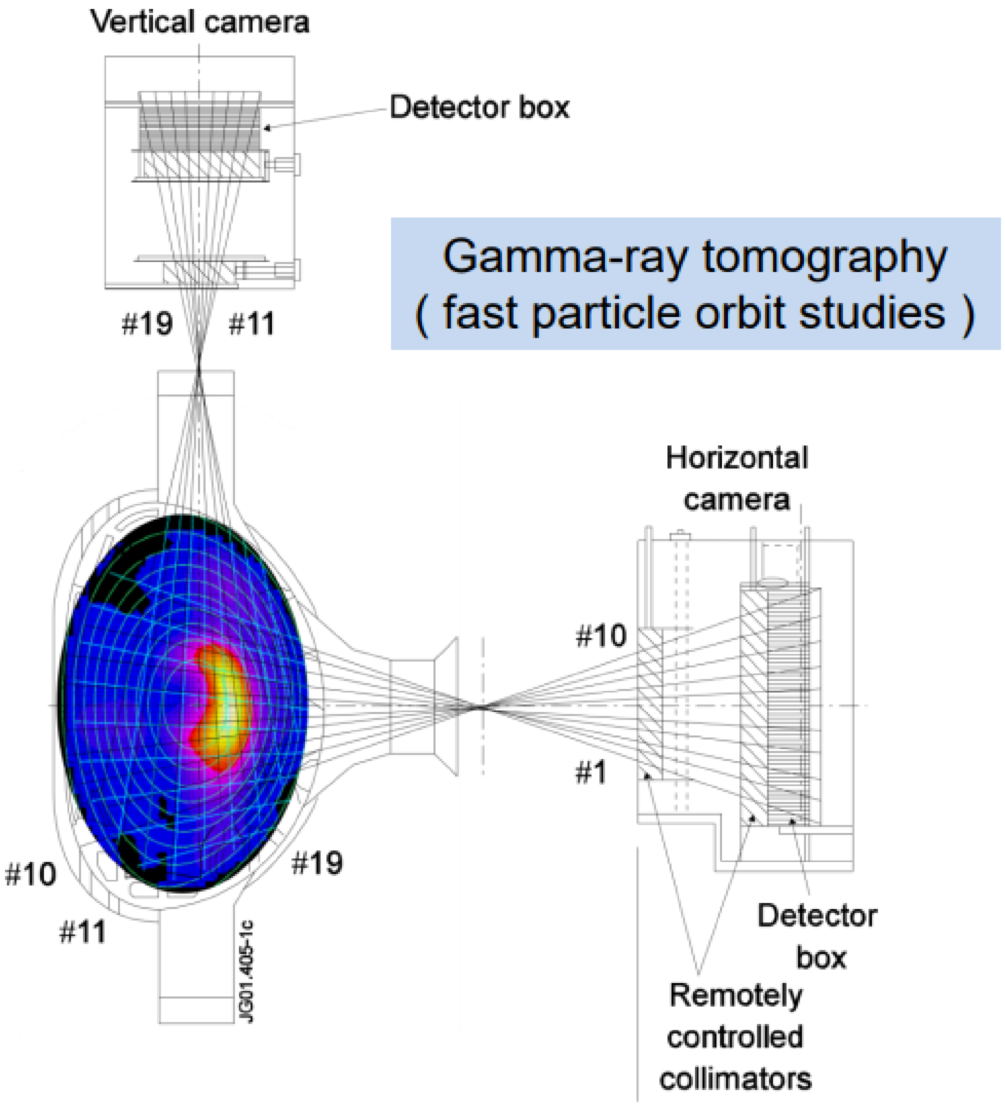
Gamma-ray tomography

Fast Ion Loss Detector (alpha losses)

High-resolution sub-divertor residual gas analyser

**Some diagnostics removed prior to DTE2** – incompatible with high neutron flux environment

**Some diagnostics sacrificed** – removal considered too complex

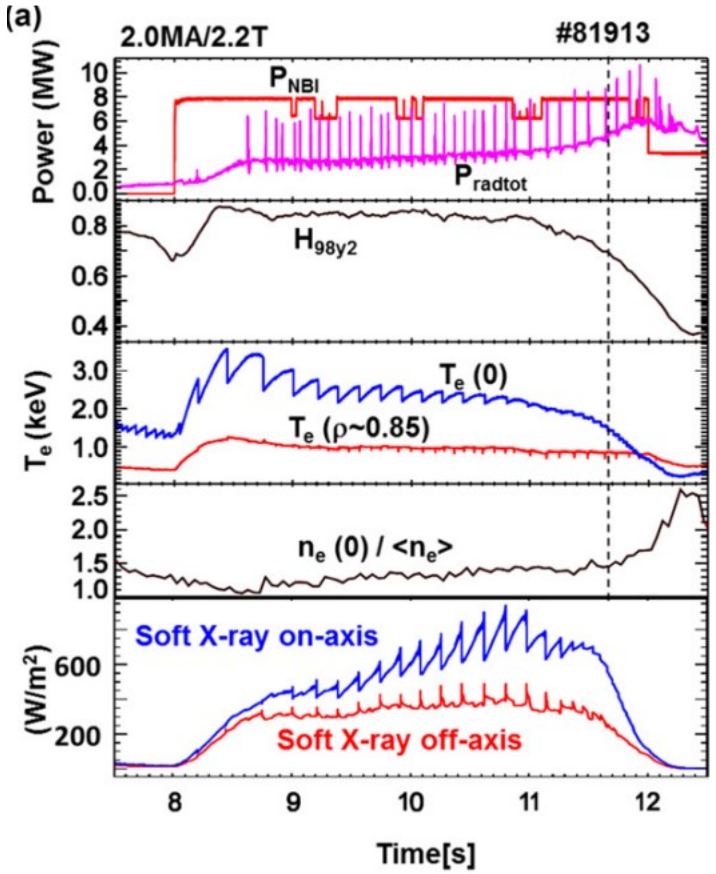


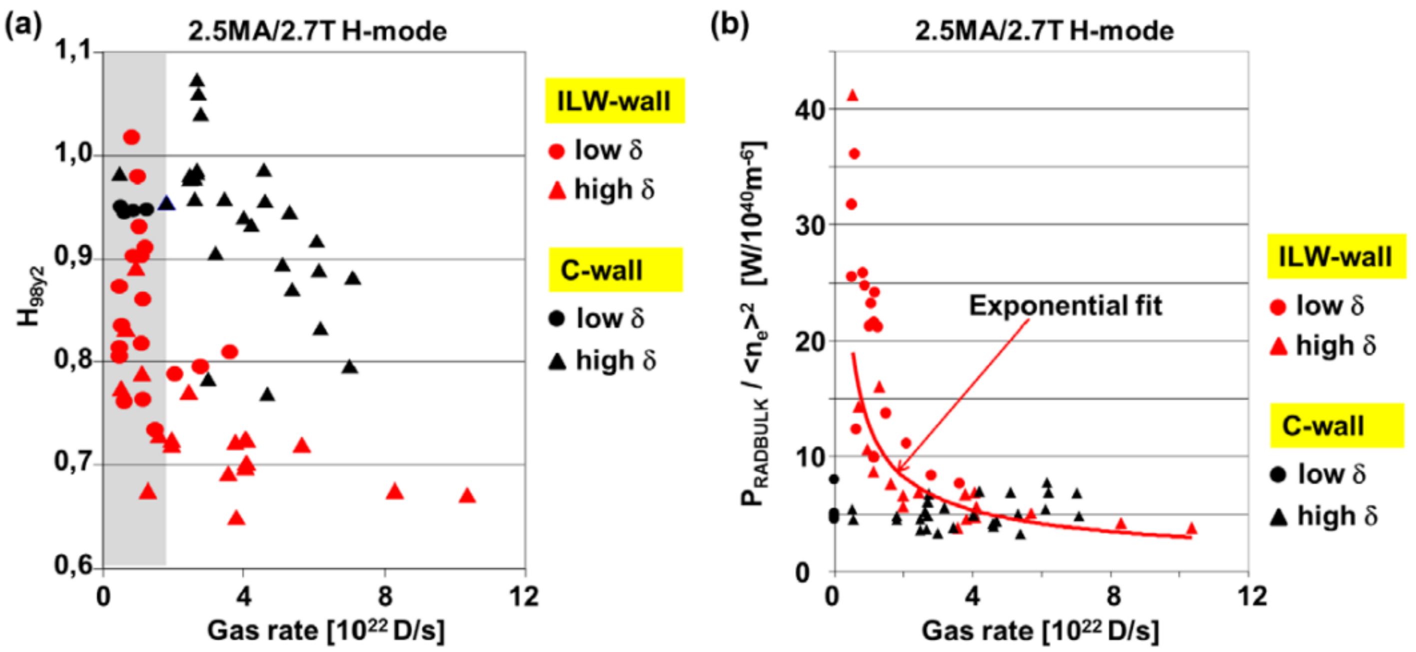
# Plasma operation in JET-ILW challenging due to W

JET

**JET-ILW first campaigns:**

- plasma prone to impurity (W) accumulation and disruption
- ELMs have key role in flushing impurities
- but increasing gas to ensure fast enough $f_{ELM}$ degrades plasma confinement

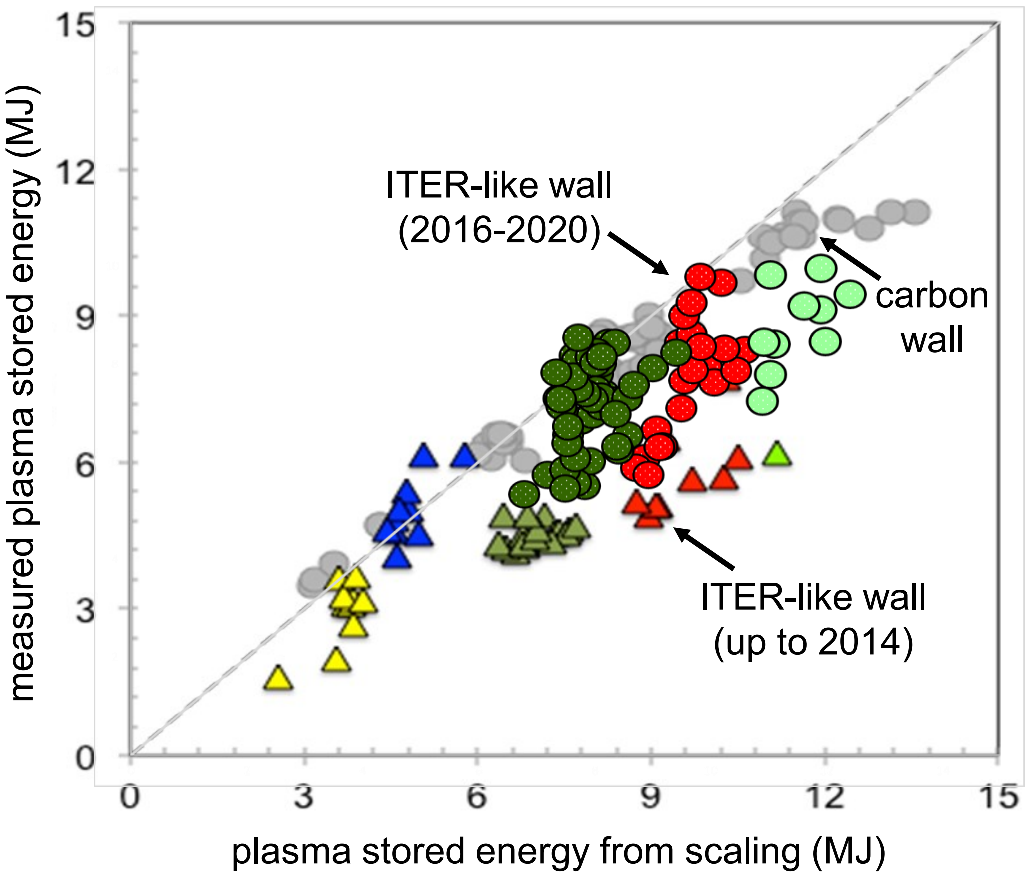



E. Joffrin et al. NF 54 (2014) 013011

# High performance recovered

JET




## Plasma development (with deuterium fuel)

- **ILW up to 2014**: Difficult to match plasma performance achieved with carbon wall in early experiments after installation of ILW due to W
- **ILW 2016-2022** confinement recovered 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
    - Use of high pedestal temperature to screen impurities in hybrid plasma scenario

**This development (and several others) demonstrated readiness for DTE2**

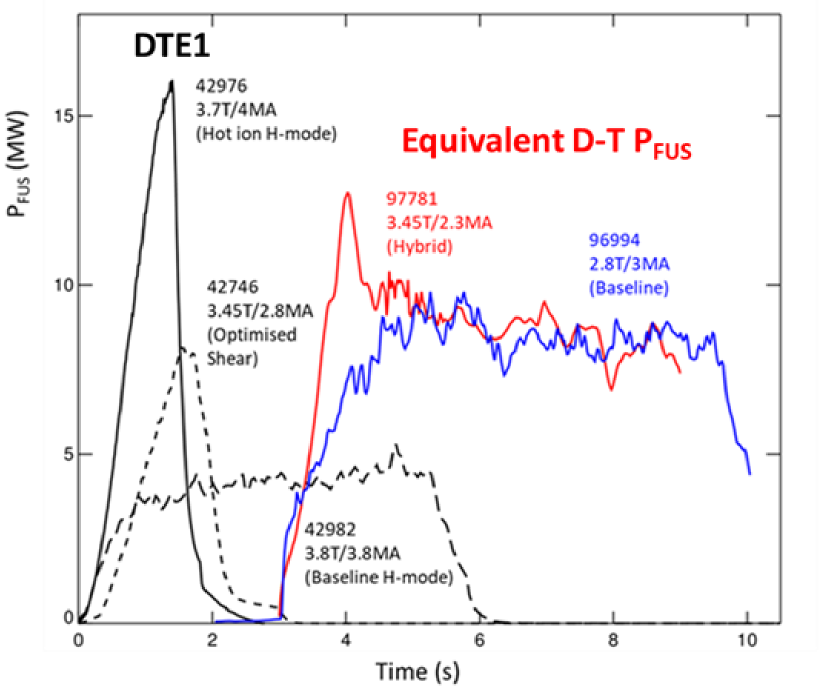
J. Mailloux et al 2022 Nucl. Fusion 62 042026

# All conditions met for Tritium operations approval in 2020

## All KPIs met

| | | |
|---|---|---|
| **Fusion Performance** | 1 | Achieve NBI power of 32 MW (averaged over 3s in 20 highest NBI power pulses) |
| | 2 | Achieve ICRH power of 6 MW (averaged over 3s in 20 highest ICRH power pulses with NBI power >10 MW) |
| | 3 | Achieve neutron rate of $5\times10^{16}$ $s^{-1}$ (averaged over 5s in 20 highest neutron rate pulses) |
| **D-T Prediction** | 4 | Update equivalent DT fusion yield after every deuterium campaign |
| **Alpha Physics** | 5 | Demonstrate deuterium discharges with equivalent DT conditions expected to reveal alpha particle effects |
| **Isotope Physics** | 6 | Complete hydrogen campaign, including reference pulses for later use in T and DT campaign |
| | 7 | Complete deuterium reference pulses for later use in T and DT campaigns |
| **Reference Pulses** | 8 | Complete list of all pulses to be repeated in tritium campaign (for performance, modelling, alpha and isotope physics |
| **Diagnostics** | 9 | Produce high fraction (0.8) of validated ion temperature profiles for high neutron rate pulses (KPI 3) |
| | 10 | Produce validated ion temperature profiles for all pulses within the list of pulses to be repeated in tritium (KPI 8) |
| | 11 | Carry out measurement of TAE damping in an X-point plasma |
| | 12 | Maximise resolvable toroidal mode number (target n=12) |
| | 13 | Complete14MeV neutron calibration using neutron generator |
| | 14 | Demonstrate reliable operation with two DT compatible camera views (wide angle and divertor) |
| **Technical Preparations** | 15 | Carry out successful DT rehearsals |
| | 16 | Adopt DT Safety Case |
| | 17 | Demonstrate reliable operation of tritium introduction modules |
| | 18 | Demonstrate safe deuterium plasma operation with limited first wall protection (WALLS and DT compatible cameras only) |
| | 19 | Complete tritium gas delivery |

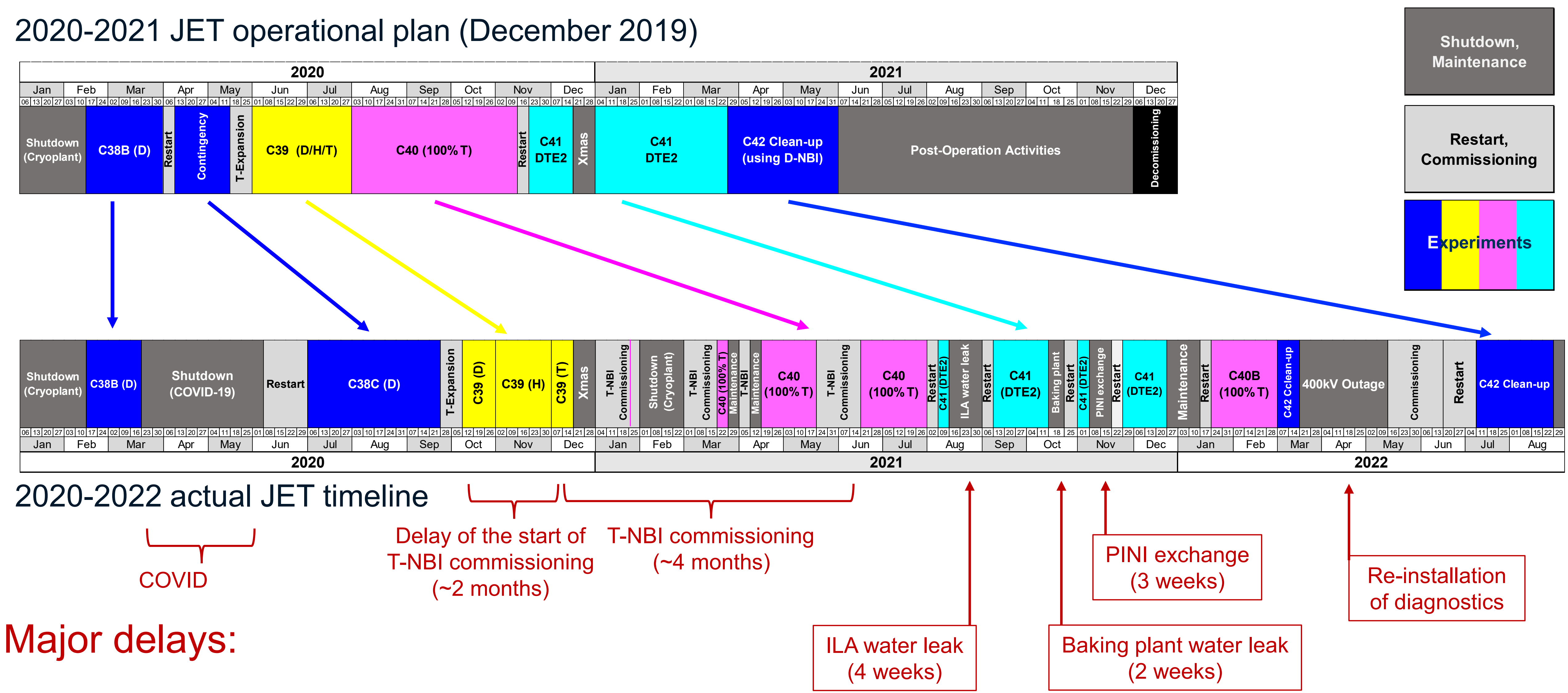
## Scenarios for sustained high fusion power ready




## Deuterium reference pulses extrapolated to DT to demonstrate adequate performance

# Operations

# Actual JET Timeline – 2020-2022



# Operational Constraints – Tritium

| | |
|---|---|
| Total tritium available | 69g* |
| Maximum tritium on machine | 11g (44 bar litres) |
| Total H-D-T inventory | 90 bar litres |
| Regenerations are typically daily (can be more frequent) | |
| Gas must be collected and processed by AGHS | |
| Limit on the number of DT, 14MeV neutrons - pulses must fit within a budget | |

**5-week operational plan during DD**

| Week No | Mon | Tue | Wed | Thu | Fri | Sat | Sun |
|---|---|---|---|---|---|---|---|
| 1 | Ops | Ops | Ops | Ops | Ops | | |
| 2 | Ops | Ops | Ops | Ops | Ops | | |
| 3 | Ops | Ops | Ops | Ops | Ops | | |
| 4 | Ops | Ops | Ops | Ops | Ops | | |
| 5 | Ops | Ops | Ops | Ops | Ops | | |

**5-week operational plan during DTE2**

| Week No | Mon | Tue | Wed | Thu | Fri | Sat | Sun |
|---|---|---|---|---|---|---|---|
| 1 | Ops | Ops | | | Ops | Ops | |
| 2 | | Ops | Ops | | Ops | | |
| 3 | | Ops | Ops | | Ops | | |
| 4 | AGHS tritium processing & accounting | | | | | | |
| 5 | | | | | | | |

**Tritium usage during DTE1 and 100%T & DTE2**

| Tritium quantity | DTE1 | 100%T & DTE2 |
|---|---|---|
| Total inventory (g) | 21 | **69** |
| NBI throughput (g) | - | **763** |
| Tokamak throughput (g) | - | **240** |
| Total throughput (g) | 100 | **1003** |

*(this was 42g for DTE3)

# Operational Constraints – Access

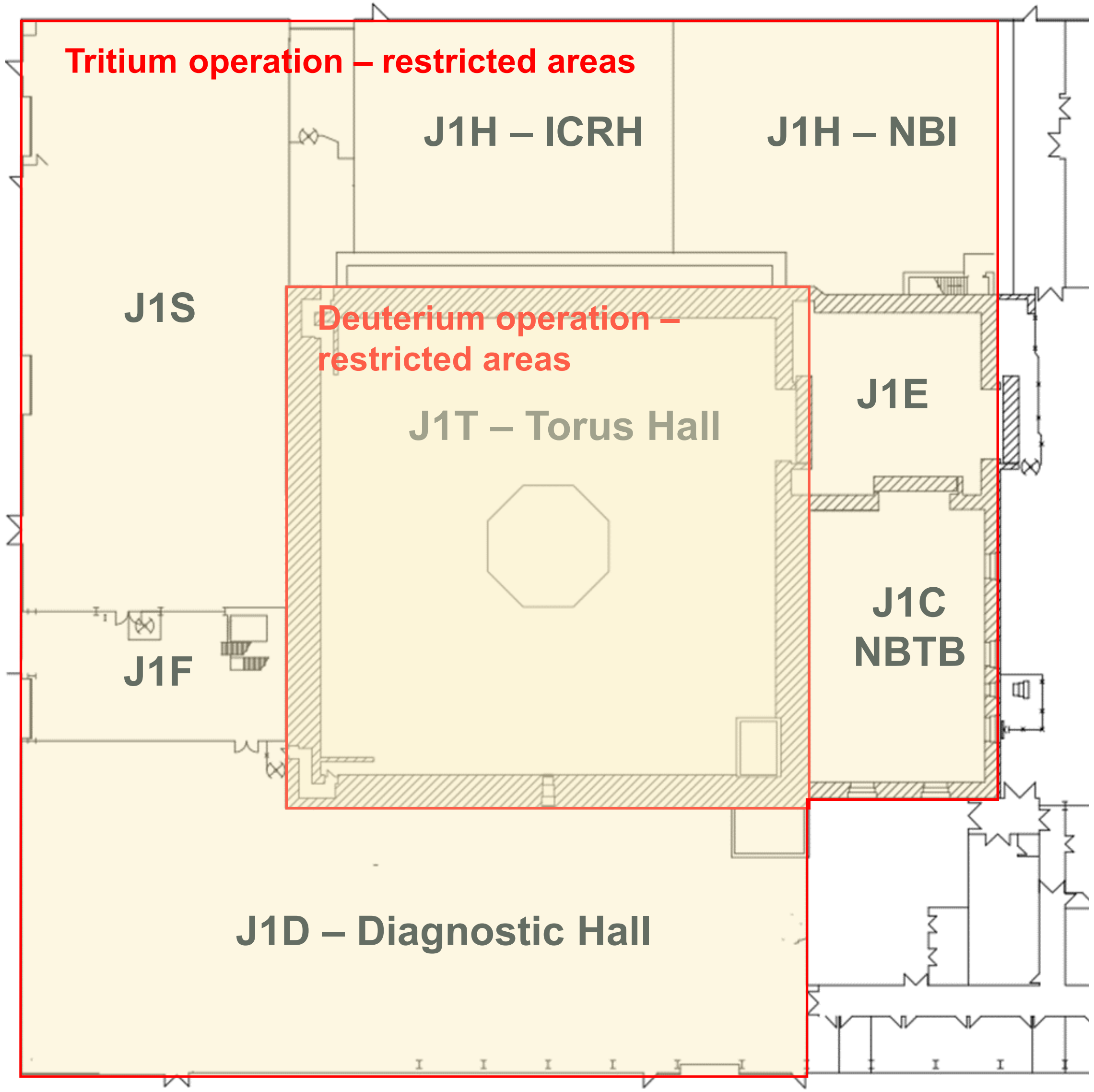
**J1H – ICRH**
ICRH equipment
Control & DAQ cubicles

**JS**
Baking plant;
Cryoplant;
NBI gas introduction;
Control & DAQ cubicles;
HRTS enclosure

**J1F**
DT compatible cameras;
Compressed air

**J1D**
Various diagnostics;
Control & DAQ cubicles

**J1B – Basement (not shown)**
Various services;
Control & DAQ cubicles




**J1H – NBI**
NBI power supplies
Control & DAQ cubicles

**J1E**
Demin water

**J1L Roof Lab (not shown)**
HTRS and LIDAR lasers

## Tritium operation - Area access requirements

**All areas**
- Stop operation
- Chaperon and RFID controlled entry

**Torus hall and basement**
- HV isolation
- Cryopumps regeneration (~8h)
- Tritium transfer to AGHS (~7h)
- Restore nominal oxygen level (J1T)
- Radiological survey (J1T)
- Radiological risk assessment (J1T)

# Daily Operational Plan

## Operational Day

06:30-08:00 Machine startup: Transfer of tritium to TIMs; Access to restricted operational areas (Cryoplant, Diagnostic Hall, ICRH and NBI power supply areas) followed by areas lock-up.

08:00 Dry run

**08:30-14:00 Plasma operation – Early shift**

- 13:00-13:20 Tritium monitoring meeting (review of daily tritium trends, inventory, interspace monitoring, etc.)
- 13:30-14:00 Machine status meeting (review of status, including machine faults and remedial actions)
- 14:30-15:00 Shift changeover meeting (review of programme progress on early shift and plan for the late shift)

**15:00-22:00 Plasma operation – Late shift**

22:00-22:30 Machine shutdown: Access to restricted operational areas (Cryoplant, Diagnostic Hall, ICRH and NBI power supply areas)

22:30-06:30 Regeneration of all JET cryopumps; Off-line NBI commissioning and preparation for filling of tritium introduction modules (if next day is operational); Transfer of tritium from TIMs to AGHS (if next day is non-operational)

## Non-Operational Day

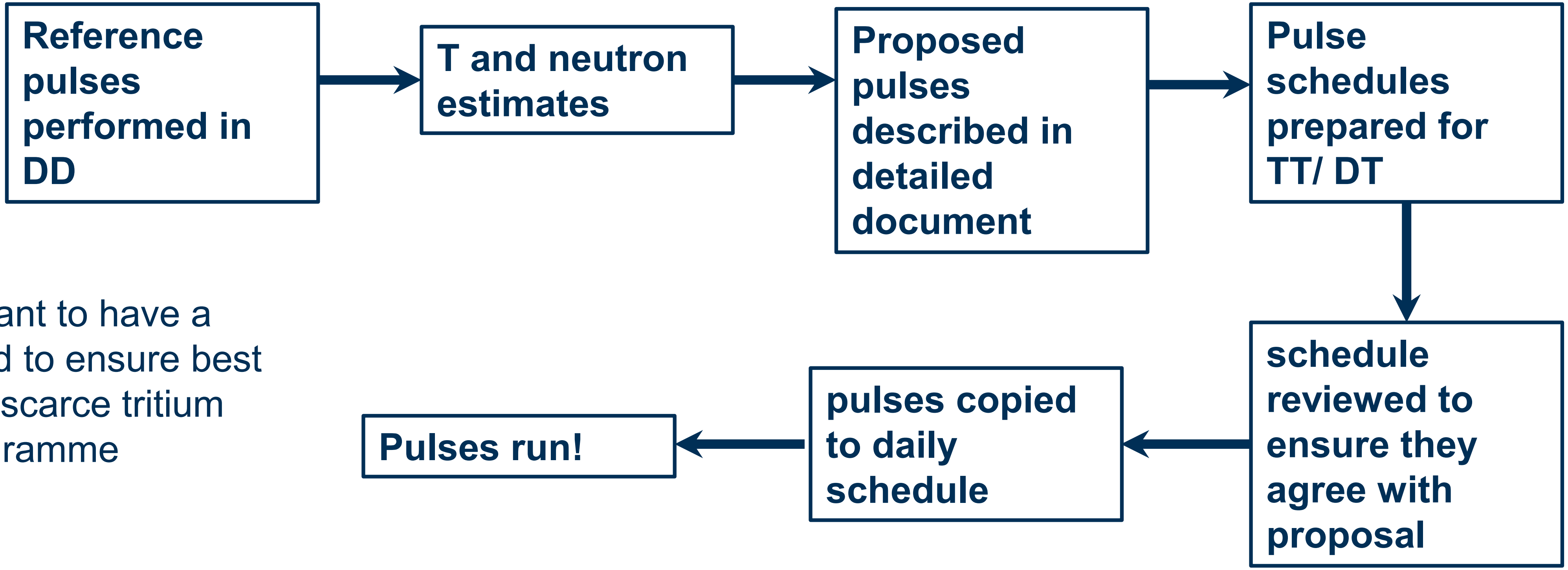
06:30-12:00 Access to restricted operational areas (Cryoplant, Diagnostic Hall, ICRH and NBI power supply areas) and (exceptionally) JET basement for maintenance and urgent repairs

13:00 Dry run to check that machine is ready for next day operation and to allow time for some repairs if necessary

# Pulse Preparation – DTE2

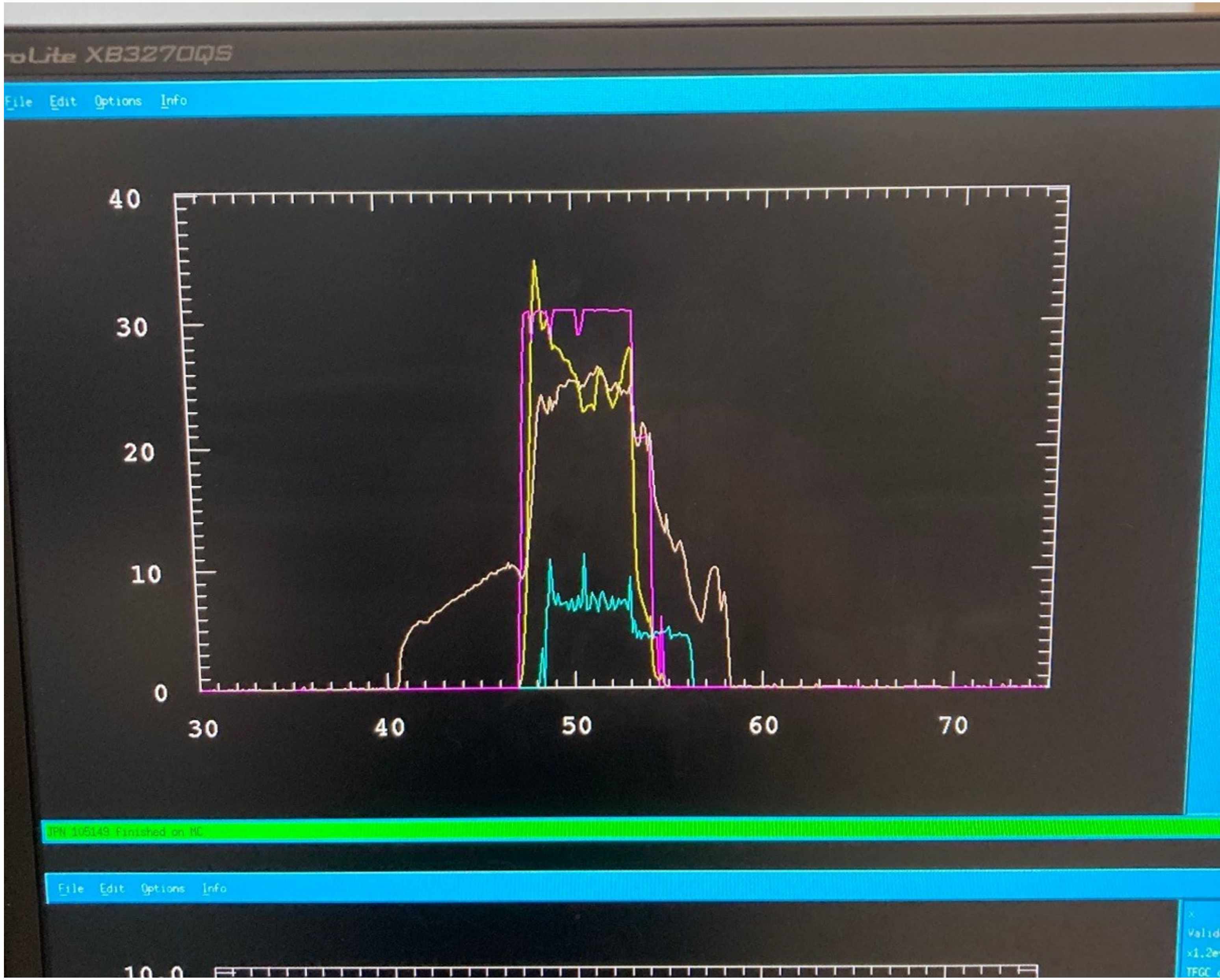
**The limitations on neutrons and tritium available meant that programme was *strictly* controlled to ensure priority scientific goals were met**

**This was done via a pulse approval process that involved programme leaders, not just operational staff**




Important to have a method to ensure best use of scarce tritium in programme

# What have we learned? - Operations



# Lessons Learnt - General

After DTE2 experiment we carried out lessons learnt exercise with involvement of all staff that participated in operation and scientific exploitation of the machine.

Most of the lessons learnt are JET specific but there are some general observations:

**Extensive training & rehearsals are essential**

**Strict control of work and access is required for planning and safety purposes, but this must be managed well to avoid delays -** 2165 access requests over 2 years!

**Exercise essential systems on non-operational days**

**Maintenance and upgrades must be prepared years in advance**

**Communication of the ongoing status of machine and programme helps the team**

**Access to JET re-established gradually depending on exact location as activation went down**

# Lessons Learnt – Plasma Operations

It was expected that Tritium would change plasma behaviour – indeed this is part of scientific programme!

Tritium Introduction Modules characteristics different to standard modules (calibrations and speed)

Heat load due to NBI reionisation on limiters

Limitations on pulse rate

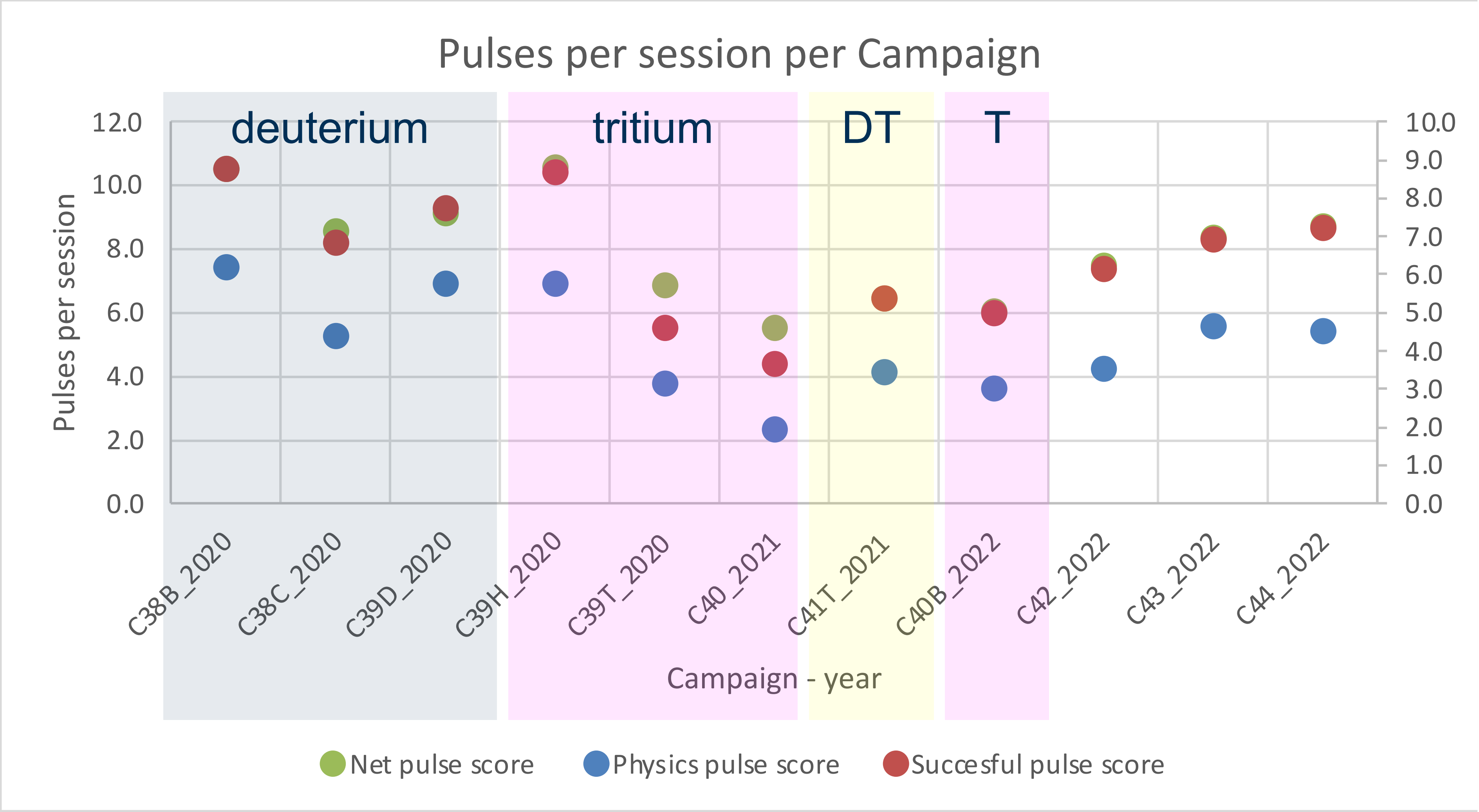
Clean up of tritium took place with variety of methods, done as a Eurofusion experiment

Advised to separate the clean up from ongoing plasma experiments

# Lessons Learnt – Plasma Operations

Only previously approved pulse types could be executed

Ensure best use of budgets for maximum scientific gain ⇒ low pulse repetition rate



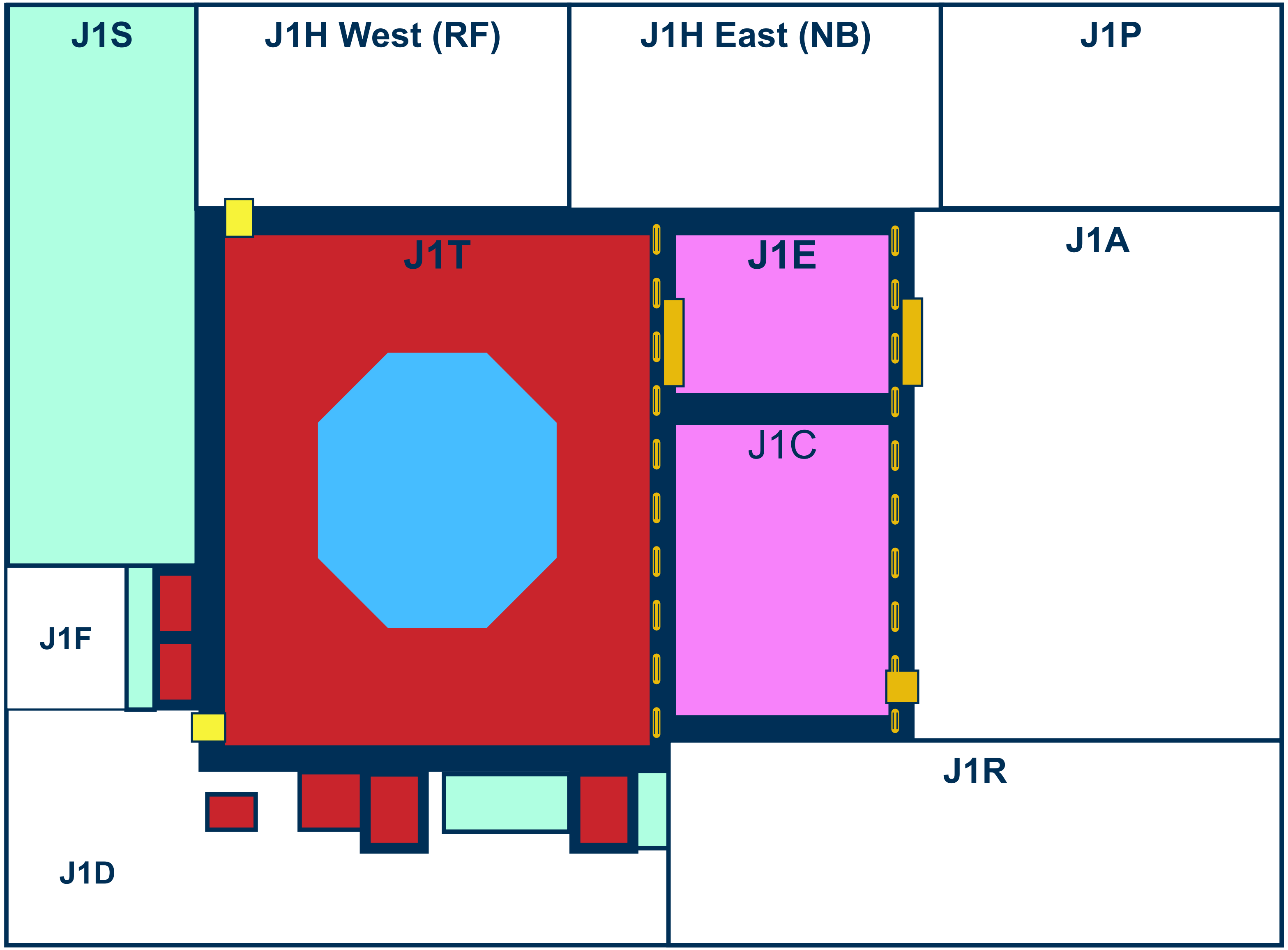
# DTE3

**A further, 7 week campaign took place in 2023 to explore different physics topics to DTE2 and take advantage of the recent experience**

# DTE3

Some areas removed from access restrictions

Access procedures simplified as much as possible



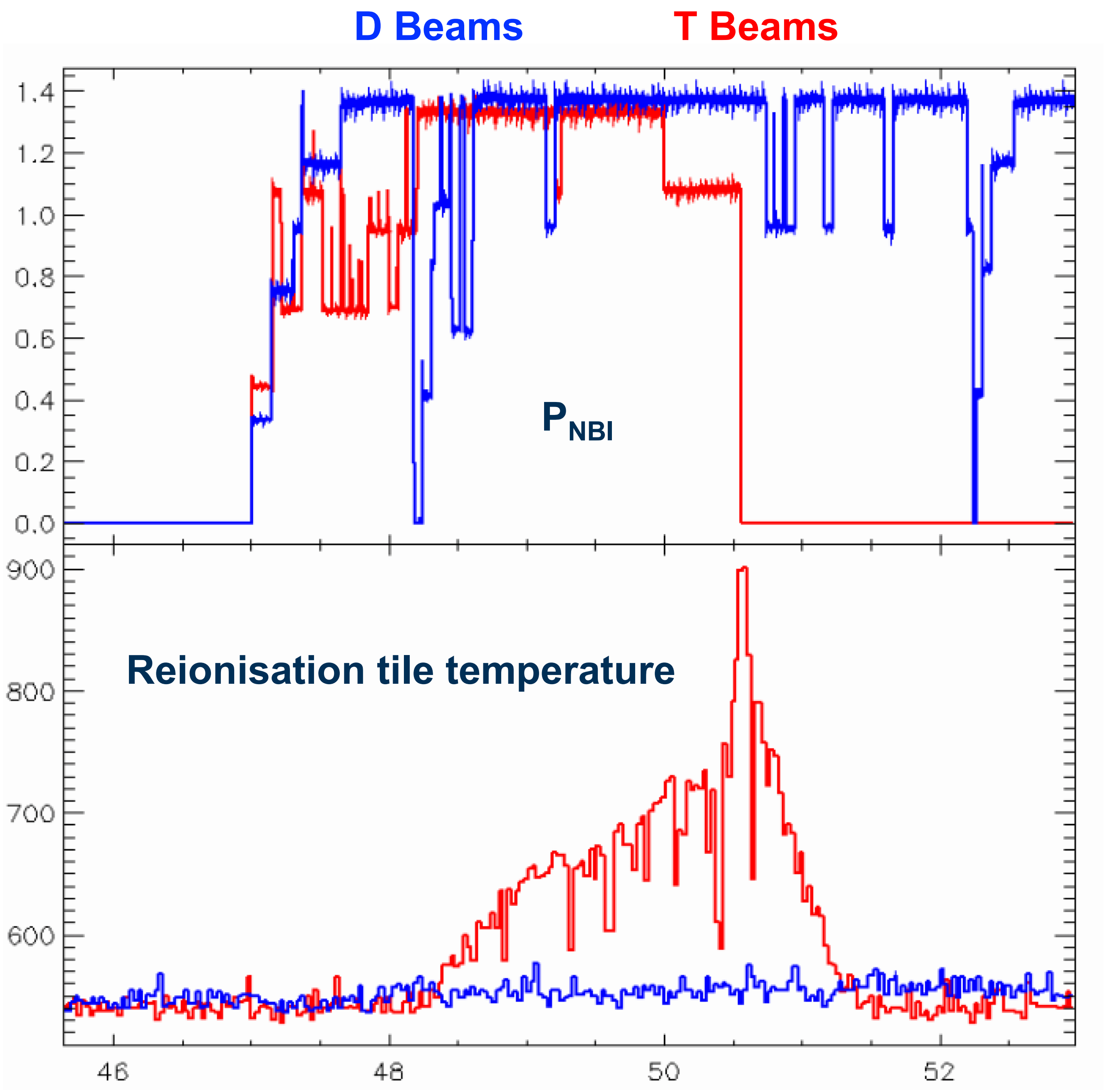
# DTE3

Neutral beams in deuterium only (not compatible with key goals of DTE2, in particular TT campaign)

Conversion to T NBI would have taken too long

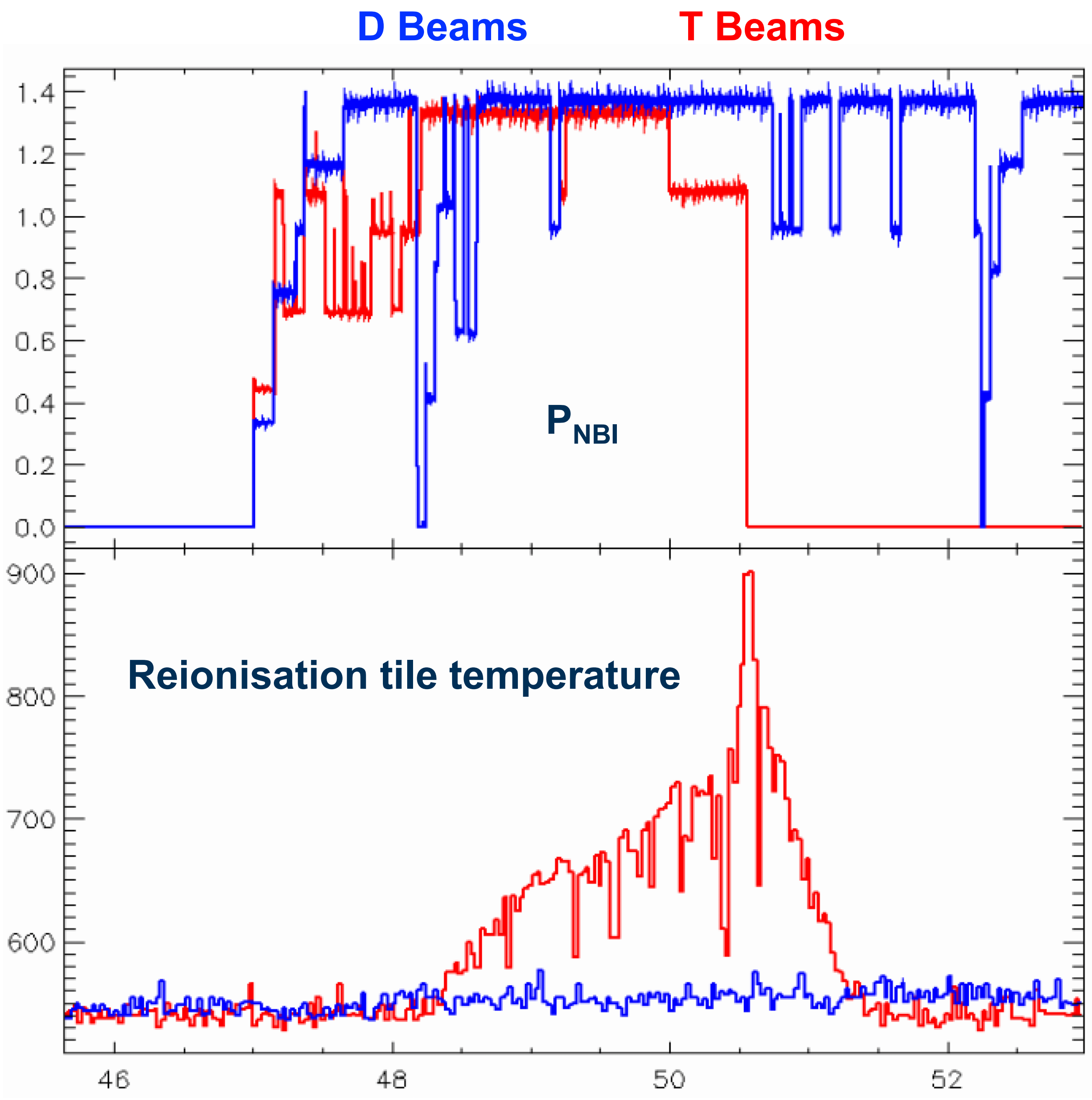
Different organisation of experiment planning and budgets – standard session based

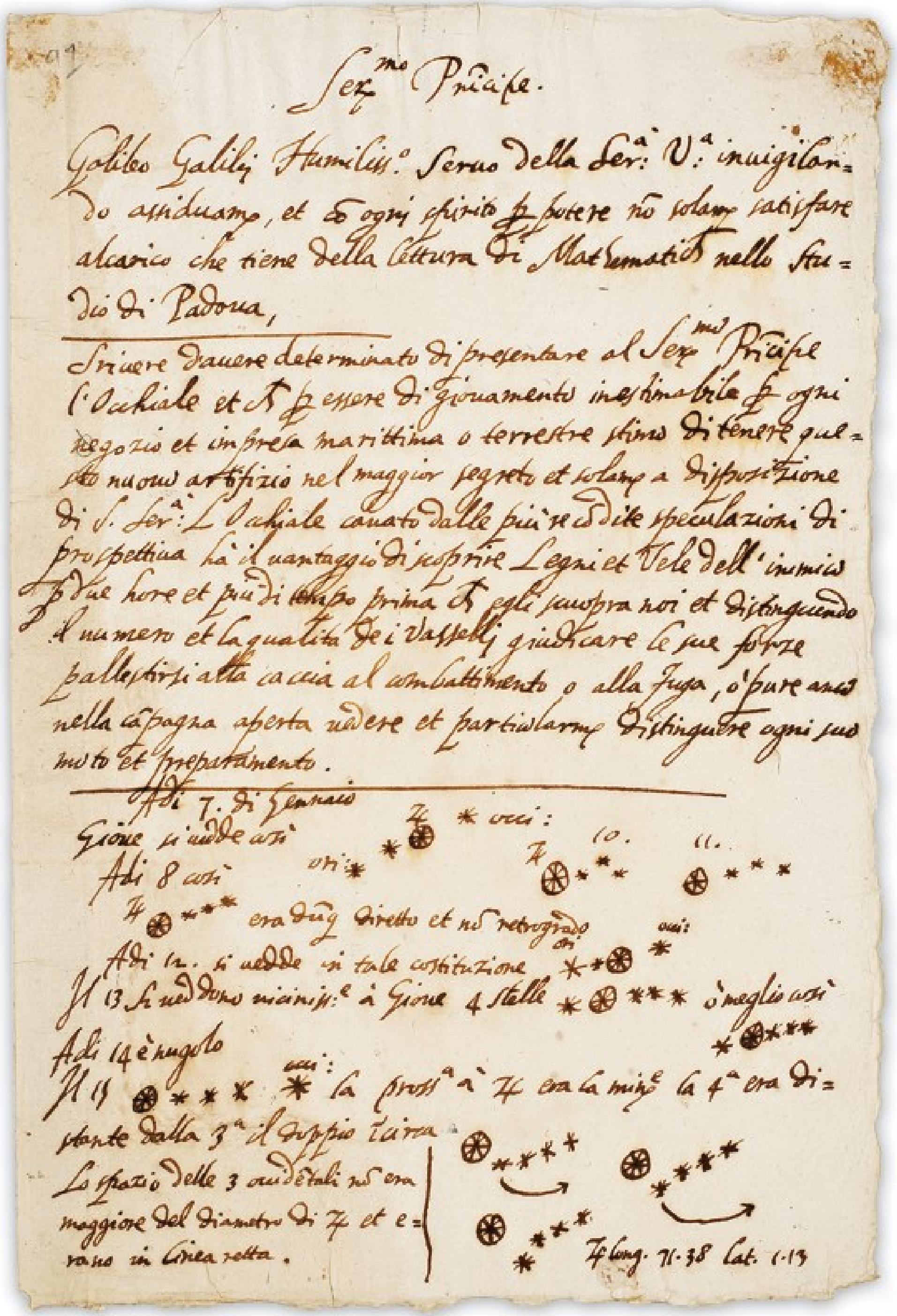
Training and Preparation – benefitted from recent DTE2 experience of staff



# DTE3

This experimental campaign was very successful for such a limited amount of time thanks to the experience gained in DTE2…




Ser.mo Principe.

Galileo Galilei Humiliss.o Servo della Ser.tà V.a invigilando assiduam.te, et con ogni spirito per potere non solam.te satisfare al carico che tiene della lettura di Matematiche nello Studio di Padova,

Scrive d'havere determinato di presentare al Ser.mo Principe l'Occhiale et di poter essere di giovamento inestimabile per ogni negozio et impresa marittima o terrestre stimo di tenere questo nuovo artifizio nel maggior segreto et solam.te a disposizione di V. Ser.tà L'Occhiale cavato dalle più recondite speculazioni di prospettiva ha il vantaggio di scoprire Legni et Vele dell'inimico per due hore et più di tempo prima che egli scuopra noi et distinguendo il numero et la qualità dei vasselli giudicare le sue forze pallestirsi alla caccia al combattimento o alla fuga, o pure anco nella campagna aperta vedere et particolarm.te distinguere ogni suo moto et preparamento.

Adì 7. di Gennaio Giove si vedeva così * * ♃ * così:

Adì 8 così ♃ * * * era dunque diretto et non retrogrado

10. * * ♃ * 11. ♃ * * *

Adì 12. si vedde in tale costituzione * * ♃ * così

Il 13 si veddono vicinissime à Giove 4 stelle * ♃ * * * o meglio così * ♃ * * *

Adì 14 è nugolo

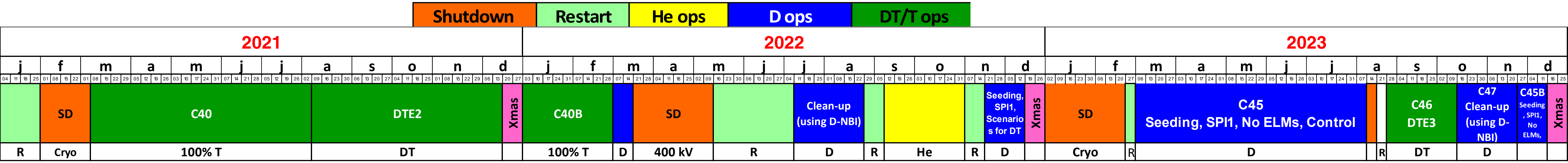
Il 15 ♃ * * * * così: la pross.a à ♃ era la minore la 4.a era distante dalla 3.a il doppio in circa.

Lo spazio delle 3 occidentali non era maggiore del diametro di ♃ et erano in linea retta.

♃ long. 71.38 lat. 1.13

# Selected Scientific Results

# JET D-T campaigns 2021 & 2023




**2021/22: 100% T campaign + DTE2**

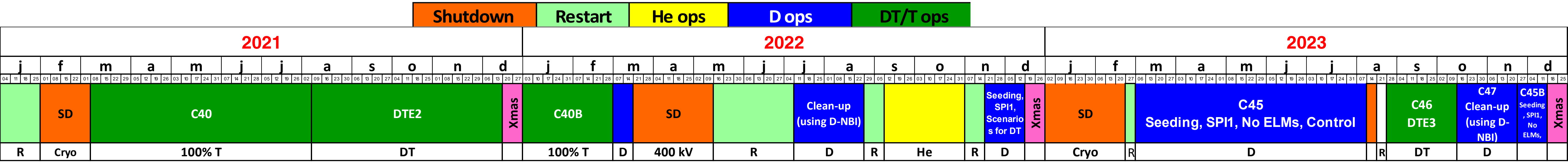
<u>DTE2 objectives:</u>

1. Demonstrate $P_{FUS}$ up to 10 MW, sustained for 5 s
2. Demonstrate integrated radiative scenarios in conditions relevant to ITER
3. Demonstrate clear $\alpha$-particle effects
4. Clarify isotope effects on energy and particle transport & explore consequences of mixed species plasma
5. Address key plasma-wall interaction issues
6. Demonstrate RF schemes relevant to ITER D-T operation

(+ Neutronics and materials programme)

# JET D-T campaigns 2021 & 2023

JET

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6. Demonstrate RF schemes relevant to ITER D-T operation

(+ Neutronics and materials programme)

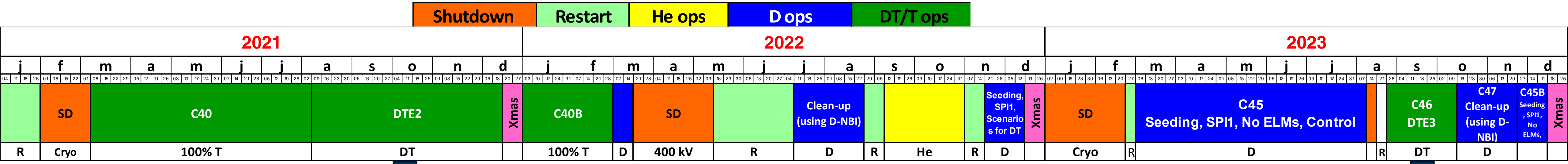
## 2023: New scenarios in D + DTE3

<u>DTE3 objectives:</u>

1. Radiative high current scenario (core-edge integration)
2. No/small ELMs scenarios
3. Real-time control
4. Fuel retention studies (including LID-QMS demonstration)
5. Conclude/complement DTE2 experiments

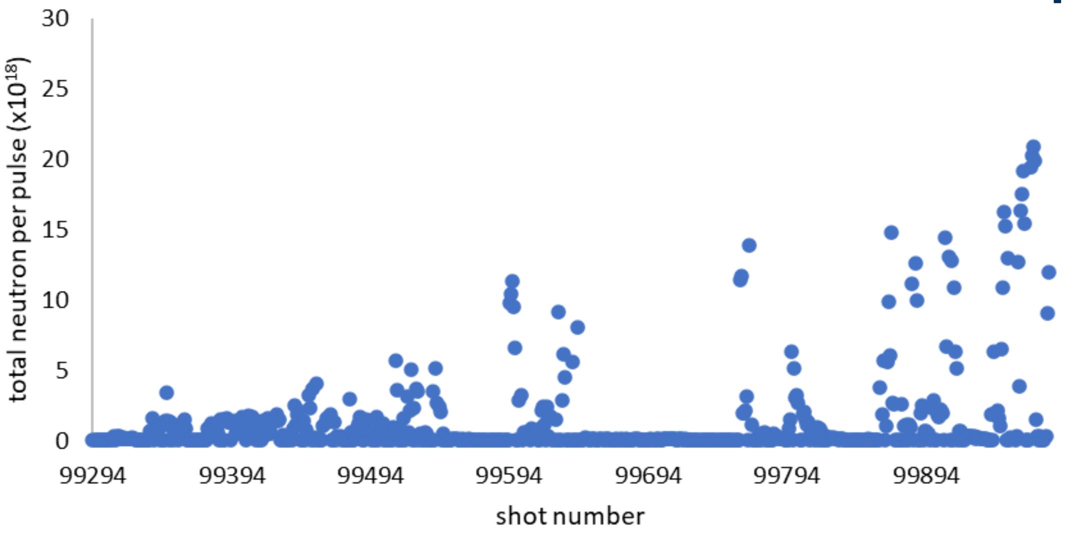
Showing mainly T & DTE2 results today & just a few DTE3 results as DTE3 experiments not yet published

# JET D-T campaigns 2021 & 2023

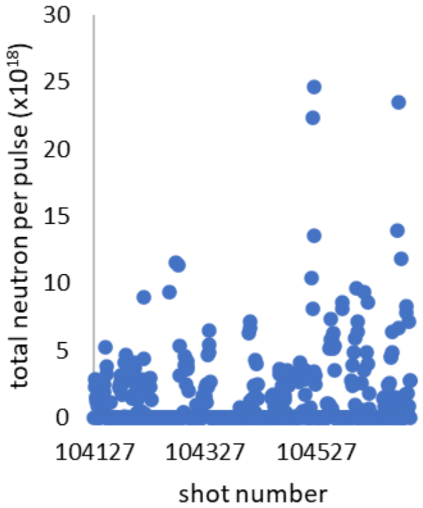



**DTE2 13 Aug 2021 - 21 Dec 2021**
**250 experimental plasma shots***
**Total neutrons = 8.48x10$^{20}$**
**Several technical issues slowed down pace**

**DTE3 30 Aug 2023 – 14 Oct 2023**
**268 experimental plasma shots***
**Total neutrons =7.31x10$^{20}$**




**DTE2 experience benefited DTE3!**




*technically successful, not necessarily useful for the experiment

# Wide ranging physics programme in T & D-T

Physics programme defined to address ITER questions and to prepare T and D-T pulses

-Included investigation of JET-specific effects (e.g. rotation, divertor config, etc) to disentangle various effects and help identify physics relevant to ITER

Goal to test and improve physics models and physics-based codes used to predict future fusion devices for:

-Plasma-wall interaction

-SOL plasma

-Pedestal

-Core

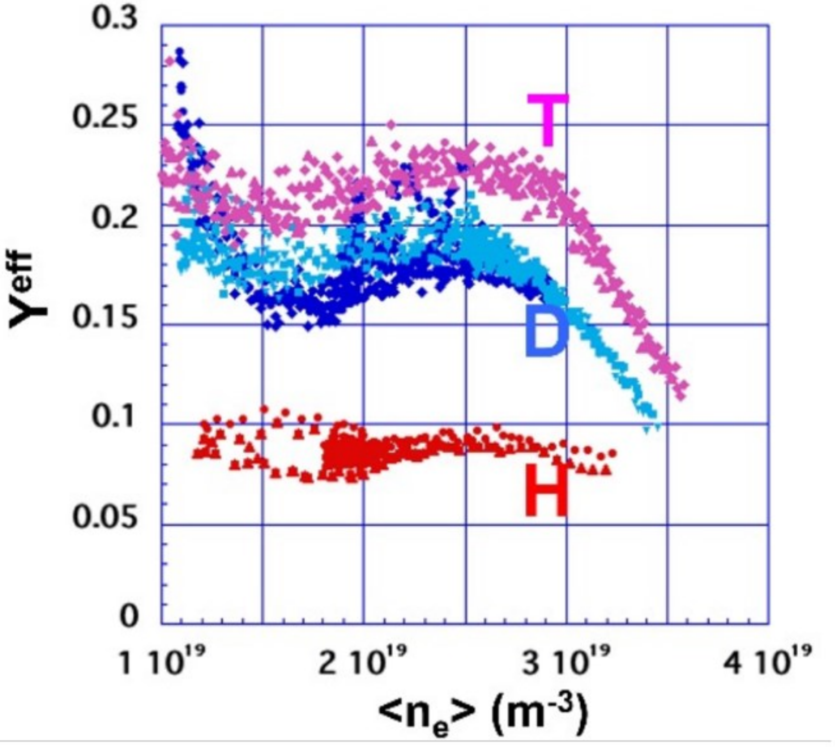
-Integrated impact of isotope mass (SOL-edge-core coupling)

Understanding the implications for ITER still on-going, will take a few years to disentangle all effects and identify key physics mechanisms in ITER relevant conditions

Small part of results shown today

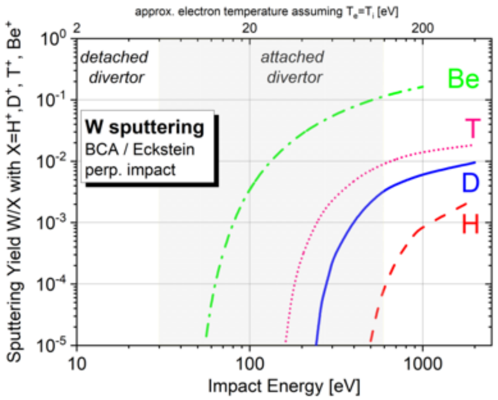
# Tritium leads to higher wall material sputtering than D

Be effective sputtering yield measured by spectroscopy (L-mode) ($Y^{eff} = F_{BE}^{OUT}/F_{H,D\ or\ T}^{IN}$)



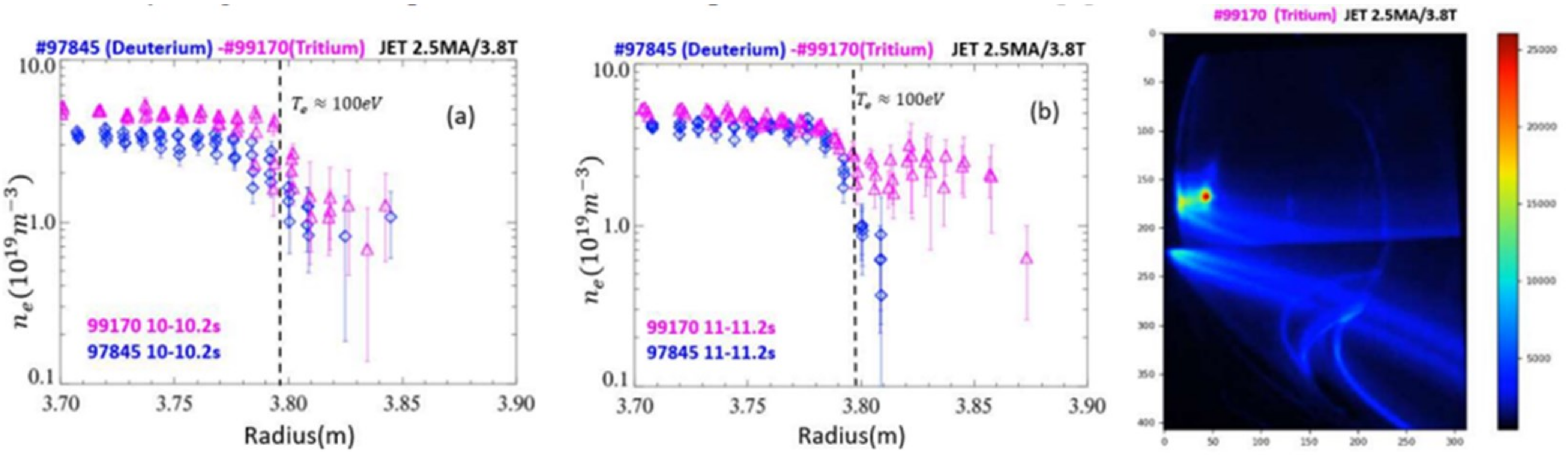

H&D results: E. De la Cal *et al.,* Nucl. Fusion 62 (2022) 126021
T results: E de la Cal et al., submitted to Nucl. Fusion

- Higher wall material sputtering in T compared to D is expected due to higher n




- But Plasma-Wall Interactions complex:
  - Impurities (e.g. Be) play a role, as do molecules
  - Transport in SOL & re-deposition take place
- Predicting accurately wall lifetime requires including 3D geometry and all these effects
- Several JET experiments documented Be and W sputtering in L-mode and H-mode, analyses on-going

# SOL broadening at higher isotope mass

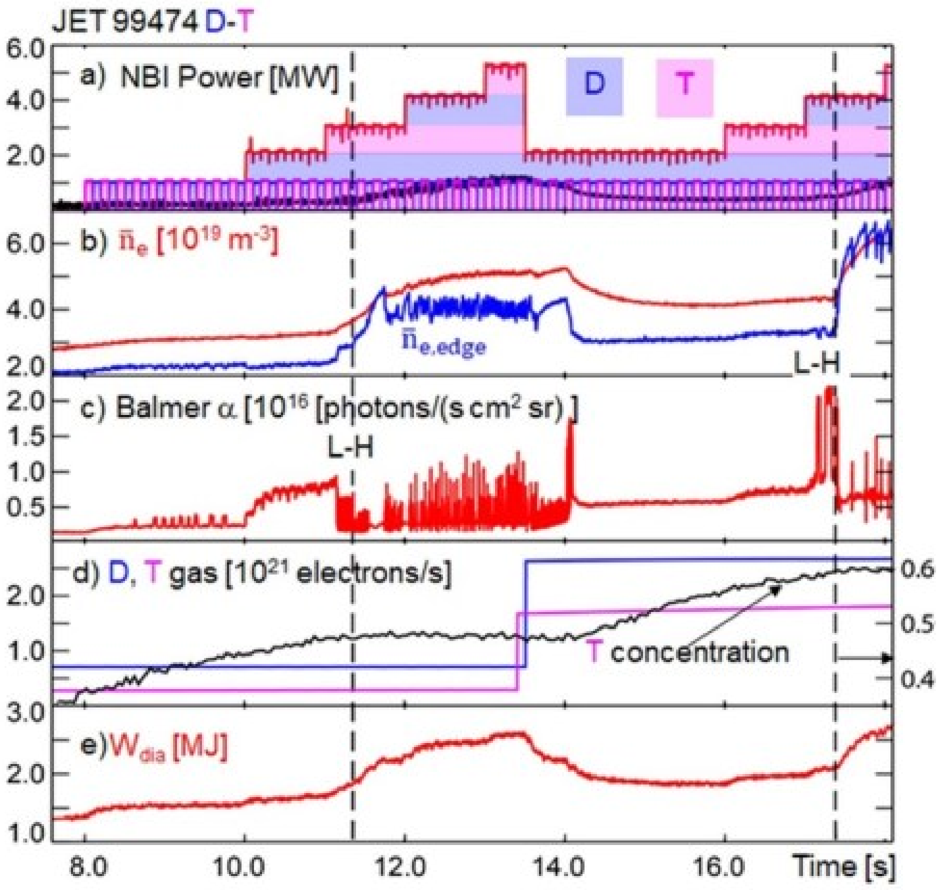



H. Sun *et al.*, 2023 Nucl. Fusion 63 016021

- Scrape-off layer (SOL) density broadening in T compared to D due to enhanced cross-field particle transport, in some cases leading to a ‘density shoulder’
- Combined with larger ion Larmor radius in T, causes higher re-ionisation power flux to wall components → larger number of wall protection stops & dedicated work to avoid them
- Re-ionisation may not be an issue for ITER D-NBI, but SOL change has other implications

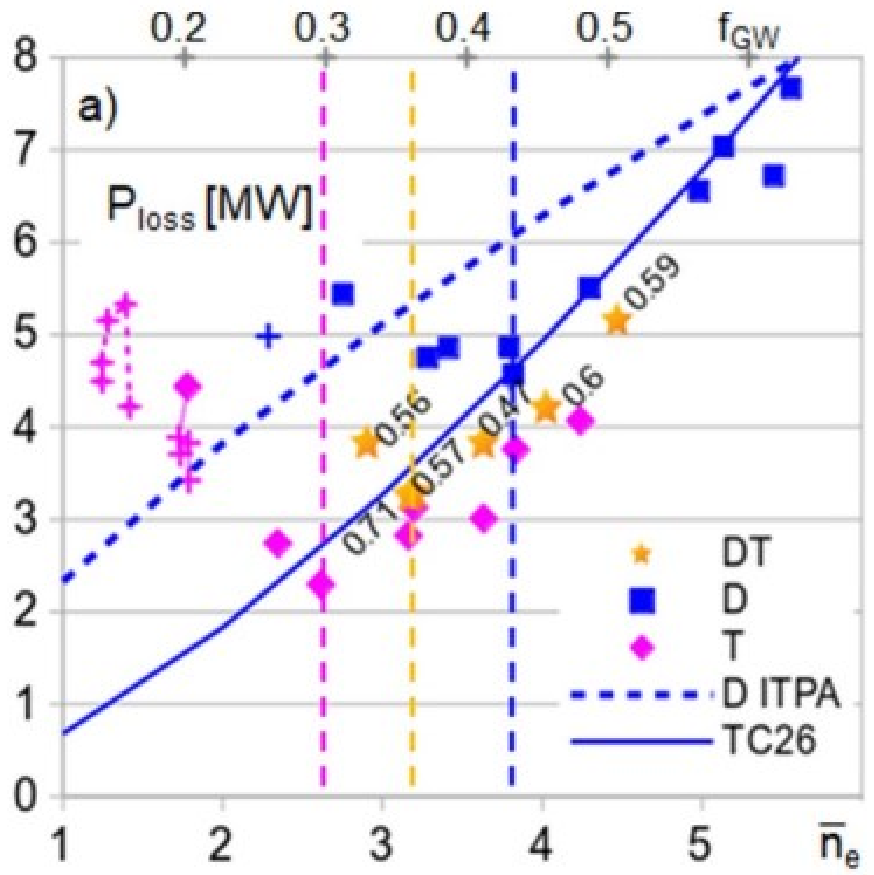
# Impact of isotope mass on L-H transition (1/2)

- Power at which the plasma goes to H-mode is an important parameter for designing reactors
- Extensively studied on many tokamaks, with JET providing unique opportunity to test with tritium
- Carefully designed experiments in JET H, D, T, D-T
  - Controlled auxiliary power ramp-up
  - Same magnetic configuration and engineering parameters




E.R. Solano *et al* 2023 Nucl. Fusion 63 112011

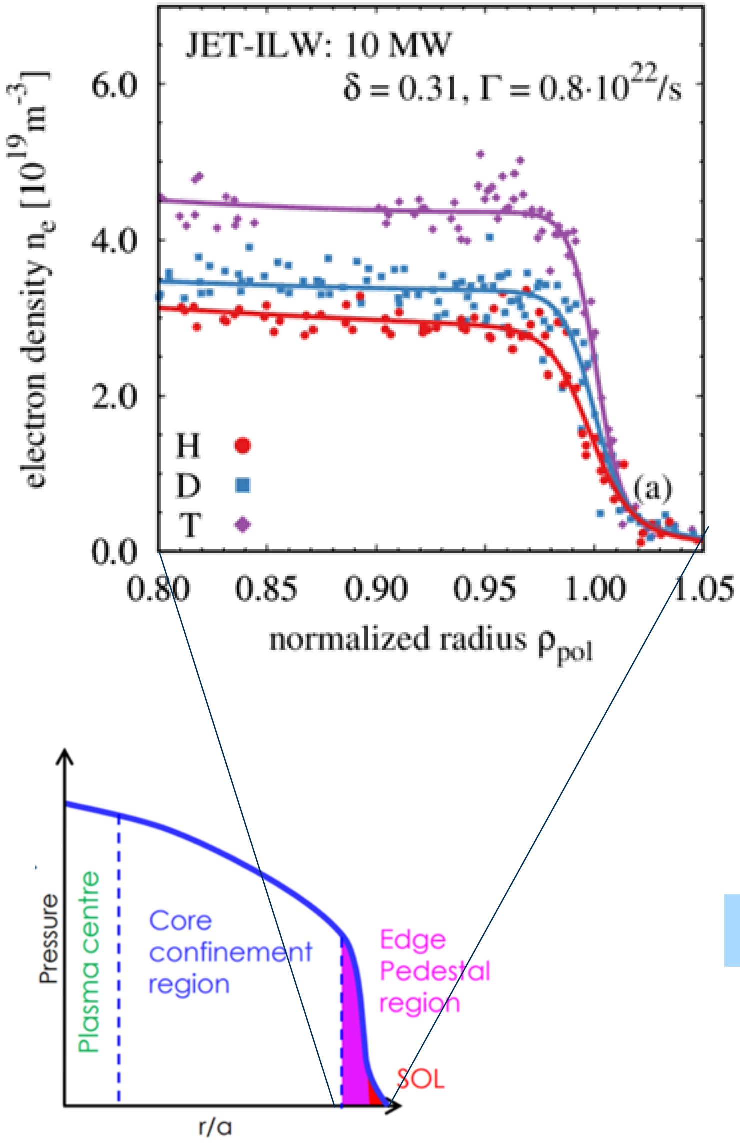
# Impact of isotope mass on L-H transition

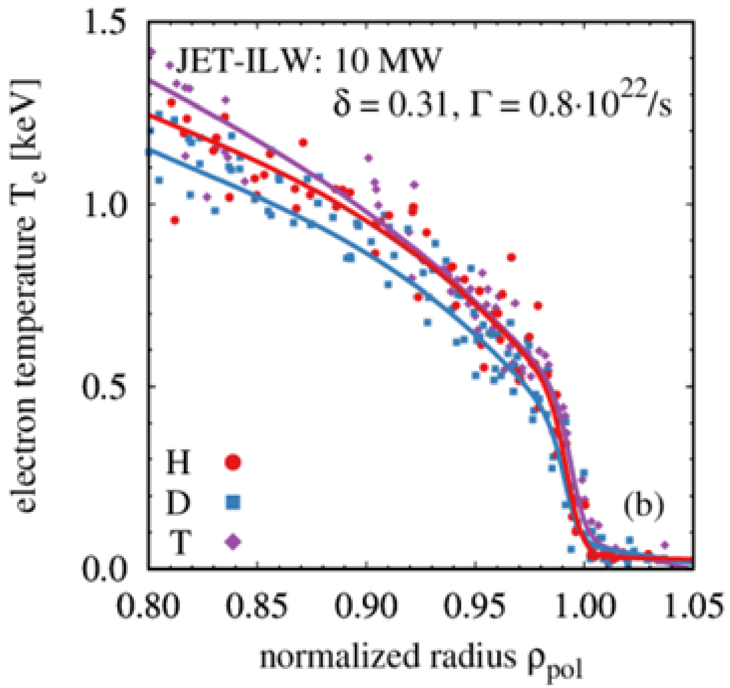



E.R. Solano *et al* 2023 Nucl. Fusion 63 112011

- With increasing fuel mass, reduction of:
  - Density at which the threshold for accessing H-mode is minimum ($n_{e,min}$)
  - Power required for accessing H-mode
- Scaling laws for L-H power threshold (high density branch) do not account for isotope effect & overestimate $P_{L\_H}$
  - adding term (2/Aeff) provides better match (not shown here)
- Theory-based model needed for improved predictions of fusion power plant
- JET unique dataset provides crucial new data to test physics hypothesis

# Impact of isotope mass on plasma pedes

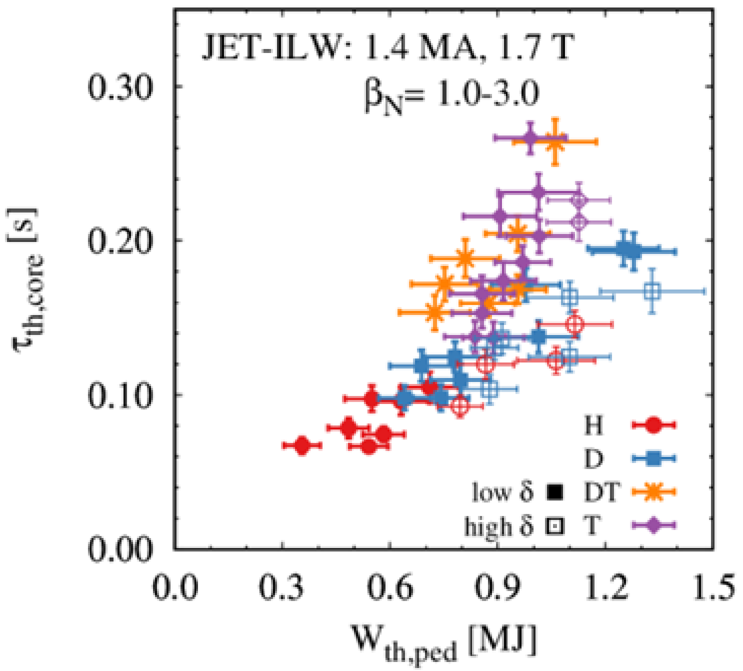


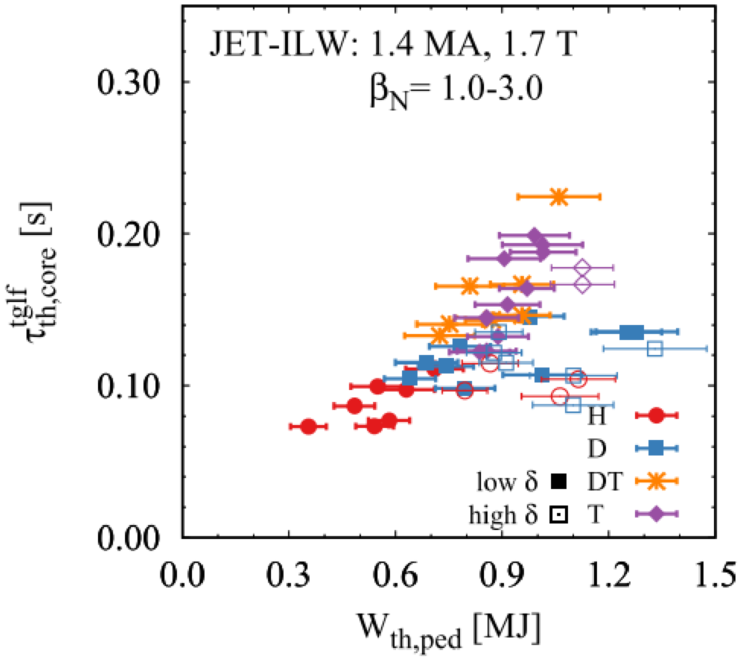




- At same engineering parameters: pedestal electron density higher at higher fuel mass, for similar electron temperature
- Pedestal models based on MHD stability can't reproduce the experimental trends, but resistive models promising

P.A. Schneider et al 2023 Nucl. Fusion 63 112010

# Impact of isotope mass on plasma core



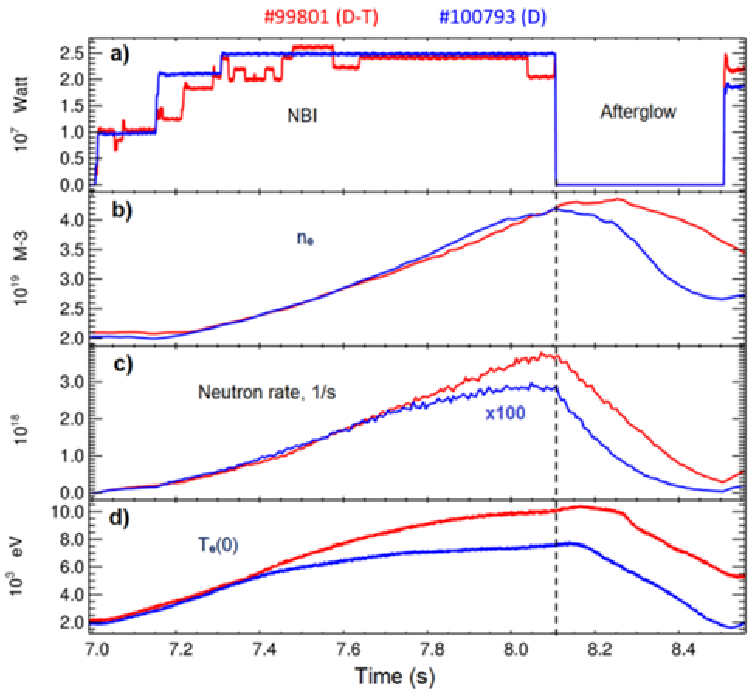

- At matched pedestal: core confinement better in T & D-T plasmas
- Analysis with predictive modelling indicate:
  - Main isotope effects correctly included in physics model
  - But electromagnetic effects (fast particles) lead to overestimation of transport → model needs improvement
- Core & pedestal confinement linked → integrated core-edge modelling needed to predict future tokamaks performance

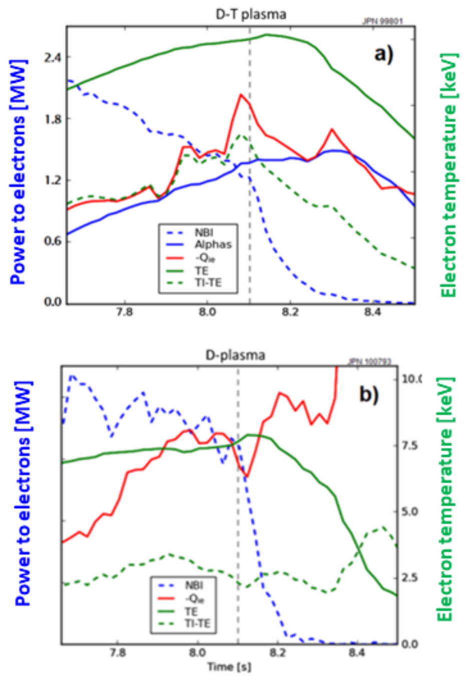
$\tau_{th,core}$ = core thermal confinement time
(core thermal stored energy/$P_{heat}$-$P_{rad}$)

P.A. Schneider et al 2023 Nucl. Fusion 63 112010

# Direct evidence of $\alpha$-particle effects

## Plasma heating by $\alpha$-particles



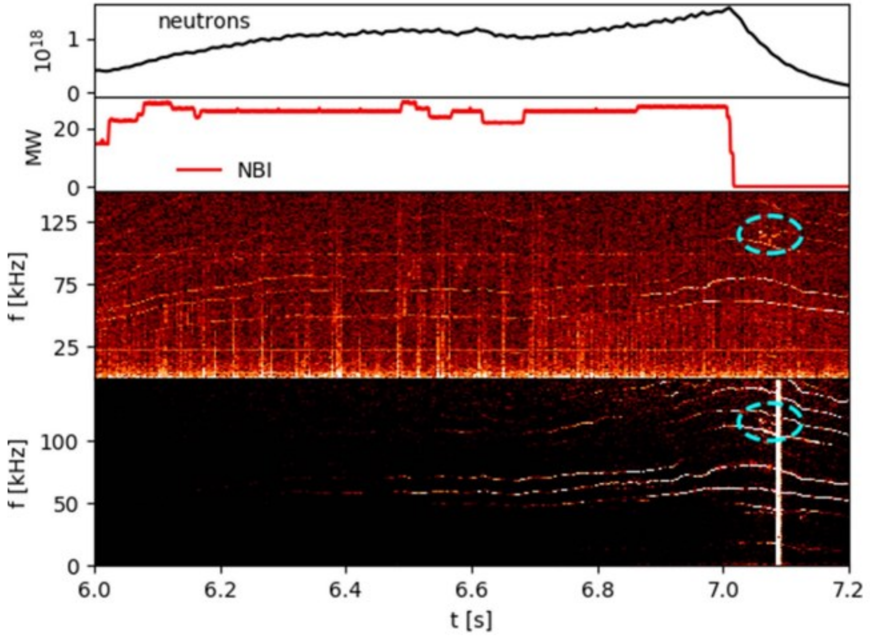




‘afterglow’ scenario to help distinguish $\alpha$ effects

Modelling reproduce observed $\alpha$ heating

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

## $\alpha$-particles driven instabilities



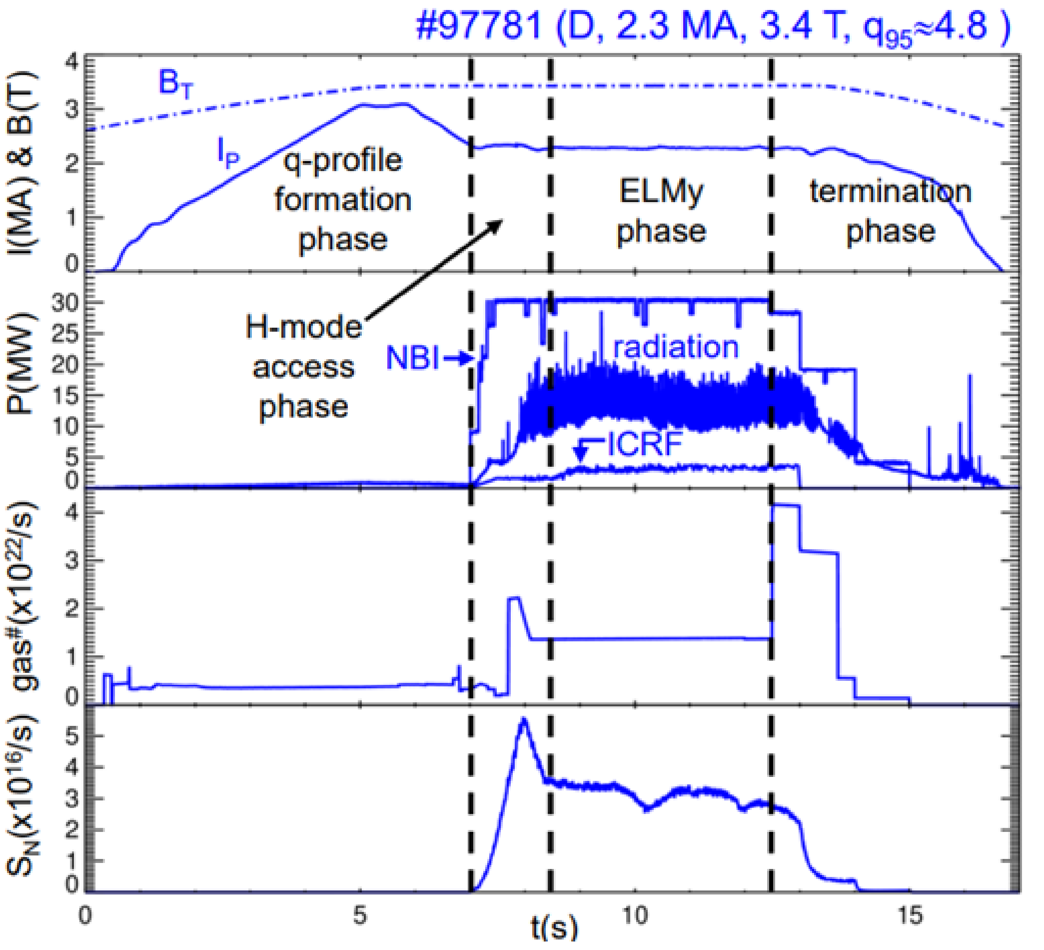

M. Fitzgerald *et al.*, 2023 Nucl. Fusion 63 112006

# Integrated impact on high fusion power scenarios

- Plasma scenarios integrates plasma effects and machine capabilities & constraints
  - Challenging in JET-ILW: control of W
- Two routes prepared for high D-T $P_{FUS}$:
  - ‘High current’ based on full $I_P$ ITER **Baseline** scenario for Q=10 milestone, $q_{95}\approx3$, $q_0\approx1$, sawtooth
  - ‘High beta’ based on reduced $I_P$ ITER **Hybrid** scenario, $q_{95}\approx4.8$, $q_0\geq1$; improved confinement; Sensitive to initial q-profile
- Approach:

***D plasmas*** *Develop scenario* → ***T plasmas*** *Investigate & mitigate isotope effects* → ***D-T plasmas*** *Maximise fusion power for $n_D\approx n_T$*

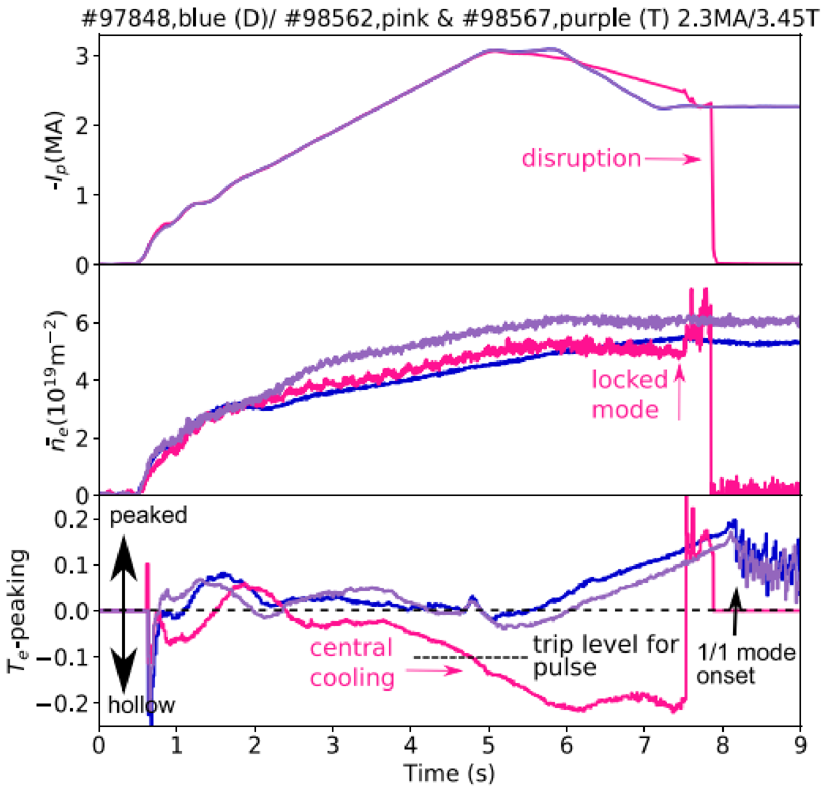
JET hybrid scenario main phases




J. Hobirk *et al* 2023 Nucl. Fusion 63 112001

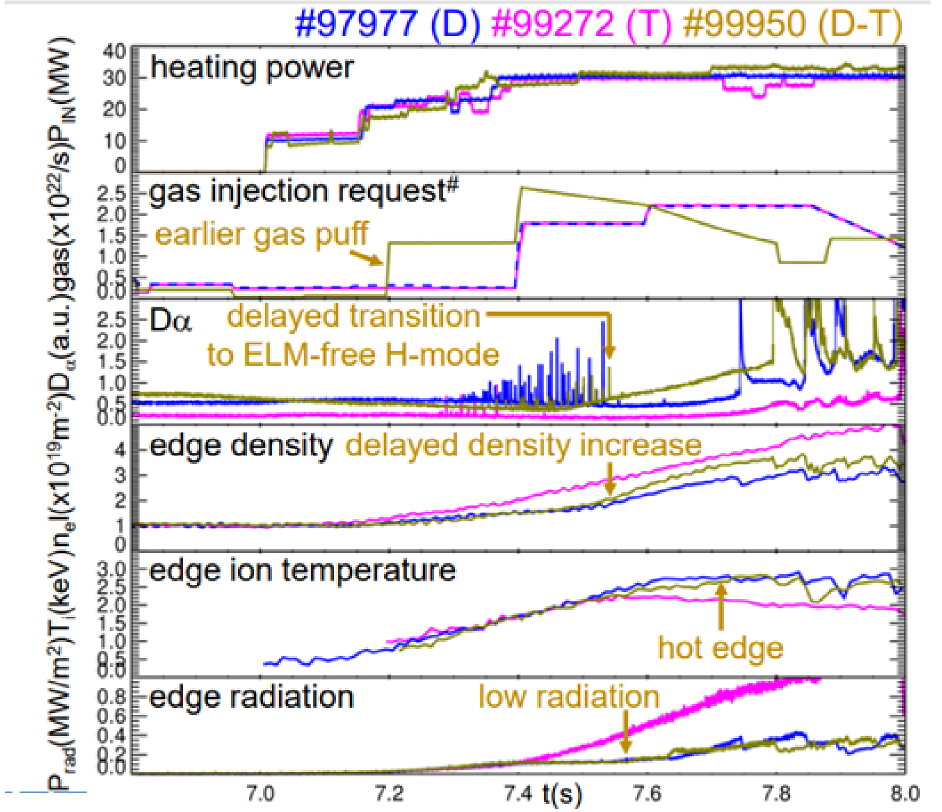
# Re-optimisation of hybrid scenario in T, D-T

## Favourable q-profile recovered




- Increased W sputtering & reduced ion temperature in tritium with a 'hollow' $T_e$ profile → locked mode develop & disruption
- q-profile matched to D by increasing $n_e$, as predicted (A. Ho *et al*., Nucl. Fusion 63 (2023) 066014)
  - Also in D-T (not shown)

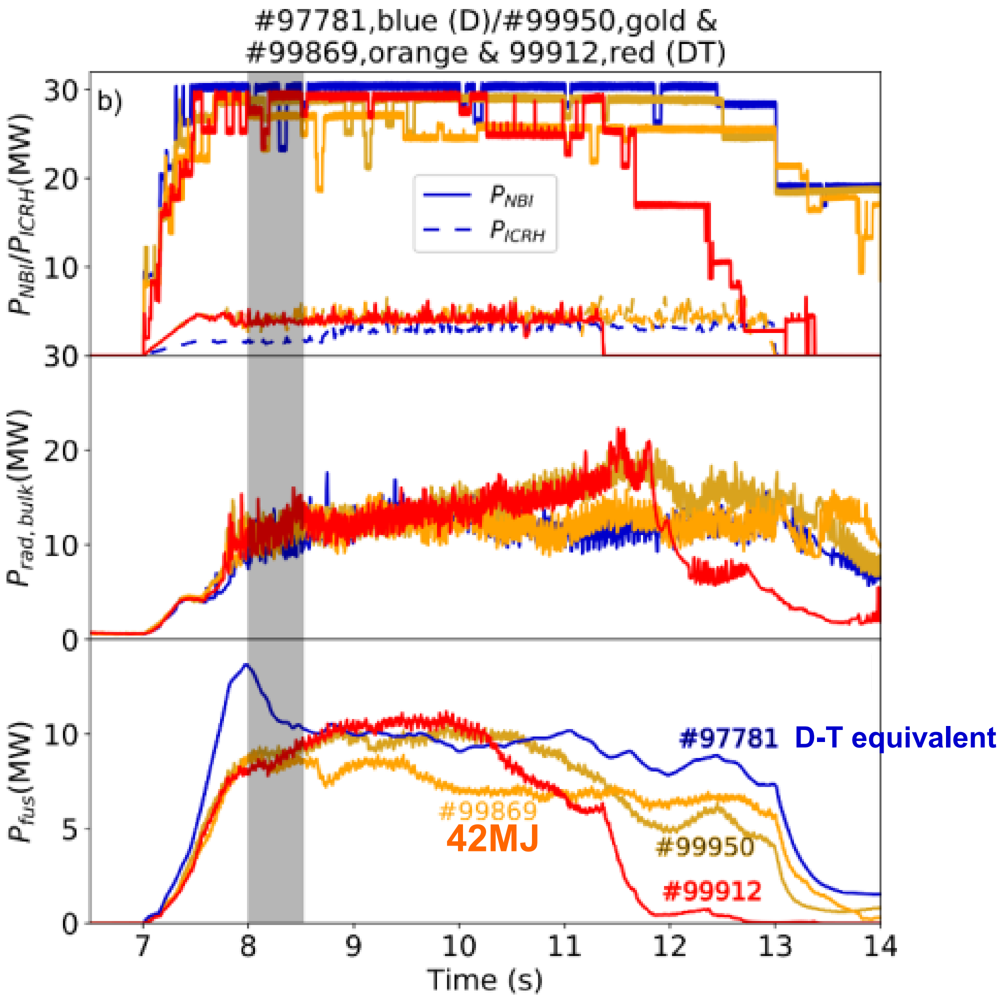
## Transition to H-mode re-optimised after learning from T




- In T: earlier L-H transition (ELM-free) & earlier $n_e$ increase seen in tritium = Impurity influx & edge cooling
- In D-T: hot pedestal recovered after adjusting fuelling gas
- High $T_i$ gradient 'screens' W, crucial for sustained performance

J. Hobirk *et al* 2023 Nucl. Fusion 63 112001

# Sustained high fusion power successfully




Fusion energy record for 50/50 D/T plasmas

J. Hobirk *et al* 2023 Nucl. Fusion 63 112001

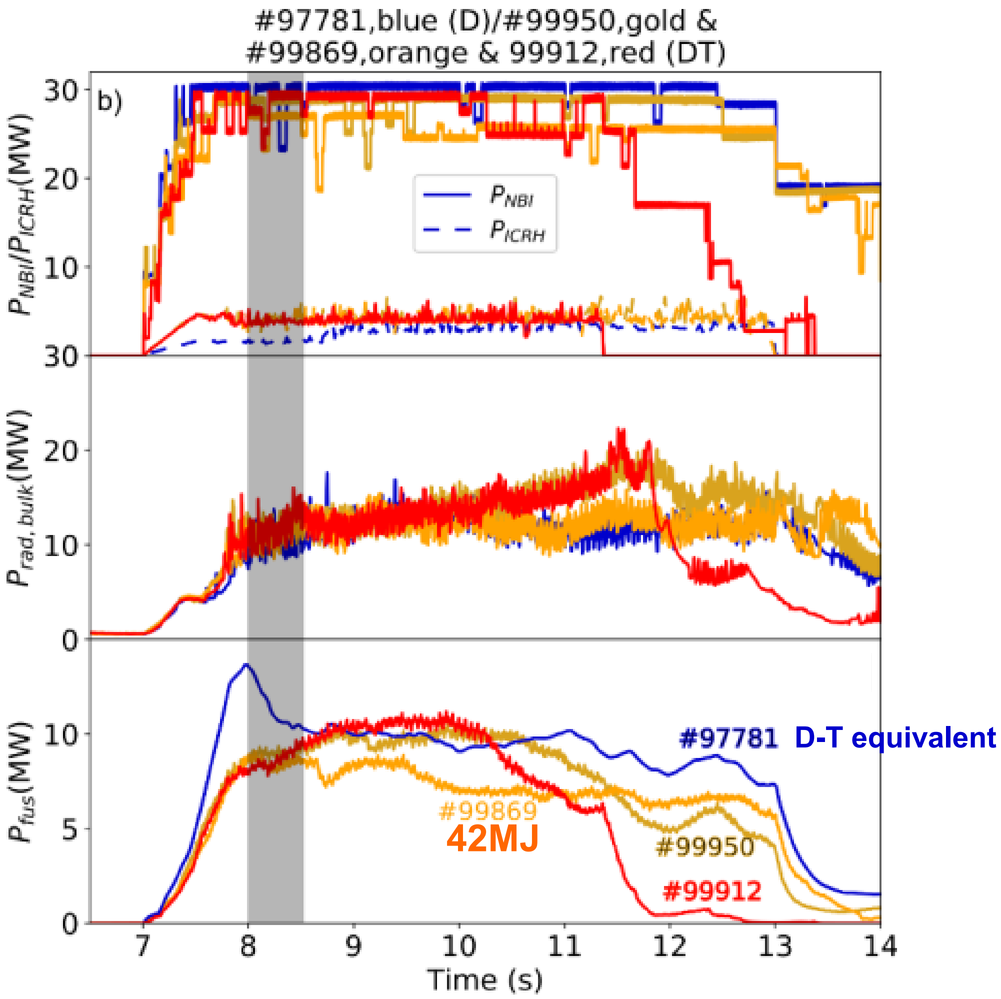
Scient Duty TFL: Joelle Mailloux
Session Leader: Damian King / Unknown
Diagnostic Coordinator: Emilia Solano
Engineer in Charge: Simon Hotchin
Session Aims: C41: M21-01 and M21-17

SC M21-01: **CD Challis, A. Kappatou, J. Hobirk, E. Lerche**

Date: Monday 01/11/21
Shift: Early
Week: n/a

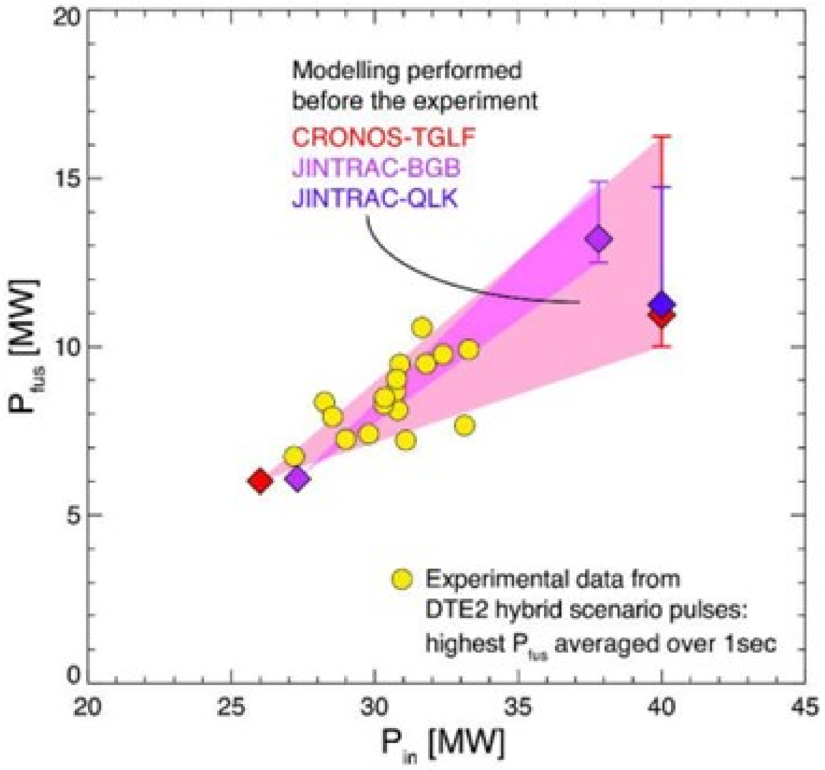
| Pulse | Time | Bt | Ip | PulseType | $n_e$ dl ($x10^{19}$) | $T_e$ (keV) | $P_{NBI}/P_{ICRH}$ (MW) | $T_{pulse}/T_{day}$/ | 14 MeV neutrons [$10^{18}$] R14/RNT | T conc (%) | *Pre & Post Pulse Comments* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 99597 | 13:22 | 3.4 | 2.3 | M21-17 PT 2062 | 13.2-17.7 | 8.2 | 28/2.7 | 2.83/28.43 | 4.5/9.5 | 52 | *M21-17 PT 2062,ref for diags is 99596* Mb at 50.3, poor RF coupling? JTT from low Wdia at 51.2 |
| 99596 | 11:57 | 3.4 | 2.3 | M21-01 PT 2028 | 13.4 | 8.6 | 26.7/4.7 | 3.31/25.62 | 5.87/11.3 | 49 | *3rd try: optimise gas, higher ICRH* PINI 8.6 down. 31.9 MJ fusion energy record. |
| 99595 | 10:57 | 3.4 | 2.3 | M21-01 PT 2028 | 14.4 | 7.0 | 26.7/4.3 | 3.09/22.34 | 5.85/10.4 | 46 | *try again, optimise gas, higher ICRH* Lost some PINIs. 29.2 MJ, new fusion energy record. |
| 99594 | 09:51 | 3.4 | 2.3 | M21-01-PT2028 | 13.4 | 8.0 | 28.8/3.6 | 2.92/19.27 | 5.86/9.77 | 40 | *Aim for steady high power. LBO at 49s* Fusion energy record, 27.5 MJ. Reioniz stop at 51.58s |
| 99593 | 08:33 | 2.3 | 1.7 | M21-98-2120 | 5.9 | 1.5 | 0/0 | 0.133/15.06 | 6e-4/5.8e-4 | 70-85 | *Cycling ohmic pulse to recover T content* |

# Sustained high fusion power successfully




Fusion energy record for 50/50 D/T plasmas

J. Hobirk *et al* 2023 Nucl. Fusion 63 112001



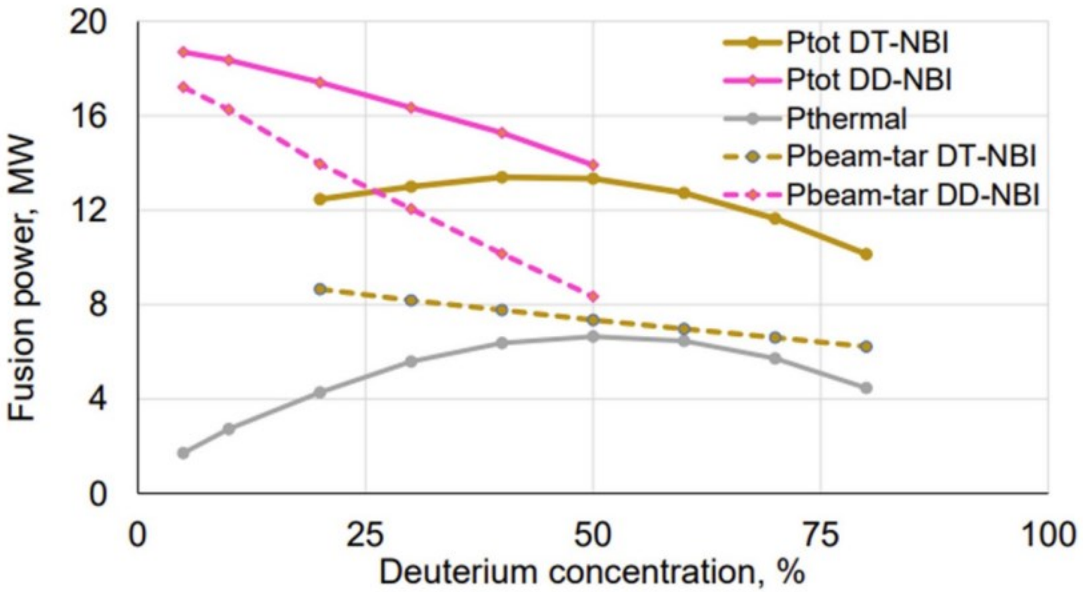

- D-T fusion power achieved in hybrid plasmas in range predicted before DTE2 → give confidence in predictive capabilities
- Improvements to models and codes are needed to reproduce details of the experiments

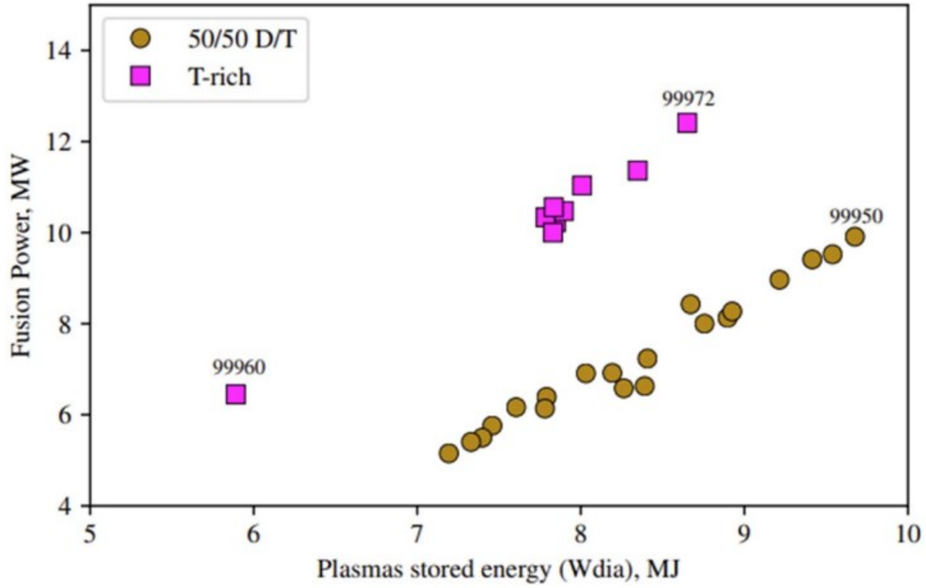
J. Garcia *et al* 2023 Nucl. Fusion 63 112003

# JET fusion power boosted by optimising heating & fuel mix in Hybrid scenario

- Non-thermal D-T reactions optimum at low D/T
- Further boost with RF ion cyclotron heating of D (not shown)

At same plasma energy, clear increase in fusion power, as expected




M. Maslov *et al* 2023 Nucl. Fusion 63 112002

# Successful integrated core-edge seeded ‘ITER-baseline’ plasma

ITER relevant configuration: high triangularity and strike-point on vertical tiles, with neon seeding for $P_{EXHAUST}$ control

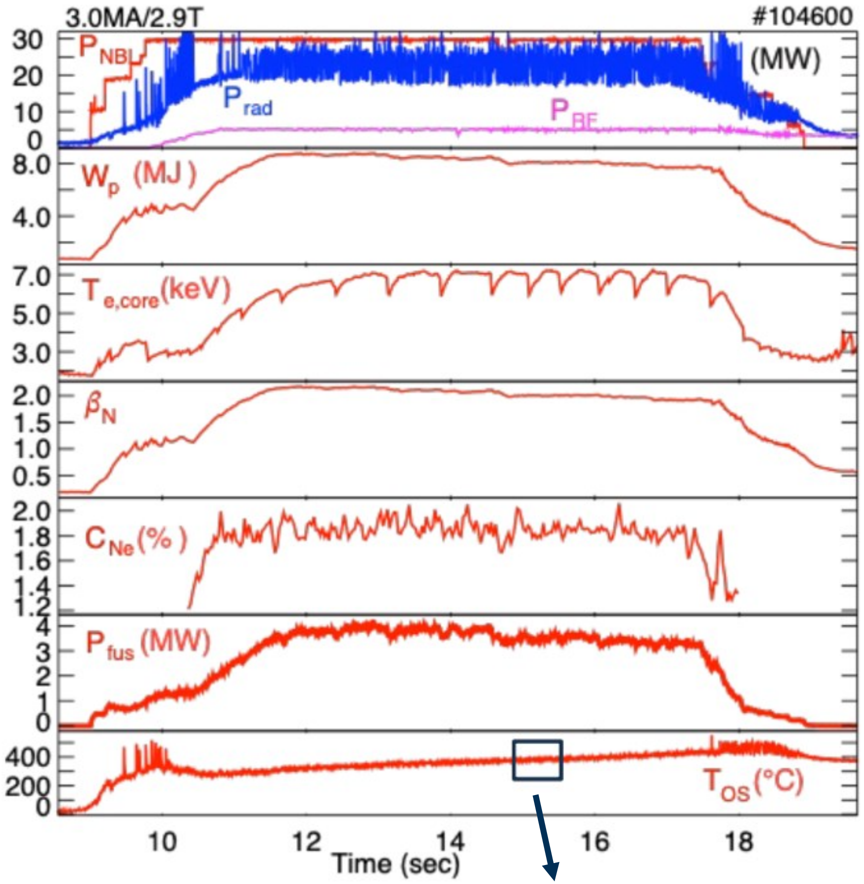
First seeded plasmas performed in D-T

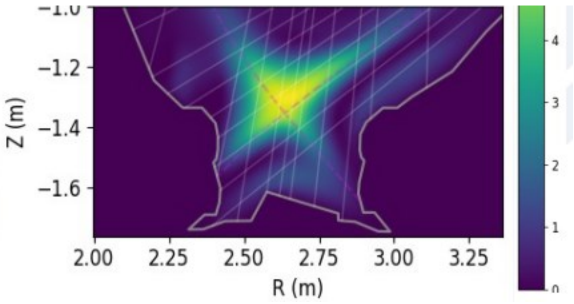
Sustained for duration of high power phase:

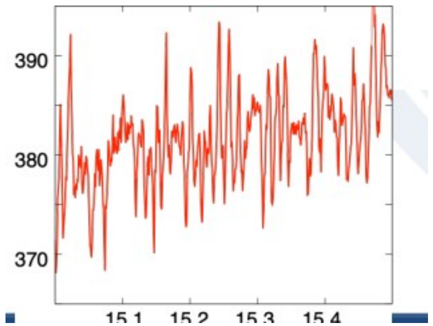
- -Stationary, with partially detached divertor
- -With natural small/no ELMs
- -without W accumulation

Improved plasma performance in D-T compared to D (not shown)

Unique information for predicting & preparing ITER plasmas

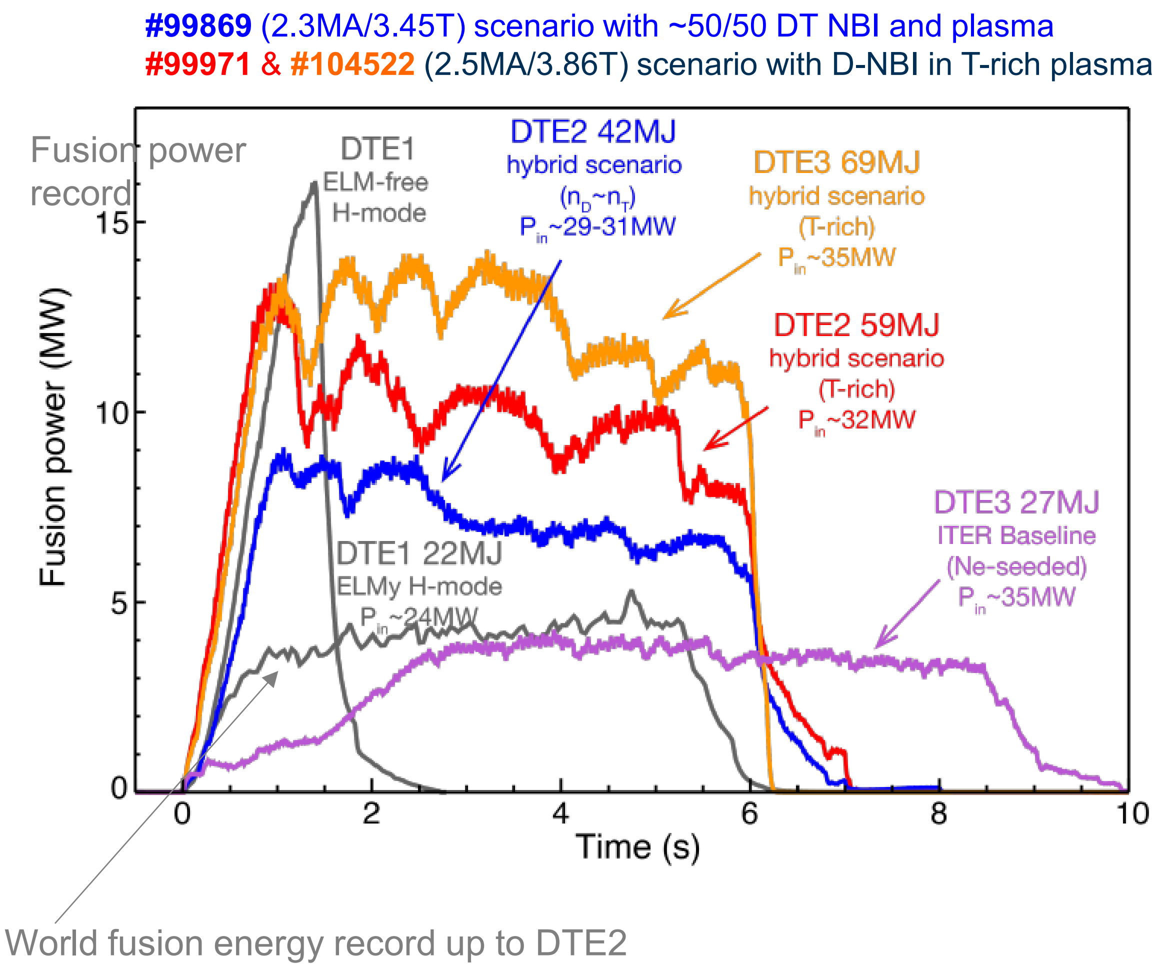


C. Giroud et al. PSI 2024

# Fusion energy world record

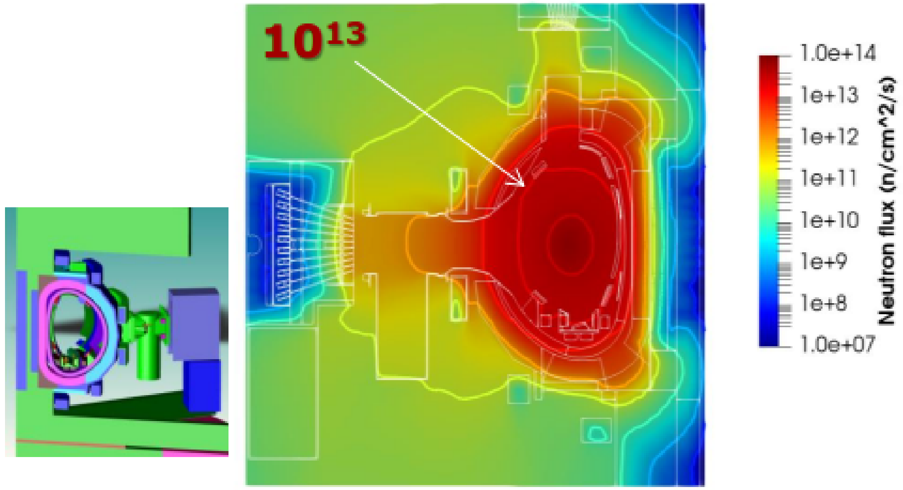



- Fusion energy world record:
  - Surpassed in DTE2 with 59MJ
  - Bettered in 2023 with 69MJ
    - Thanks to enhanced D acceleration by higher ICRH, suggested after DTE2 results analysis
- Demonstrated:
  - Compatibility of metal wall with sustained high fusion performance
  - Know-how
- Fusion power achieved is in range predicted

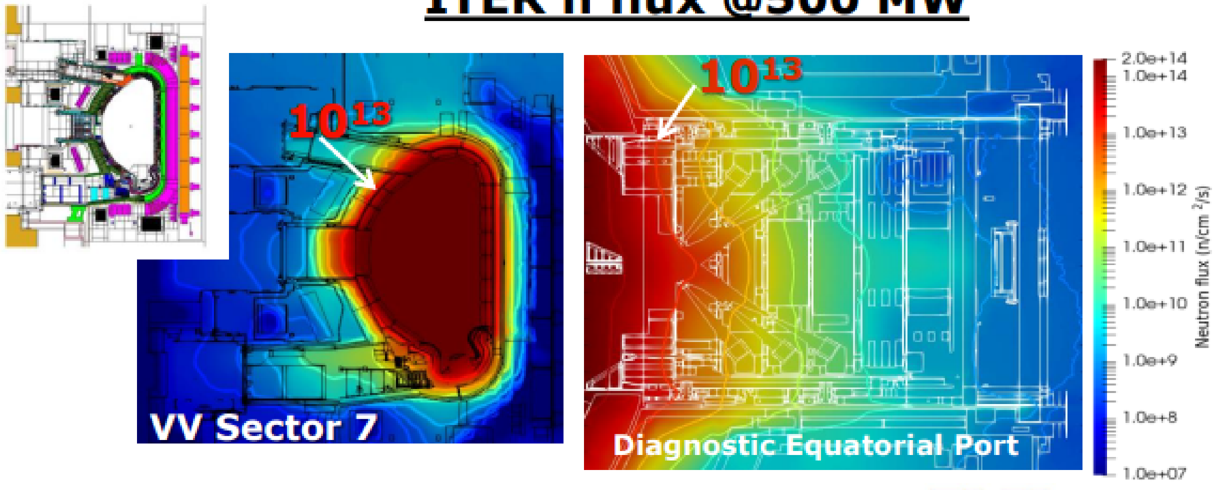
DTE2 results: C.F. Maggi *et al*. Nucl. Fusion 2024 https://doi.org/10.1088/1741-4326/ad3e16
DTE3 results: A. Kappatou *et al*., EPS 2024

# JET D-T neutron fluence relevant for ITER

**JET n flux @ shot 99971 – peak $\sim 4.8 \times 10^{18}$ n/s**




**ITER n flux @500 MW**




ENEA

**$10^{13}$ 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 @ end of ITER DT-1 (TBD)**

**JET DTE relevant for ITER technologies!**

**JET experience crucial for supporting demonstration**

# Wide range of neutronics projects

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

**Provide:**

- Test of computational tools
- Experimental validation
- Development of measurement techniques
- Calibration protocols

**in support of the design and operations of the next step fusion machines**

# Scientific Highlights – DT Special Issue

The JET hybrid scenario in Deuterium, Tritium and Deuterium-Tritium

J. Hobirk, C.D. Challis, A. Kappatou, E. Lerche, D. Keeling, D. King, S. Aleiferis, E. Alessi, C. Angioni, F. Auriemma *et al*

JET D-T scenario with optimized non-thermal fusion

M. Maslov, E. Lerche, F. Auriemma, E. Belli, C. Bourdelle, C.D. Challis, A. Chomiczewska, A. Dal Molin, J. Eriksson, J. Garcia *et al*

Modelling performed for predictions of fusion power in JET DTE2: overview and lessons learnt

J. Garcia, F.J. Casson, L. Frassinetti, D. Gallart, L. Garzotti, H.-T. Kim, M. Nocente, S. Saarelma, F. Auriemma, J. Ferreira *et al*

Validation of D–T fusion power prediction capability against 2021 JET D–T experiments

Hyun-Tae Kim, Fulvio Auriemma, Jorge Ferreira, Stefano Gabriellini, Aaron Ho, Philippe Huynh, Krassimir Kirov, Rita Lorenzini, Michele Marin, Michal Poradzinski *et al*

Tritium neutral beam injection on JET: calibration and plasma measurements of stored energy

D.B. King, R. Sharma, C.D. Challis, A. Bleasdale, E.G. Delabie, D. Douai, D. Keeling, E. Lerche, M. Lennholm, J. Mailloux *et al*

Stability analysis of alpha driven toroidal Alfvén eigenmodes observed in JET deuterium-tritium internal transport barrier plasmas

M. Fitzgerald, R. Dumont, D. Keeling, J. Mailloux, S. Sharapov, M. Dreval, A. Figueiredo, R. Coelho, J. Ferreira, P. Rodrigues *et al*

Experiments on excitation of Alfvén eigenmodes by alpha-particles with bump-on-tail distribution in JET DTE2 plasmas

S.E. Sharapov, H.J.C. Oliver, J. Garcia, D.L. Keeling, M. Dreval, V. Goloborod'Ko, Ye.O. Kazakov, V.G. Kiptily, Ž. Štancar, P.J. Bonofiglo *et al*

Toroidal Alfvén eigenmodes observed in low power JET deuterium–tritium plasmas

H.J.C. Oliver, S.E. Sharapov, Ž. Štancar, M. Fitzgerald, E. Tholerus, B.N. Breizman, M. Dreval, J. Ferreira, A. Figueiredo, J. Garcia *et al*

Effect of the isotope mass on pedestal structure, transport and stability in D, D/T and T plasmas at similar $\beta_N$ and gas rate in JET-ILW type I ELMy H-modes

L. Frassinetti, C. Perez von Thun, B. Chapman-Oplopoiou, H. Nyström, M. Poradzinski, J.C. Hillesheim, L. Horvath, C.F. Maggi, S. Saarelma, A. Stagni *et al*

Isotope physics of heat and particle transport with tritium in JET-ILW type-I ELMy H-mode plasmas

P.A. Schneider, C. Angioni, F. Auriemma, N. Bonanomi, T. Görler, R. Henriques, L. Horvath, D. King, R. Lorenzini, H. Nyström *et al*

L-H transition studies in tritium and deuterium–tritium campaigns at JET with Be wall and W divertor

E.R. Solano, G. Birkenmeier, C. Silva, E. Delabie, J.C. Hillesheim, A. Baciero, I. Balboa, M. Baruzzo, A. Boboc, M. Brix *et al*

Isotope mass scaling and transport comparison between JET Deuterium and Tritium L-mode plasmas

T. Tala, A.E. Järvinen, C.F. Maggi, P. Mantica, A. Mariani, A. Salmi, I.S. Carvalho, A. Chomiczewska, E. Delabie, F. Devasagayam *et al*

Divertor power load investigations with deuterium and tritium in type-I ELMy H-mode plasmas in JET with the ITER-like wall

M. Faitsch, I. Balboa, P. Lomas, S.A. Silburn, A. Tookey, D. Kos, A. Huber, E. de la Luna, D. Keeling, A. Kappatou *et al*

Tritium removal from JET-ILW after T and D–T experimental campaigns

D. Matveev, D. Douai, T. Wauters, A. Widdowson, I. Jepu, M. Maslov, S. Brezinsek, T. Dittmar, I. Monakhov, P. Jacquet *et al*

Experiments in high-performance JET plasmas in preparation of second harmonic ICRF heating of tritium in ITER

M.J. Mantsinen, P. Jacquet, E. Lerche, D. Gallart, K. Kirov, P. Mantica, D. Taylor, D. Van Eester, M. Baruzzo, I. Carvalho *et al*

https://iopscience.iop.org/issue/0029-5515/63/11

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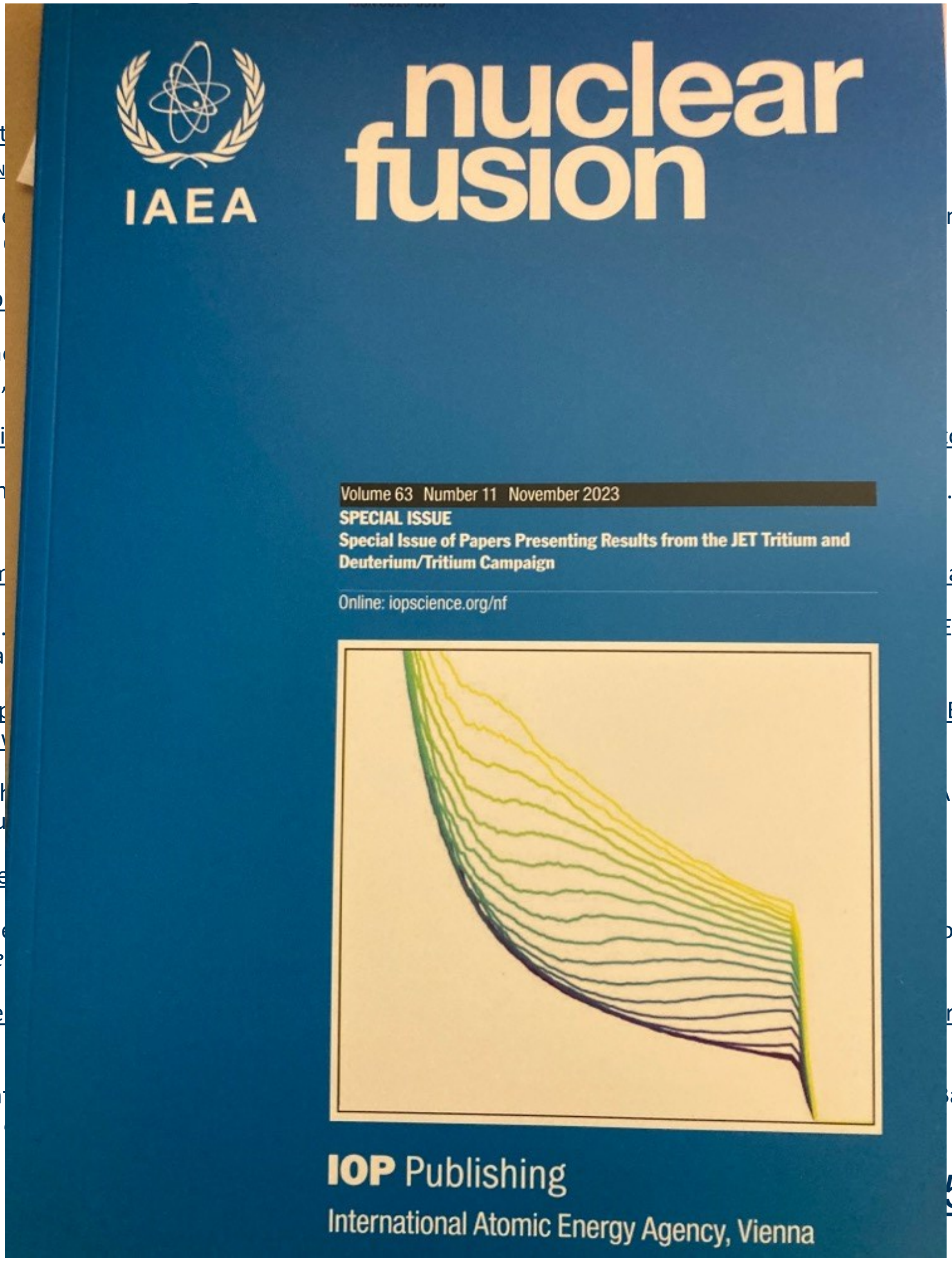



5/63/11

# JET Operations– PPCF Special Issue

- Further special issue still being worked on for operations – coordinated by H. Sun and E. Belonohy

- Papers published so far on overview of operations, safety case, tritium handling, IR diagnostics and many more…

Overview paper by the JET team (presented by D King) includes the references so far
Nuclear Fusion 2024, **64** 106014

https://iopscience.iop.org/article/10.1088/1741-4326/ad6ce5

https://iopscience.iop.org/journal/0741-3335/page/Special%20Issue%20on%20the%20Physics%20and%20Engineering%20of%20Toroidal%20Fusion%20Plasma%20Operations

# Summary – Key Requirements

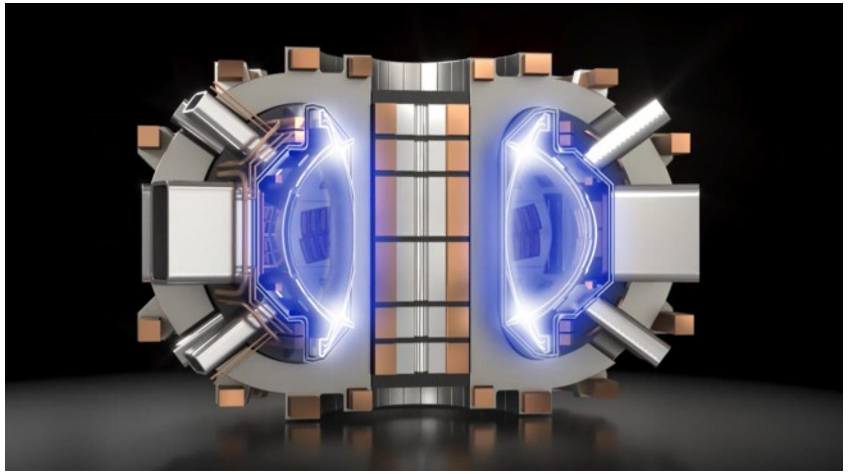
The above items show a number of the requirements before even introducing tritium into a tokamak but here is a brief summary

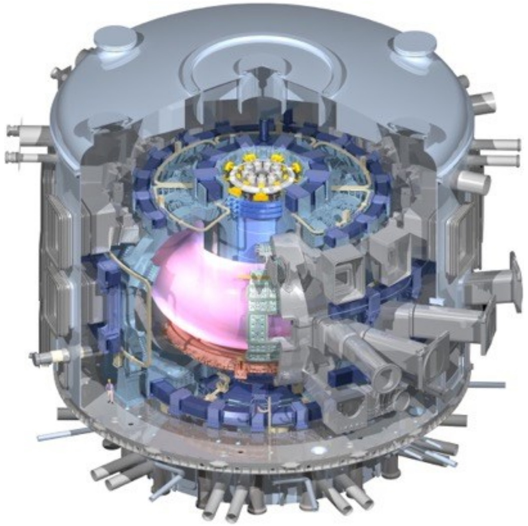
- **A focussed strategy on an end goal**
- **A robust and mature operational regime in DD**
- **A safety case that defines operation of the machine in a tritium mode**
- **Suitable tritium containment measures in ALL parts of the cycle**
- **Buildings that are fit for purpose (shielding, monitoring, access control…)**
- **A strategy for what is and is not in the torus hall**
- **Training and rehearsals for anyone who may be involved (from directors to cleaners)**
- **A considered approach to DT diagnostics (what's in and what's out)**
- **Know what you will do after DT**

- **Lots of patience and a backup plan!**

# Summary – Future Machines

- A new generation of experiments and reactor concepts are preparing for their own DT operations
- The JET experience is (or should be) used to guide this and accelerate their progress
- Scaling up systems can solve some of the constraints shown here, e.g. more shielding, different/larger tritium handling facilities…
- But of course the difficulties of scaling up are far larger, e.g. greater tritium inventory requirements, radiation damage, risks to machine integrity at higher Ip/Bt…
- The JET team are keen to help support and train operators in readiness for these new devices





**The DTE3 campaign successfully complemented and expanded the experiments in Deuterium in 2022-2023**

**JET shut down at the end of 2023, after 40 years of unique contributions to fusion research**

**None of this would have been possible without the dedication and hard work of the JET team!**