The JET D- T campaign: technology impact and physics results

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why we do research into Nuclear Fusion ?

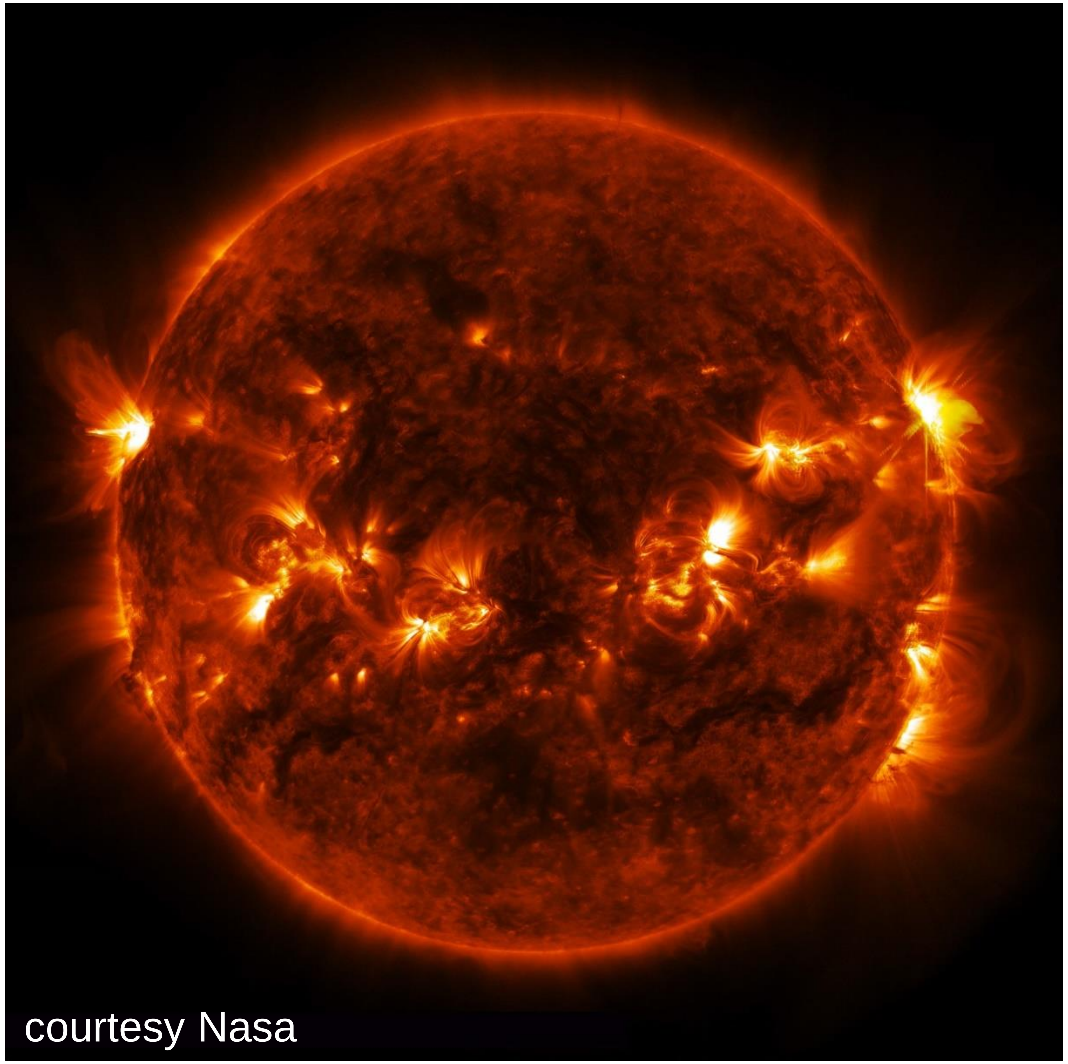
“What problem do you hope scientists will have solved by the end of the century?”

“Nuclear fusion…would provide an inexhaustible supply of energy without pollution or global warming.

We know how to do fusion as physicists, how it works.
It is an engineering solution that is within our grasp”

Prof. Stephen Hawking and Prof. Brian Cox - 2010

Controlled Nuclear Fusion for energy production


courtesy Nasa

fusion processes are the source of energy in the stars

although the media love to talk about

bringing the sun to earth

in fusion research we are actually exploring very different conditions from the high density & pressure inside the stars

two main lines of research :

magnetic vs inertial confinement

Magnetic Confinement Fusion

- a very hot, low density, fully ionized gas (plasma)
- confined in a toroidal vacuum vessel by means of magnetic fields

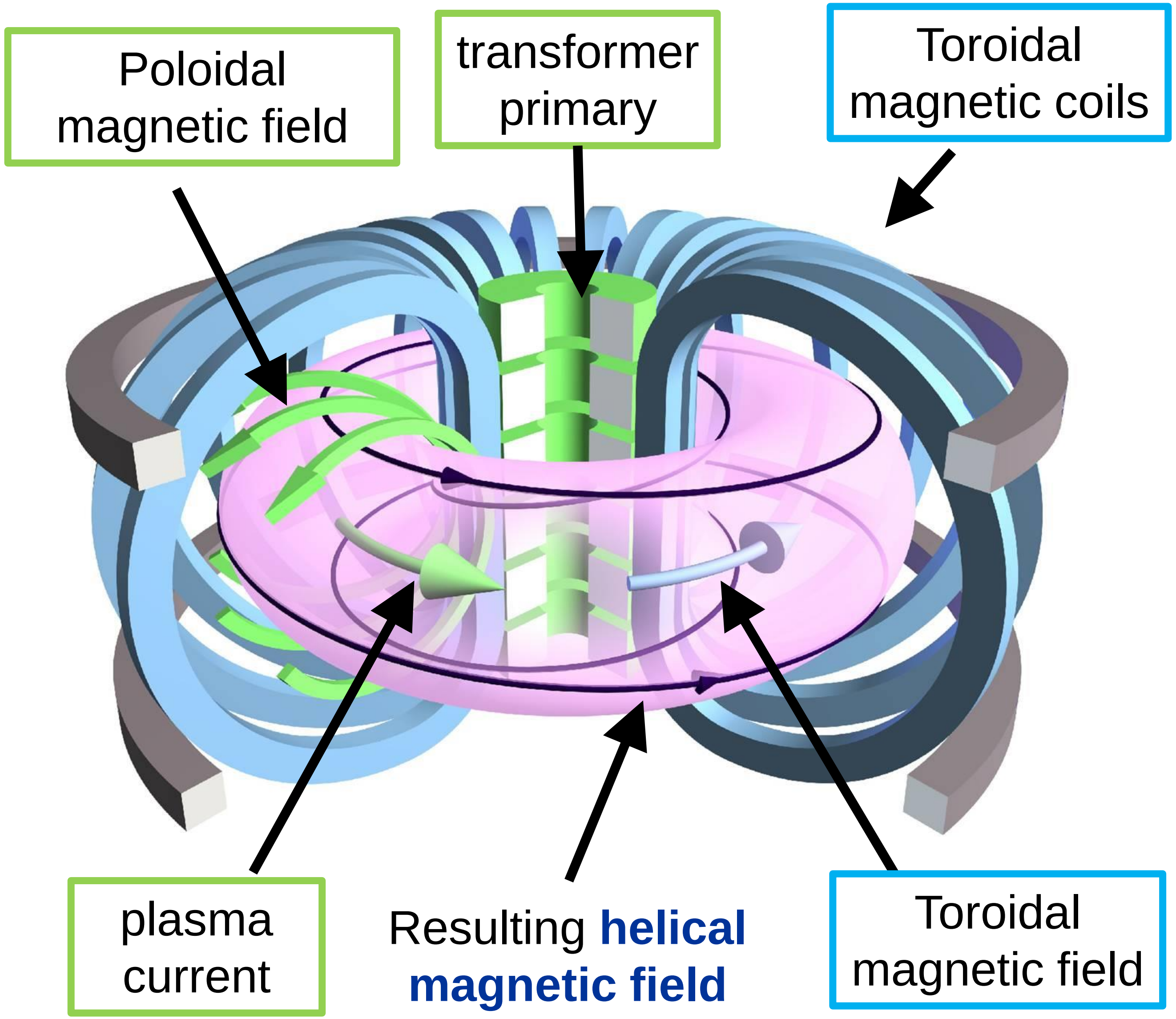
in the following I will concentrate on a specific type of magnetic confinement

the **tokamak**

external magnetic fields

+

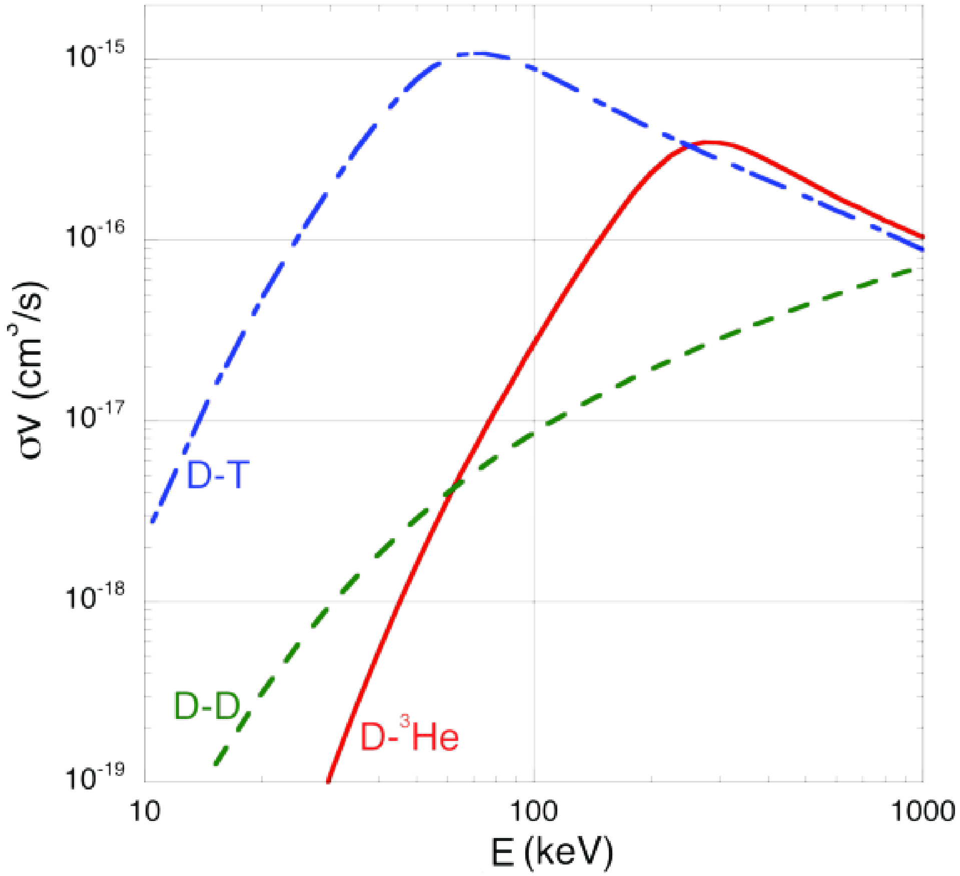
the field produced by the current flowing in the plasma itself

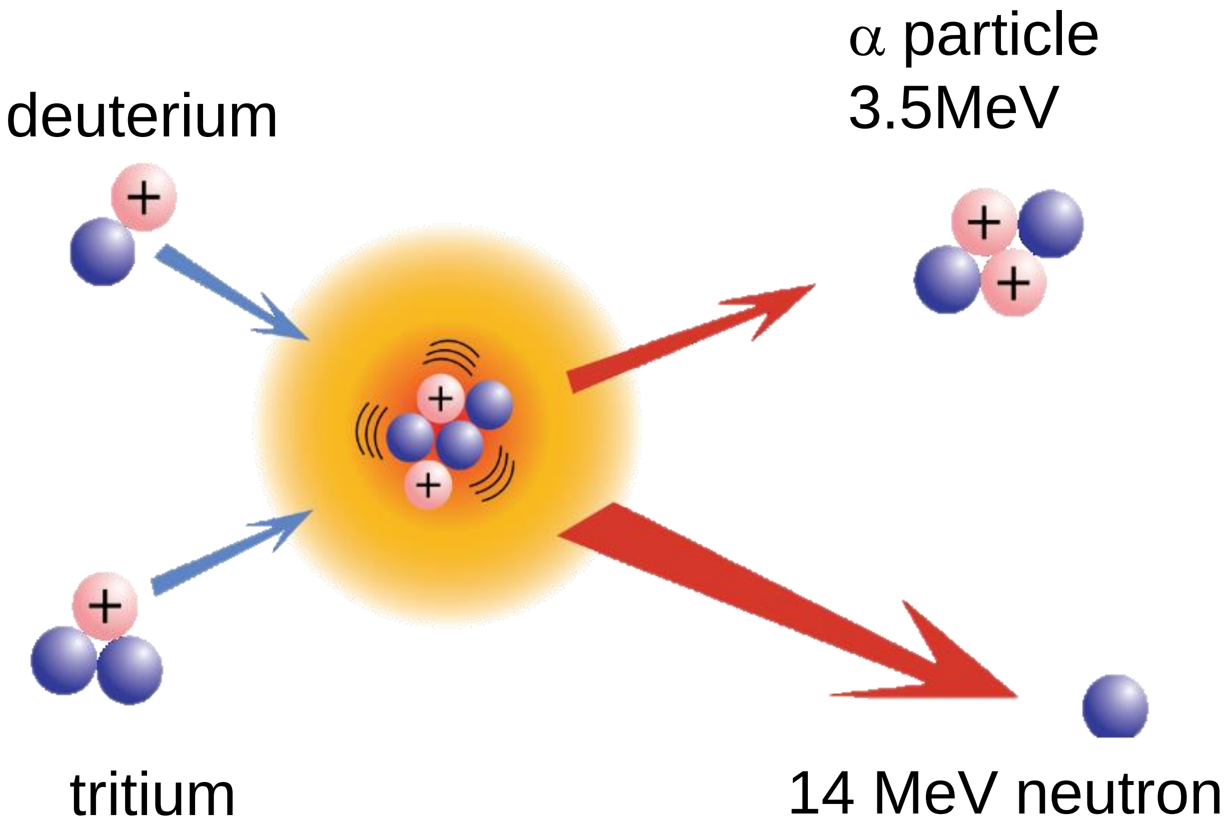


deuterium-tritium fusion

a large number of possible fusion reactions but, for the first generation of reactors, the research is focussing mainly on **deuterium-tritium** processes

higher cross section at lower energies





outline

(short) background on JET and past D-T tokamak experiments

DTE2 : Engineering upgrades & operational experience:

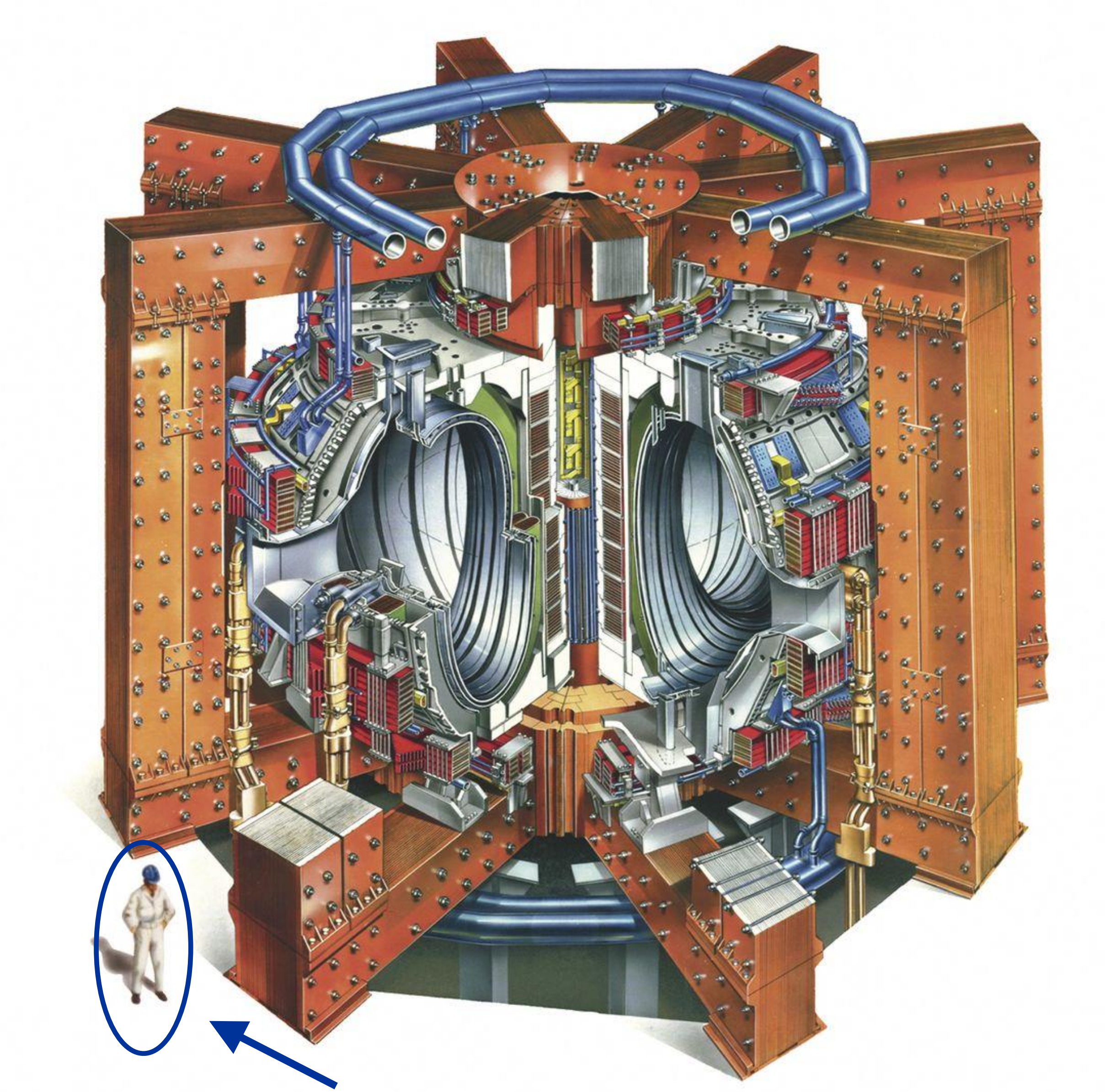
- JET ITER-like metal wall
- Tritium management
- Tritium clean-up
- Diagnostics

Selected highlights of scientific results:

- impact of fuel mass on plasma properties
- α-particle studies
- high, sustained fusion energy production with ITER-like wall
- D-T results confirm modelling predictions

caveat : some of the results are preliminary, detailed analysis ongoing

the JET tokamak



originally built & operated by EU

now owned by UKAEA and jointly operated with European Consortium (EUROfusion)

operational at Culham (UK) since 1983

with several major upgrades since

(still) the largest working tokamak

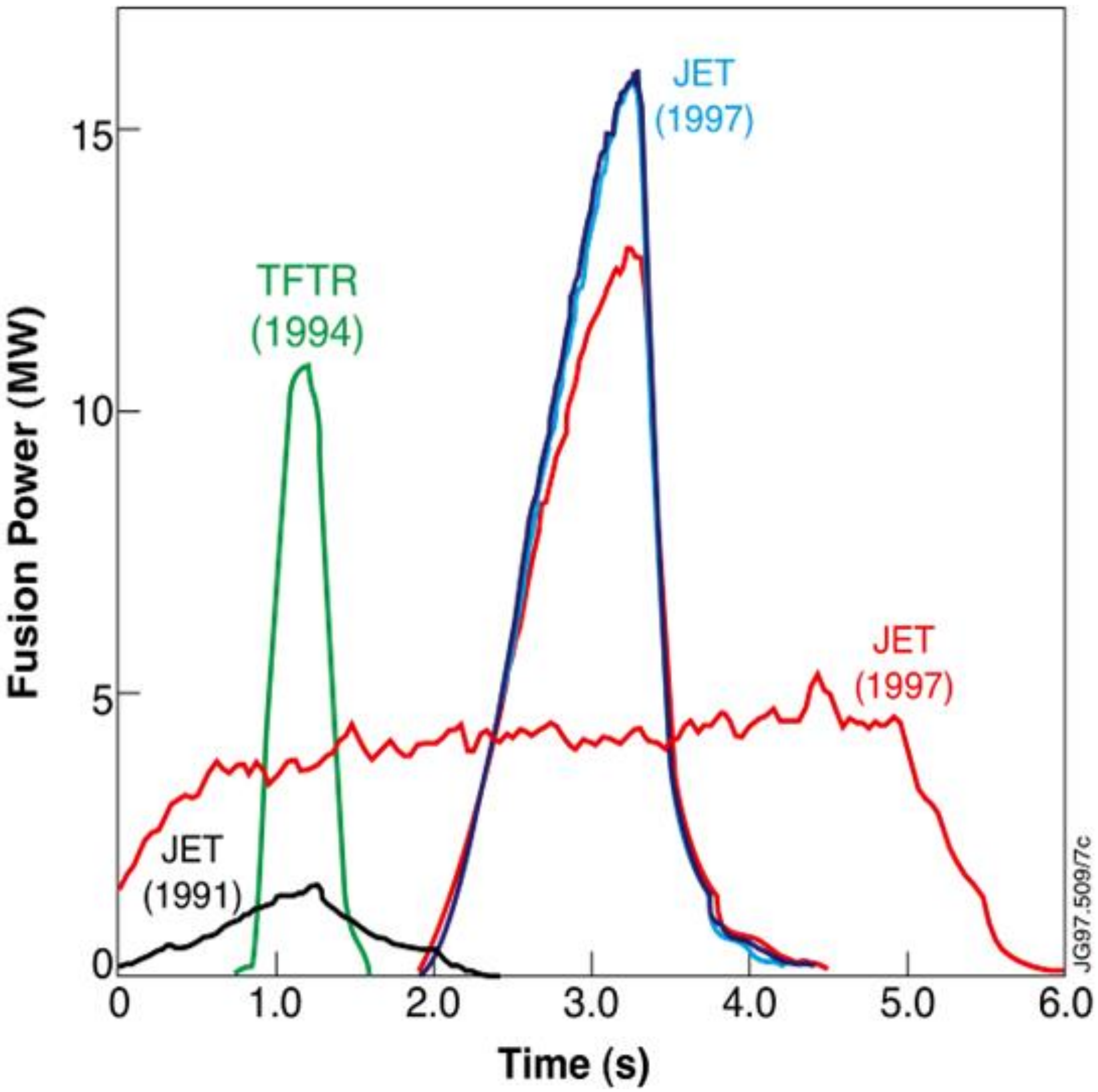
closest in size and plasma parameters to ITER

and the only one capable of experiments with D-T mixture

JET Technical specs

Major / minor radius (m)	2.96 / ~0.8-0.9	Size
Max plasma current (MA)	4.5	Confining magnetic fields
Max toroidal field (T)	3.9 (Galden cooled copper coils)	
Discharge duration (s)	Up to 20s flat top	
Main fuel	H / D / T / He	
Ion Cyclotron Heating	Up to ~ 6MW / 25-56 MHz	Plasma heating systems
Neutral Beam Injection	≤ 32 MW (D / T) ~24MW in DTE1	

D-T in Magnetic Confinement Fusion before 2021



D-T experiments were carried out in

1991 (PTE - JET)

1994-96 (TFTR – Princeton USA)

1997 (DTE1 on JET)

D-T Fusion production was demonstrated un-ambiguously

also found clear physics effects linked to use of D-T mixture (*isotope* effects)

Although some α-particles effects were observed on TFTR (MHD) , the JET DTE1 results were more ambiguous

➔ **open questions for DTE2**

from JET to ITER

iter_organization

8 July 2022

Europe's toroidal field coil #14 arrived at ITER

129 likes

iter_organization On 8 July, the European Domestic Agency, @fusion4energy, delivered toroidal field coil #14 to the #ITER site. This is the eighth of altogether ten D-shaped vertical coils from Europe.

- early 1990s : start of International Tokamak Experimental Reactor (ITER) design
- 2007/8 agreement between 7 international partners to start ITER construction

ITER will be ~10x JET volume

construction is well advanced

plasma operations expected ~ 2025

with D-T experiments in ~2035 aiming aiming at Pfus ~ 500MW and

Q=10 (P_{fus}= 10 x P_{in})

back to early D-T experiments : tritium retention

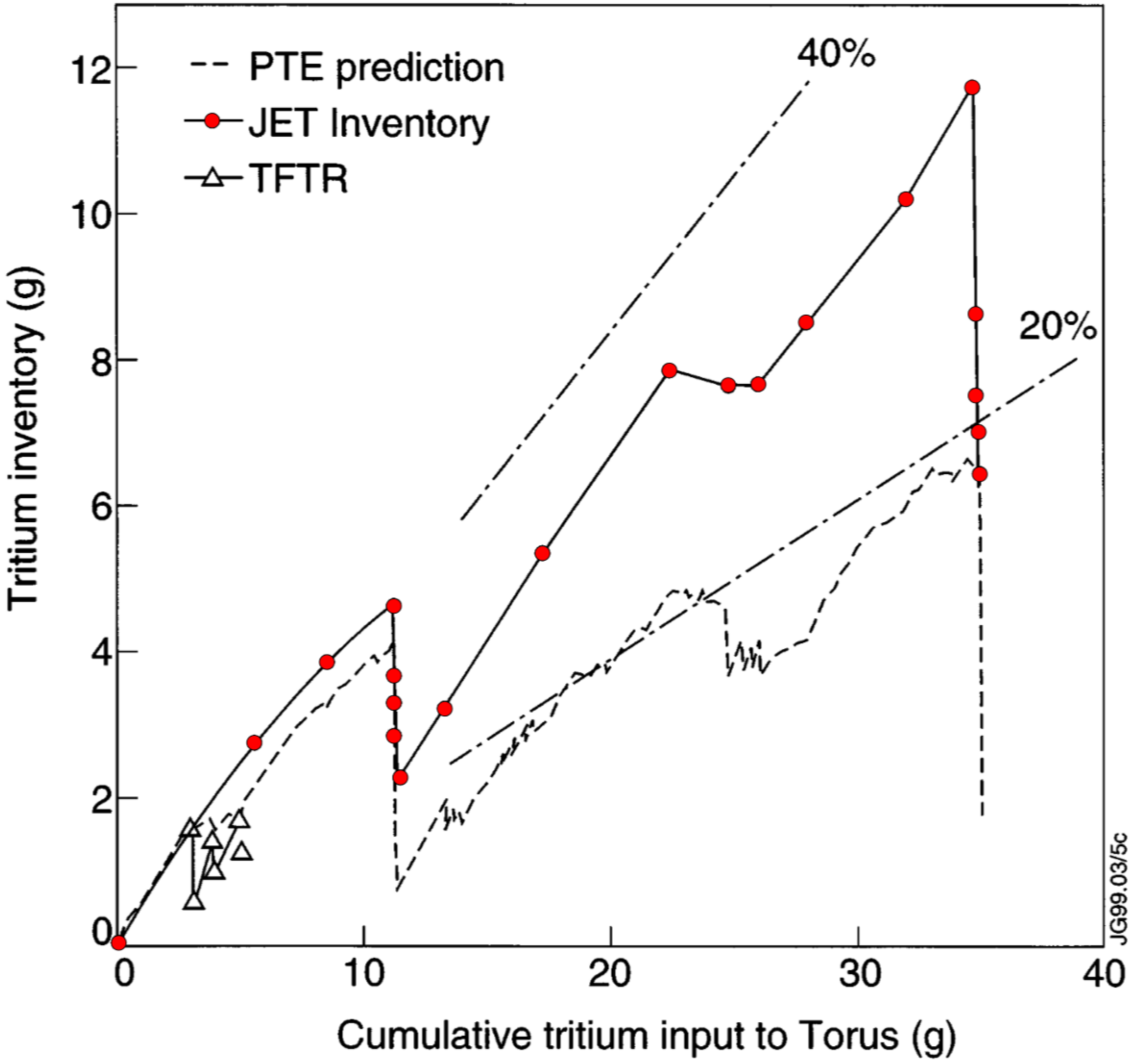
TFTR & JET DTE1 experiments carried out with CFC-based Plasma Facing Components

Both devices showed **large retention of tritium in the vessel wall ,** unacceptable for a reactor

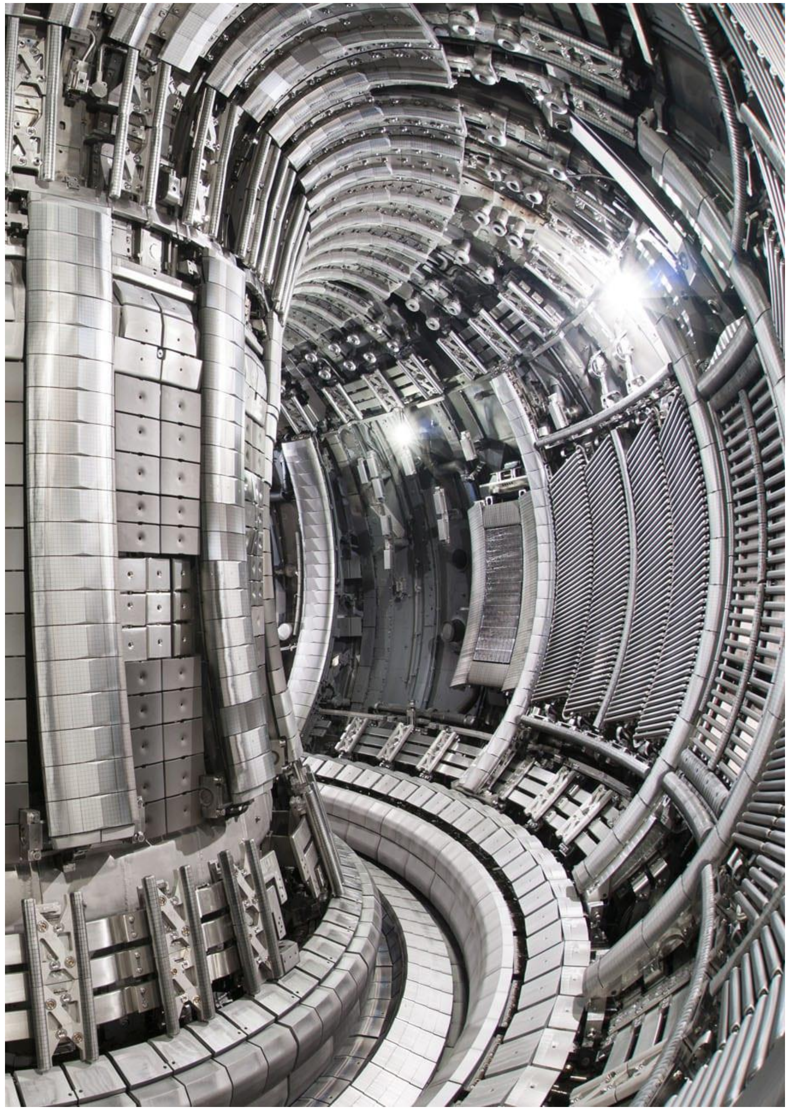
This motivated shift towards different (metal) wall materials for ITER

➔ Installation of an **ITER-like metal wall** at JET and experimental tests to confirm ITER decision and prepare ITER operations

[P. Andrew - FED 47 (1999)]



JET Be/W ITER-like Wall

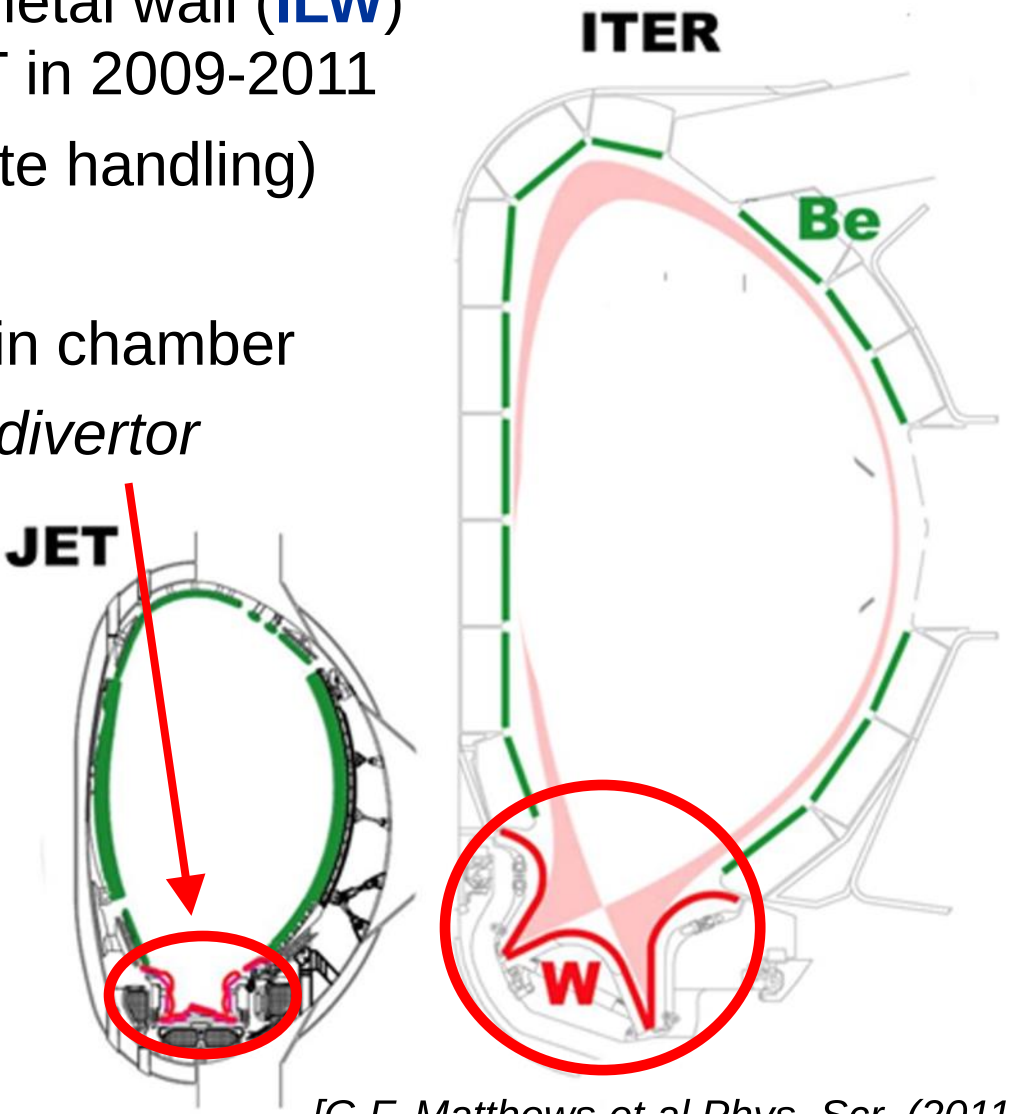


An ITER-like Be/W metal wall (**ILW**) was installed at JET in 2009-2011

(entirely by remote handling)

Beryllium in main chamber

Tungsten in *divertor*



to note :

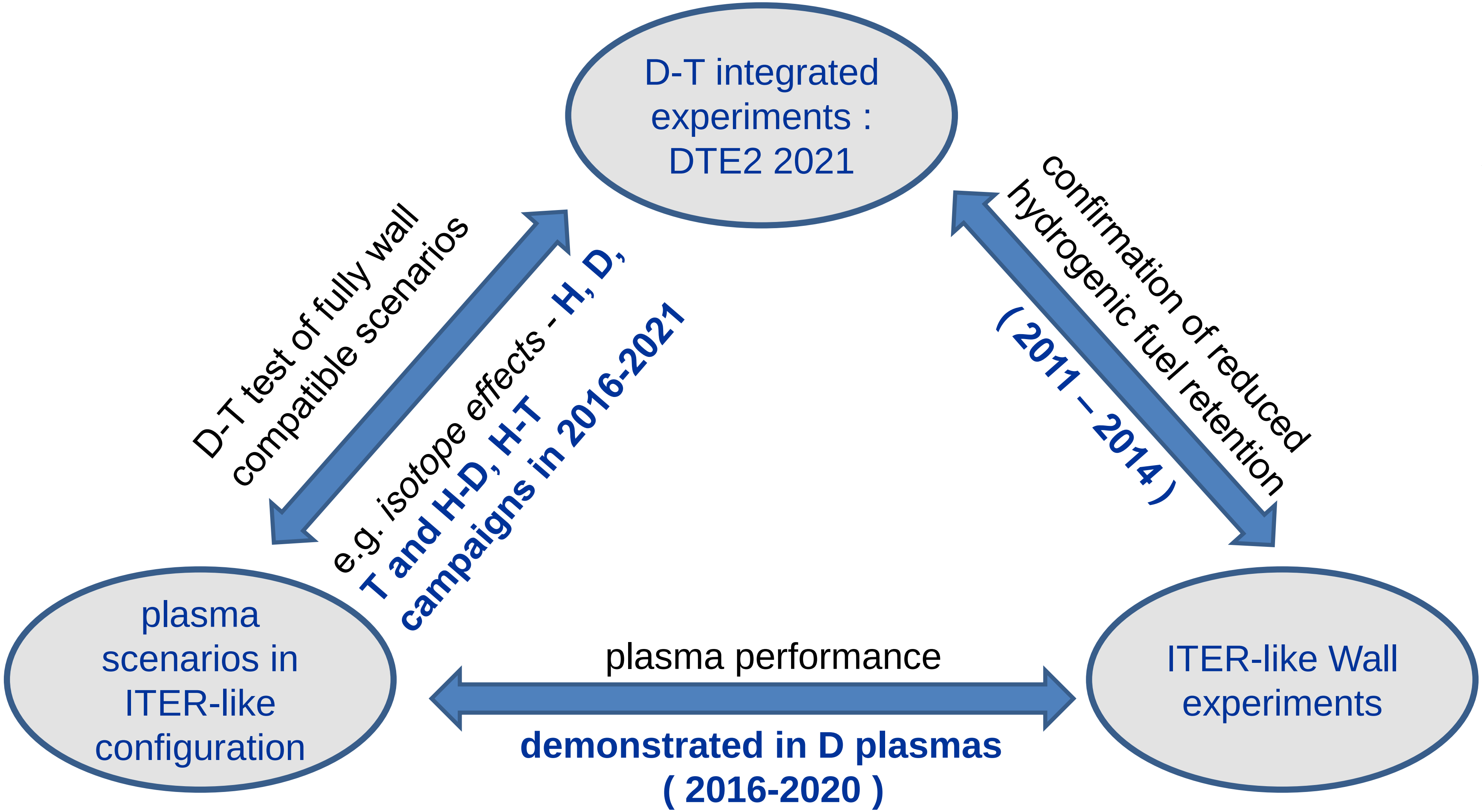
Divertor is the area receiving the highest heat & particle flux

and JET wall is NOT actively cooled

[G.F. Matthews et al Phys. Scr. (2011)]

JET DTE2: culmination of plan started in 2006

Demonstration of Be/W ITER-like Wall compatibility with high fusion power operation



D-T integrated experiments : DTE2 2021

D-T test of fully wall compatible scenarios

e.g. *isotope effects* - **H, D, T and H-D, H-T campaigns in 2016-2021**

confirmation of reduced hydrogenic fuel retention

(2011 – 2014)

plasma scenarios in ITER-like configuration

plasma performance

demonstrated in D plasmas (2016-2020)

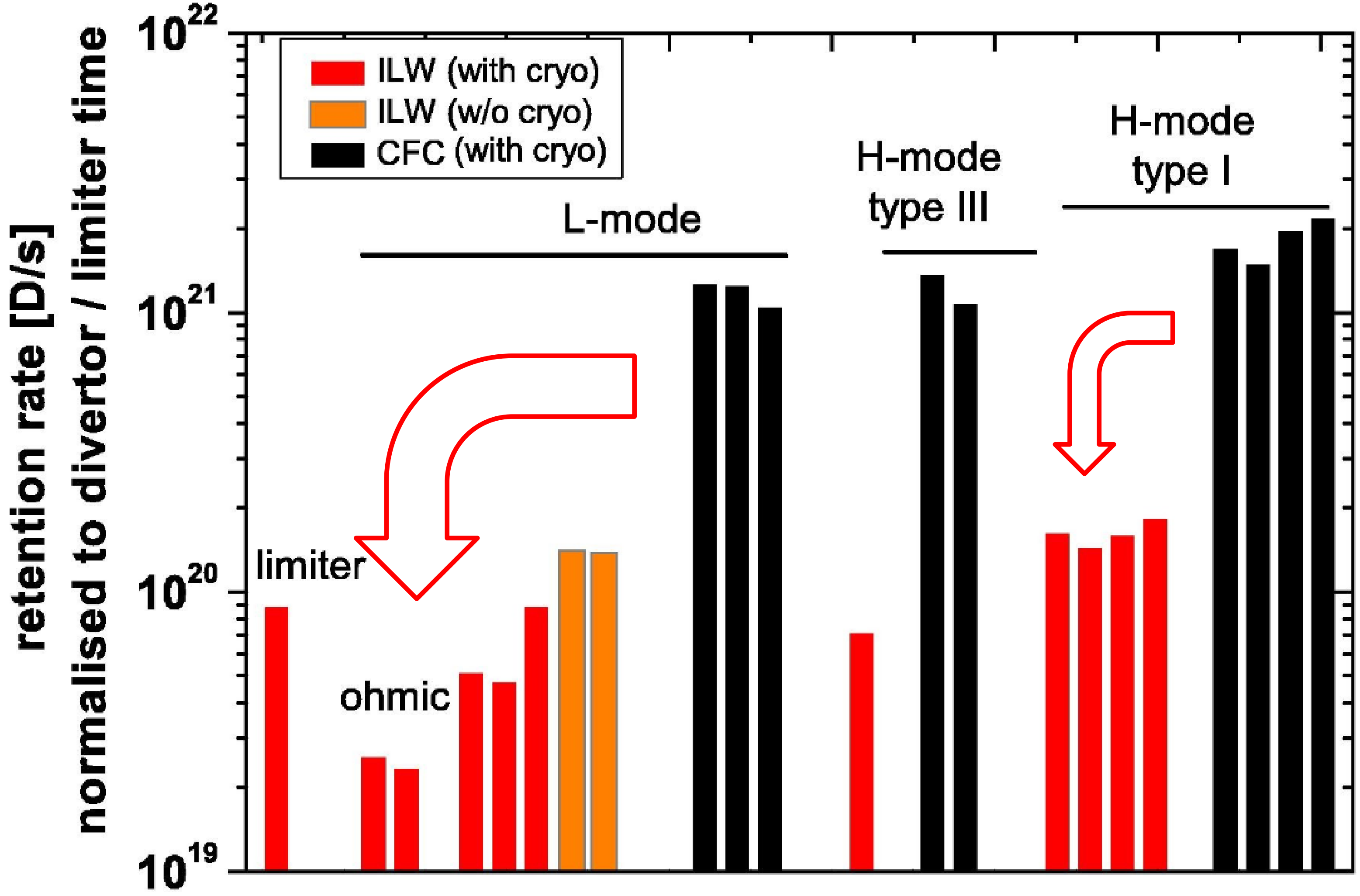
ITER-like Wall experiments

schematic adapted from Pamela et al, FED 2007

ITER-like wall : fuel retention

In JET with ILW **H/D fuel retention reduced by a factor 10**

(in a wide range of plasma conditions)



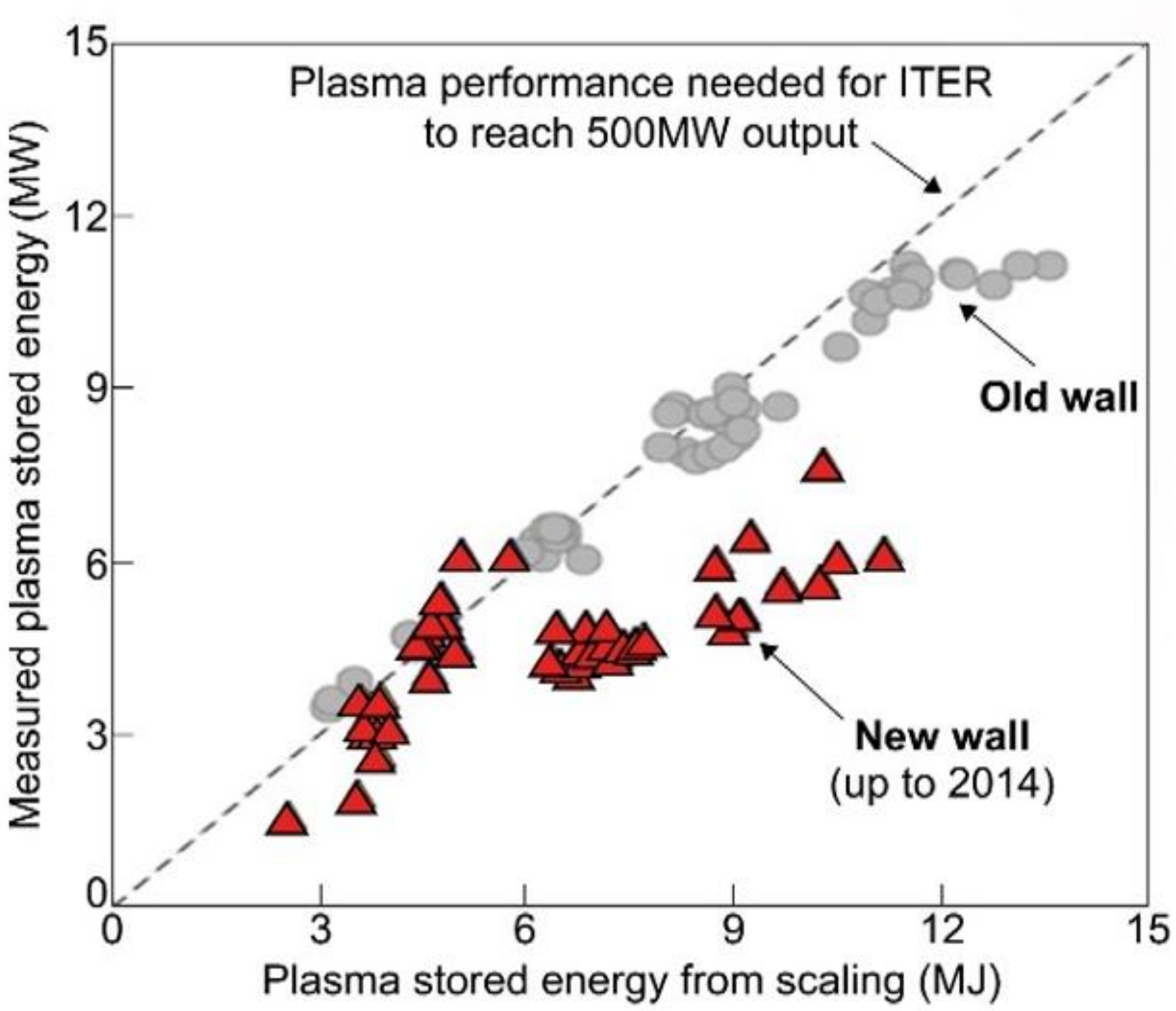
[S. Brezinsek – JNM (2015)]

ITER-like wall : plasma behaviour (I)

We know that the *confined* plasma behaviour is deeply influenced by the interaction with the vessel wall

Initially with the ILW, the plasma in JET did not reproduce the performance obtained with the previous Carbon wall

e.g. stored energy well below what is expected for ITER

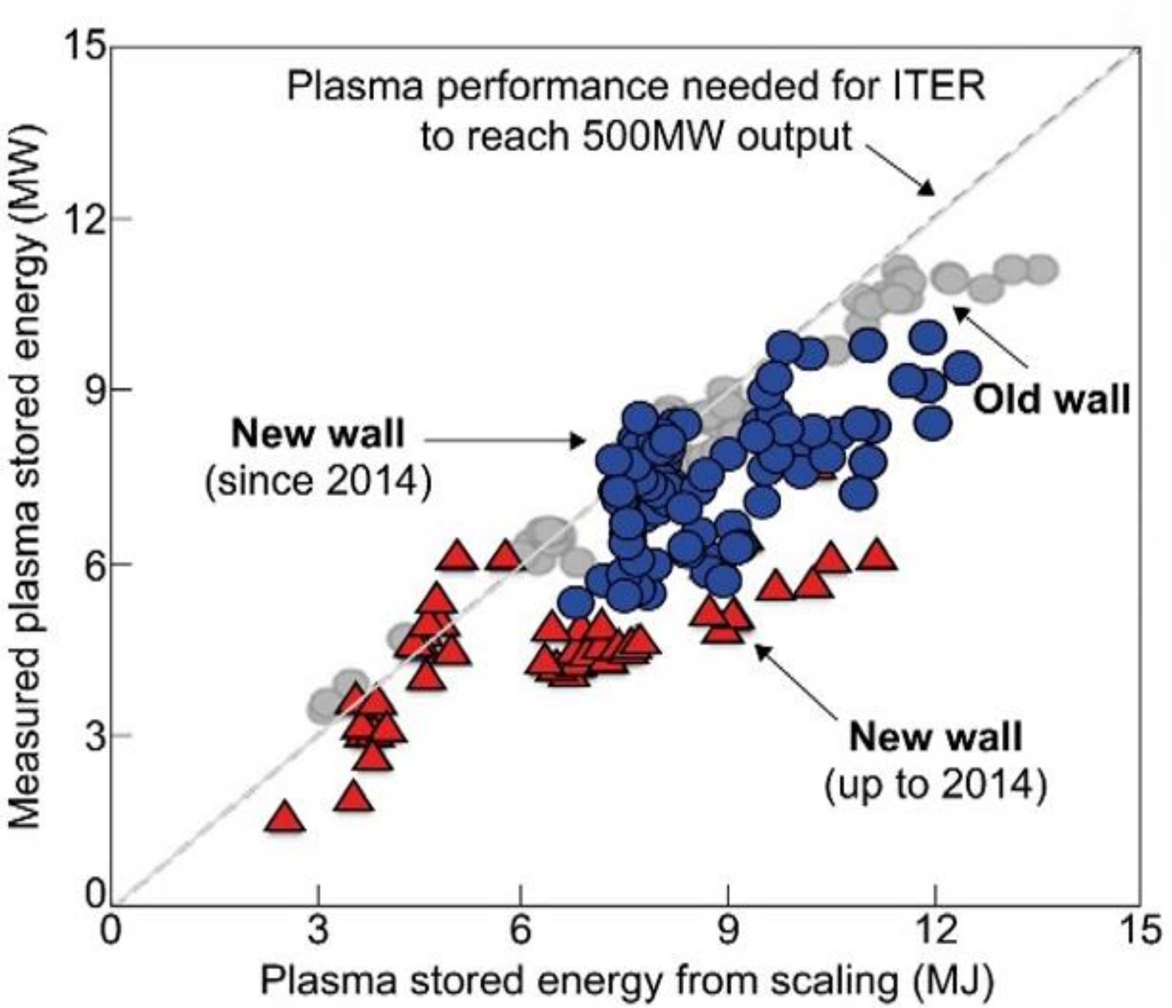


J. Mailloux IAEA 28th FEC conf. 2021

ITER-like wall : plasma behaviour (II)

It took several years to recover high performance, with experiments supported by physics understanding & improved physics modelling

The learning curve is, in itself, a valuable experience for future machines



J. Mailloux
IAEA 28th FEC conf. 2021

In 2021, having

- demonstrated the beneficial effects of the metal wall on hydrogenic fuel retention
- recovered good plasma performance, in line with predictions for ITER
- prepared the experiments to study isotope and alpha particle effects

JET was ready, from a physics point of view, to embark on a D-T campaign

In parallel, many of the D-T systems were subject to major upgrades

Tritium management : Active Gas Handling System (AGHS)

JET acquired a given amount of tritium gas, which is regularly recycled & purified via the Active Gas Handling Systems (extensively refurbished for DTE2)

AGHS provides:

- Daily gas feed to tokamak fuelling systems, gas exhaust recovery and overnight storage
- Weekly reprocessing and accountancy every 3 weeks

To match the scientific scope, in September 2020
the **Tritium on site for DTE2 was ~69g** **(**21g in DTE1)

Tritium *used*:

T + D-T (until Feb 2022) : **~ 1kg !!**
vs. DTE1 : ~ 100g (shorter campaign)

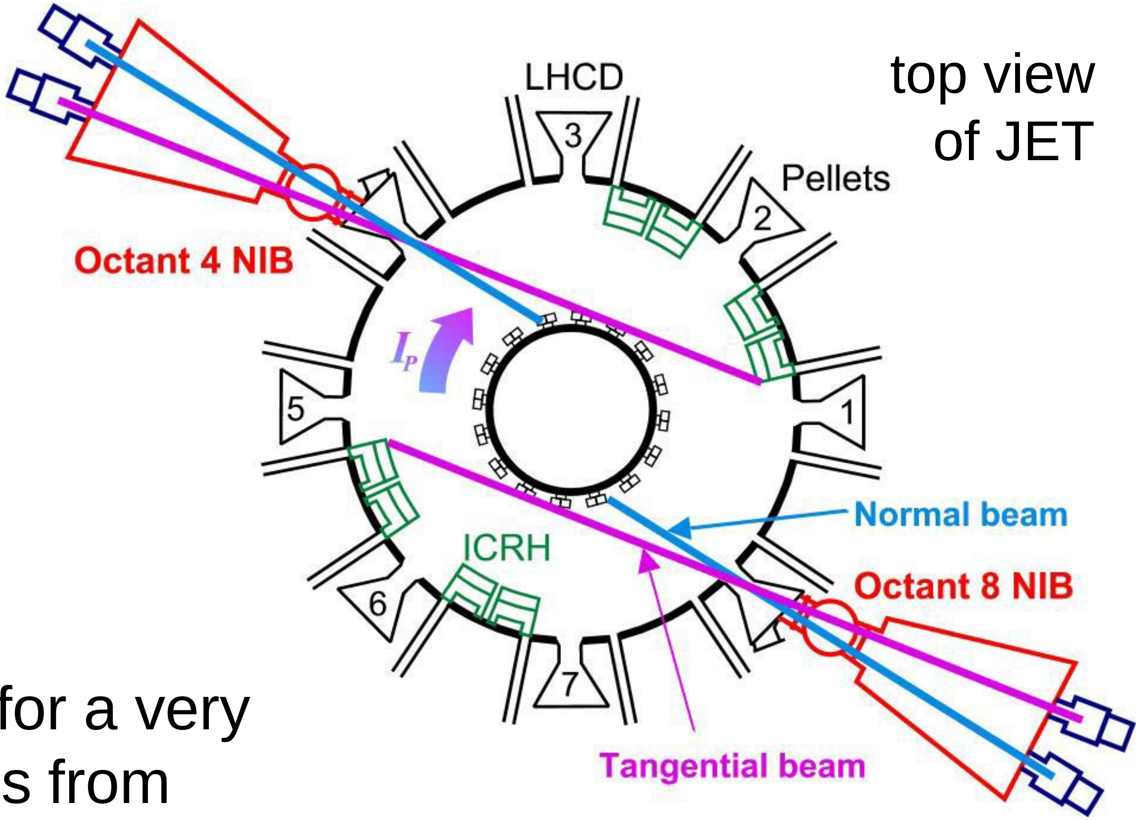
Tritium gas injection in 2021 campaigns

Tritium is injected in the JET vessel as gas or via the Neutral Beam heating system

In 2021

- T gas injection from **5 Tritium Injection Modules (TIMs)** vs. only 1 injection module in DTE1
- T could be fed into **both NBI Boxes** vs. only 1 NBI box in DTE1

➔ these increased capabilities we exploited for a very extensive exploration of isotope effect physics from hydrogen, via deuterium, to pure tritium to accompany DTE2



top view of JET

DTE2 Tritium accounting

Tritium used :

	DTE2	DTE1
gas	240g	30g
Neutral Beams	763g	70g

T **accountancy** measurements by AGHS (up to end May 2022):

out of the initial 69 g T stored, decayed to ~ 62.5g in May 2022

12.89 g not accounted for as of May 2022

but analysis not complete

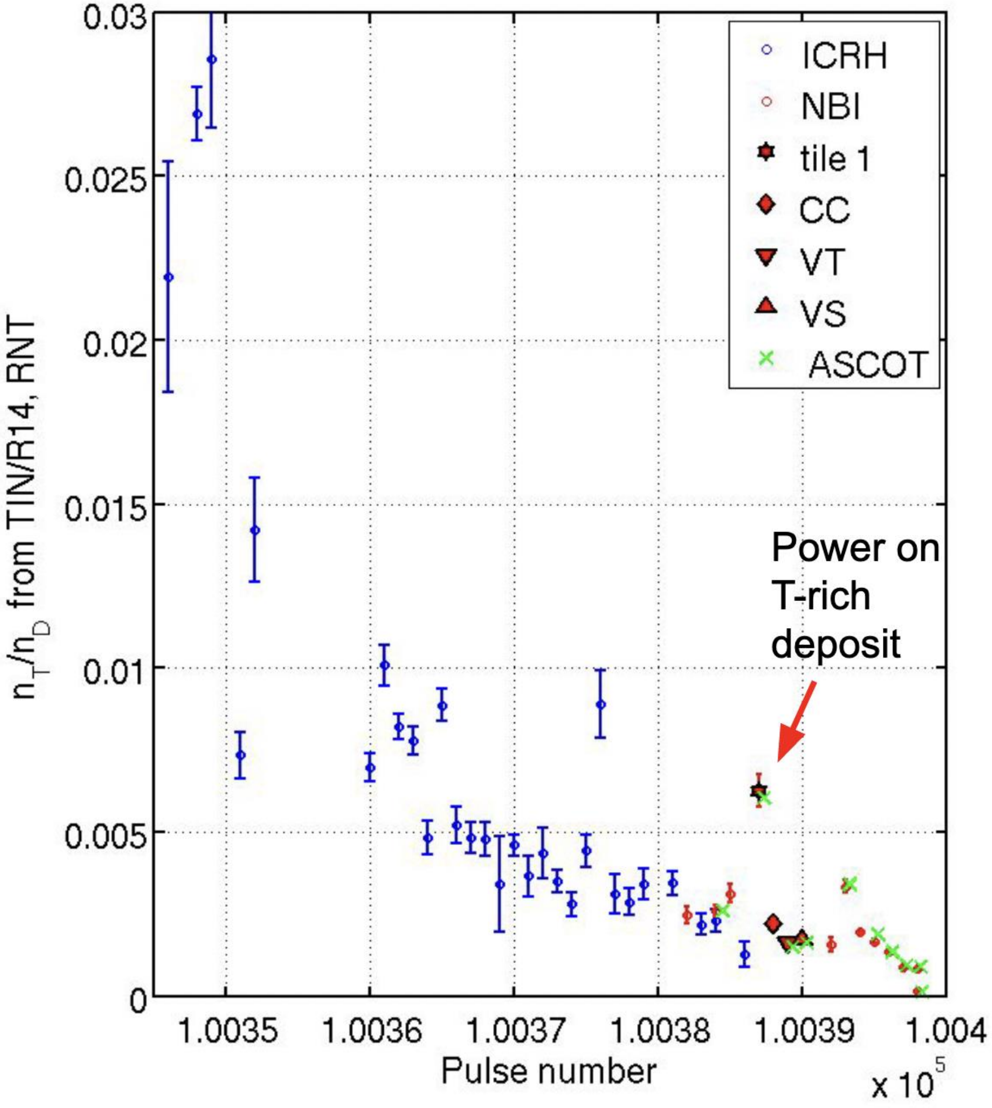
DTE2 tritium clean-up

managing the in-vessel tritium inventory is one of the crucial issues for ITER (& JET)

🡇

after the end of DT and T experiments, JET carried out an extensive tritium clean-up phase with combination of various techniques (targeting different vessel wall areas)

- starting from 100% T
- reached $n_T/n_D < 0.1\%$(neutron measurements) in a couple of weeks
- then clean-up consolidated by further plasma operation



Power on T-rich deposit

[D Matveev et al., PSI 2022]

DTE2 Diagnostics capabilities

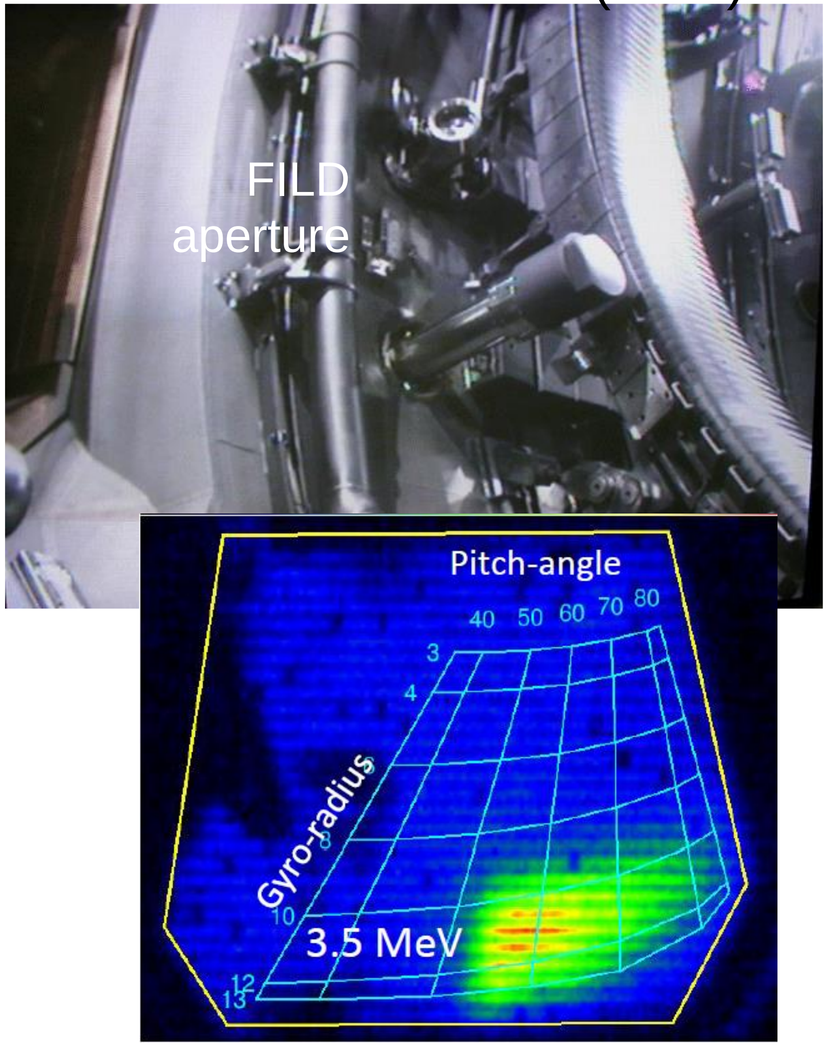
Since DTE1 we had a significant increase in JET diagnostic capabilities, to improve coverage of:

- plasma edge (kinetic parameters)
- impact of ILW on plasma core/edge behaviour

Plus new / upgraded diagnostics for DT fusion:

- TAE antenna (alpha instabilities)
- Neutron camera & spectrometer
- γ-ray tomography
- high-resolution sub-divertor residual gas analyser
- **Fast Ion Loss Detector** (alpha losses)

Fast Ion Loss Detector (FILD)



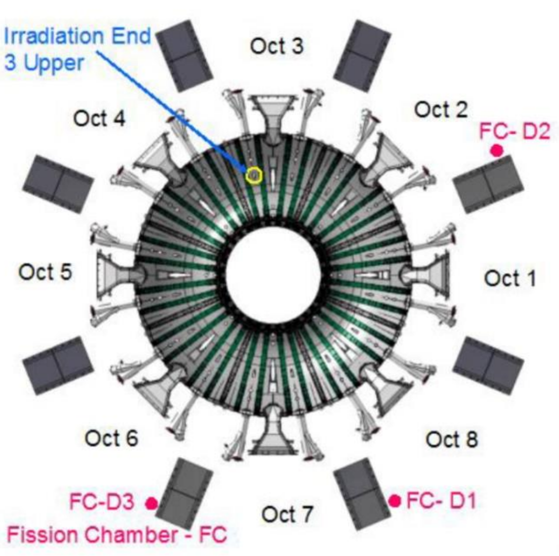
[Kiptily V.G. et al Nucl. Fusion 2009]

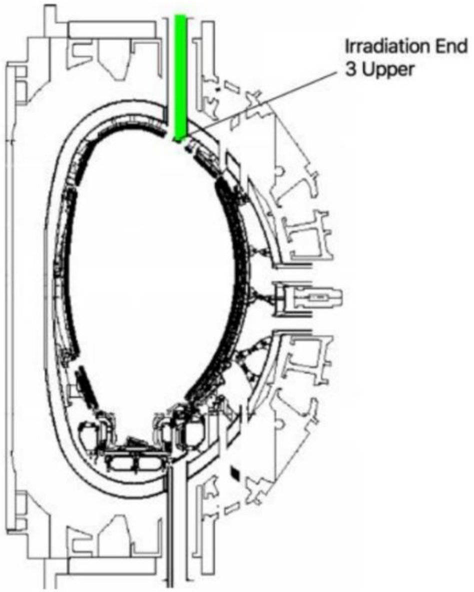
Neutronics

DTE2 has been a **unique** opportunity for neutronics:

- in-situ (in vessel) **calibration** in 2017 with 14MeV neutron generator deployed by remote handling : 76 hours of irradiation in 73 different positions

  ➔ Calibration within ±6%
- installation of samples to study neutron induced activation and damage in ITER materials
- validation of Neutron Streaming modelling
- exposure to ~ 8.5×10^{20} 14MeV neutrons (vs. 3×10^{20} in DTE1)





[P. Batistoni et al. Nuclear Fusion 2018]

Fusion power measurements with gamma rays

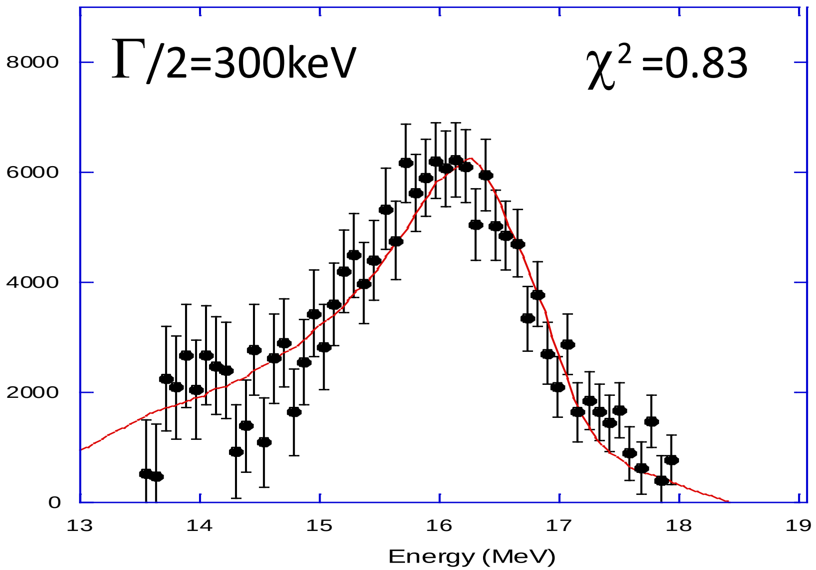
project GETART : assess feasibility of **t(d,γ)^{5}He** γ-ray measurements as a method to determine the fusion power (for possible applications to ITER)

$$D + T \rightarrow {}^5He^* \rightarrow {}^5He + \gamma\ (\sim 16.7\ MeV)$$

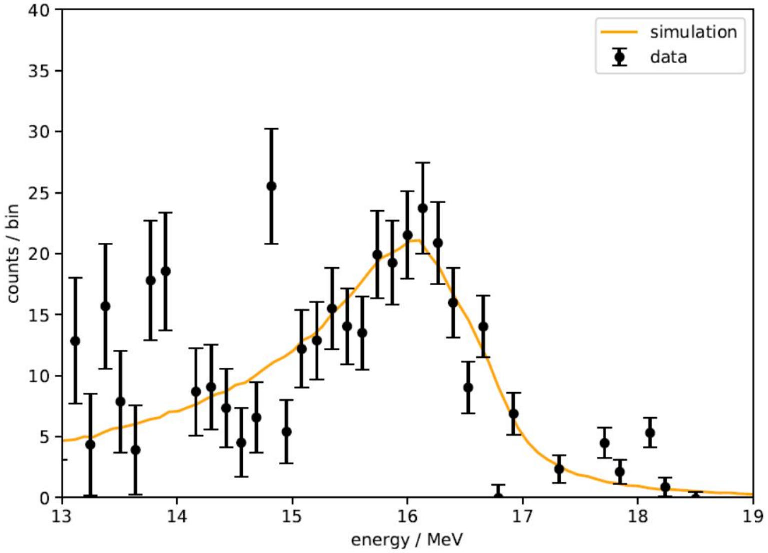
but weak & not well known γ/n branching ratio BR~10^{-5}-10^{-6}

JET γ ray spectrometer successfully provided **first BR measurement in a tokamak**

Courtesy M. Tardocchi and CNR+UNIMIB team



17 MeV γ ray spectrum measured at the FNG14 MeV **neutron source**

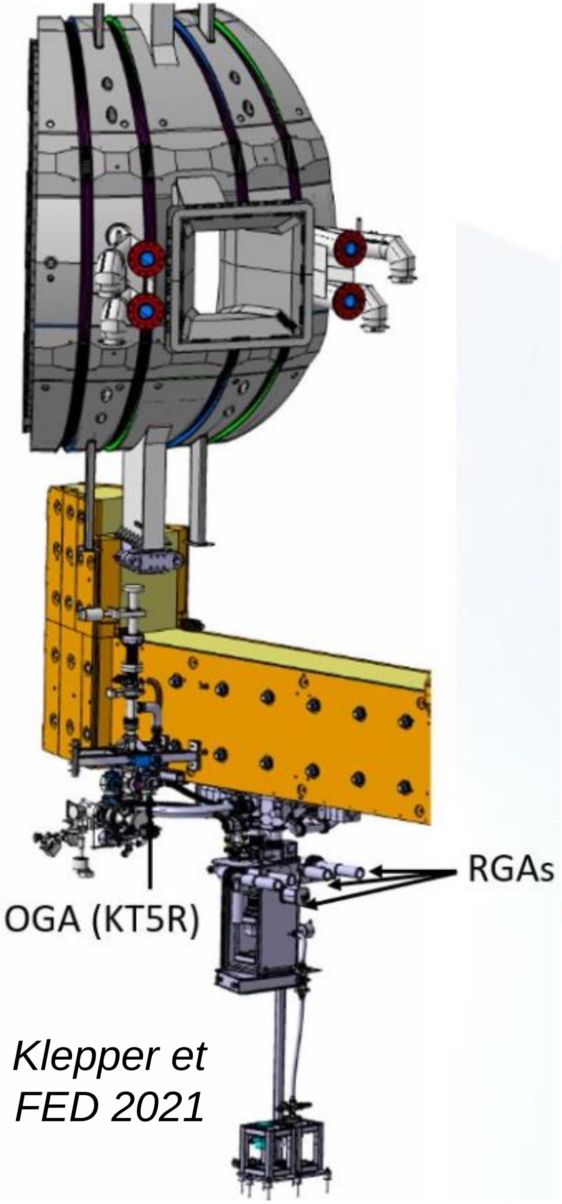


JET DT #99608 : **measured** 17MeV γ ray spectrum

Provisionally : spectral shape in agreement with expected Breit-Wigner

Analysis ongoing

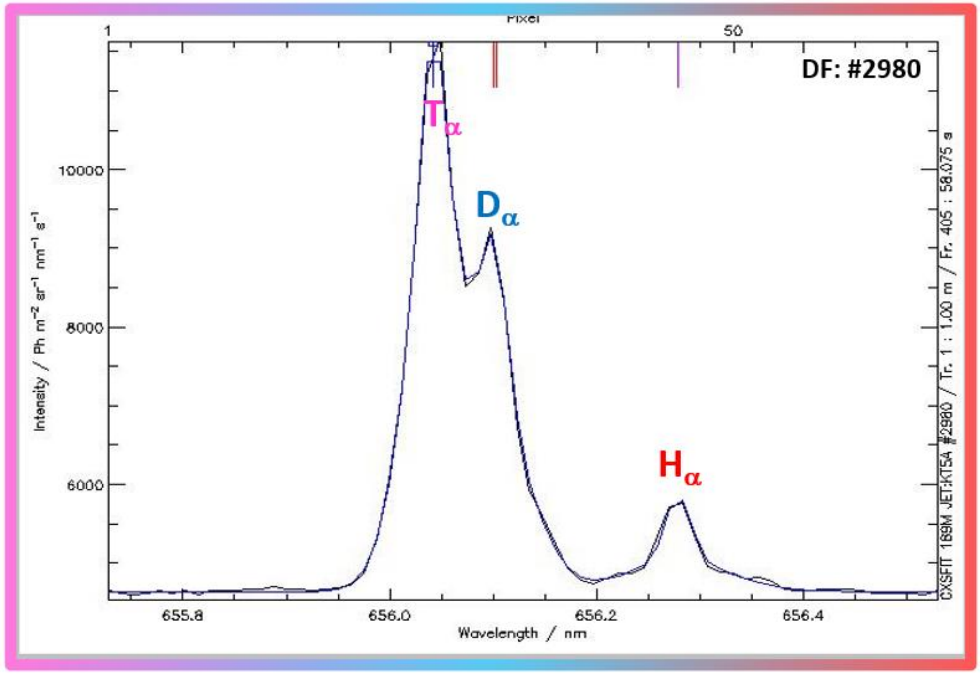
Residual Gas Analysis system

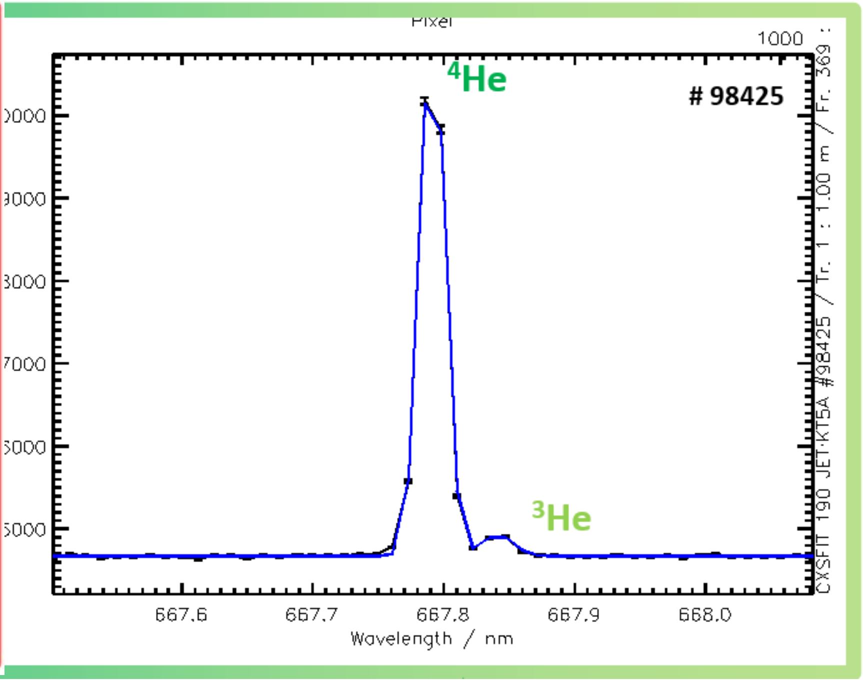


C. Klepper et al., FED 2021

A cluster of instruments: optical spectroscopy + mass spectrometry + absolute pressure gauges with magnetic and neutron shielding

➔ designed and built for the D-T campaign



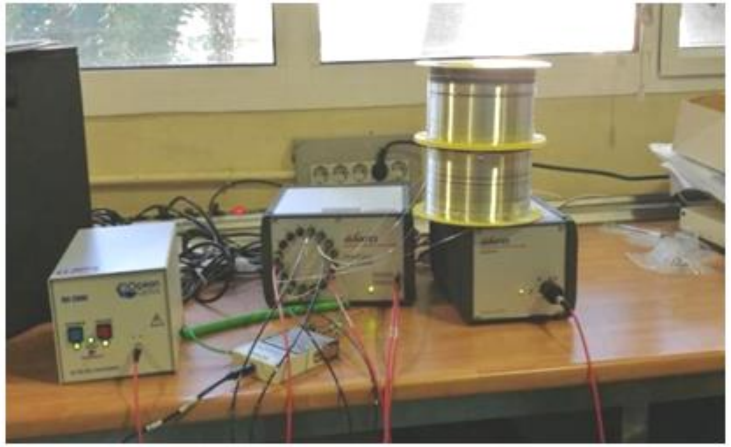


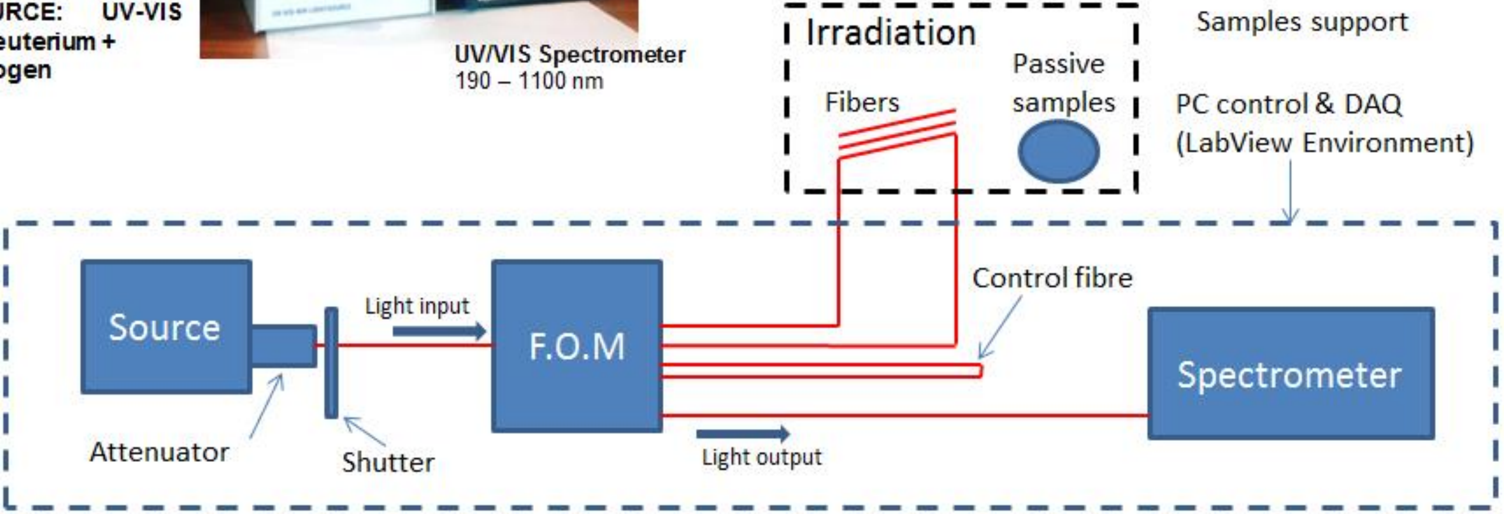
Courtesy I. Jepu

Measurements : pulse based isotopic ratio content (T%; H%, D%) and separation of ^{3}He and ^{4}He in dedicated experiments, while also covering the T/H/D ratios

Radiation Damage in functional Materials (RADA)

Measure transmission of optical fibers to assess Radiation Induced Attenuation (RIA) effects





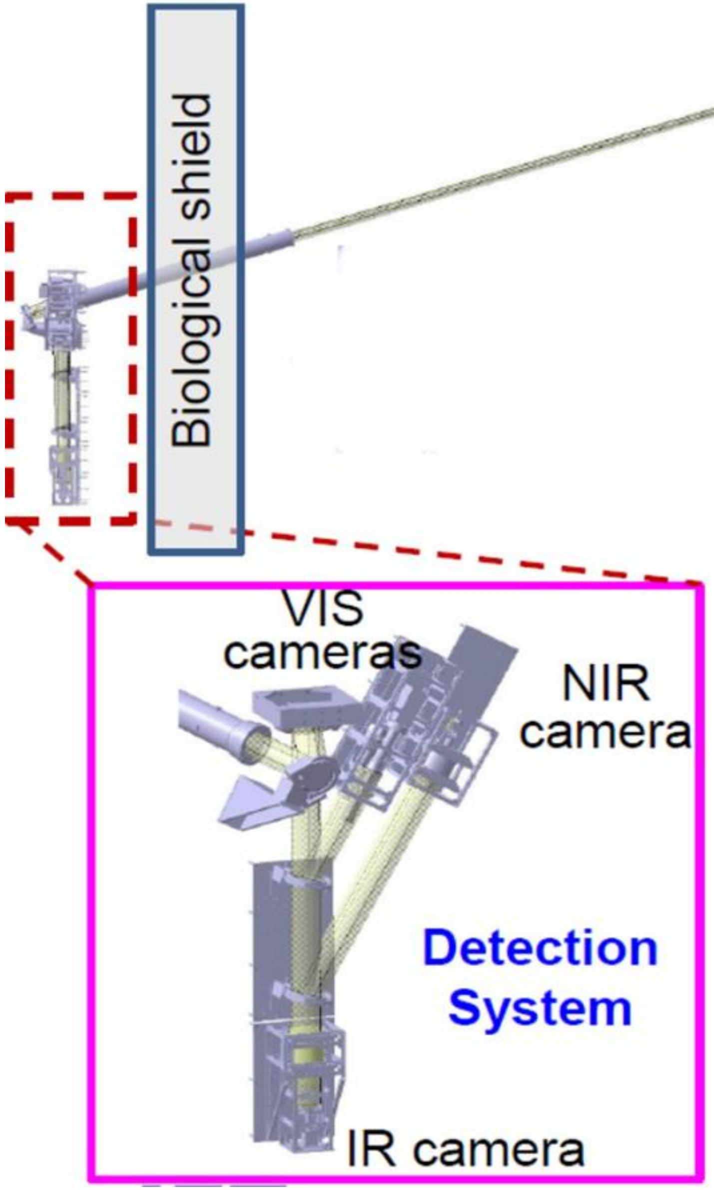
[courtesy R. Vila and E. León - Fusion NL - Ciemat (Spain)]

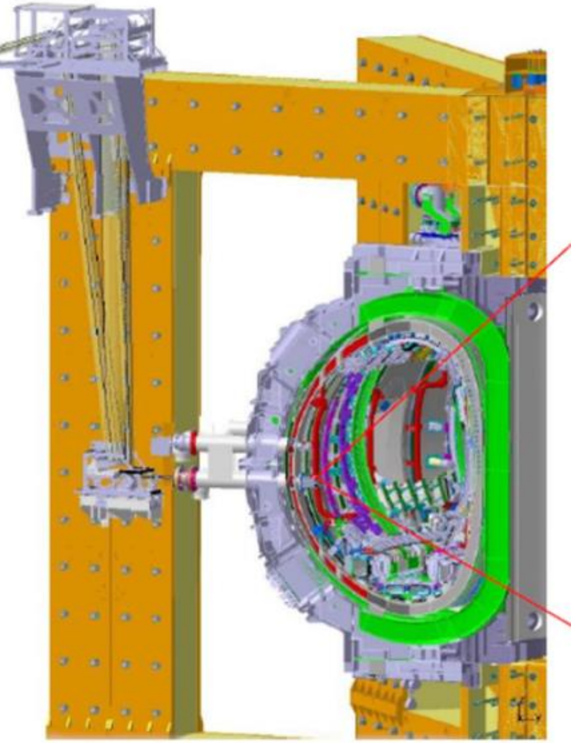
Acquisition between pulses is just as important as during them & low acquisition frequencies are required

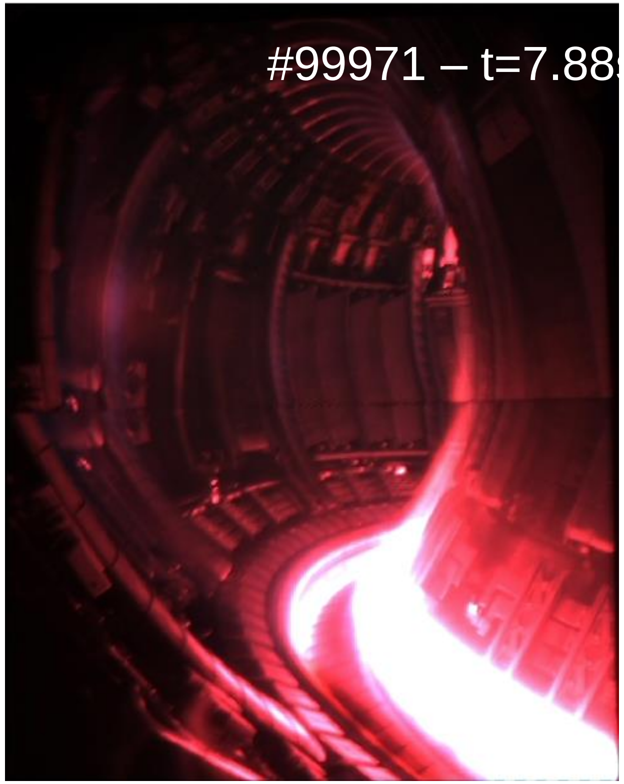
Measurements have been carried out continuously since the start of the D-T campaign and are ongoing

Provisional results : neutron effects on RIA have been observed, although at a very low level

Infrared views for physics & machine protection







Since DT high neutron flow were expected to cause failure of camera electronics in the Torus Hall, an optical relay system was installed to take the image to *protection* and *scientific* cameras outside the tokamak's biological shield

DTE2 physics aims

for the DTE2 experiments, JET had some very specific goals agreed with, and managed by, EUROfusion :

- Demonstrate **high Fusion Power** sustained for 5 s
- Demonstrate integrated radiative scenarios in plasma conditions relevant to ITER
- Demonstrate clear **α-particle effects**
- Clarify **isotope effects** on energy and particle transport and explore consequences of mixed species plasma
- Address key plasma-wall interaction issues
- Demonstrate RF schemes relevant to ITER D-T operation

Only a few selected highlights shown here

parenthesis : thermal confinement and H-mode

to achieve efficient fusion conditions, it’s not enough to throw a massive amount of power into the plasma if the plasma leaks too much heat (*poor insulation*)

confinement time : τ_E = Energy/Power

typically

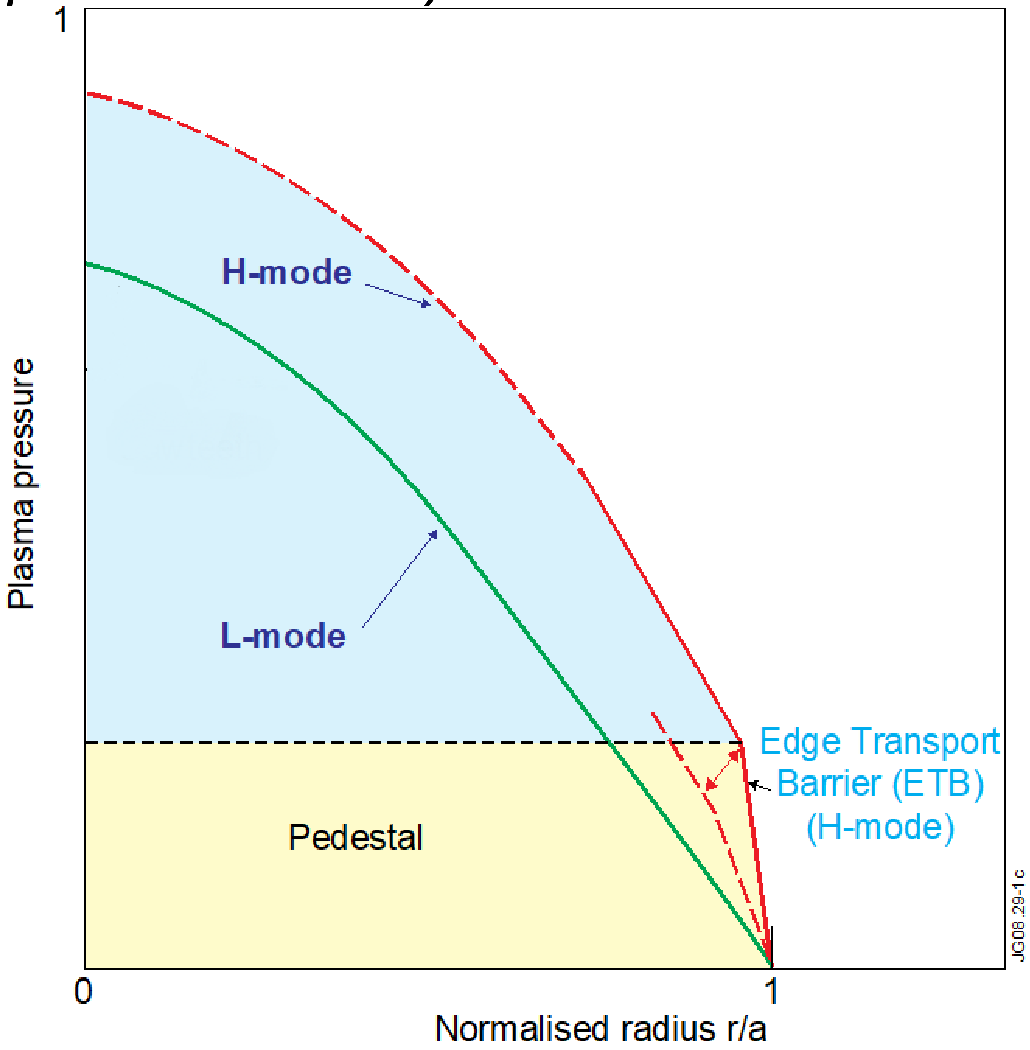
τ_E ↘ when Power ↗

➔ diminishing energy gain for power increase

but in certain conditions (*threshold*) the plasma enters an improved confinement regime:

H-mode

➔ roughly double confinement time & more fusion for same heating power (major gain)



Influence of fuel isotope: L-H threshold

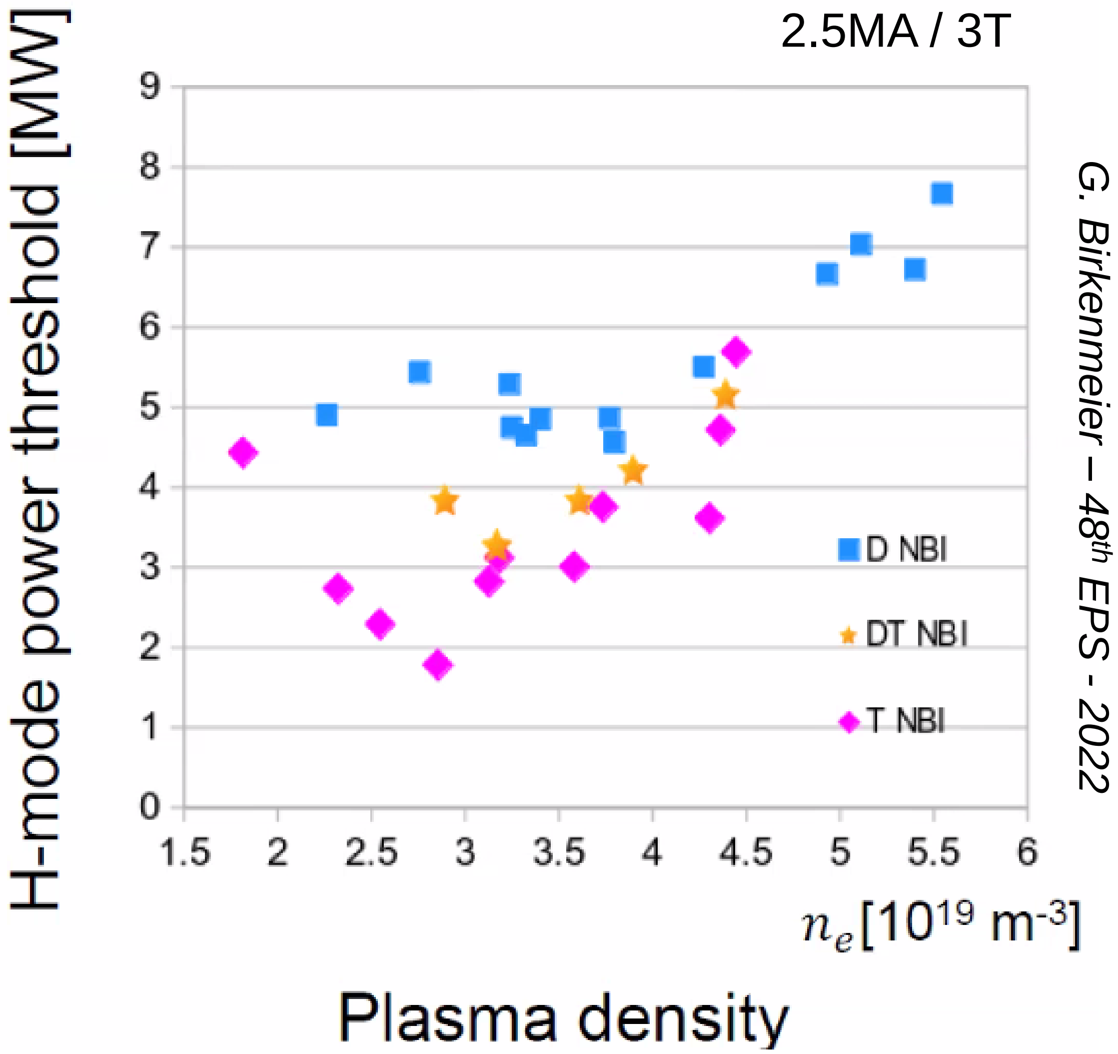
Isotope effects : different mass of plasma fuel has an impact on flow of heat, particles and plasma – wall interaction

➔ importance for predicting behaviour in future fusion power plants

for example : access to high confinement H-mode regime requires heating power above a given minimum value (power threshold) ...

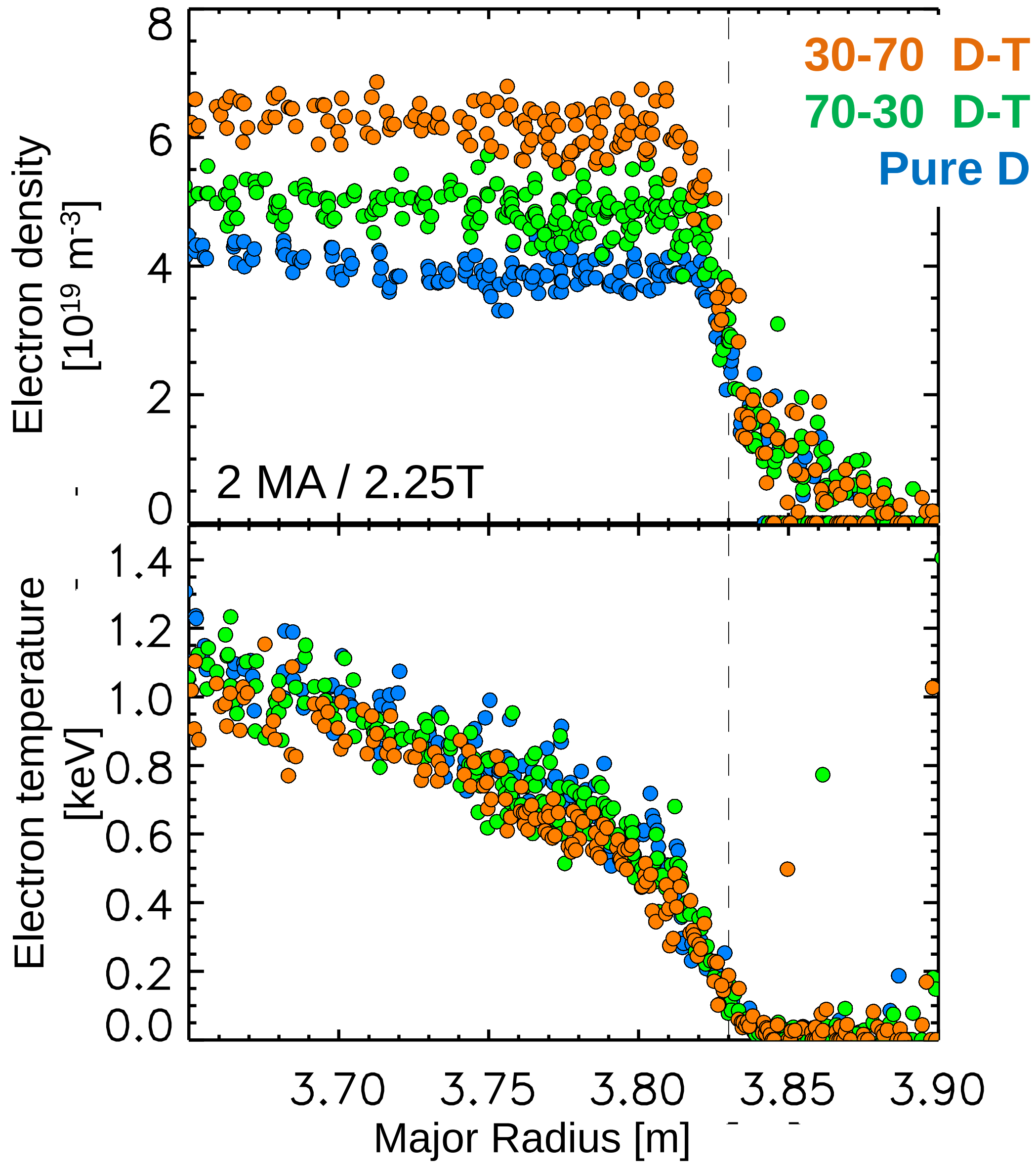
... and H-mode threshold depends on plasma mass and composition

DTE2 results confirm the (complex) inverse mass dependence



G. Birkenmeier – 48th EPS - 2022

Influence of fuel isotope: H-mode edge pedestal



H-mode: pedestal density & pressure increase with isotope mass in H ➔ D ➔ T

Likely driven by changes in the particle transport channel with increasing isotope mass

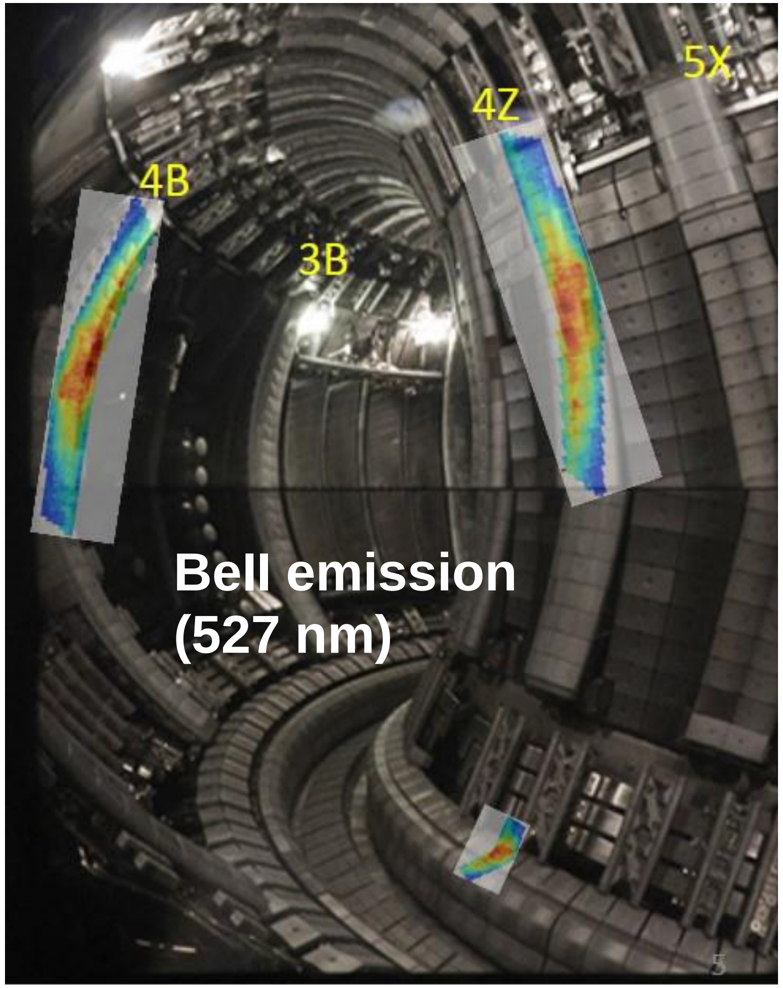
Data confirm 1997 DTE1 observations + fills in key missing pieces of 1997 experiments

Crucial data for improving ITER predictions

Influence of fuel isotope: plasma-wall interaction

Important question for ITER is the erosion of plasma-facing components by tritium

➔ increasing concentration of *impurities,* e.g. tungsten, can *poison* and cool plasma

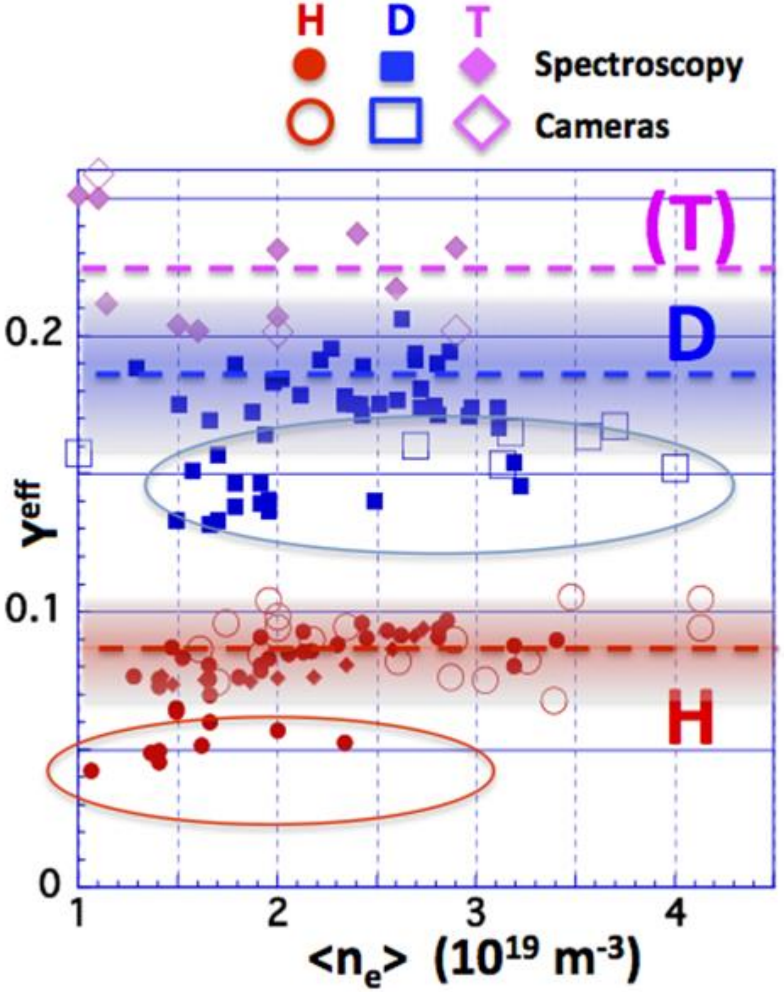


example : studies of Be erosion in D, DT and T

(tritium retention & impact on W sputtering)

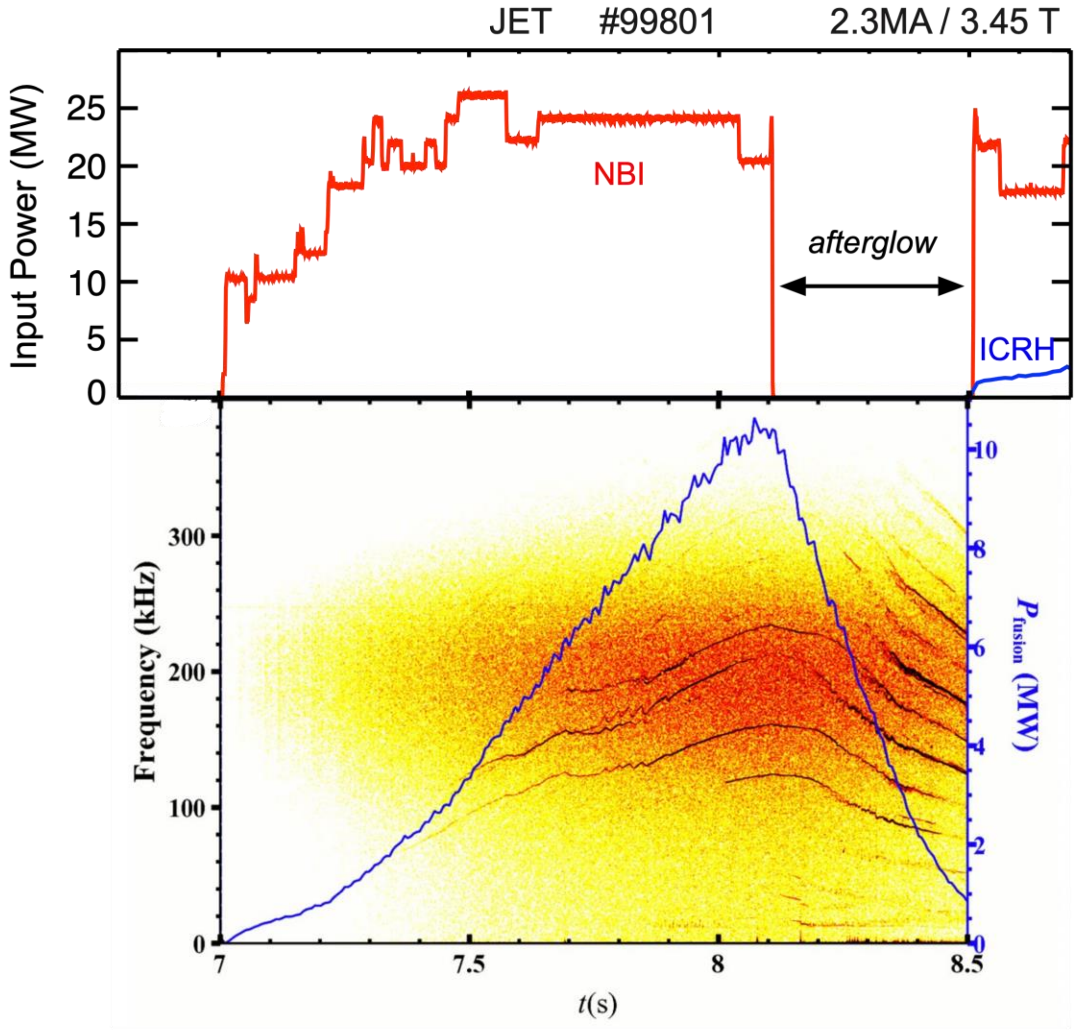
in DTE2 increase in erosion by heavier tritium ions was observed

crucial input for code validation and ITER prediction



[D Borodin et al., PSI 2022]

Observation of instabilities triggered by α-particles



α-particle effects were the weakest point of DTE1 experiments

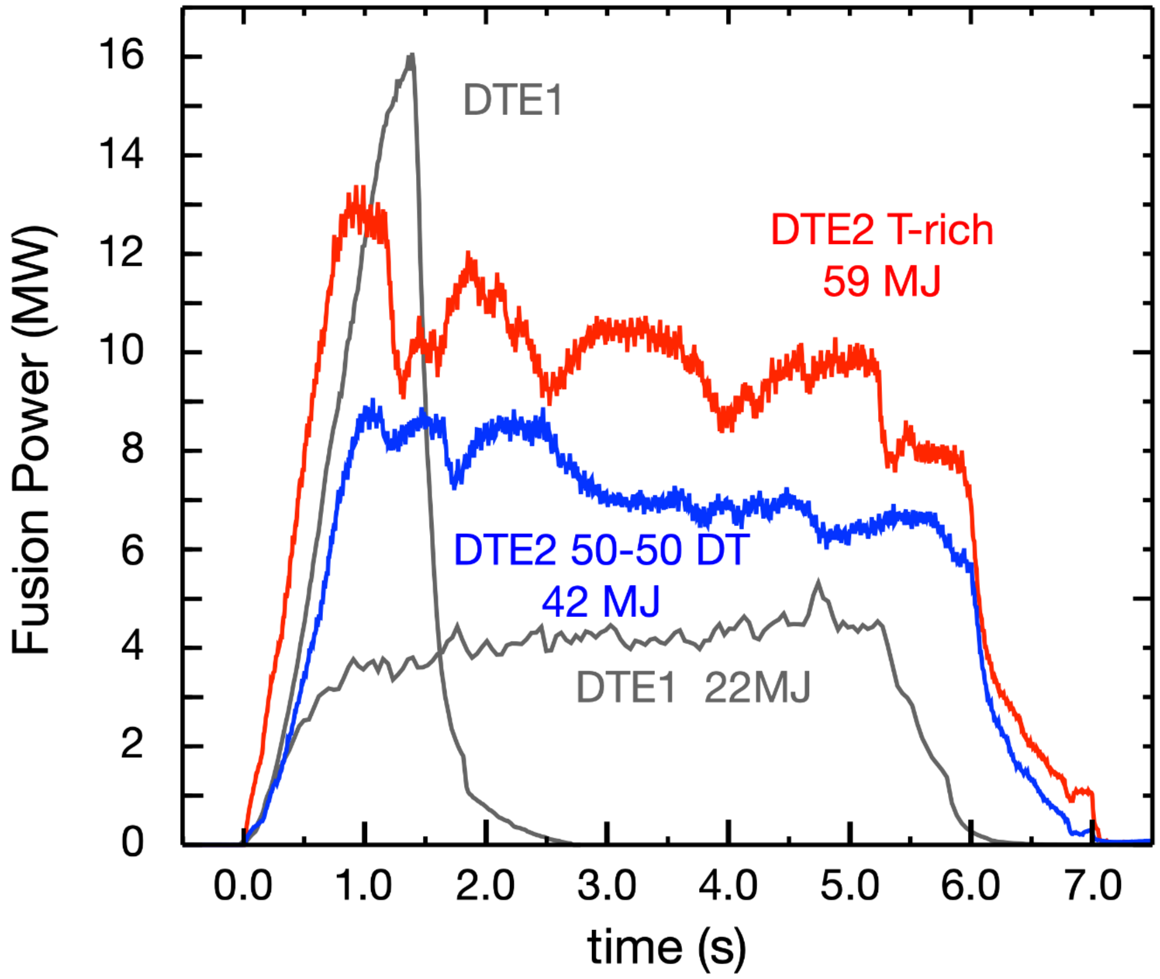
In DTE2, improvements in

- scenario design (*afterglow*) , to minimize effects due to other fast ion populations
- Diagnostics

Clearly observed effects of α's triggering high frequency instabilities in plasma

Only seen in D-T

High sustained Fusion Power



Fusion performance with JET-ILW beyond that of DTE1

By tuning heating and plasma composition, the H-mode scenario produced record *steady* high fusion energy

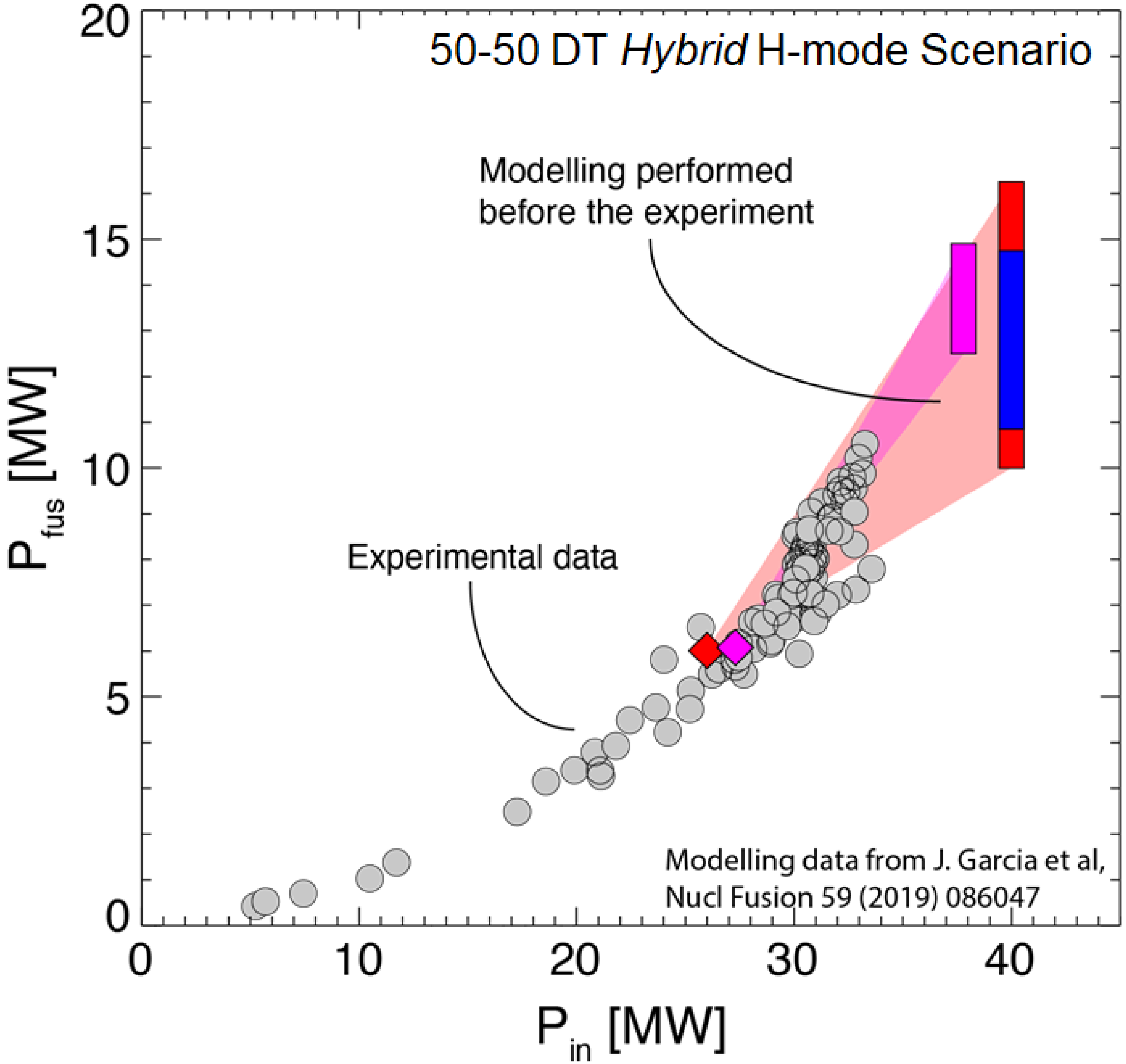
E_{fus}= 59MJ

To note :

duration limited by wall and coils cooling

non-thermal fusion dominant ➔ fusion power follows input power waveform

D-T fusion power confirms modelling predictions



Predict-first approach applied as part of preparing for DTE2

Various codes used, with different isotope and energetic particle effects

D-T fusion power achieved is **in agreement with predictions**, when taking into account power available

in conclusion

The JET 2021/22 D-T experiments have :

- provided unique and novel results on a broad range of physics areas in conditions closest to ITER as we can with any fusion facility in the world
- **confirmed ITER engineering choices** and **fusion power modelling predictions**
- increased confidence for extrapolations to ITER and future reactors

This exceptional source of **physics and engineering** data will be exploited by the fusion community for years to come to support fusion technology, improve theory based models and help accelerate ITER research plan

backup slides

the future of JET

the experiments on JET will continue, in the framework of EUROfusion, until the end of 2023

the main areas of research will privilege direct support to ITER , e.g. :

- helium H-mode studies for the non-active ITER phase
- exploration of H-mode with with a radiative mantle for high performance
- assessment & optimisation of the use of Shattered Pellet Injection to mitigate fast, catastrophic events (disruptions) and avoid damage to the vessel

an additional, short D-T phase is possible if needed by the programme

fusion research in Europe

The European fusion programme is based on the Roadmap to the Realisation of Fusion Energy, with the main aim of

providing fusion electricity to the grid by the middle of the 21st century via a comprehensive integrated science, technology and engineering programme

in the short term:

- preparing for ITER experiments with a step-ladder approach : JET + medium-size tokamaks
- tests on plasma facing components
- co-ordination of modelling activities, developing improved physics models and improving predictive capabilities
- training of ITER experts/operation personnel (e.g. Tritium)

EUROfusion https://www.euro-fusion.org

ITER research plan

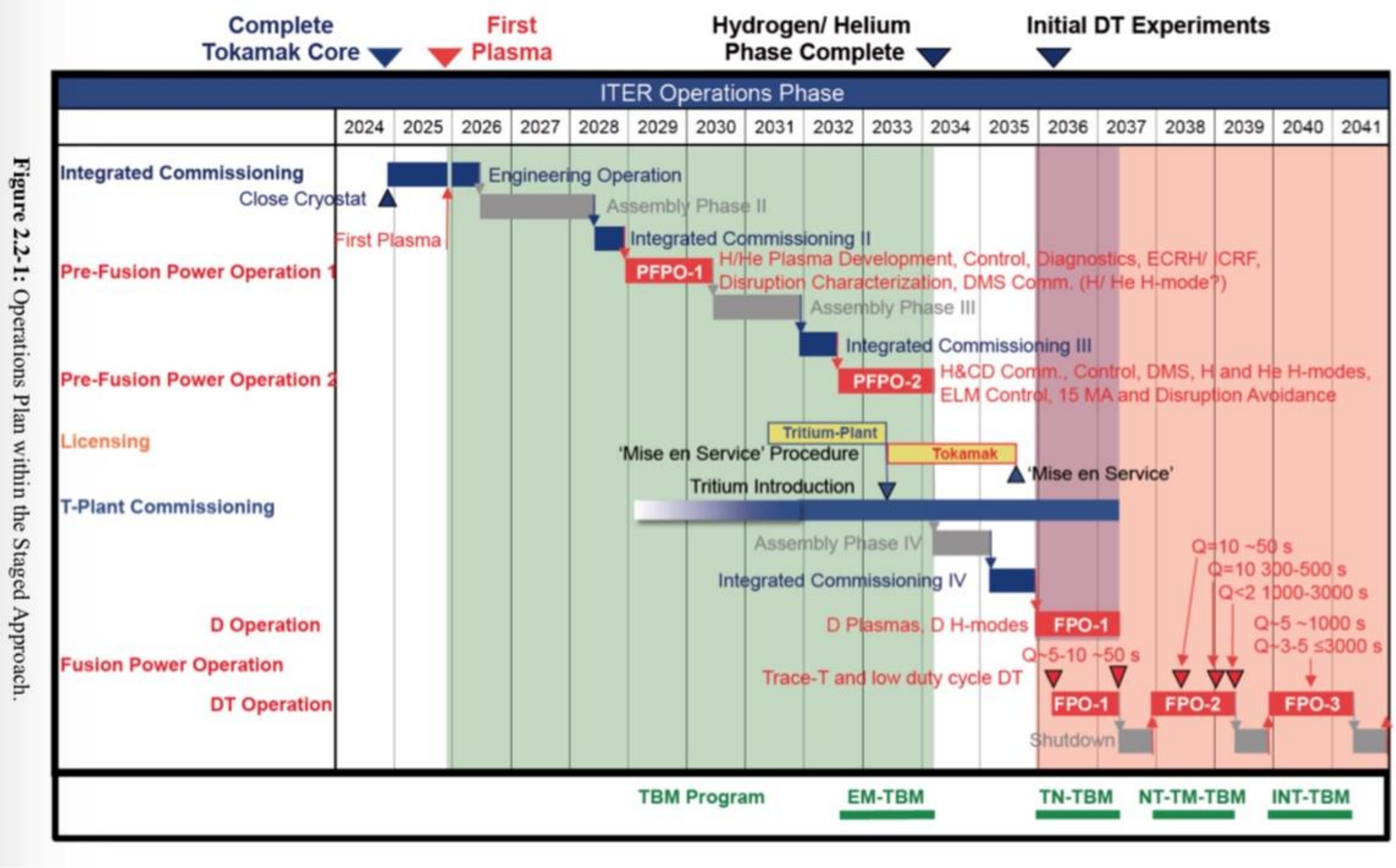


Figure 2.2-1: Operations Plan within the Staged Approach.

ITER Research Plan - Staged Approach
2018 ITER Technical Report
ITR-18-003 ITER Organisation

beyond (and in parallel to) ITER

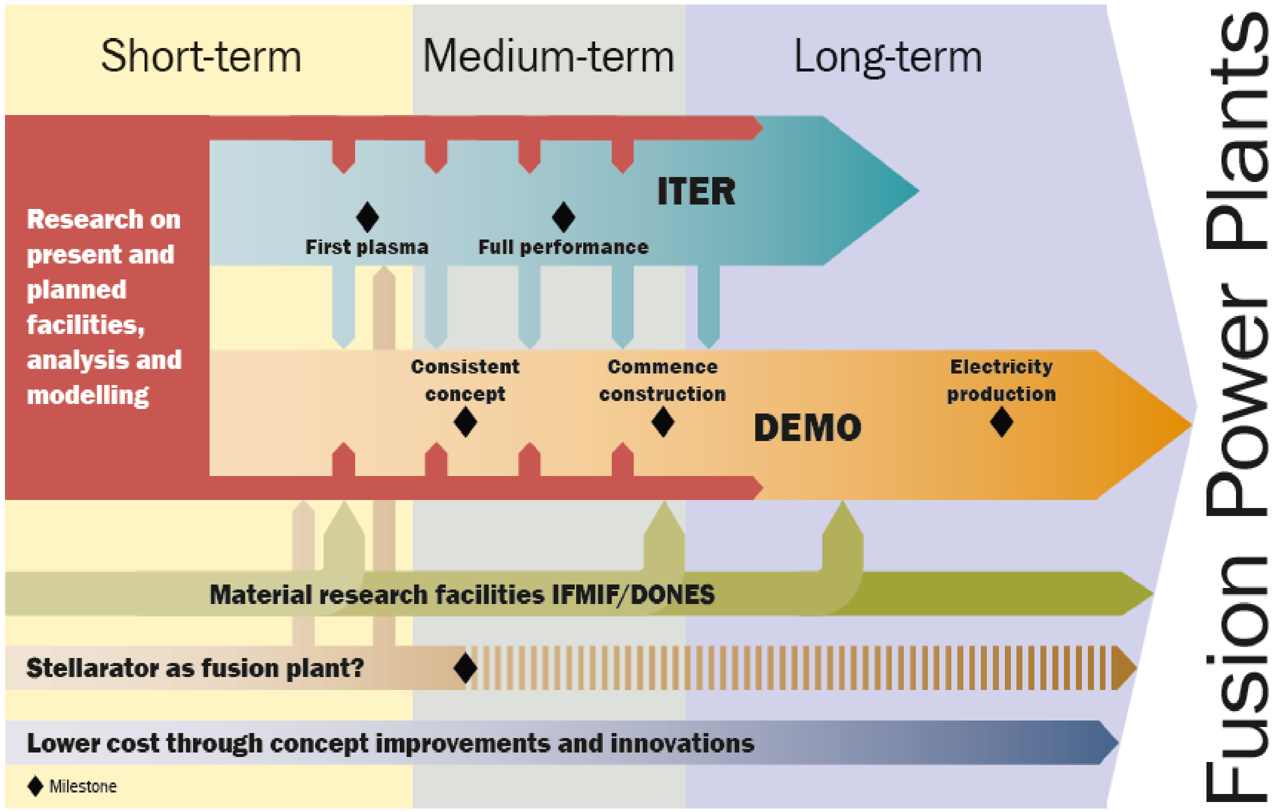
the ITER partners will embark **individually** on the development of **demonstration fusion reactors**, on the timescale of the 2050s

their activities are complemented by a rich programme of :

- material testing facilities (IFMIF)
- divertor testing devices (DTT)
- alternative magnetic confinement schemes (Stellarator, Spherical Tokamaks)

with a significant capital and resources investment by the private sector (SPARC)

EU Roadmap



Machine Activation

Dominant long term activation from bulk materials on JET i.e. Inconel, stainless steel and iron/steel

nickel ➔ Co57, 58, 60, steel ➔ Mn54

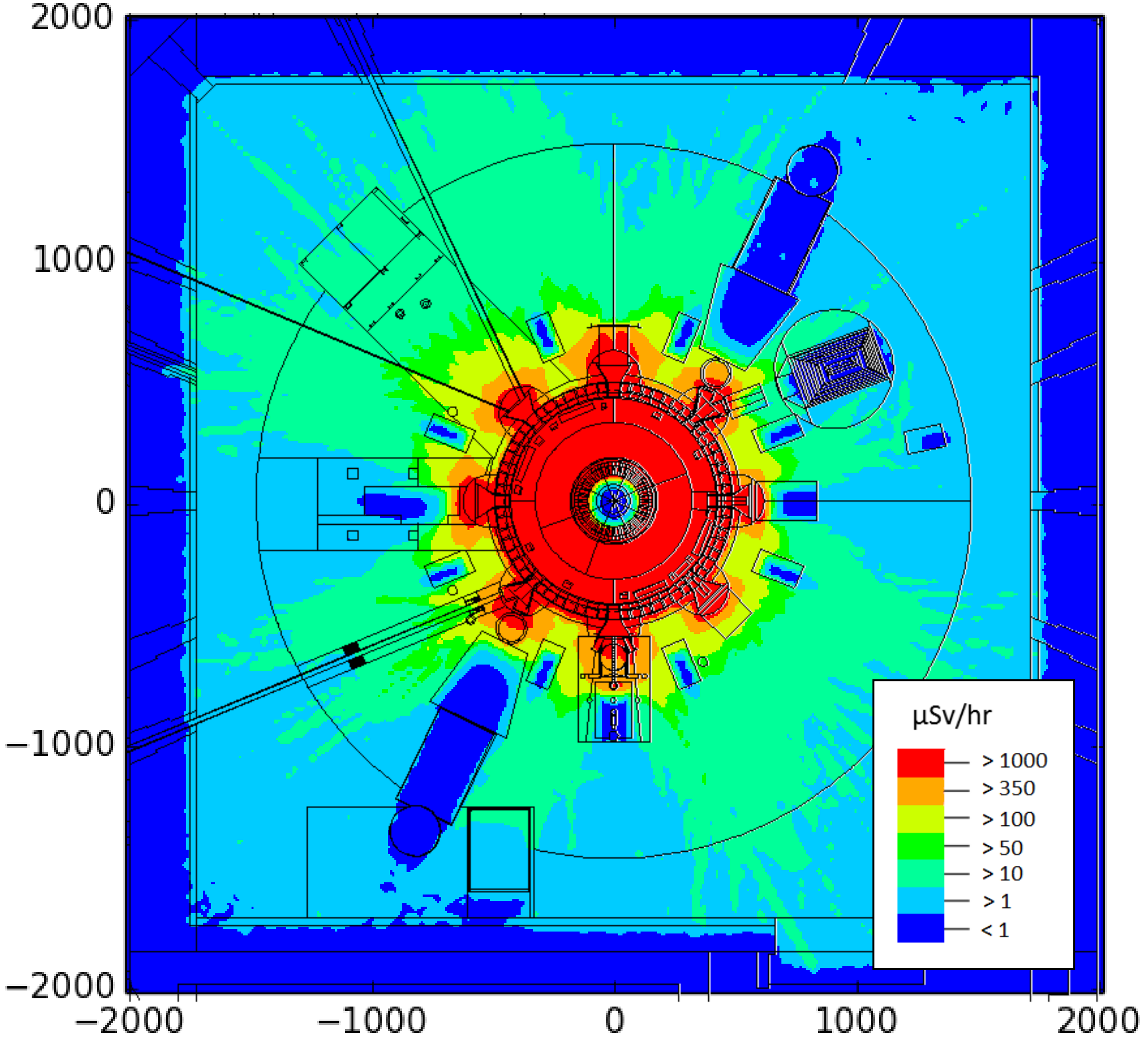
Dominant range : 77days Co58 and 5 years Co60 (most other metals in between)

Actual observed decay is a composite halflife that varies as isotopes decay and give way to longer lived isotopes

Current approx. half life is ~166days

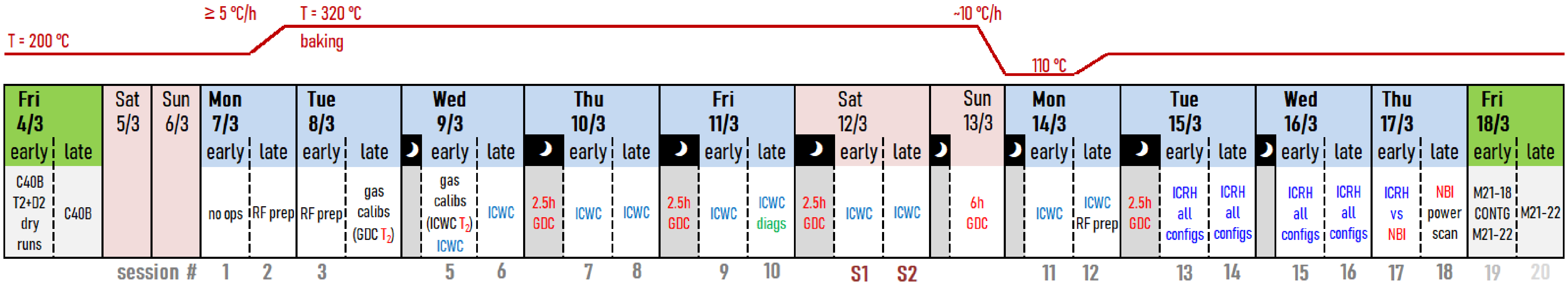
(but in due course will be dominated by the 5yr half life of Co60)

Presently : carrying out regular γ ray measurements and monitoring decay


activation modelled
z=0m T=6 Months after end of DT

DTE2 tritium clean-up

T clean-up : combination of various techniques targeting different wall areas:



Fri 4/3		Sat 5/3	Sun 6/3	Mon 7/3		Tue 8/3		Wed 9/3			Thu 10/3			Fri 11/3		
early	late			early	late	early	late	☽	early	late	☽	early	late	☽	early	late
C40B T2+D2 dry runs	C40B			no ops	RF prep	RF prep	gas calibs (GDC T_2)		gas calibs (ICWC T_2) ICWC	ICWC	2.5h GDC	ICWC	ICWC	2.5h GDC	ICWC	ICWC diags
			session #	1	2	3			5	6		7	8		9	10

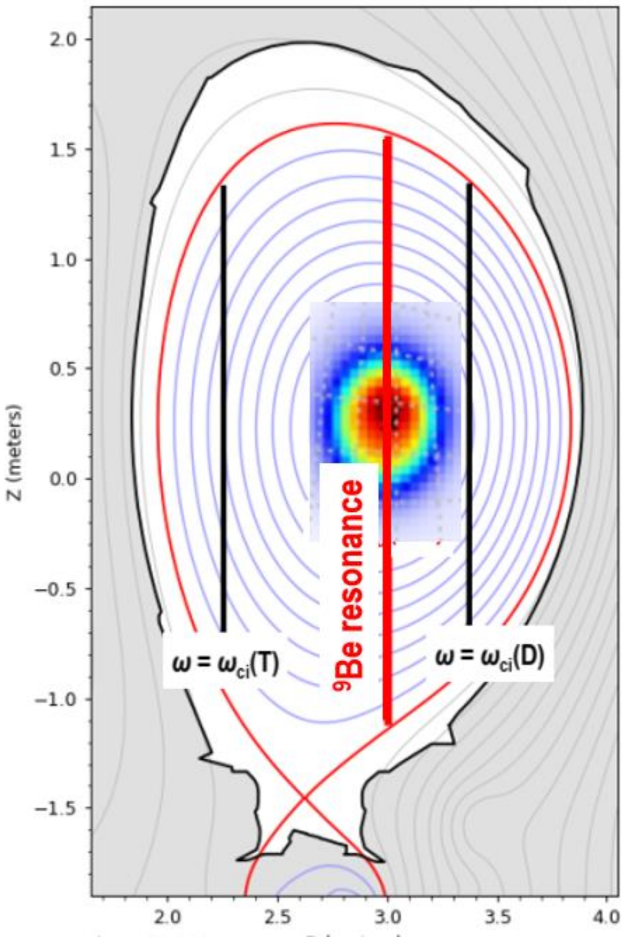
Sat 12/3			Sun 13/3		Mon 14/3			Tue 15/3			Wed 16/3			Thu 17/3		Fri 18/3	
☽	early	late	☽		☽	early	late	☽	early	late	☽	early	late	early	late	early	late
2.5h GDC	ICWC	ICWC		6h GDC		ICWC	ICWC RF prep	2.5h GDC	ICRH all configs	ICRH all configs		ICRH all configs	ICRH all configs	ICRH vs NBI	NBI power scan	M21-18 CONTG M21-22	M21-22
	S1	S2				11	12		13	14		15	16	17	18	19	20

[D Matveev et al., PSI 2022]

- Baking (320 C)
- wall conditioning with low temperature plasmas (ICWC/GDC)
- then hot plasma operation at increasing input power

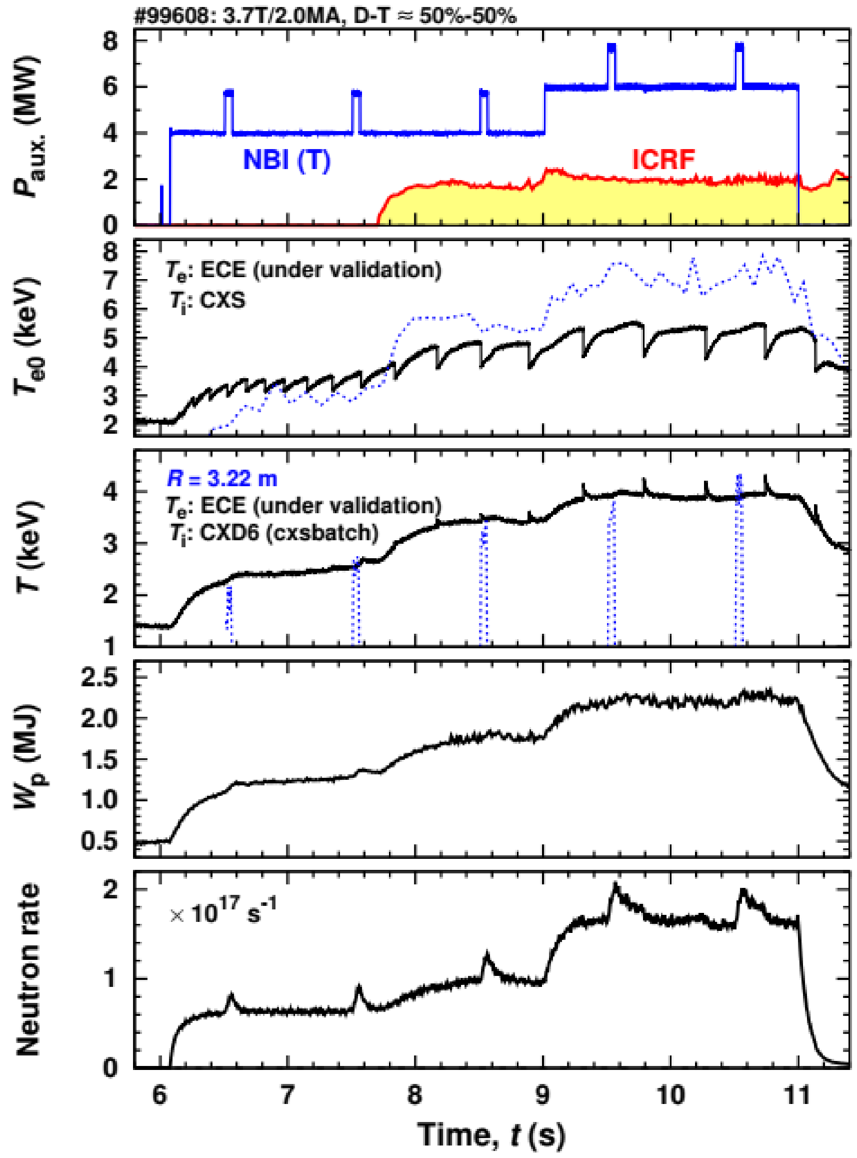
Novel 3-ion RF heating method for ITER demonstrated in D-T

- Relies on presence of 3 ion types in plasma: T - ^{9}Be – D
- Unique chance for JET to **validate** this technique



- **Efficient core heating** demonstrated by D-^{9}Be-T RF scheme considered for ITER:

- Clear increase in T_i with ICRF
- Total energy content increase
- Increased neutron rate
- Generation of α-particles

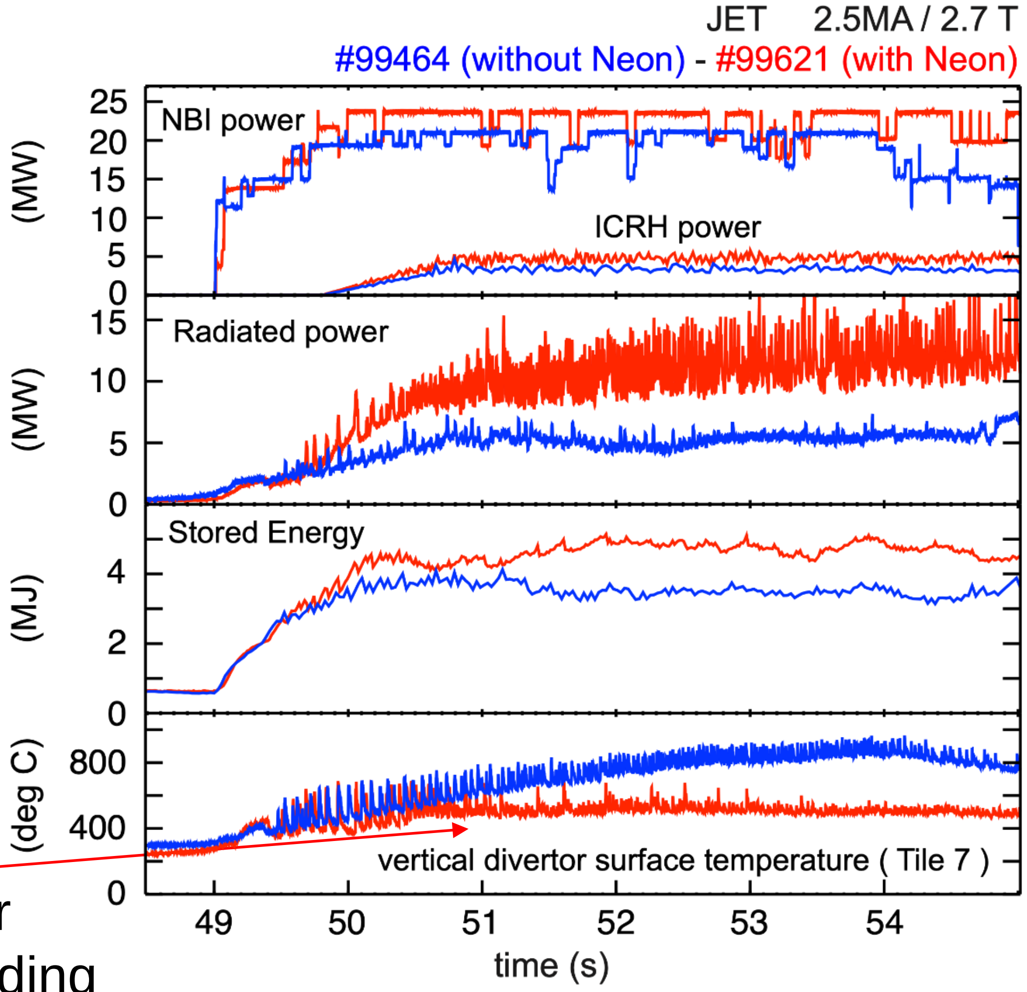


Integrated Ne seeded radiative H-mode achieved in D-T

- Fusion reactors will need to operate with high radiation from an extrinsic seeded impurity to *isolate* the hot plasma core from the wall and divertor

- **Integrated scenario with Ne seeding demonstrated for the first time in D-T with ITER-relevant Be/W wall**
- Well-controlled long pulse
- With high radiated fraction and *detached* divertor plasma
- maintaining good plasma energy confinement

➔ confirms Ne as promising extrinsic radiator for ITER



Strongly reduced divertor temperature with Ne seeding