JET Results and plans for DT operation

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on behalf of the EFDA-JET Contributors

Outline

Part I: Recent JET Results

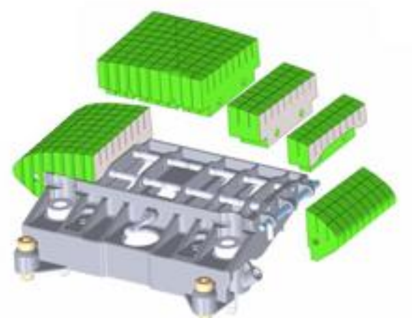
- ITER like Wall: Impurities and retention
- Disruptions, L → H transition
- H-mode confinement with the ITER-like Wall
- Tungsten Melt Experiment

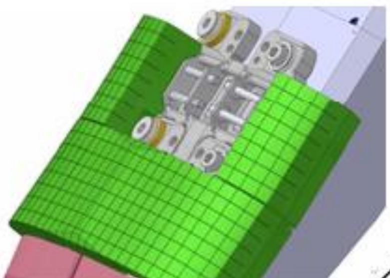
Part II: Plans for DT operation

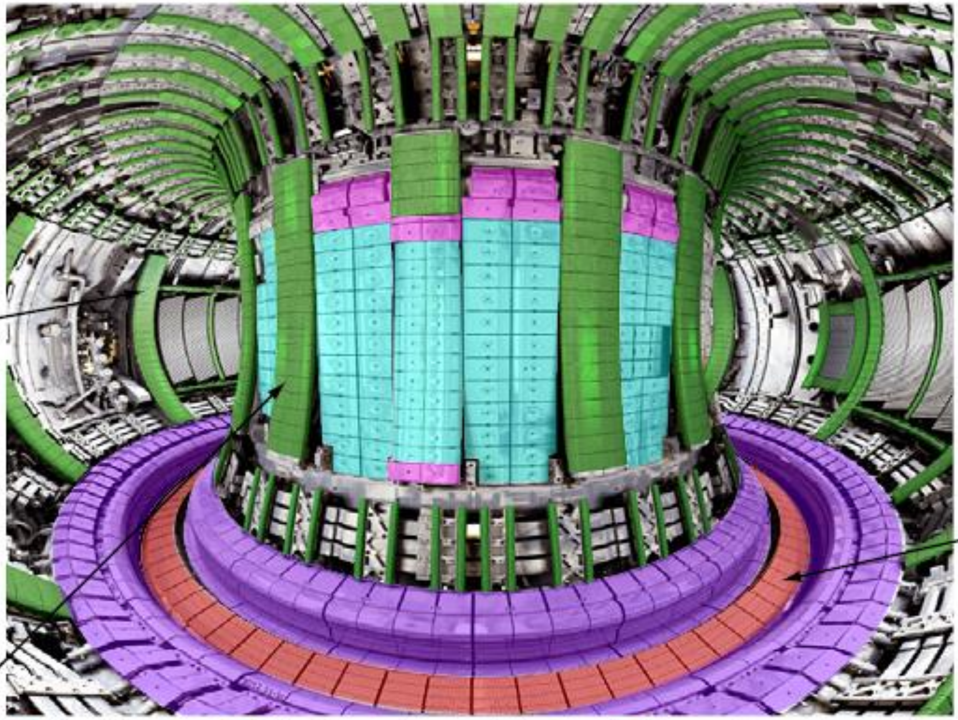
- JET & mitigation of risks to ITER
- Building a case: Physics, Operational and Technology
- Schedule, programme and shutdowns

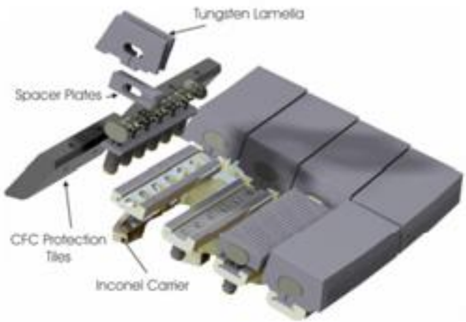
JET: ITER-like Wall

2010-2011: Remote handling installation of all new PFCs in JET


WOPL tile assembly


IWGL tile assembly





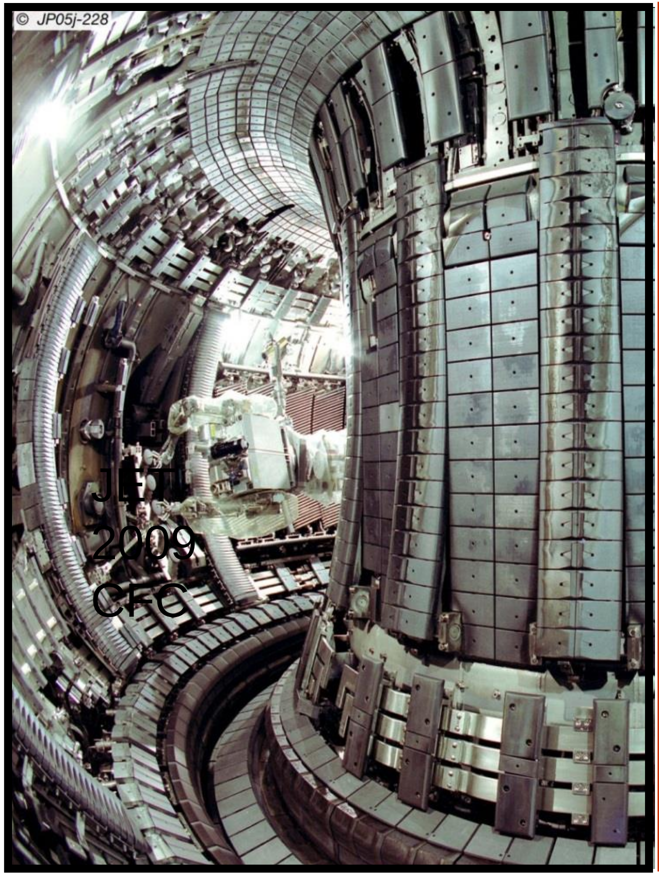
Divertor horizontal outer target tile assembly

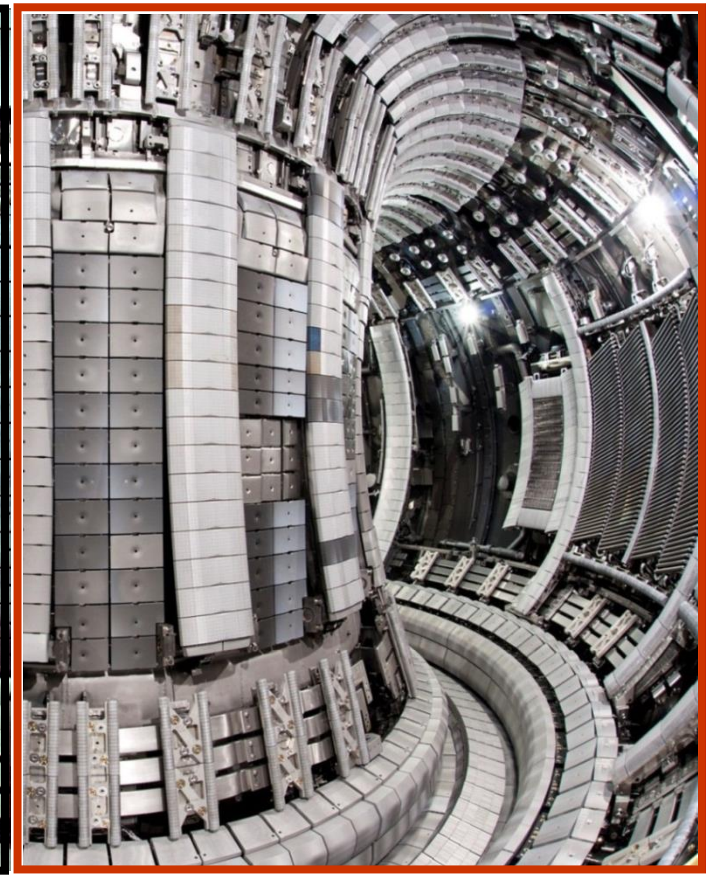
Additional W-coated CFC protection tiles installed in the main chamber

- PFCs are inertially cooled
- PFCs are optimised with respect to power handling and material stress
- Predicted power handling verified by dedicated experiments

Carbon Wall (JET-C) vs. Beryllium/Tungsten Wall (JET-ILW)

JET-C

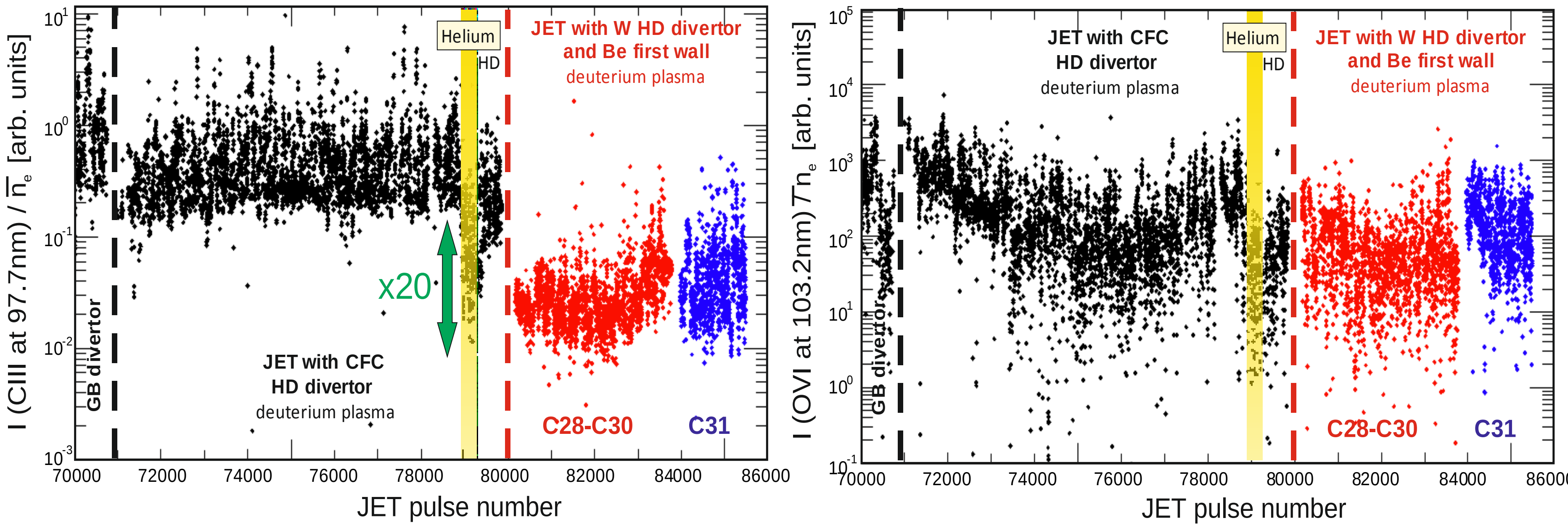




JET-ILW

- Plasma Facing Components were replaced in 1 shutdown
- More than 80 000 parts with 350 tools installed by RH
- Real-time protection ($T_{surface}$) during plasma operation

Evolution of C and O content



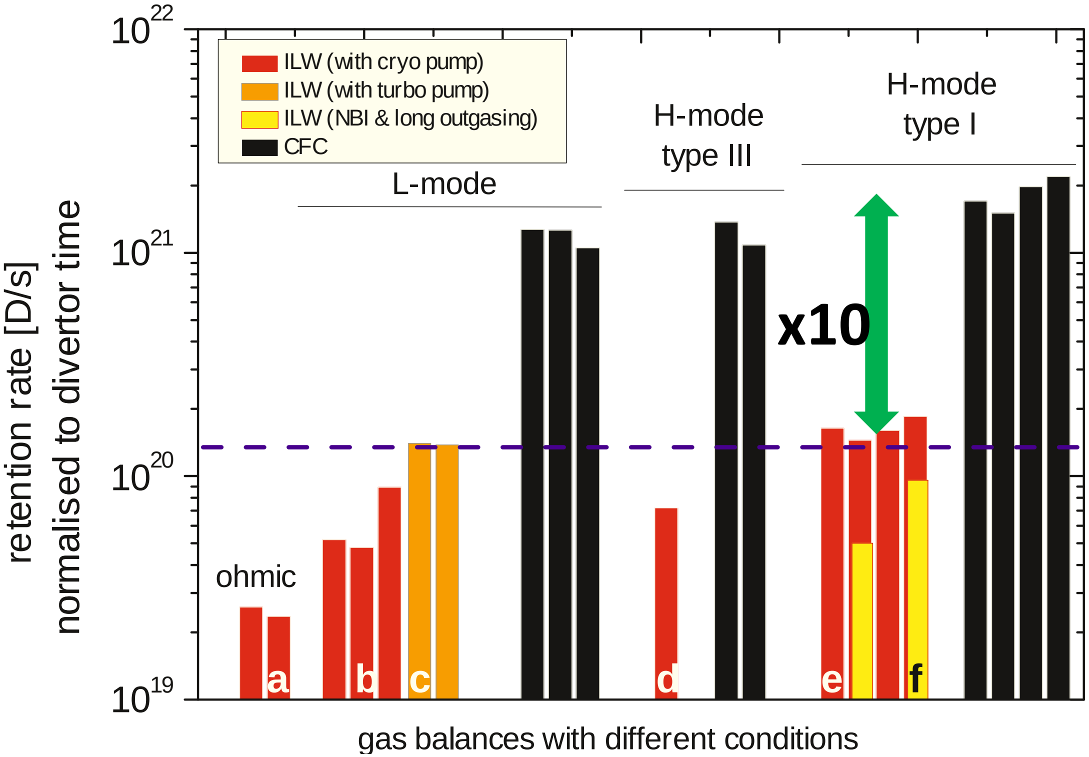
Following the installation of the ITER-like Wall:

- Very low residual C content in the plasma;
- Oxygen is gettered by Be;
- Averaged Z_{eff} dropped from 2.0 (JET-C) to 1.2-1.4 (JET-ILW), this is lower than expected (source strength also different).

→ Many operational consequences (expected and unexpected)

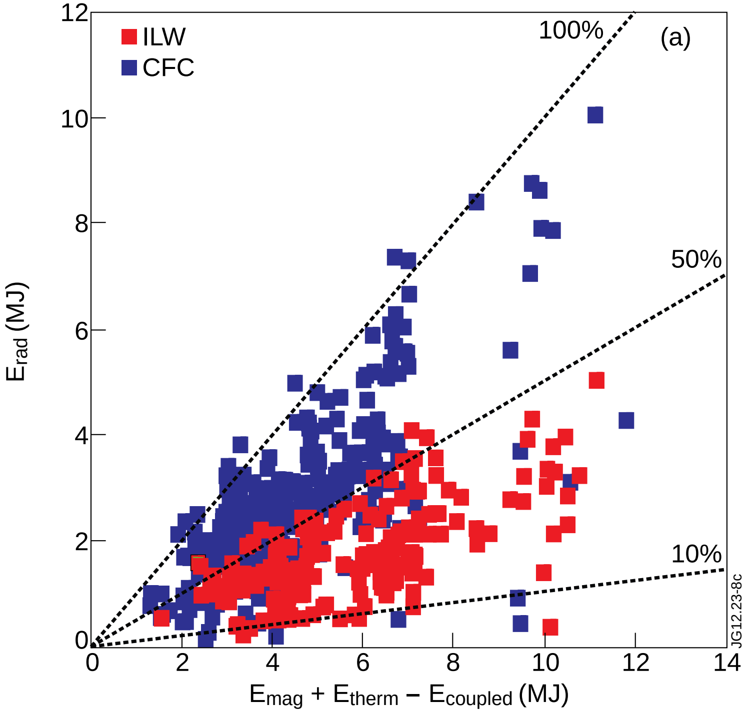
Fuel retention with the ITER-like Wall

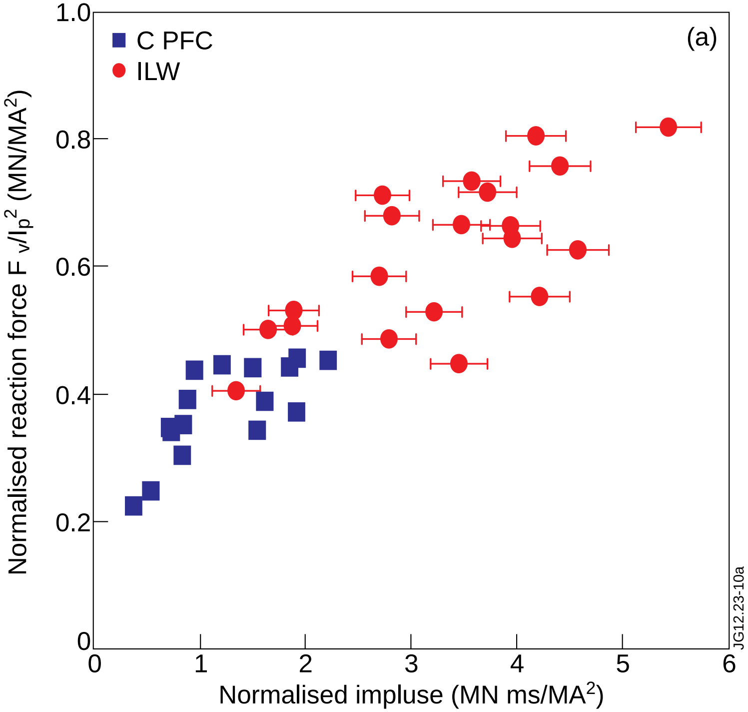
- Measured fuel retention is more than an order of magnitude lower with the ILW, consistent with predictions made before the wall was installed.
- Residual retention consistent with co-deposition in Be layers.



Loarer et al., J. Nucl. Mater. 438, S108 (2013)

- The dynamics of disruptions are very different with the ILW
  - ➢ Higher plasma purity ➞ lower radiation during disruption
    - ➞ slower current quench
    - ➞ higher heat loads and halo currents
    - ➞ higher reaction forces on the vessel

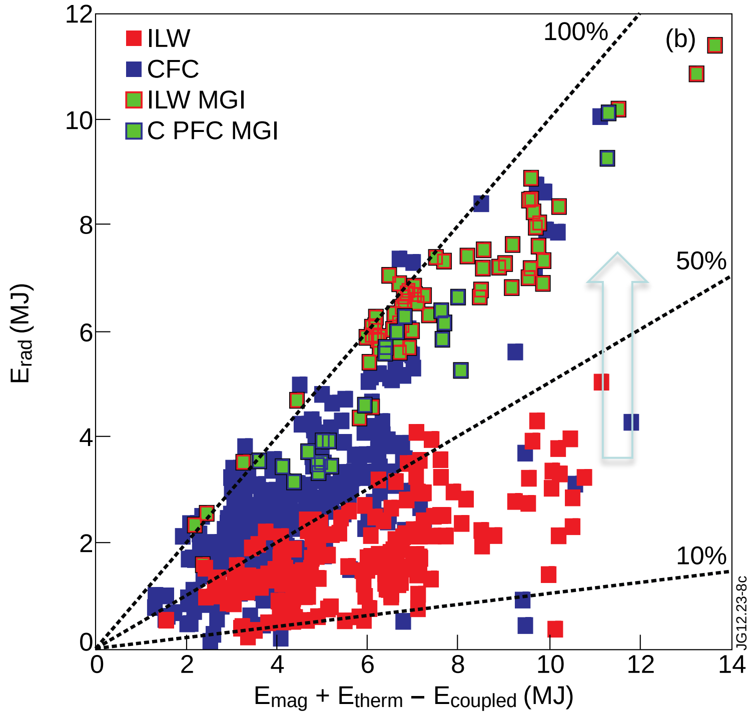


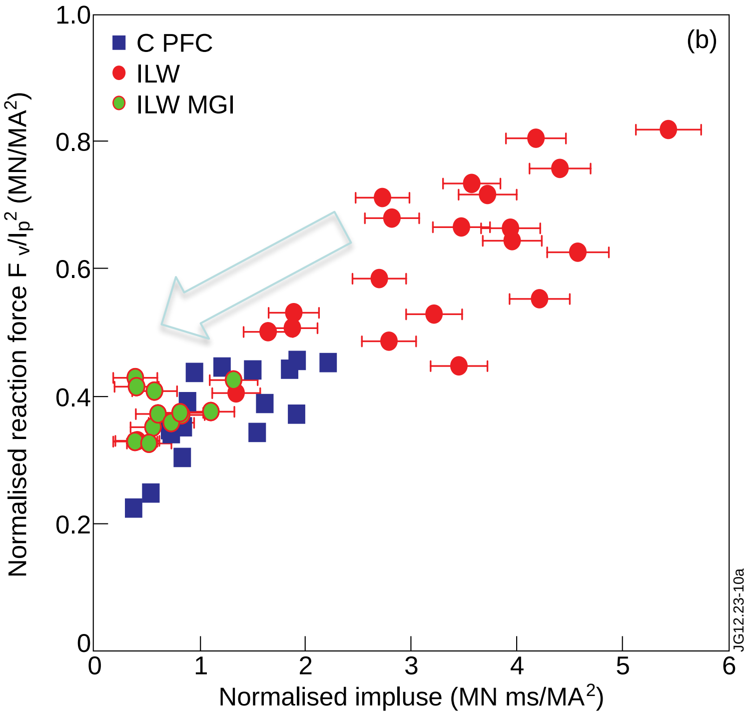


Lehnen et al., J. Nucl. Mater. 438, S102 (2013)

Disruption mitigation

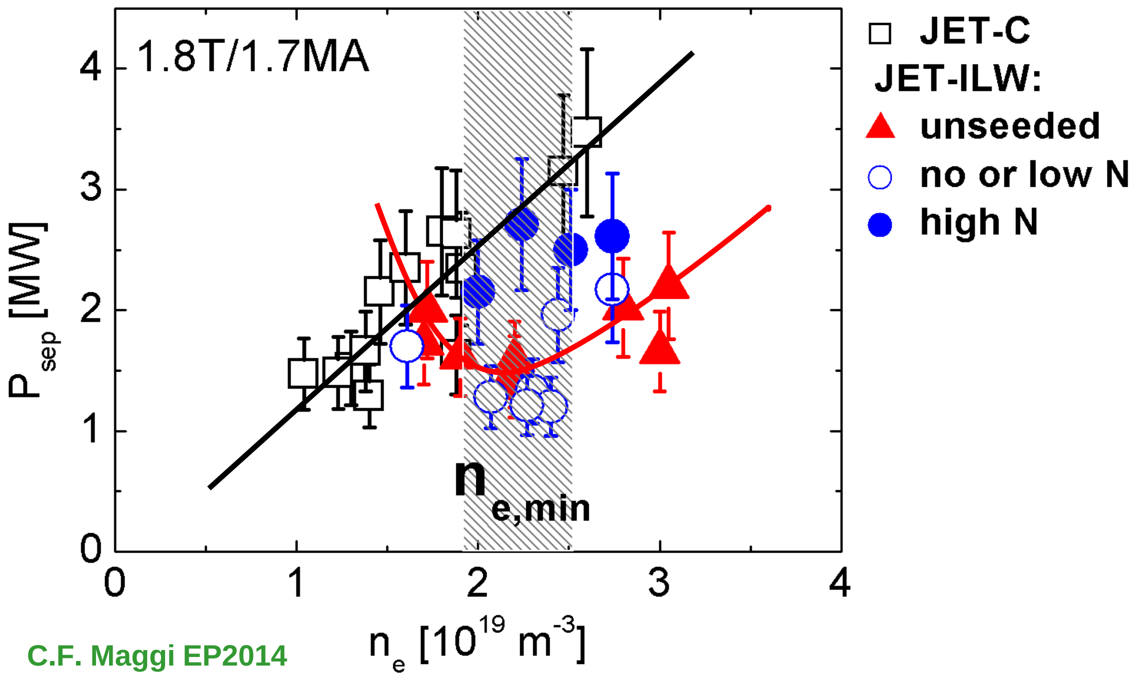
- Massive gas injection as a disruption mitigation tool is now mandatory for JET experiments at or above 2.0 MA;
- Closed loop disruption detection, avoidance and mitigation
- 2014: Two MGI valves at the top and mid-plane (2015: Add 1 top MGI)

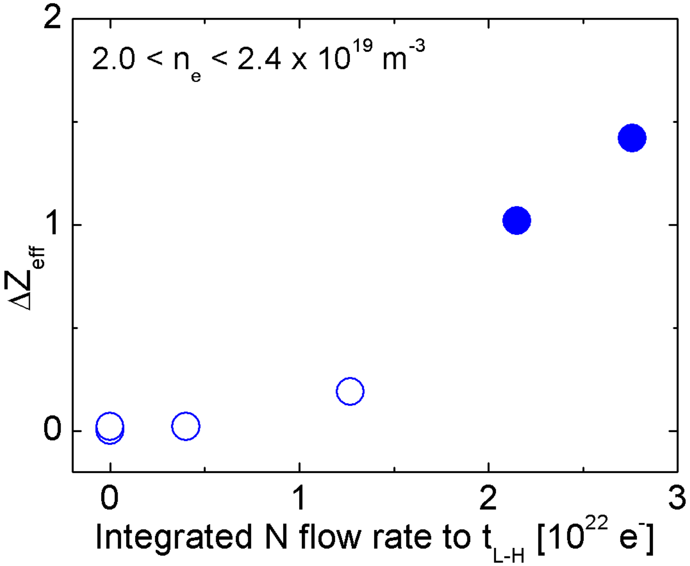




Lehnen et al., J. Nucl. Mater. 438, S102 (2013)

L → H transition: JET-C vs. JET-ILW



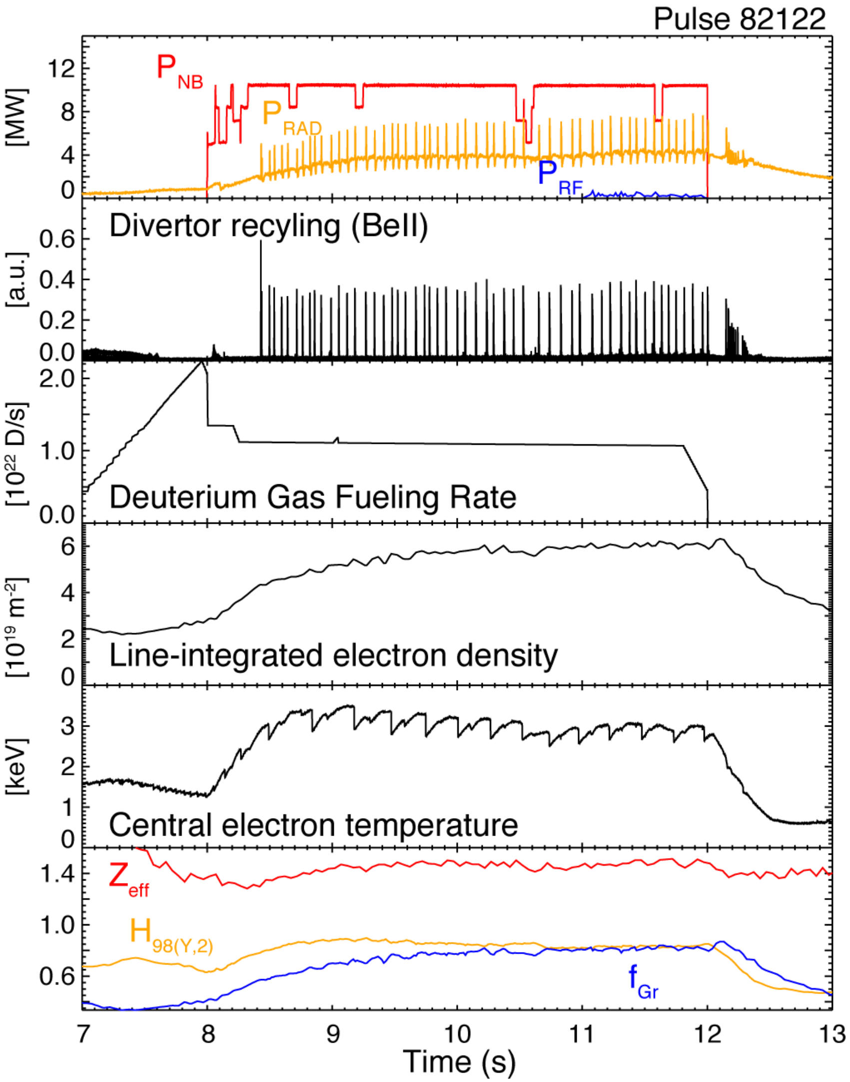


C.F. Maggi EP2014

Favourable minimum in L-H transition observed in the high density branch in Deuterium:

- Pure D plasma show reduction of threshold power as function of magnetic field, density and configuration at typical low Z_{eff} for JET-ILW [C.F. Maggi NF2014]
- Strong nitrogen seeding and associated increase of Z_{eff} recover almost JET-C behaviour

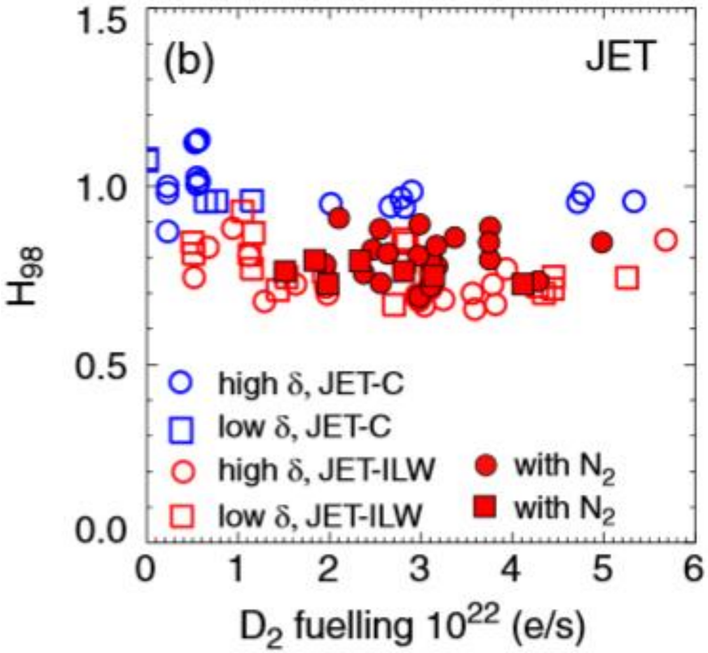
H-mode operation with the ITER-like Wall

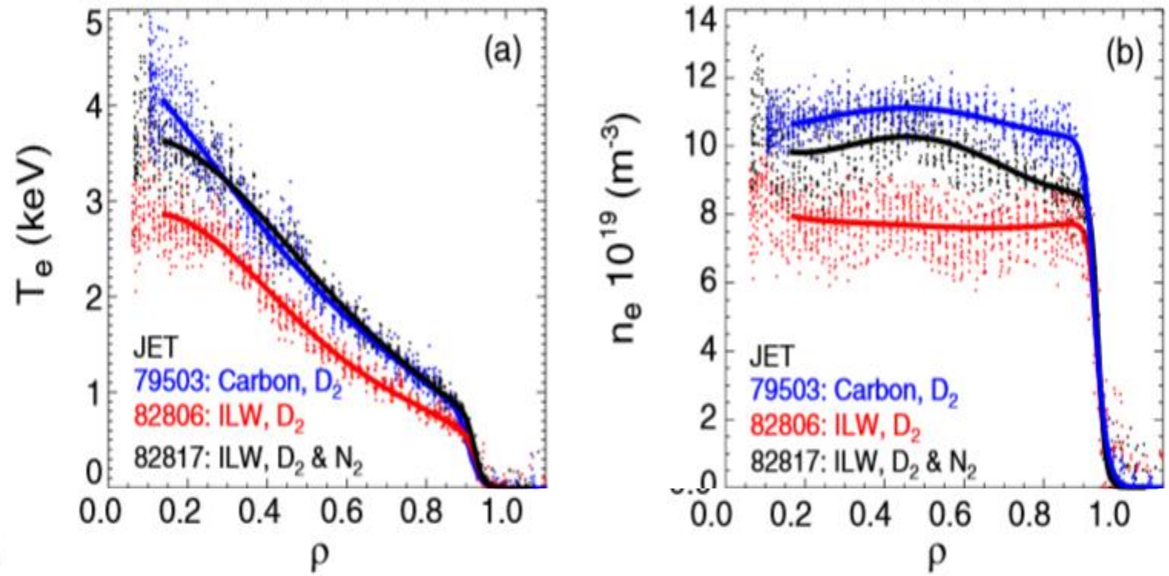


- Already in the first ILW campaigns, the reference ITER operating regime was re-established (up to 3.5 MA, 26 MW NBI + 3 MW ICRH)
- Plasma purity is higher
- Gas fuelling is required to keep the discharge stable against W accumulation

Bucalossi, EPS Plasma Phys. Conf, 2012

H-mode confinement: ITER-like Wall



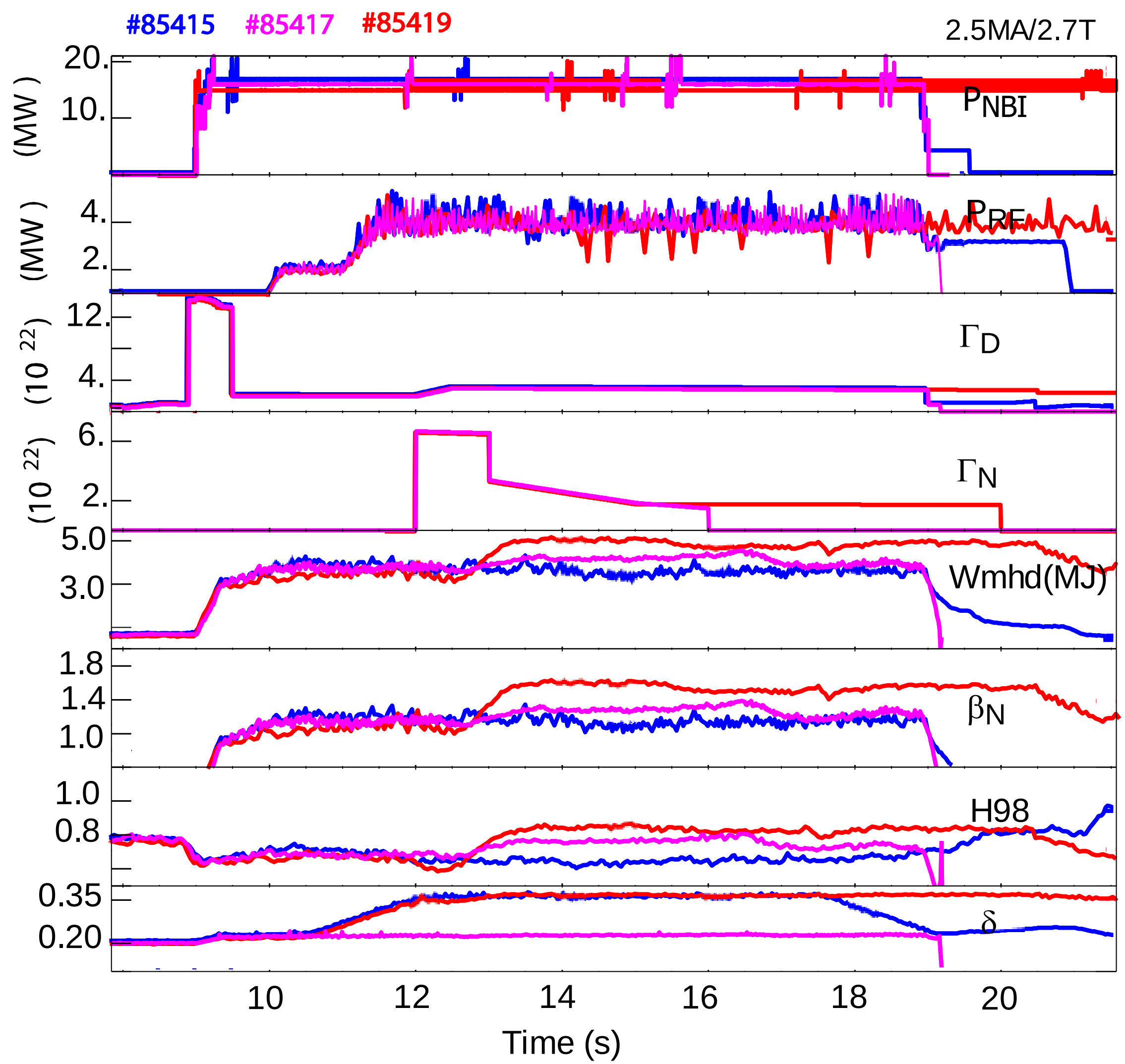


M. Beurskens and J. Schweinzer, NF2014

Both JET-ILW and AUG show degradation of confinement with respect to carbon wall operation:

- Degradation partially governed by fuelling requirements to allow safe operation in W
- Degradation is dominated by changes in the pedestal, with the strongest degradation for JET high triangularity plasmas (by about 25%)
- **Pedestal recovery: (1) by impurity seeding and (2) by increasing β_N**

(1) Nitrogen seeding in JET



Stationary H-mode operation:

#85415 : D_2 only

#85417: N_2 and D_2 – low $\delta \rightarrow \tau_E \uparrow 15\%$

#85419: N_2 and D_2 – high $\delta \rightarrow \tau_E \uparrow 40\%$

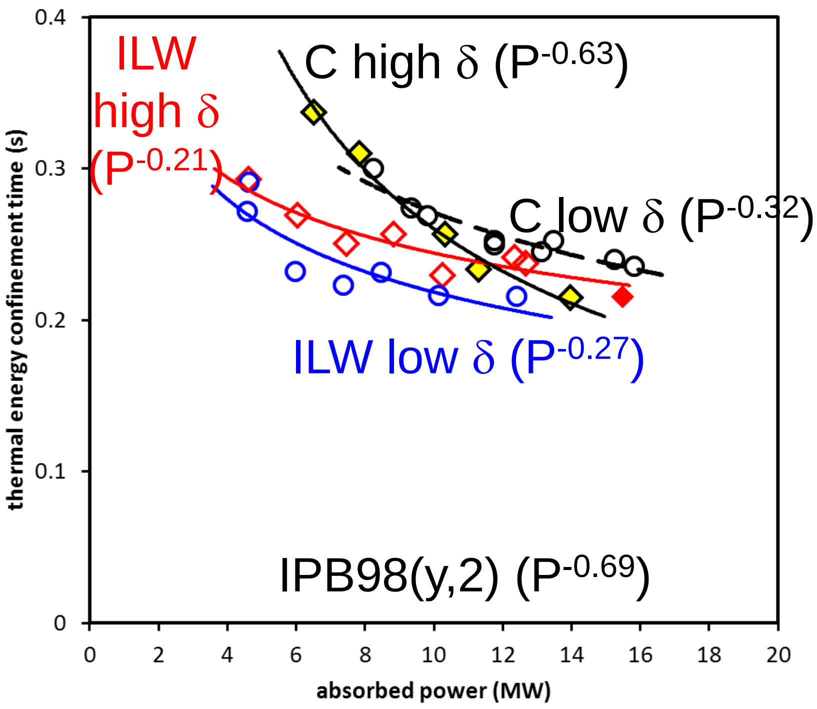
- Radiation cooling
- Semi-detached divertor operation in both legs

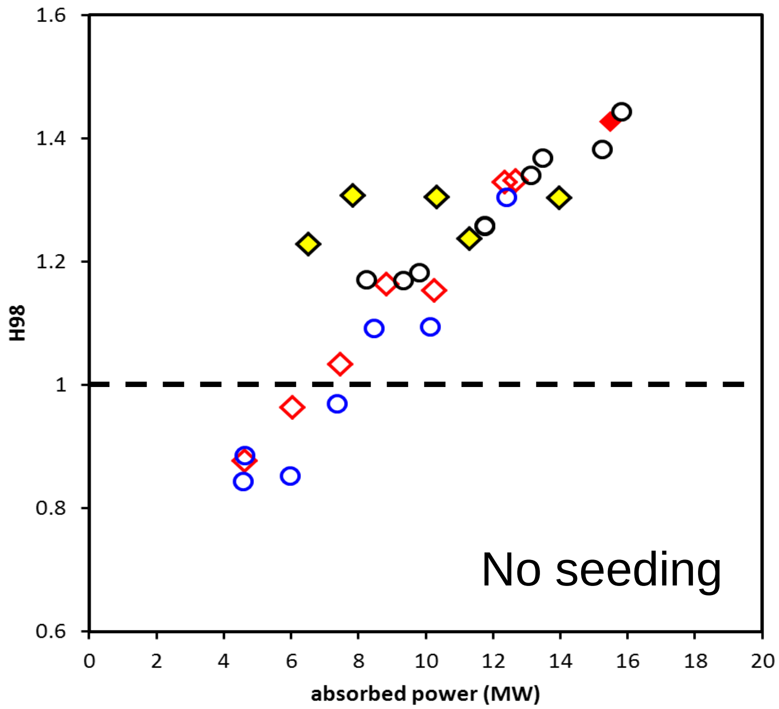
→ Strong reduction in power flow to target plates.

(2) Confinement at high beta

General observation: H_{98} increases with beta

- Experiments in DIII-D: Advanced Inductive
- Experiments in AUG, JET: Hybrid scenario

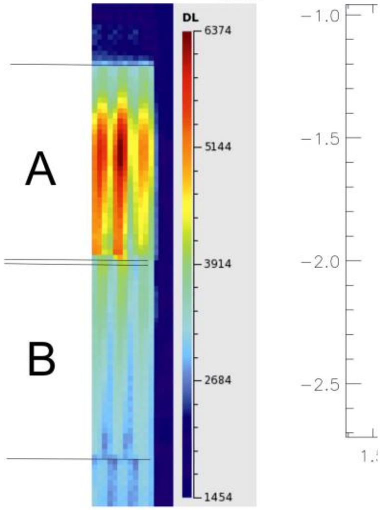




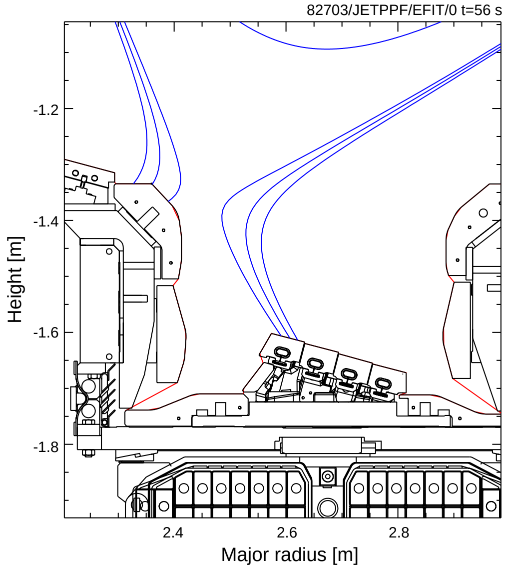
- Energy confinement time ~10% higher at high δ compared with low δ (mainly through density increase)
- Power degradation similar for both shapes and weaker than IPB98(y,2)

Special W lamellae → melt experiment

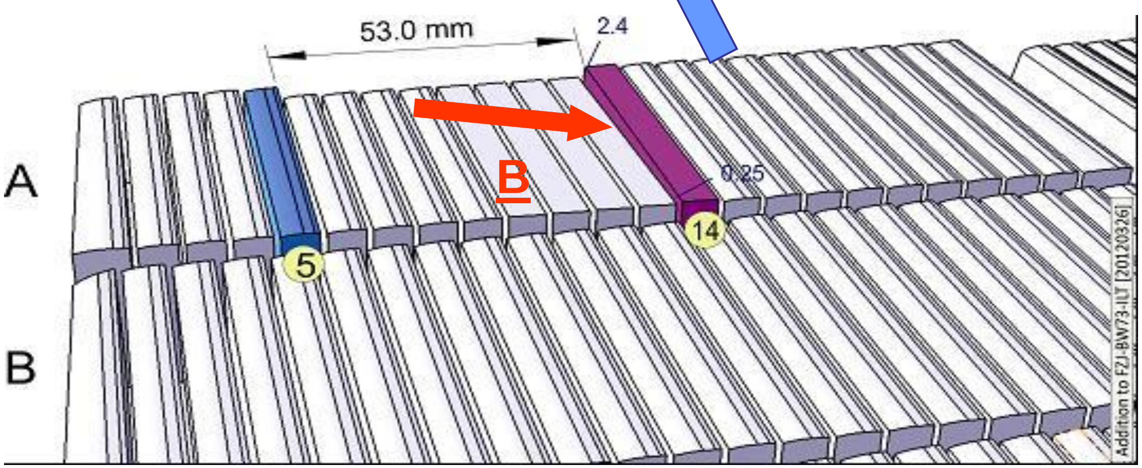
82703, t =56.178s, T_{max} = 236°C



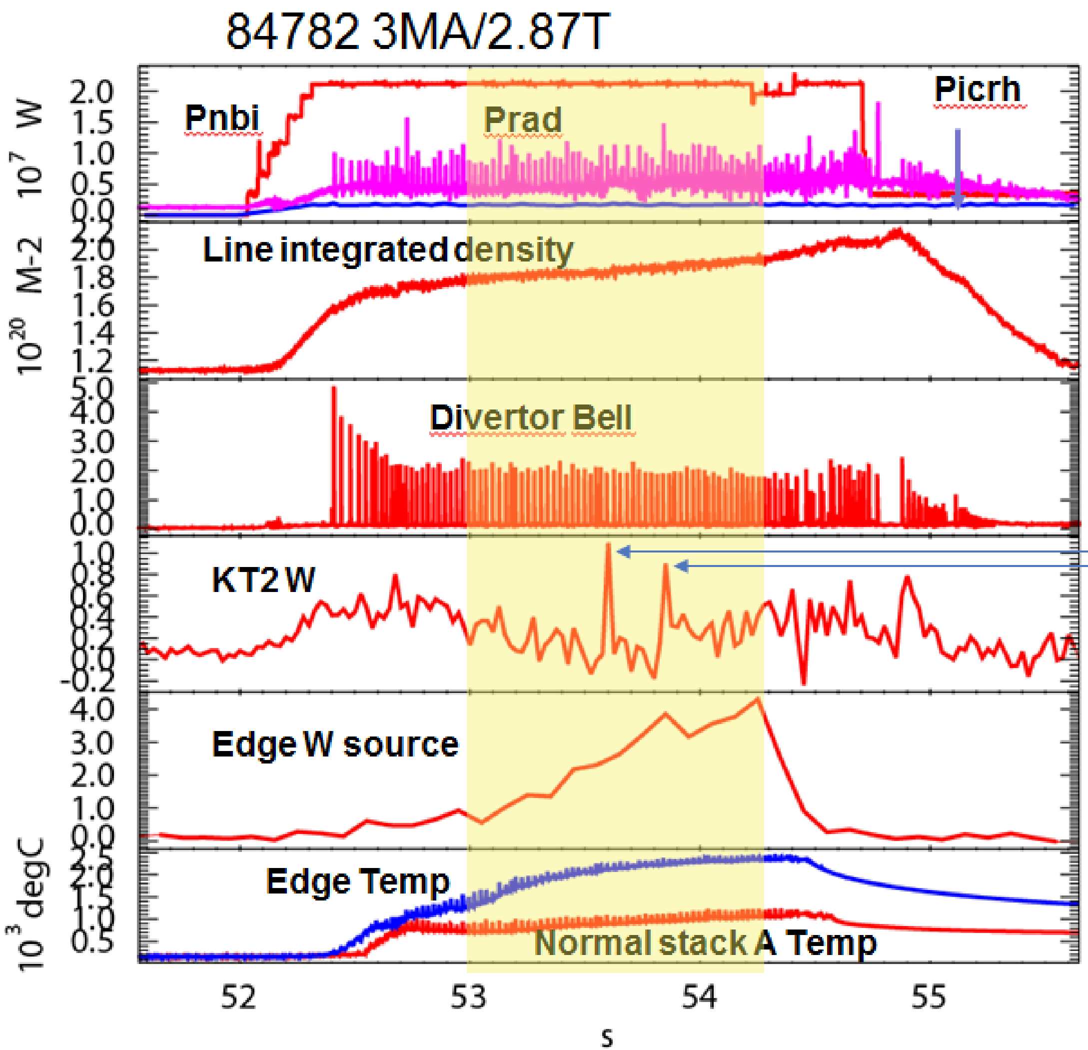
– KL9B –
[NBI ~10MW, 2s]



Melt motion



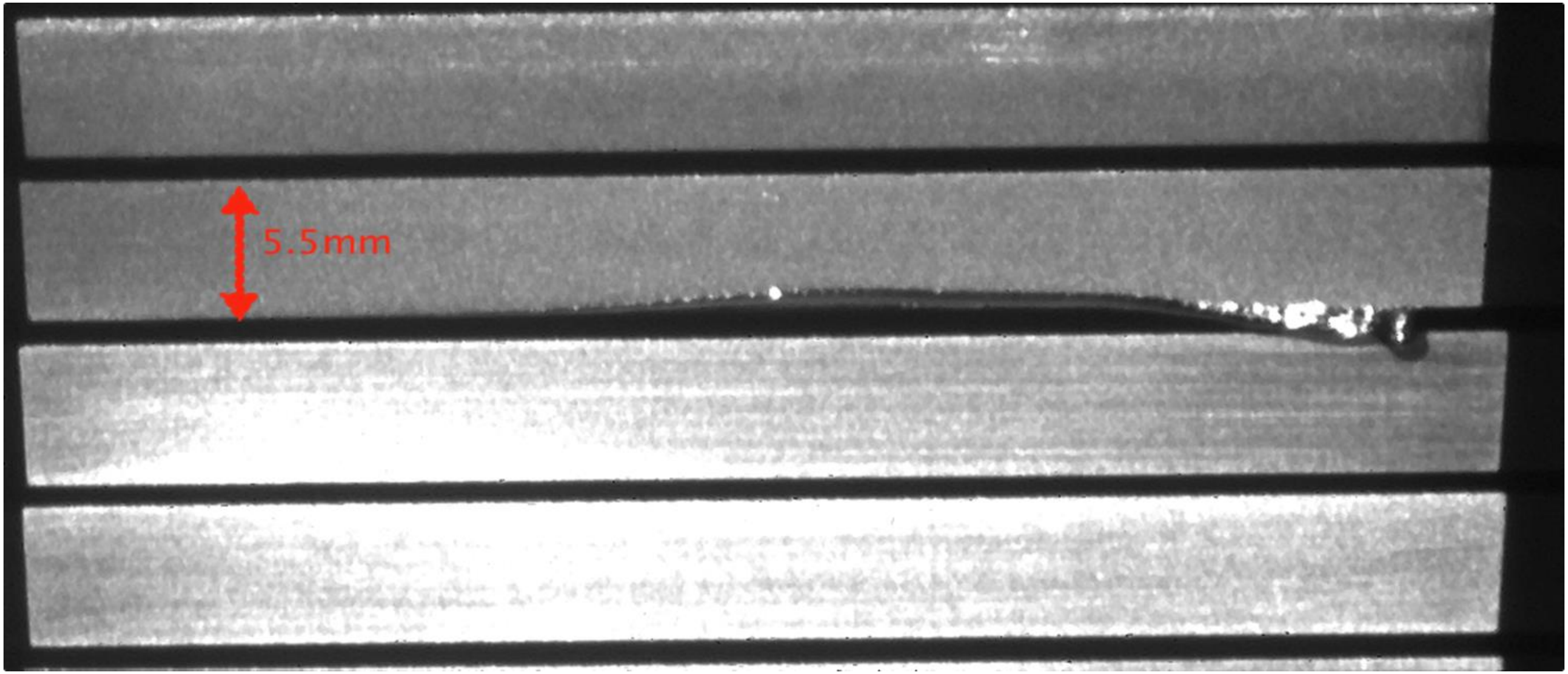
Typical pulse used ..



ELM analysis suggests ΔW=300kJ with $q_{\|}$ = 0.5-1 GW m^{-2}

Possible W droplet events size estimated at 100μm

After several H-mode discharges



Case for future DT experiments at JET

- JET & mitigation of risks to ITER
- Building a case:
  - ✓ Physics
  - ✓ Operational
  - ✓ Technology
- Schedule, programme and shutdowns

Introduction: JET capabilities

A new DT campaign is being proposed:

- With the ITER-like Wall;
- Enhanced heating systems (compared to 1997);

Parameter — Neutral beam heating:	Gas species			
	H_2	D_2	T_2	^4He
Maximum beam energy (keV)	90	125	118	120
Maximum beam current (A)	50	65	45	42
Maximum power per PINI (MW)	1.0	2.16	2.2	1.56
Maximum power per NBI box (MW)	8.0	17.3	17.6	12.5
Maximum total power (MW)	**16.0**	**34.6**	**35.2**	**25.0**
DTE1 (1997), maximum power (MW)	**10.0**	**18.6**	**10.7**	**14.0**

- Active gas handling system, providing/reprocessing tritium to JET and provide accurate accounting of the tritium used;
- Specific (new) diagnostics…

JET → Mitigate ITER risks

The ITER research plan calls for a rapid development of DT operation. JET DT experiments will demonstrate:

Operation with various hydrogen isotopes and helium

- Transfer of ITER scenarios from H (He) → D → DT and T
- Operation with 100% tritium, using 35 MW NBI power
- Optimise performance in DT (not just repeats of DD)

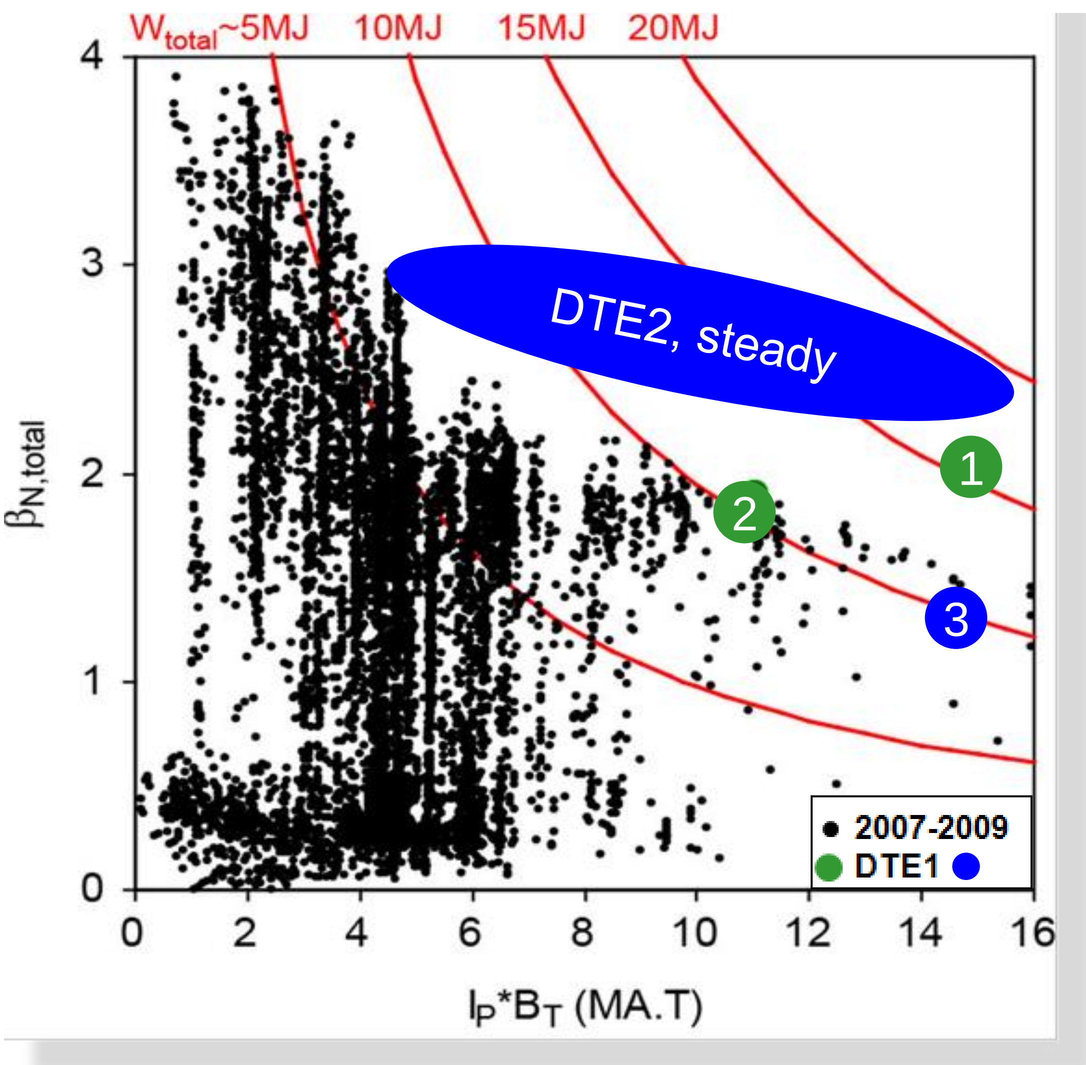
Tritium inventory control during operations

- Test and validate tritium removal techniques with tritium
- Accurate tracking the inventory during operation

Operational experience with tritium

- Prepare and operate in DT, competence in using tritium
- Develop and implement safety procedures (nuclear installation)
- Training of staff (IO operators) + international involvement

ITER regimes of operation in DT



DTE1 scenarios:

1. Transient Hot-ion H-mode
2. Transient strong ITB
3. Steady ELMy H-mode

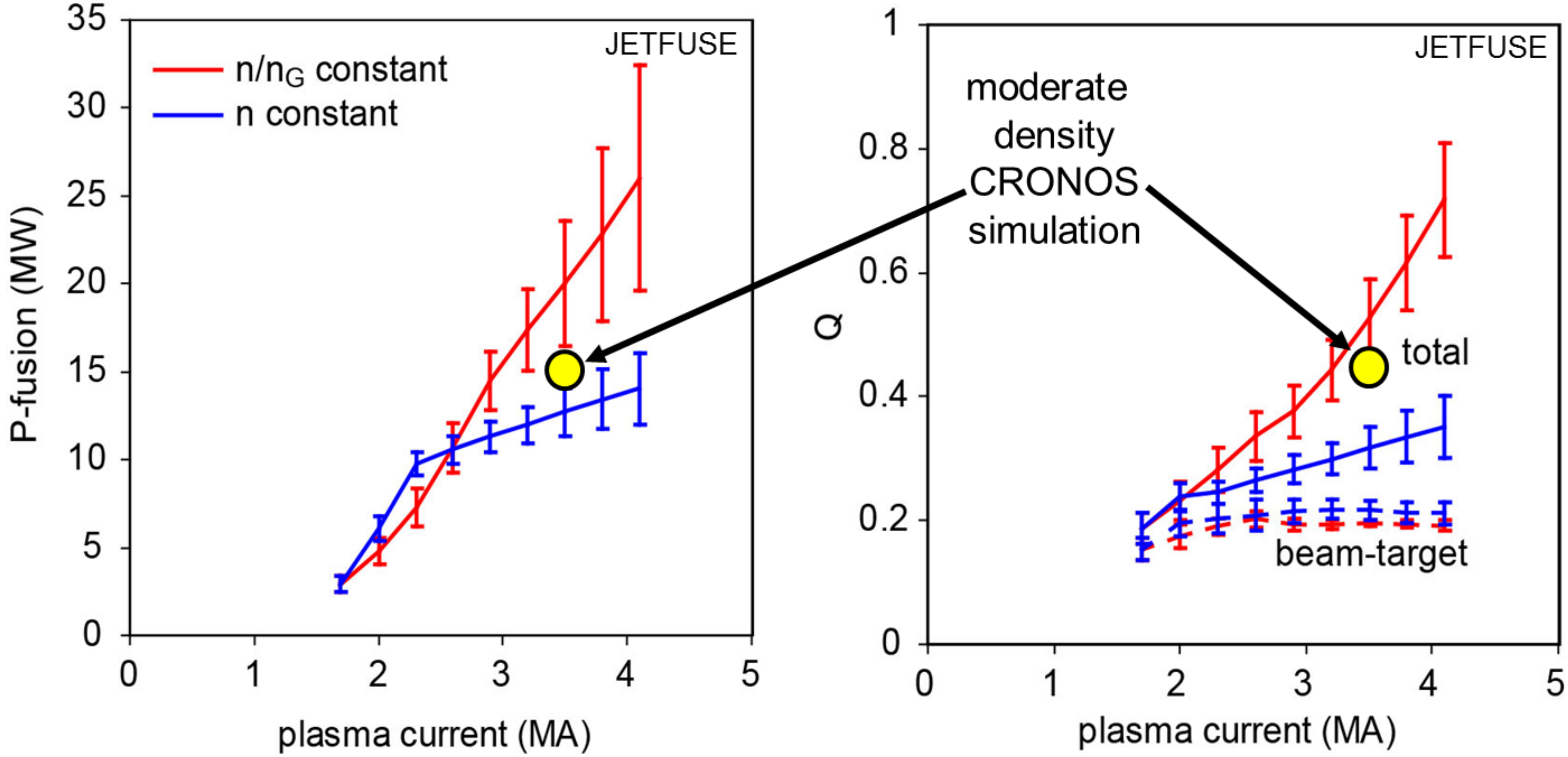
Substantial ITER scenario development since DTE1

Aim for sustained high fusion performance

Scenarios at high plasma beta (β_N=2.5-3) with their control requirements in DT (ITER regimes of operation).

Physics case: Plasma performance

- Stationary H-modes → Verification of ITER operating scenarios
- Steady 10-20 MW fusion power with margin (higher I_P)
- Realistic range of uncertainty : Q_{total}~0.3-0.5



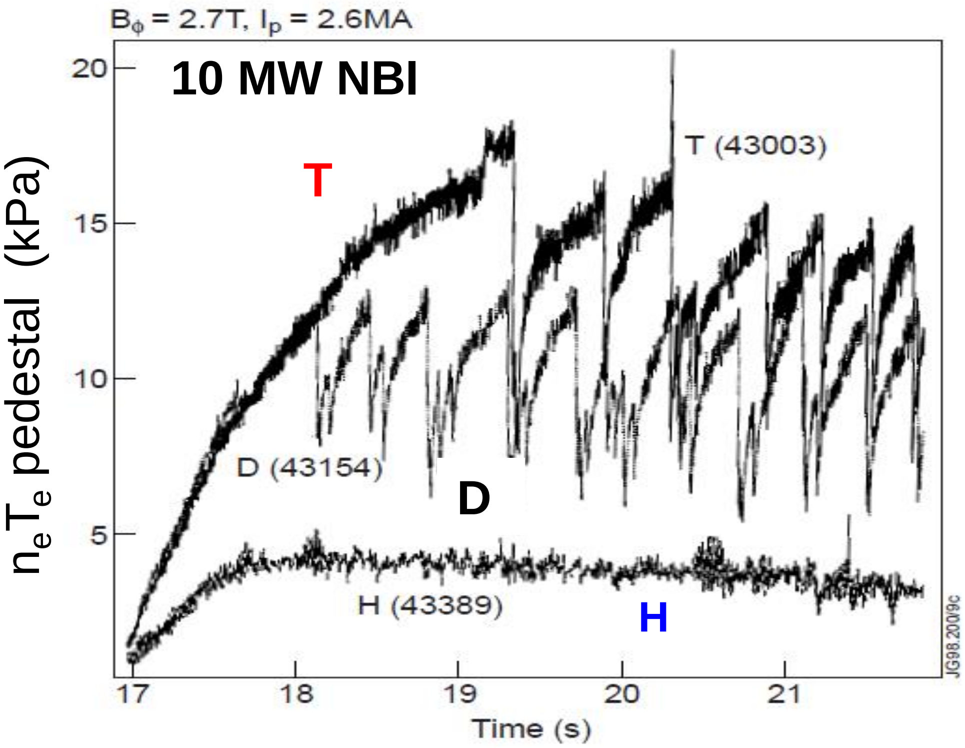
→ JET operation at maximum plasma current (3.5-4.5 MA) and toroidal field (3.85T)

Physics case: Isotope effects

- Compared to 1997, JET has superior diagnostic capabilities
    - Isotope effects, fuel retention, ICRF heating and alpha particles

Example from DTE1 (1997)

- Tritium plasmas had lowest frequency of instabilities at the plasma edge (ELMs)
- How does this scale to ITER ?



Operational: DT Campaign options

DT Campaign options		Full DT phase	DT phase ~DTE1	100% tritium only	Trace tritium
	14 MeV budget	**1.7×10^{21}**	**2.5×10^{20}**	**5.0×10^{19}**	**5.0×10^{18}**
ITER Scenarios in DT*	Baseline	20	8	200	
	Hybrid	40	2	200	
	Steady State	20	0	50	
Technology	Tritium retention				
	14 MeV calibration				
	Use 14 MeV Fluence				
Physics	Retention removal				
	Isotope scaling				
	α-particle effects				
	Fuelling & DT mix control				transport

**Number of high power (>25MW, 5s) pulses in DT (or 100% tritium) is indicated.*

ITER risk mitigation

Impact of DT at JET

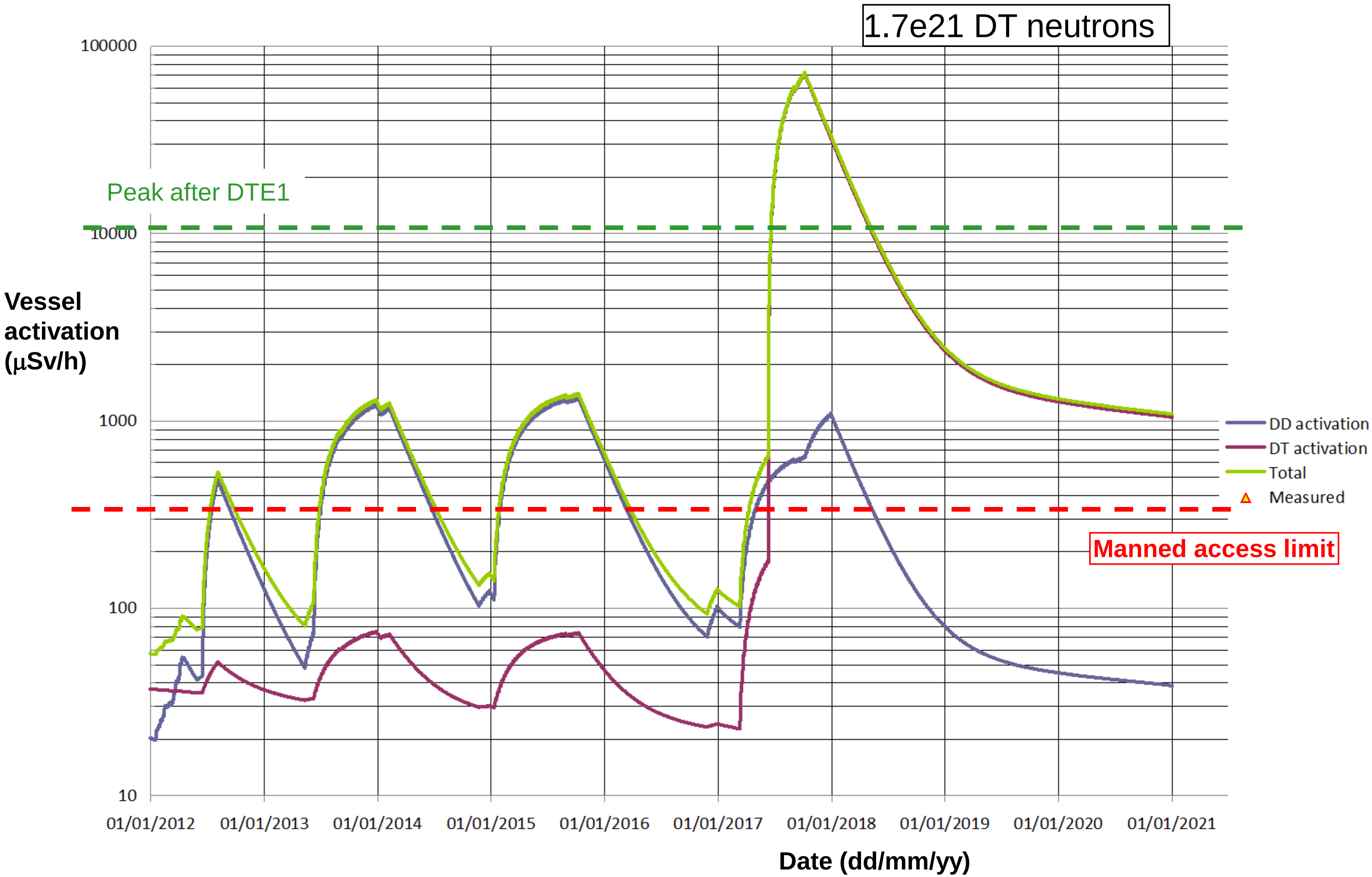
Maximum

Limited

No

→ 1.7×10^{21} budget: Full exploitation of JET for mitigating the risks for ITER.

Vessel - Activation



Technology: In-vessel 14 MeV neutron calibration

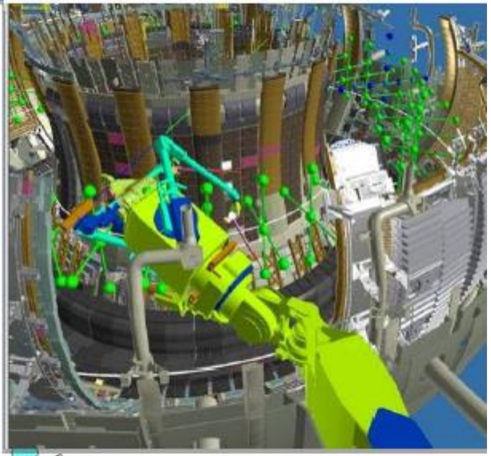
Neutron detector calibration at 2.5 MeV was completed in April 2013.

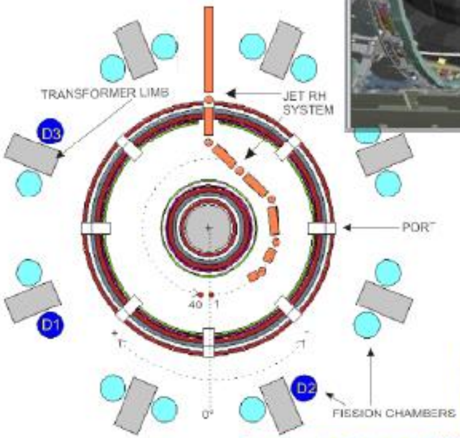
Plans for in-vessel 14 MeV neutron calibration in 2016

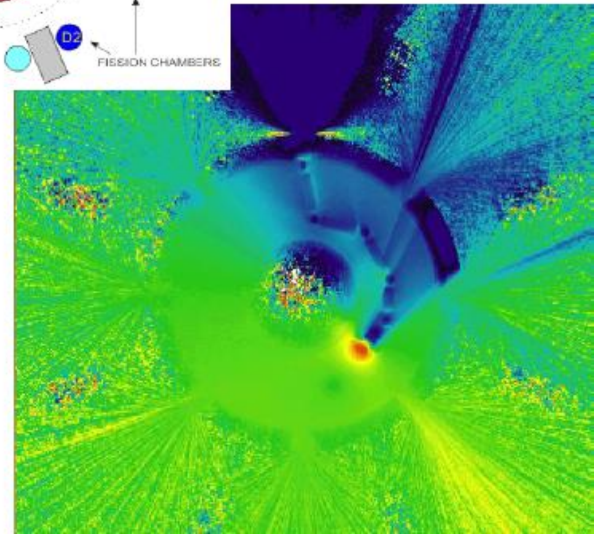
- Benchmark the calibration procedure for ITER
- Assess the sources of uncertainties (point source, RH tools, streaming)

Now:

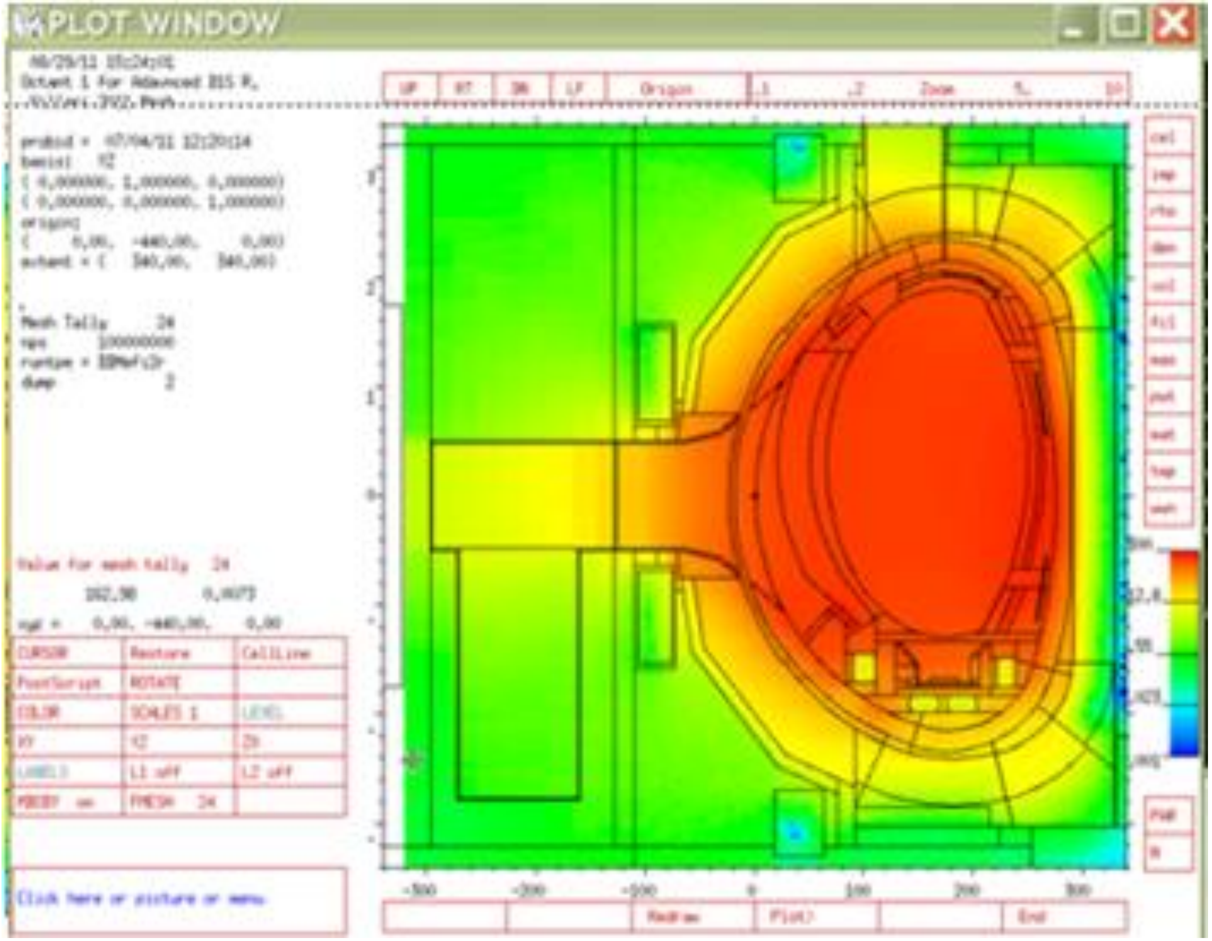
Procurement of DT neutron generator of suitable intensity







Numerical tools for calculation of shutdown dose-rates in JET and ITER



JET:

Following DT operation:

Compare measurements with numerical predictions

Reference schedule: 2014-2018

2014: Extend operation to 4.5MA, high power (34 MW NBI + 6 MW ICRH)

2014 shutdown (October 2014 – March 2015)

- ITER-like antenna, DT diagnostics, optimise pellet tracks
- Take samples from the ITER-like Wall

High power campaigns (mid 2015 – early 2016)

- Full exploitation of ITER-like wall
- Prepare scenarios for DT

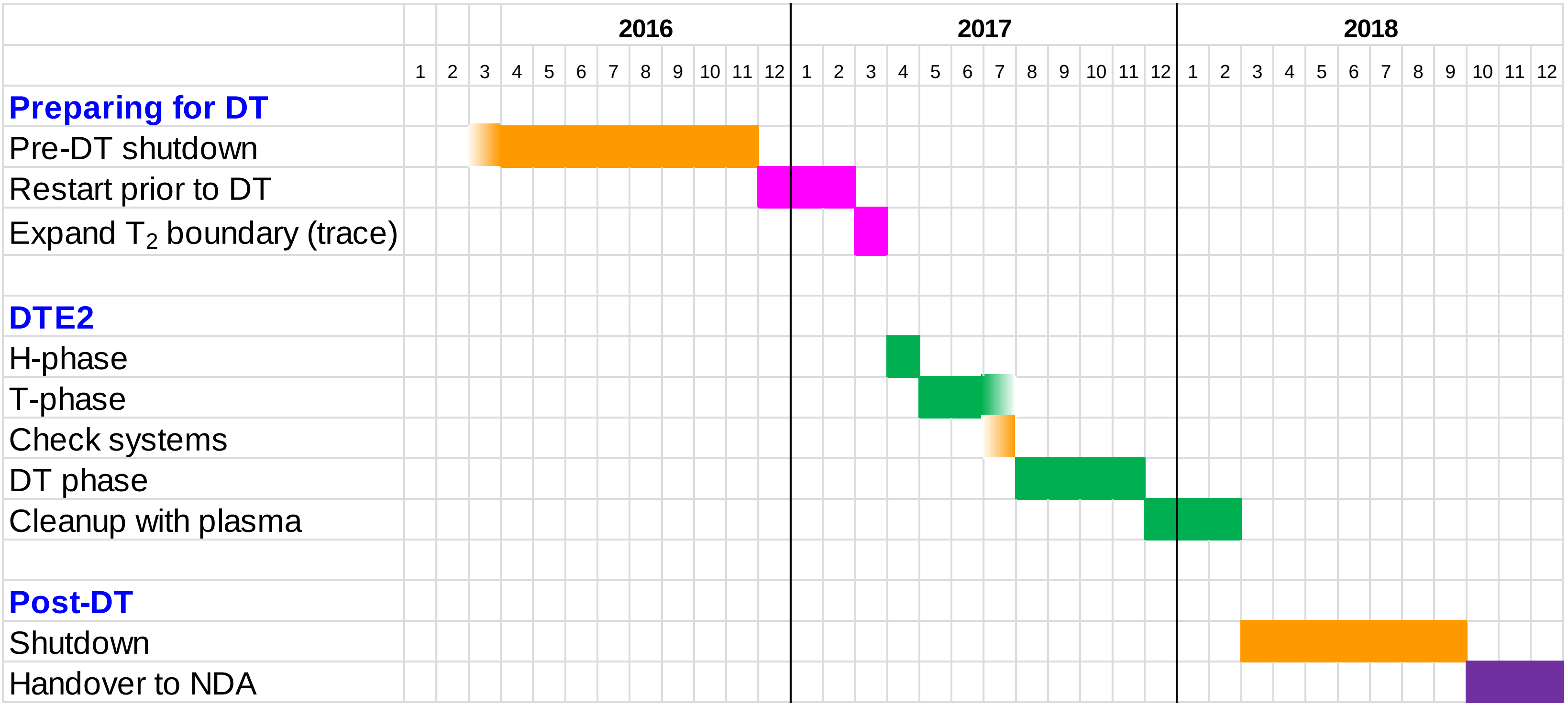
Pre-DT shutdown (early 2016 – November 2016)

- 14 MeV neutron calibration, install and mount samples.
- Remove some diagnostics and complete DT modifications

DT operation (2017 – early 2018)

Post DT shut down (2018)

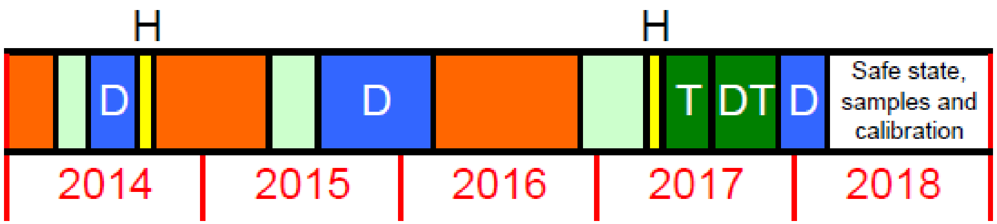
DT campaigns



- Restart after pre-DT shutdown, expand the tritium boundary (trace)
- Operation in hydrogen for 1-2 months
- Operation in 100% tritium for 2-3 months
- DT operation for 3-4 months (100 high power discharges)
- Tritium removal and taking final references in deuterium, ~3 months

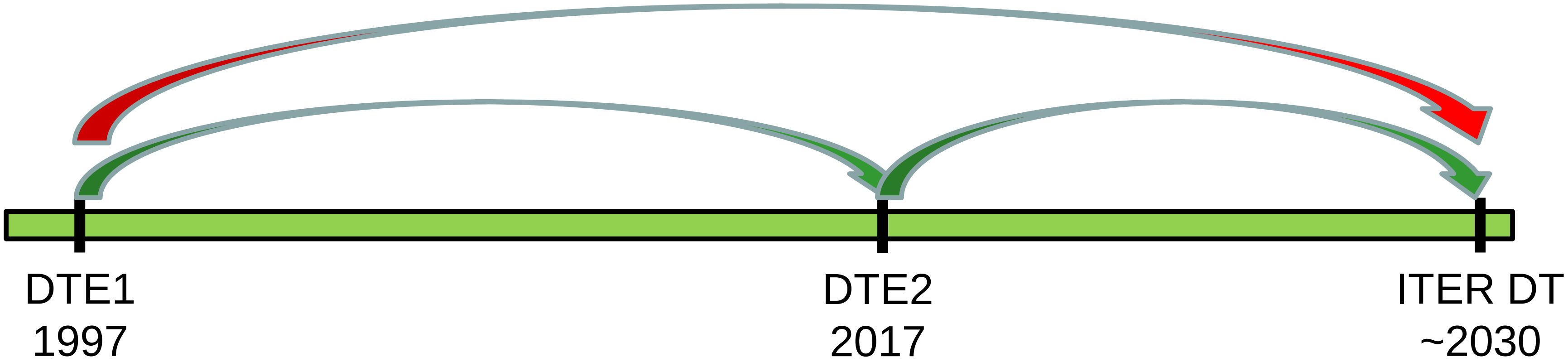
Possible longer term plans for JET

Reference Scenario:



Alternative Scenario:

Conclusion: We "must do" DT experiments in JET



2.5×10^{20} - 14 MeV budget
CFC – wall
21 MW – NBI
Transient performance
Diagnostics: 10cm resolution, every 50-250 ms
20 g – tritium in AGHS
Long term retention Activation samples

1.7×10^{21} - 14 MeV budget
Be/W - wall
35 MW - NBI
Stationary plasma conditions
Diagnostics: ~2cm resolution, every 1-20 ms 14 MeV calibration
60 g – tritium in AGHS
Long term retention Activation samples Neutron streaming - damage