PART IV

FUSION PERFORMANCE ACHIEVED IN JET DEUTERIUM AND DEUTERIM-TRITIUM PLASMAS

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OUTLINE

- Introduction: what does the difference between D-D and D-T fusion mean?
- Joint European Torus (JET) Reference D pulse before DTE1 campaign (1997)
- High fusion power DT discharges in H-mode and ITB scenarios (1997)
- JET Reference deuterium results before DTE2 campaign (2020)
- DT discharges in baseline H-mode and in hybrid scenarios
- Summary

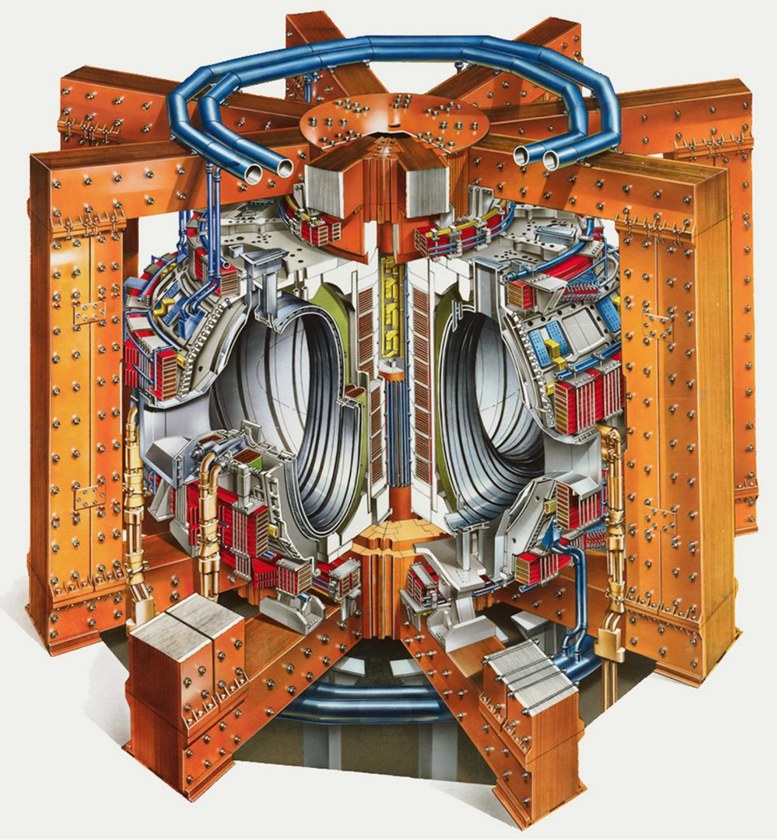
JET RECORDS IN D AND DT PLASMAS

- **JET tokamak was designed and built to "operate in conditions where α-particles are produced and confined" in DT plasmas**

The JET Project, Scientific and Technical Developments in 1976, CEC, Brussels (1977) p.35.

1983 First plasma in JET;
1991 First experiments with tritium (PTE);
1997 High performance deuterium-tritium experiments (DTE1). JET achieves world record fusion power of 16.1 MW;
2009 JET installs a new beryllium/tungsten plasma facing wall to test this configuration for ITER;
2019 – 2020 Preparations for new D-T experiments designed to sustain high fusion performance for longer periods;
2021-2022 High performance D-T experiments (DTE2&DTE3). JET achieves world record fusion energy 59 MJ.

TOKAMAK JET (JOINT EUROPEAN TORUS)



Volume ≈ 100 m^3; B$_{max}$ = 4 T; I$_{max}$ = 7 MA; P$_{FUS}$ ≈ 16 MW

SELF-SUSTAINED MAGNETIC FUSION

- **The "ignition" Wesson triple-product criterion for self-sustaining fusion:**

$$n\ T\ \tau_E > 5 \times 10^{21}\ \mathrm{m}^{-3}\ \mathrm{keV\ s}\ (\approx 10\ \mathrm{atm\ s}) \qquad (*)$$

Parabolic n, T profiles and peak values were used for (*) [1].
For easier understanding what (*) means for *magnetic* fusion machines, we multiply and divide (*) by B^2 and represent the ignition criterion in the form:

$$\beta\ \tau_E\ B^2 > 4\ T^2\ \mathrm{s}, \text{ where } \beta = P_{plasma}/P_{magnetic} = 4\mu_0\,(nT)/B^2$$

[1] J. Wesson, Tokamaks, Oxford Uni. Press, 4th Edition, p.11 (2011).

How did best JET discharges with deuterium-tritium plasmas compare to the triple-product criterion?

Note: Tritium was used on two machines only, TFTR and JET!

Work with Deuterium-Tritium (DT) plasmas on JET

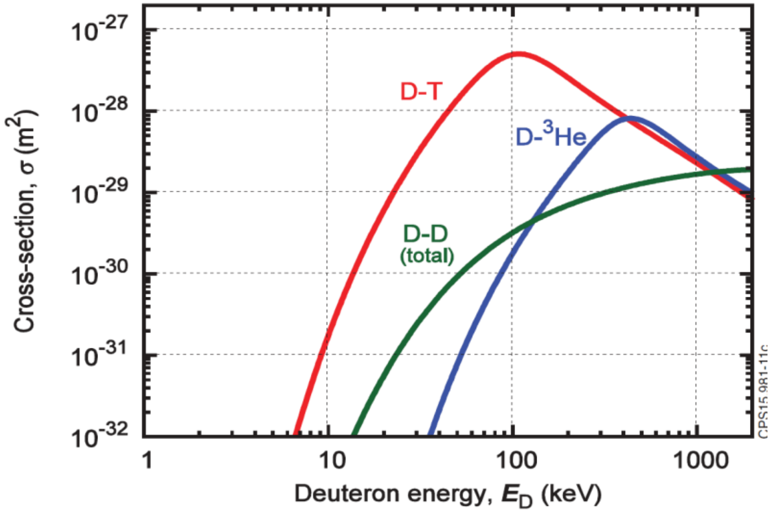


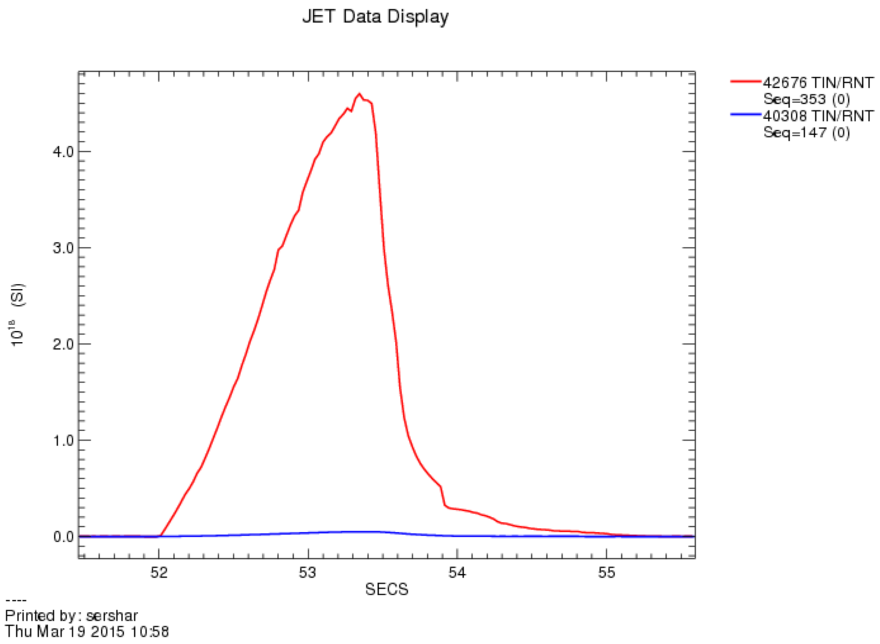
Figure 1. Cross-sections for fusion reactions D–D, D–^{3}He, and D–T as functions of the deuteron projectile energy.

$D + D \rightarrow {}^3He$ (0.82 MeV) + n(2.45 MeV)
$D + D \rightarrow T$ (1.01 MeV) + p(3.02 MeV)

$D + T \rightarrow {}^4He$ (3.52 MeV) + n(14.1 MeV)

Fusion performance (as measured in neutron yield) in D versus DT plasmas on JET

Assume we reproduced a DT discharge with mix D:T=50:50 and plasma/ machine parameters exactly like in a reference D discharge. How the neutron rates compare for the DD reference (blue) and DT (red) pulses?



Comparing DD and DT thermonuclear fusion rates

How to extrapolate DD neutron yield $R_{NT}(DD)$ to DT neutron yield $R_{NT}(DT)$ in discharges with a similar plasma and machine parameters?

For *dominant thermonuclear fusion* yields, the comparison discharges, e.g. #40308 (DD) and #42676 (DT) gave the ratio

$$R_{NT}(DT)/\ R_{NT}(DD) \approx 90.$$

The number ≈100 could be obtained by comparing the D-D and D-T cross-sections and by taking into account:

Single collision in D plasma involves two D ions,

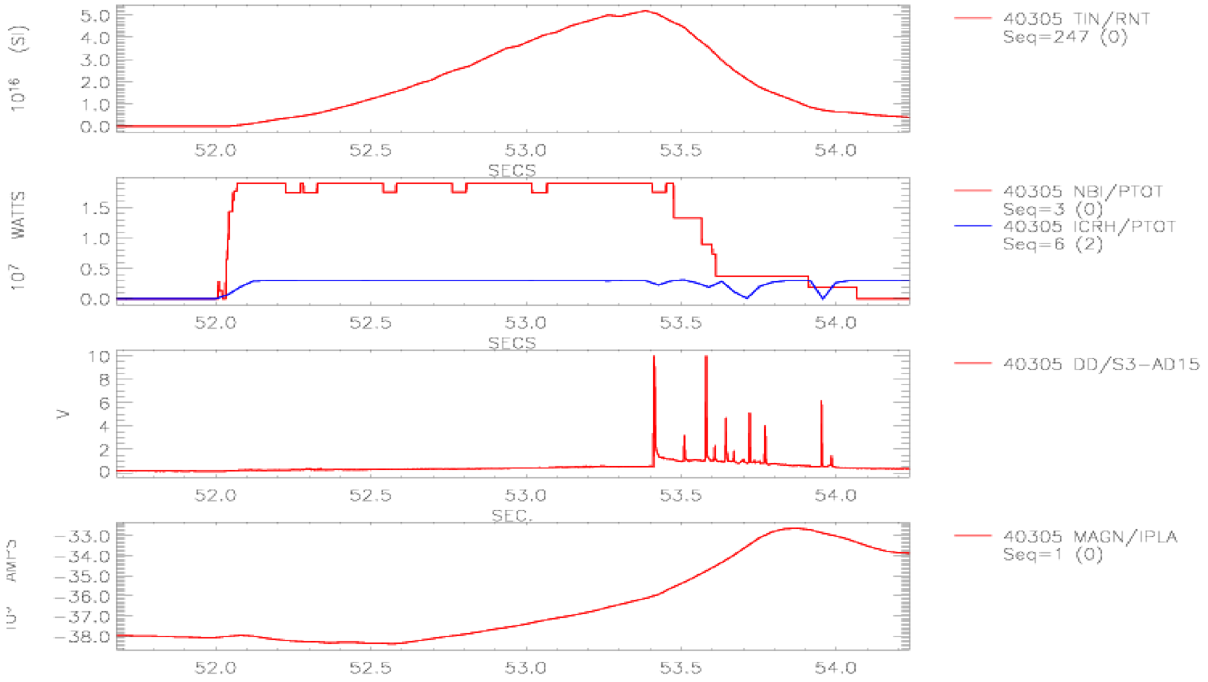
Only 50% of all D-D fusion reactions generate DD neutrons.

High performance JET deuterium-tritium experiments. DTE1 campaign with Carbon wall (1997).

Two main scenarios developed for achieving highest fusion performance:

- **Hot-ion H-mode with Edge Transport Barrier (ETB) near the separatrix;**
- **Advanced Tokamak Scenario with Internal Transport Barrier (ITB).**

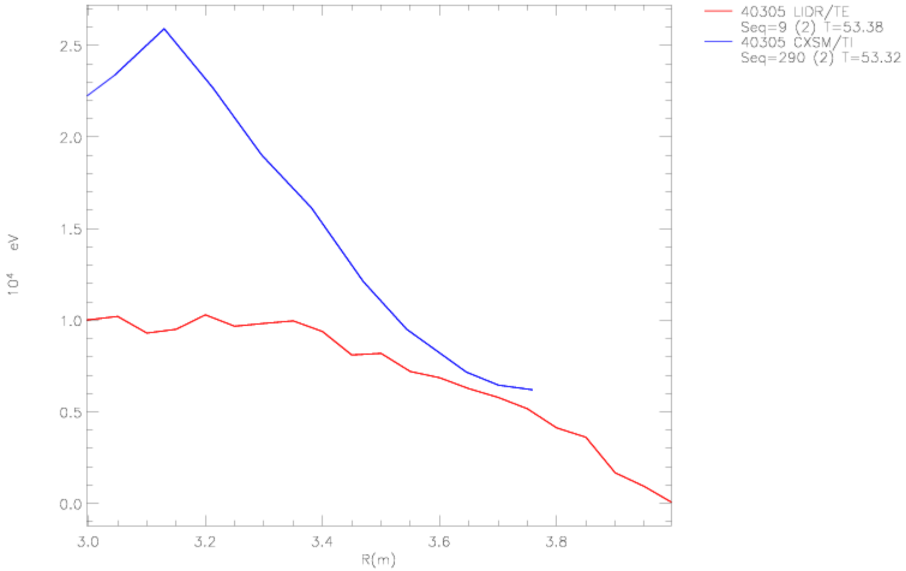
Reference *deuterium* discharge in H-mode before DTE1 (#40305)



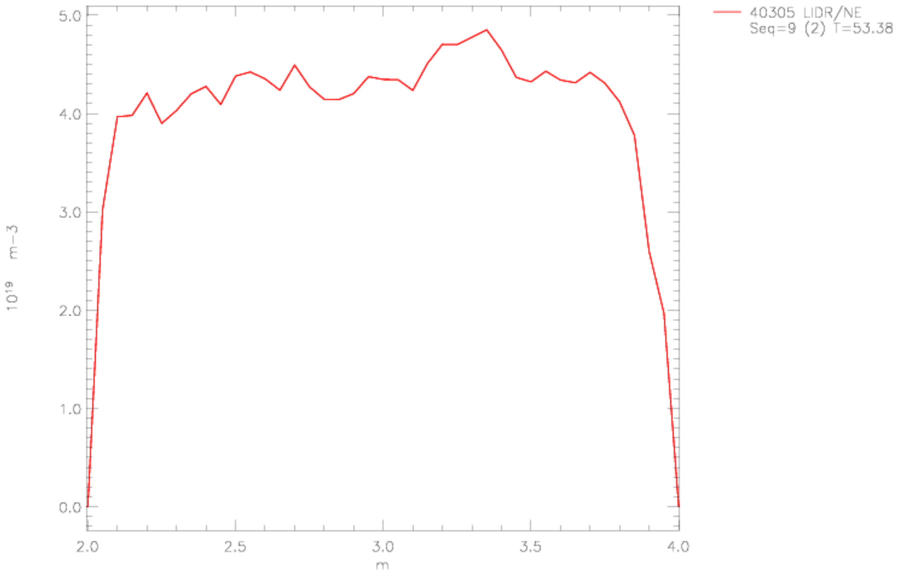
Time traces of DD neutron rate R_{NT}, NBI and ICRH power waveforms, D_α, and current I(t). P_{NBI}=19 MW, P_{ICRH}=3 MW, R_{NT}=5.2x10^{16}, B_T =3.46 T,

I_P =(3.8 →3.3) MA for delaying the first ELM.

Plasma profiles in D reference discharge (hot ion H-mode #40305)

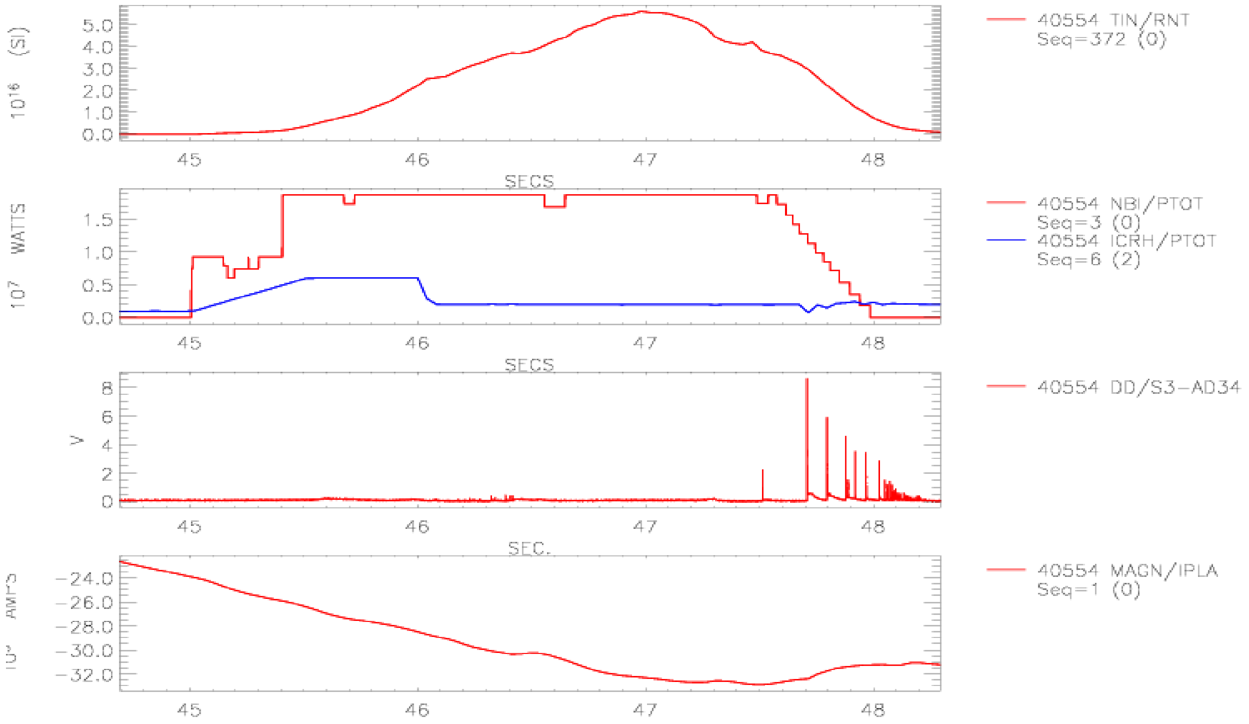


T_i (blue) and T_e(red) profiles at t=53.3 sec.
$T_i(0)$=25 keV > $T_e(0)$=10 keV was obtained



Density $n_e(R)$ in #40554.

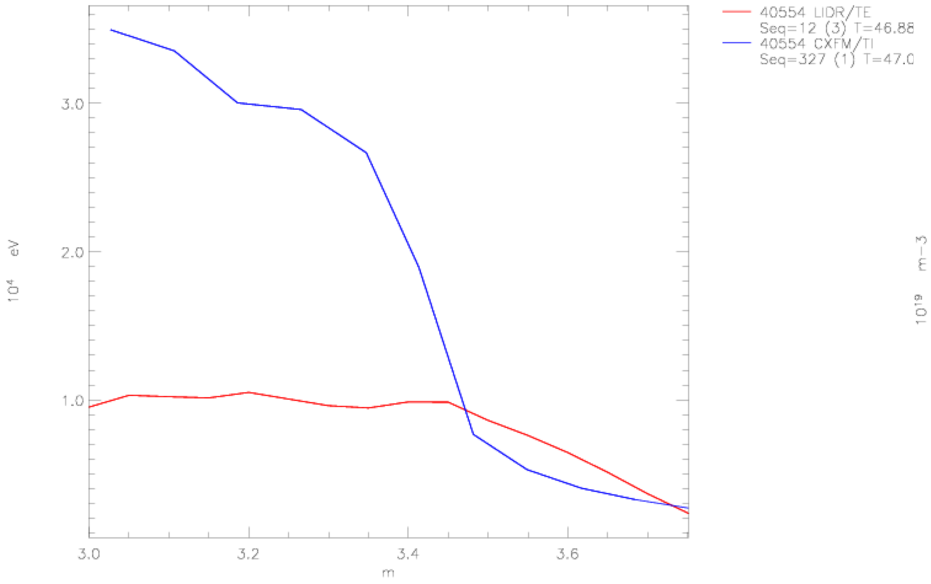
Record DD fusion power discharge with ITB (#40554)



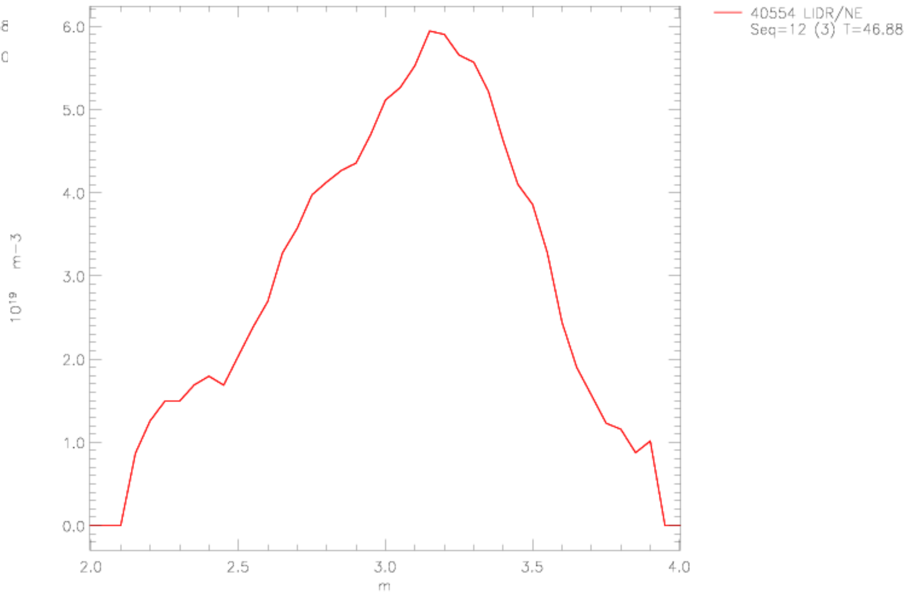
Time traces of R_{NT}, NBI and ICRH power waveforms, D_{α}, and current I(t).

R_{NT}=5.6x10^{16}, P_{NBI}=19 MW, P_{ICRH}=5 MW, B_T =3.46 T, I_P(max) =3.2 MA.

Record DD fusion power discharge with ITB (#40554)

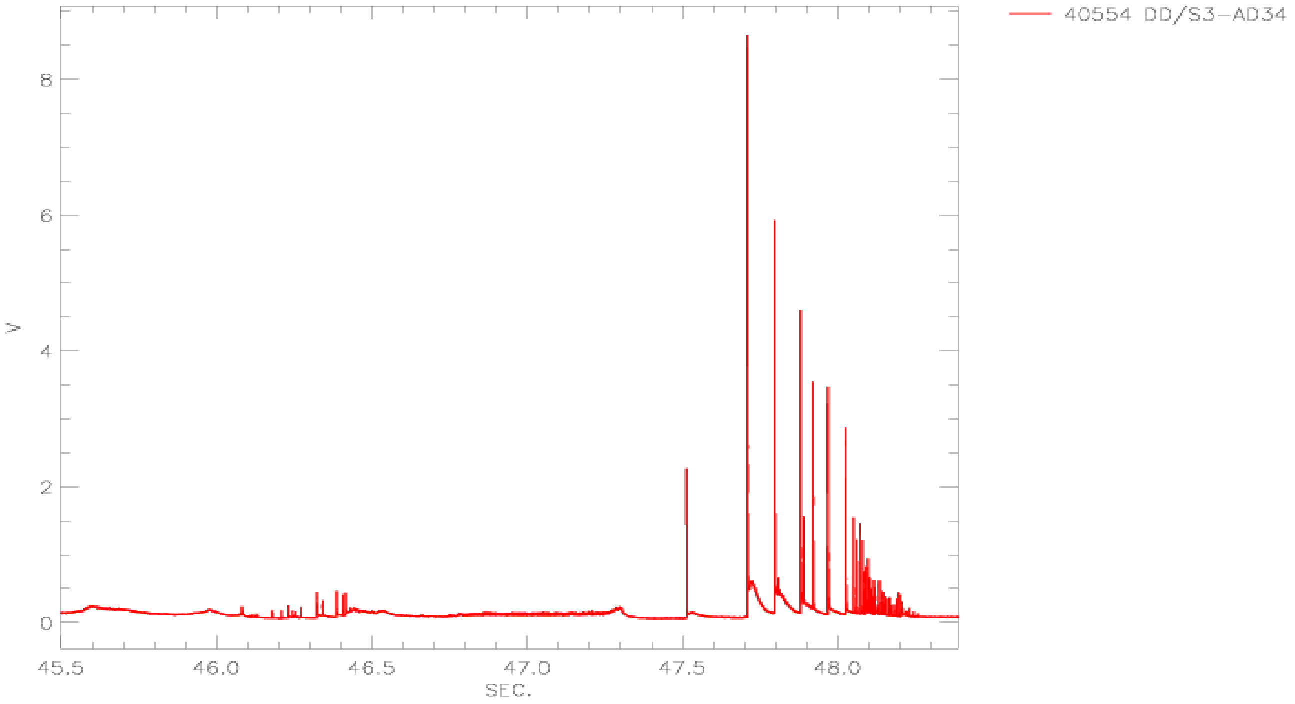


T_i (blue) and T_e(red) profiles at t=47 sec.
$T_i(0)$=35 keV was achieved providing strong increase in DD cross-section



Density $n_e(R)$ in #40554.

The record DD power in ITB pulse #40554 achieved in L-mode!



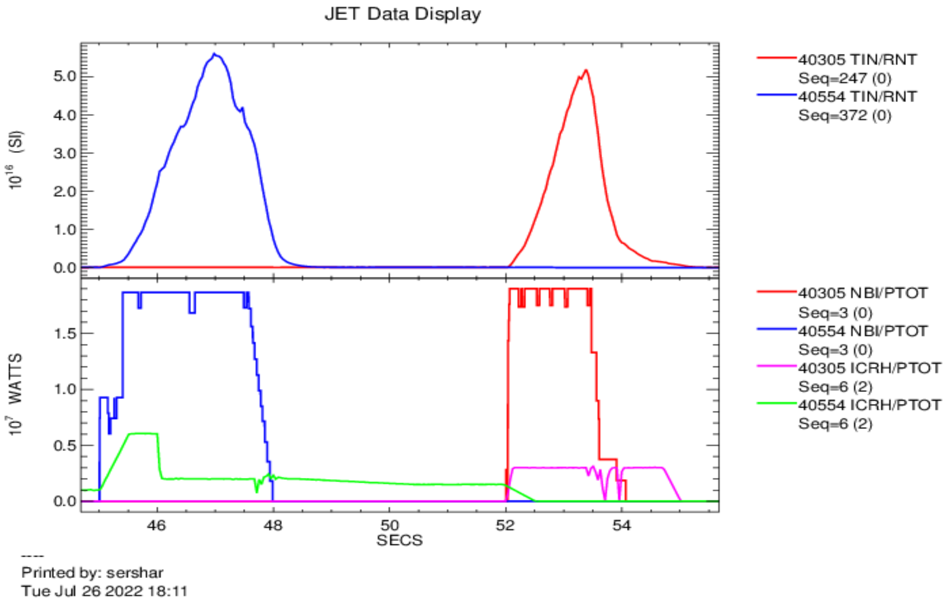
L-mode at t=47 sec when record R_{DD} was achieved!
Power threshold for L-H transition significantly changes during current ramp-up.

Expectations just before DTE1

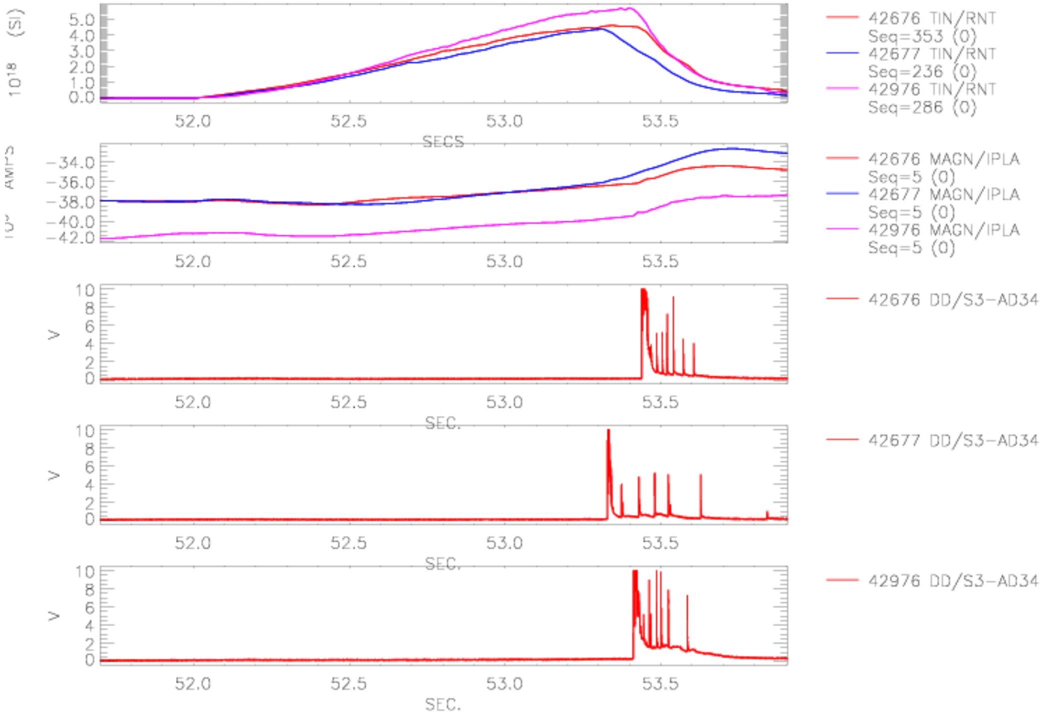
Good solid and reproducible ELM-free hot ion H-mode is the most reliable candidate for obtaining record fusion power

A fair chance exists that ITB scenario may actually perform better than H-mode

Crucial question in both H-mode and ITB scenarios was L-H transition



Three highest fusion power *DT discharges in H-mode*



R_{NT}, I(t), and D_{α} in DT discharges with 3.4 T (#42676 and #42677) and in record 16.1 MW DT discharge with 3.6 T (#42976) [4]

[4] M. Keilhacker et al., Nucl. Fusion 39 (1999) 209

DT fusion power scaling P_{fus} ~B^4 validated in H-mode with ETB

- The fusion power produced by DT plasma scales as

$$P_{fusion} \cong n_i^2 \langle \sigma v \rangle V$$

where n_i is the ion density, V is the plasma volume, and $\langle \sigma v \rangle$ is the fusion rate averaged over the velocity distribution of ions. In the temperature range of 10-20 keV, $\langle \sigma v \rangle$ scales roughly as T_i^2. The product $n_i T_i$ scales as $\beta_i B^2$ so

$$P_{fusion} \propto \beta_i^2 B^4 V$$

The comparison discharges #42676 (Maximum $R_{NT} = 4.6\text{x}10^{18}\ \text{s}^{-1}$, B_{vac} =3.46 T) and #42976 (Maximum $R_{NT} = 5.7\text{x}10^{18}\ \text{s}^{-1}$, B_{vac} =3.66 T) confirm the scaling

$$P_{fus} \sim B^4$$

with accuracy ≈ 4%.

High fusion power DT discharges in H-mode scenario (1997)

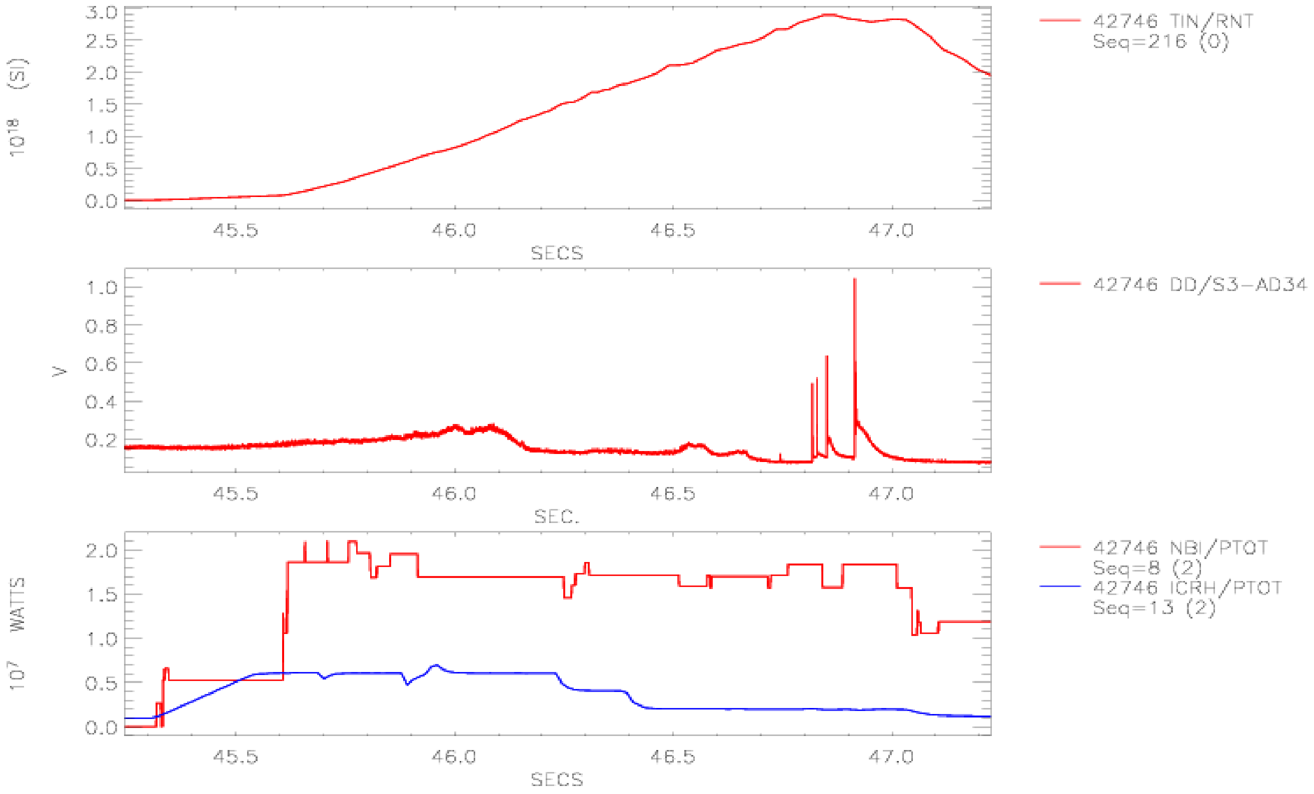
- An excellent P_{fus}~B^4 dependence as expected;
- No isotope scaling on confinement;
- Lower power threshold for L-H transition in DT plasma;

UK Atomic
Energy
Authority

JET Record Fusion Power DT Pulse #42976 (t=13.3 s), Hot Ion H-mode

Quantity	Value	Unit/ Comment
B_T	3.6	T
I_P	4.0	MA
$P_{IN}=P_{NBI}+P_{ICRH}-P_{SH}$	24.1	MW
$n_e(0)$	4.5	10^{19} m^{-3}
$(n_D + n_T)/n_e$	0.8	
$n_T/(n_D+n_T)$	0.6	From NPA
$T_i(0)$	27	keV
$T_e(0)$	14	keV
Z_{eff}	2.1	
W_{dia}	17	MJ
dW_{dia}/dt	5	MW
τ_E	1.0	s
$[n_D(0)+n_T(0)]T_i(0)\ \tau_E$	9.3 ± 10%	10^{20} m^{-3} keV s
$\beta B^2\ \tau_E$	$0.03 \times 3.6^2 \times 1.0=0.39$	T^2 s
Neutron Rate	5.7 ± 10%	10^{18} s^{-1}
Fusion Power	16.1 ± 10%	MW
Fusion Energy	13.8 ± 10%	MJ

High fusion power *DT discharge in ITB scenario (#42746) [5]*



[5] C. Gormezano et al., Phys. Rev. Lett. 80 (1998) 5544.

High fusion power DT discharges in ITB scenario

- No P_{fus}~B^4 dependence. It was more like P_{fus}~B due to the ITB volume dependence (in $P_{fusion} \propto \beta_i^2 B^4 V(P_{in},\ B,...)$);
- The lower threshold for L-H transition was good, but created a problem for ITB scenario. In particular no technique of obtaining long ELM-free period was found;
- Insufficient T-fuelling with high-energy (160 keV) tritium NBI provided D:T = 71:29 only.

JET High Fusion Power DT Pulse #42746 (t=6.82 s), ITB + H-mode Scenario

Quantity	Value	Unit/ Comment
B_T	3.45	T
I_P	3.2	MA
$P_{IN}=P_{NBI}+P_{ICRH}+P_{OH}-P_{SH}-P_{CX}$	16.9	MW
$n_e(0)$	3.8	10^{19} m^{-3}
$(n_D + n_T)/n_e$	0.8	
$n_T(0)/(n_D(0)+n_T(0))$	0.29	From TRANSP
$T_i(0)$	32	keV
$T_e(0)$	13	keV
Z_{eff}		
W_{dia}	11	MJ
dW_{dia}/dt	9	MW
τ_E	0.8	s
$[n_D(0)+n_T(0)]T_i(0)\ \tau_E$	11 ± 15%	10^{20} m^{-3} keV s
$\beta B^2\ \tau_E$	$0.02 \times 3.45^2 \times 0.8=0.19$	T^2 s
Neutron Rate	2.8 ± 10%	10^{18} s^{-1}
Fusion Power	8.0 ± 10%	MW
Fusion Energy		MJ

Extreme ion temperature and pressure gradients achieved in JET High Fusion Power DT Pulse #42940 (t=6.25 s) [5]

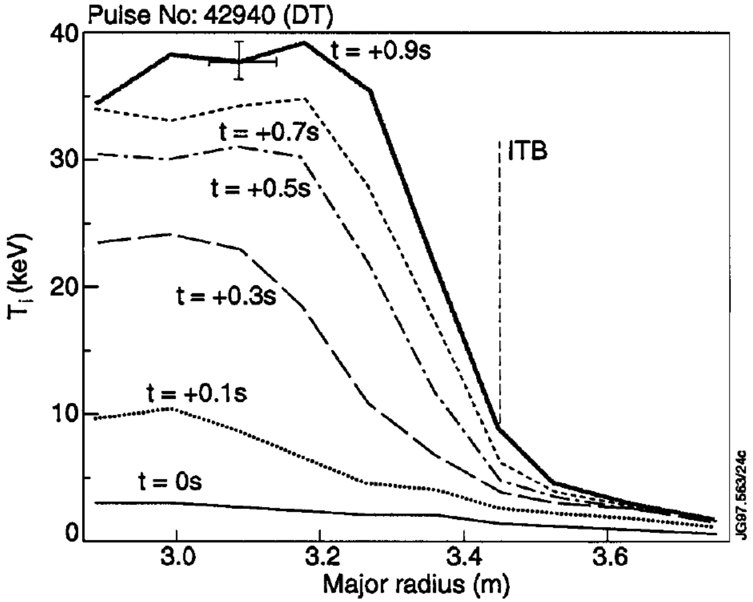


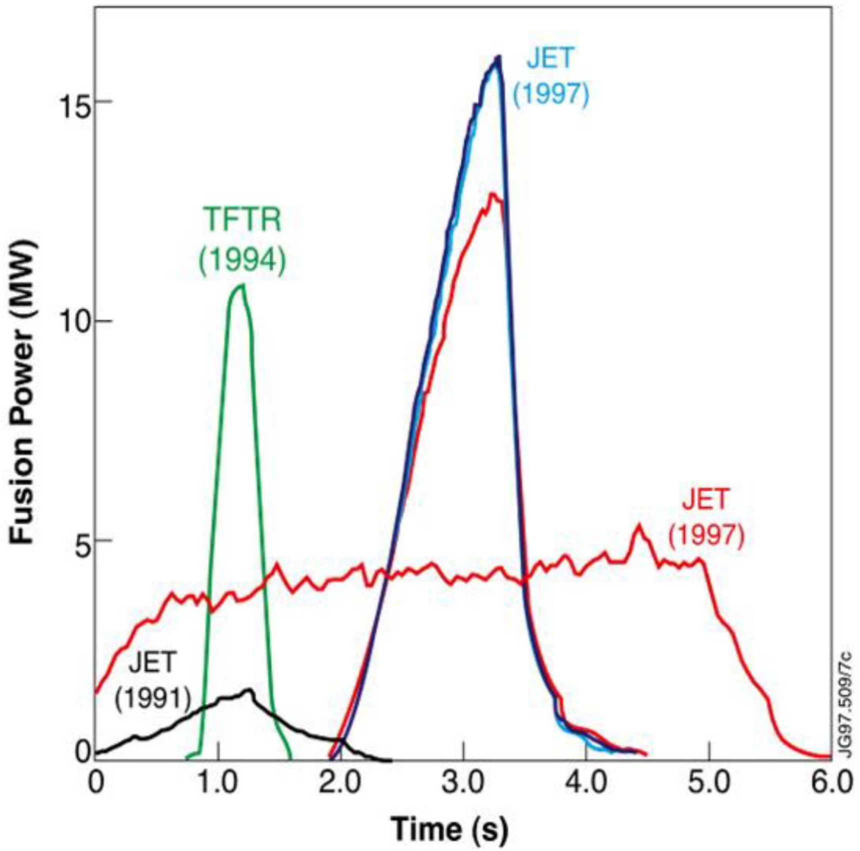
FIG. 4. Radial ion temperature profiles from charge exchange spectroscopy for pulse 42940 ($B_T = 3.8$ T, I_p up to 3.4 MA). An ITB is triggered 0.3 s after the start of the high power phase.

Ion temperature gradient achieved 150 keV/ m while ion pressure gradient achieved 10^6 Pa/ m !

JET High Fusion Power DT Pulse #42940 (t=6.25 s), Internal Transport Barrier (ITB) Scenario

Quantity	Value	Unit/ Comment
B_T	3.8	T
I_P	3.3	MA
$P_{IN}=P_{NBI}+P_{ICRH}+P_{OH}-P_{SH}-P_{CX}$	19.9	MW
$n_e(0)$	4.4	10^{19} m^{-3}
$(n_D + n_T)/n_e$	0.8	
$n_T(0)/(n_D(0)+n_T(0))$	0.34	From TRANSP
$T_i(0)$	38	keV
$T_e(0)$	12.6	keV
Z_{eff}		
W_{dia}	10	MJ
dW_{dia}/dt	8.4	MW
τ_E	0.8	s
$[n_D(0)+n_T(0)]T_i(0)\ \tau_E$	10 ± 15%	10^{20} m^{-3} keV s
$\beta B^2\ \tau_E$	$0.01x3.8^2x0.8=0.12$	T^2 s
Neutron Rate	2.6 ± 10%	10^{18} s^{-1}
Fusion Power	7.3 ± 10%	MW
Fusion Energy		MJ

D-T in Magnetic Confinement Fusion before 2021



DT experiments were carried out in

1991 (PTE - JET)

1994-96 (TFTR – Princeton USA)

1997 (DTE1 on JET)

demonstrating v. clearly:

- D-T Fusion production (14MeV neutrons)
- plasma physics effects linked to use of D-T mixture (*isotope* effects)

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

F.Rimini, TOFE, 13/06/2022.

ENERGETIC IONS IN JET VERSUS ALPHAS IN ITER

Machine	JET	JET	JET	JET	ITER
Type of fast ions	Hydrogen	He^3	He^4	Alpha	Alpha
Source	ICRH tail	ICRH tail	ICRH tail	Fusion	Fusion
Mechanism	minority	minority	3rd harm. NBI	DT nuclear	DT nuclear
$V_f(0)/V_A(0)$	≈2	≈1.5	≈1.3	1.6	1.9
τ_S (s)	1.0	0.9	0.4	1.0	0.8
P_f (0) (MW/m^3)	0.8	1.0	0.5	0.12	0.55
n_f (0) / n_e (0) (%)	1.0	1.5	1.5	0.44	0.85
β_f (0) (%)	2	2	3	0.7	1.2
$\langle\beta_f\rangle$ (%)	0.25	0.3	0.3	0.12	0.3
max$\mid R\beta'_f \mid$ (%)	≈5	≈5	5	3.5	3.8

Ratio of on-axis velocities $V_f(0)/V_A(0)$, slowing down time, τ_S , heating power per volume, P_f (0), ratio of the fast ion density to electron density, n_f (0) / n_e (0), on-axis fast ion beta, β_f (0), volume-averaged fast ion beta, $\langle\beta_f\rangle$, and normalised radial gradient of fast ion beta, max$|R\beta'_f|$, in JET vs. ITER projected parameters.

S.E. Sharapov et al., FUSION SCIENCE AND TECHNOLOGY 53 (2008) 989

JET deuterium-tritium experiments during DTE2 campaign with ITER-like wall (2021).

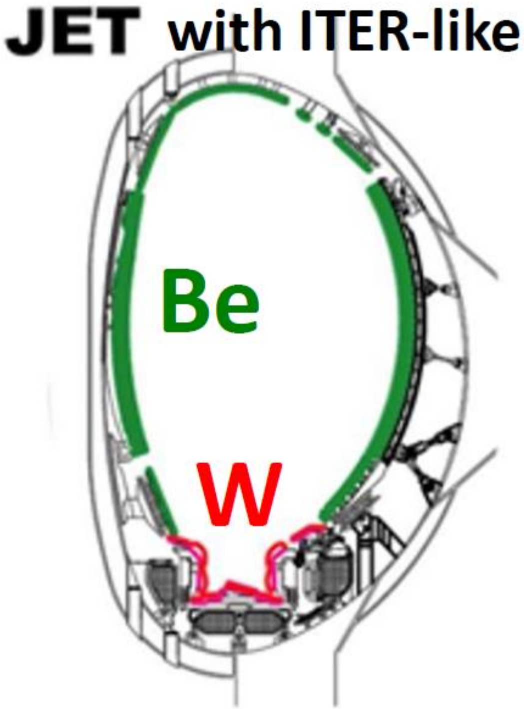
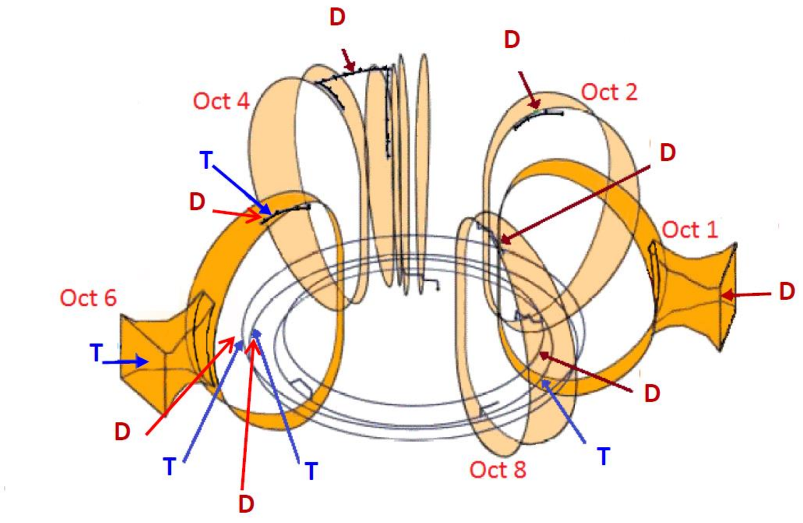


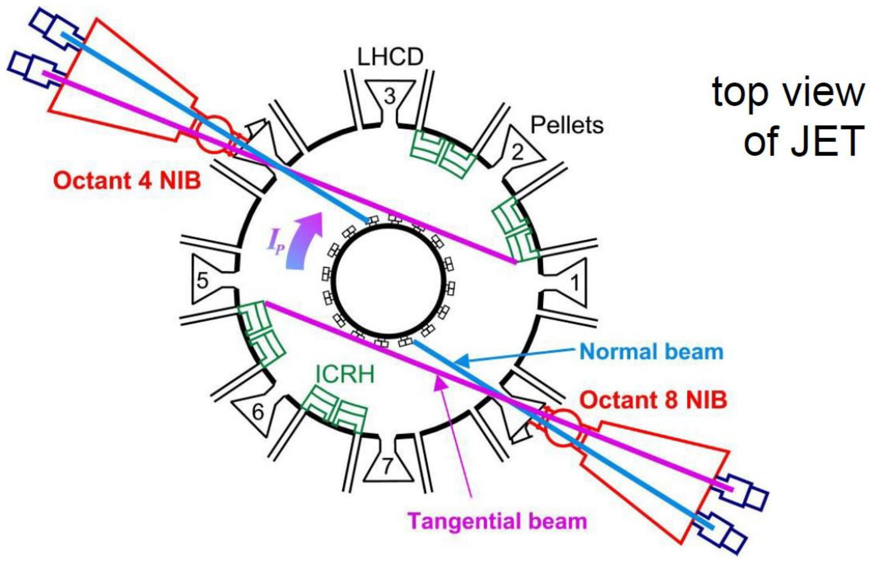
Figure from C.Maggi, 48th EPS (2022).

Tritium gas injection and T-NBI upgraded for T & DTE2 with ILW

T gas injection: **5 Tritium Injection Modules (TIMs)**, in different areas of the vessel (only 1 module in DTE1)



T-NBI: T fed into **both Neutral Beam Injection Boxes** (only 1 NBI box in DTE1)



➔ Capability for 100% high power Tritium experiments
69g Tritium on site for T and DTE2 (21g in DTE1)

C.Maggi, 48th EPS (2022).

Scenario development in D to prepare for D-T

D experiments

Baseline

- Based on full I_P ITER scenario for Q=10 milestone

Hybrid

- Based on reduced I_P ITER scenario
- Improved confinement
- Sensitive to initial plasma phase

Neon seeded scenario

- With neon to reduce divertor plates power load as needed in ITER

2 routes for demonstration of sustained high fusion power

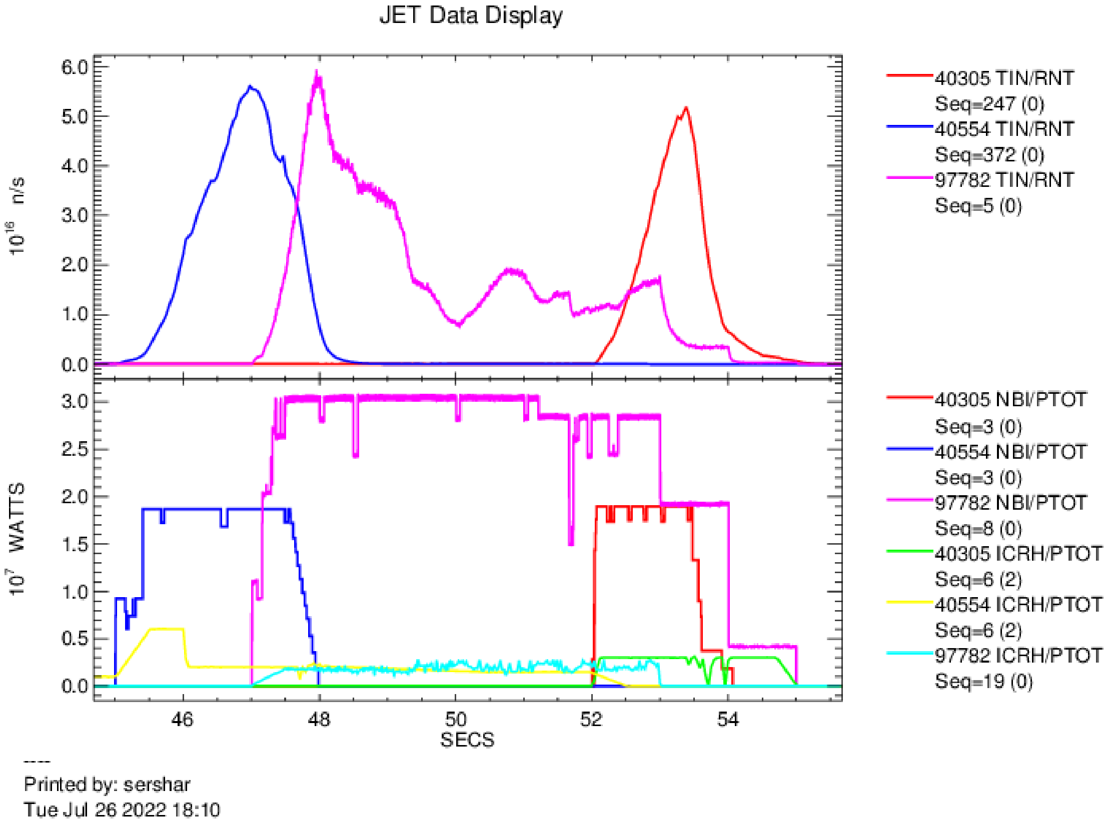
Plasma edge more ITER relevant

J. Mailloux, 48th EPS (2022).

NBI power was increased significantly, up to 32 MW

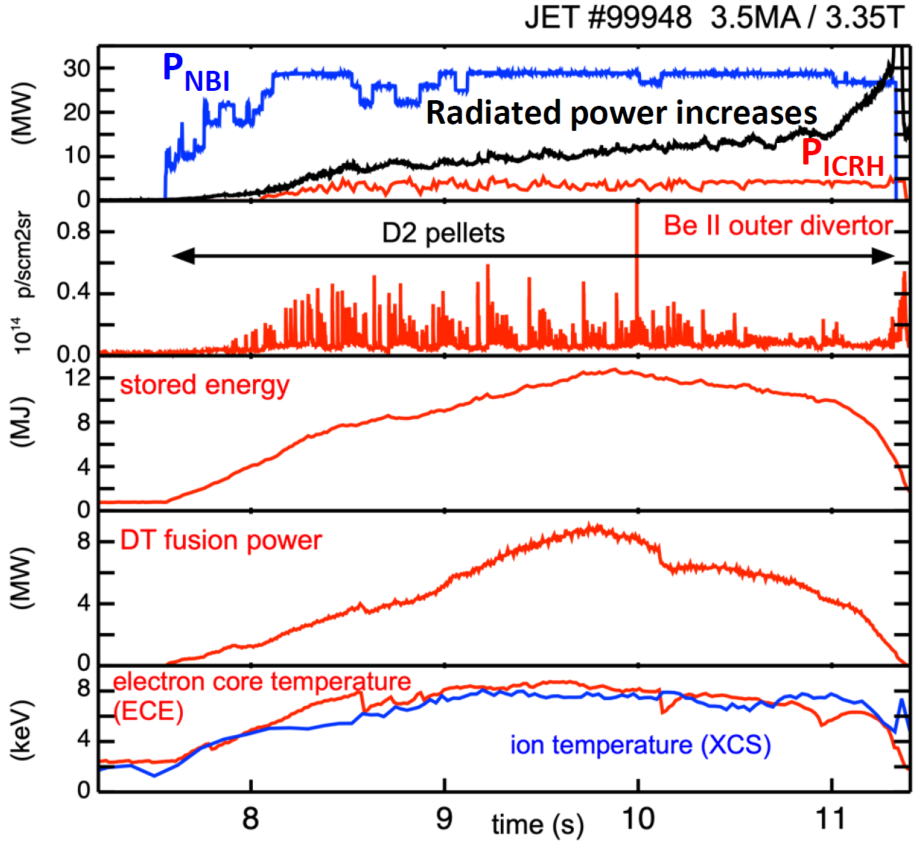
- This allowed mitigate the high level of radiative power from plasma;
- The neutron rate from beam-plasma reactions became high.
- The hybrid scenario development pre-DTE2 did set up a new DD neutron rate record in # 97782 [C.Challis et al 48th EPS (2022)]

Pre-DTE2 record in DD neutrons versus DD results in 1997



Baseline scenario: reduced operational space in D-T

50/50 D/T results

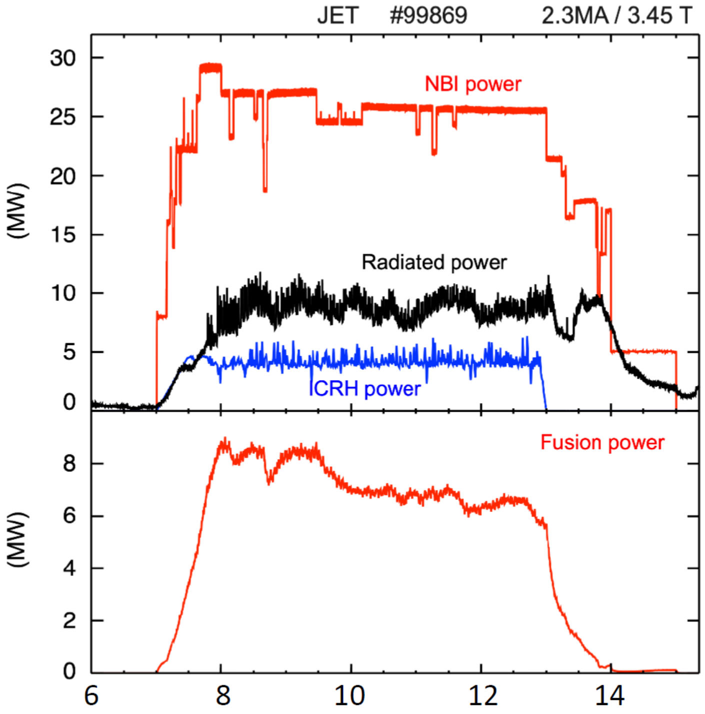


- Good access to H-mode after re-optimisation to compensate for combined isotope effects
- Stopped by too high impurity radiation due to less effective W flushing by ELMs
  - higher density in D-T + higher impurity radiation → reduced operational space
  - Complex interplay between MHD modes, sawtooth instability, energetic particles & radiation
- More time needed to complete re-optimisation in D-T

J. Mailloux, 48th EPS (2022).

Hybrid scenario: sustained performance

50/50 D/T results



- Hybrid scenario run for the first time in D-T
- Successful sustained pulse after re-optimisation
- Fusion energy record for 50/50 D/T plasmas (42MJ)
- Analysis on-going to disentangle effects on edge and core, and identify isotopic and α effects

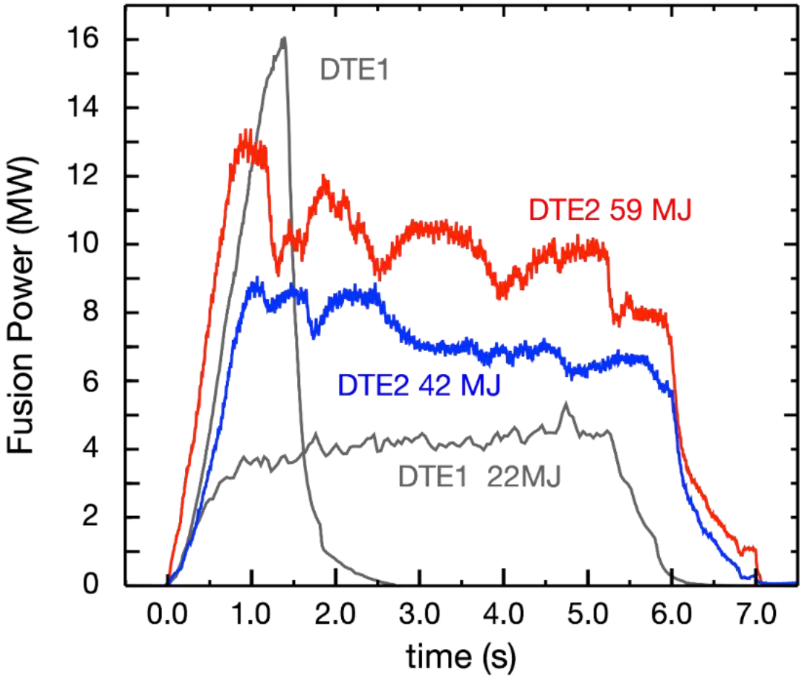
J. Mailloux, 48th EPS (2022).

DTE1 Fusion energy record surpassed

D/T results

#99869 (2.3MA/3.45T) Hybrid with ~50/50 D/T NBI and plasma

#99971 (2.5MA/3.86T) Hybrid with D-NBI in T-rich plasma



- Fusion energy record surpassed with hybrid scenarios
- Demonstrates compatibility of ILW with sustained high fusion performance

J. Mailloux, 48th EPS (2022).

SUMMARY

- **Three On JET, the ratio of thermonuclear neutron rates in DT discharges and in the reference D discharges was ≈90;**
- **Operation in H-mode of DT plasma delivered 16 MW of fusion power.**
- **The triple-product in best H-mode DT plasma was $\beta\ \tau_E\ B^2 \approx 0.4\ T^2\ s$**
- **Neutron rates in JET DT discharges in H-mode were found to have a good correspondence P_{fus}~B^4 during DTE1;**
- **High fusion power DT discharges in ITB scenario were more promising in D but less successful in DT in DTE1;**
- **Neutron rates in JET DT discharges in ITB scenario were found to be P_{fus}~B;**
- **Operation with ITER-like wall at increased NBI power delivered 59 MJ of fusion energy.**