Development of disruptions in the presence of the ITER-like wall at JET

*Peter de Vries and JET EFDA contributors**

Theory and Modelling of Disruption Workshop

Princeton 16-19 July 2013

**F. Romanelli et al, Fusion Energy 2012 (Proc. 24rd IAEA Conf., Deajeon, 2012) IAEA Vienna.*

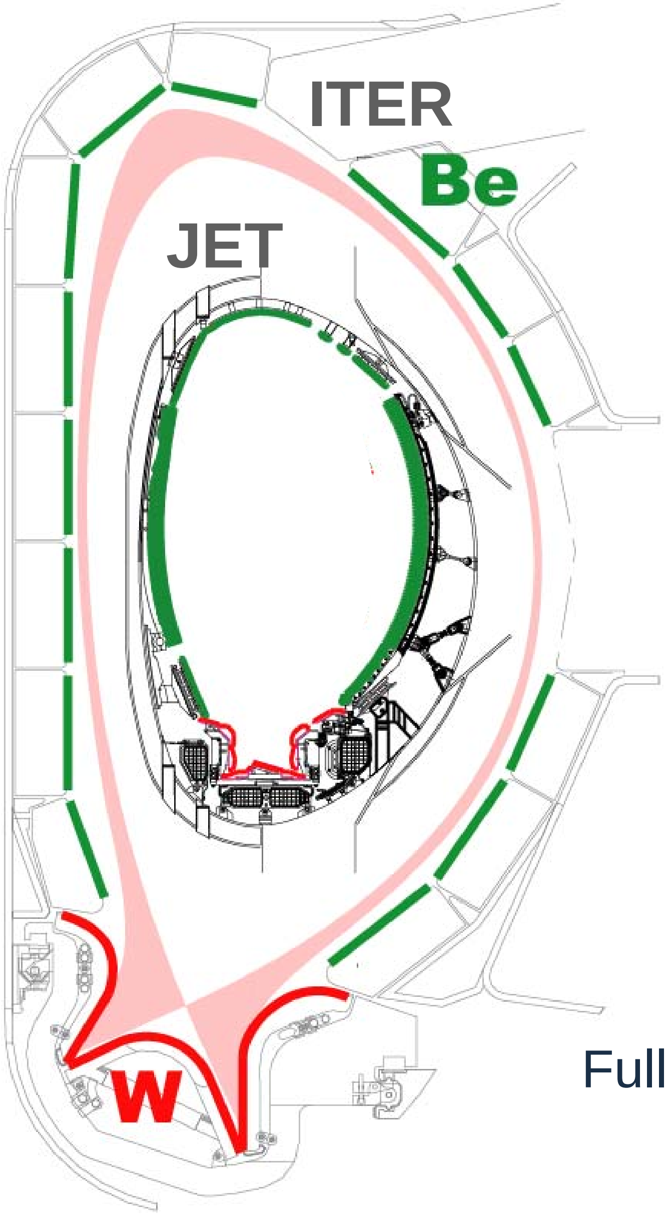
Motivation for disruption studies

- The occurrence of Tokamak disruptions is a key issue for ITER as the thermal and electromagnetic loads due to these events could restrict its operational capabilities.

- Hence, disruptive events should be avoided or their impact should be mitigated.

- In these aspects the recent replacement of carbon plasma-facing components with a **metallic wall** provided a new challenge to the operations at JET.

The new ITER-like wall (ILW) at JET



Installed 2010-2011 at JET

Bulk beryllium **Be** main chamber

Full tungsten **W** divertor: bulk and coated CFC

First operation: August 2011 – July 2012

Disruptions and the ILW

- ITER-like wall (ILW) ➔ Be main chamber and W divertor
  - Melting for Be: ➔ 20MW $s^{+1/2}$ m^{-2} or 20MJ $s^{-1/2}$ m^{-2}
  - Damaging W: ➔ 50MW $s^{+1/2}$ m^{-2} or 50MJ $s^{-1/2}$ m^{-2}

- For example the Be melt limit (1285°C) can be reached for:
  - Thermal energy quench of 1MJ in 2.5ms deposited on $1m^2$.
  - Magnetic energy quench ($\frac{1}{2} \cdot L \cdot I_p^2$) of 9MJ ($I_p$=2MA) in 50ms on $1m^2$
    - Assumes 50% of the magnetic energy is coupled back via transformer action into toroidal conductors (vessel, PF coils) and the remainder is **all conducted** to the wall area of $S=1m^2$
    - In reality however for disruptions with C PFCs a large fraction of the remaining energy is radiated (near 100%)

Outline of this presentation

- The influence of the ILW on the disruption impact.
  - ❖ The ILW affected the physics of the disruption process making it less well defined but it also enhanced heat loads to the plasma facing components (PFCs) and the forces on the vessel.

- Disruption rate indicates how well disruptions are avoided.
  - ❖ It will be shown that the disruption rate rose with the ILW

- Disruption causes and the ILW
  - ❖ The ILW influenced the density limit and density control but disruptions due to high-Z impurities dominated during the first operations with the ILW (2011-12)
  - ❖ Understanding of the main disruption causes provide information on how to detect problems or how to avoid them.

Outline of this presentation

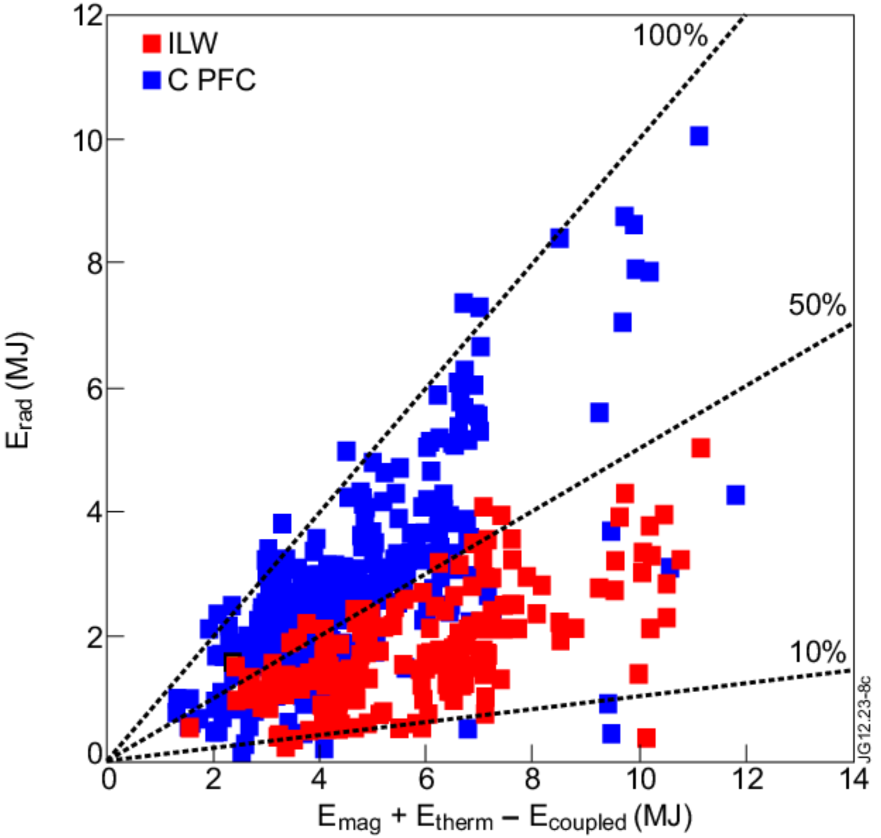
- The influence of the ILW on the disruption impact

- Disruption rate

- Disruption causes and the ILW

Less energy radiated during ILW disruptions

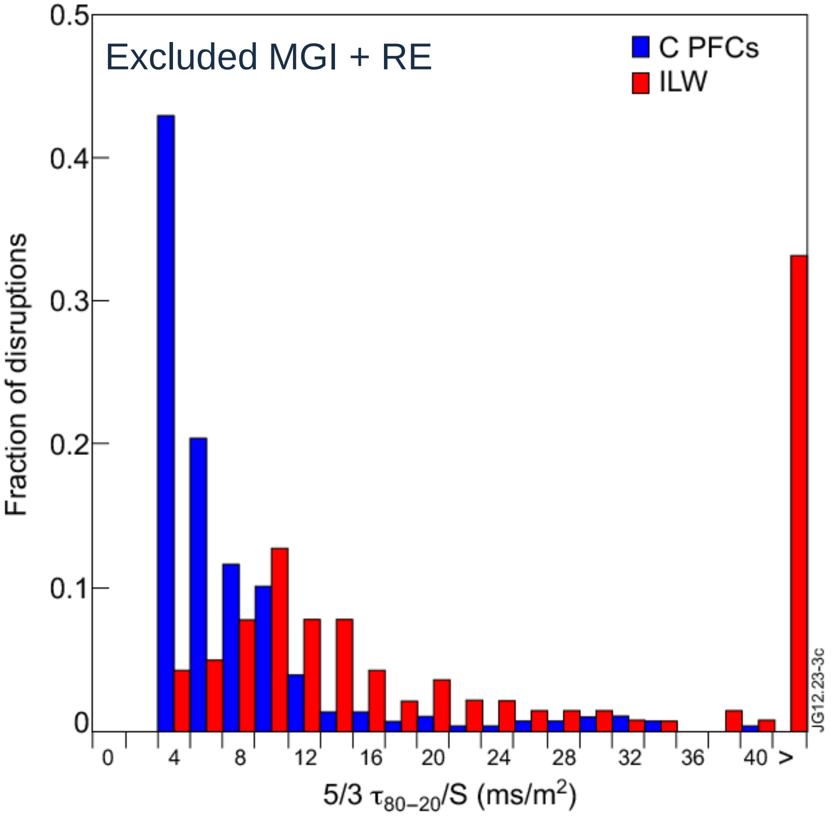
- Less energy radiated with the ILW[1]
  - Higher post-thermal quench temperatures with ILW
    - For C PFCs it settled at $\langle T_e \rangle$ temperatures at which C radiates (~10eV)
    - For the ILW one finds higher temperatures (10s eV up to several 100s eV)
    - For ILW the fraction of energy that is radiated is lower (<50%)



[1] M Lehnen, et al, Journ. Nucl. Mat. **438** (2013) S102

Consequences of lower radiation

- Higher post-thermal quench temperatures with ILW thus Longer current quench times[1] ➔ L/R time $\propto Z_{eff}^{-1} \langle T_e \rangle^{3/2}$
  - ☺ Lower induced electric fields which affects runaway generation[2]
  - ☹ A larger fraction of the total energy can be conducted to PFCs
  - ☹ Higher vessel reaction forces

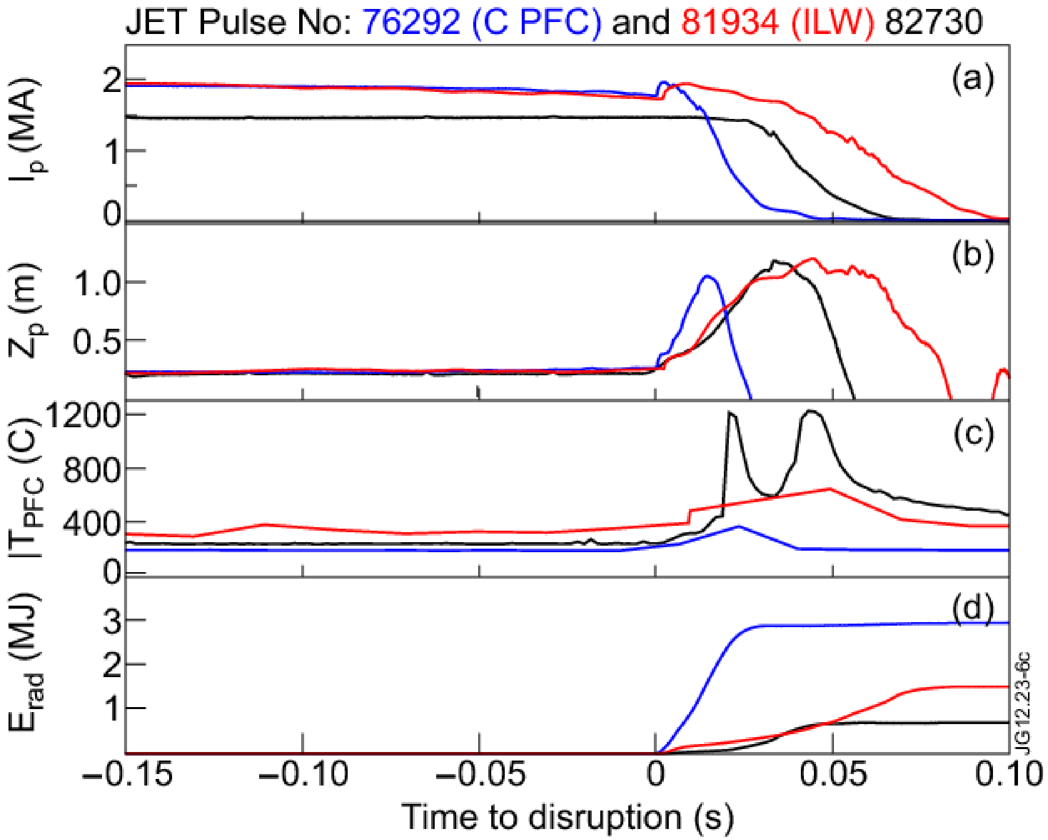


[1] J Wesley, IAEA FEC 2006

[2] G Papp et al., submitted to Nucl. Fusion (2013)

Higher temperatures on PFCs with the ILW

- For the ILW the slower current quench ➔ reduces power load
- But a smaller fraction is radiated ➔ larger conducted energy[1]



Longer current quench

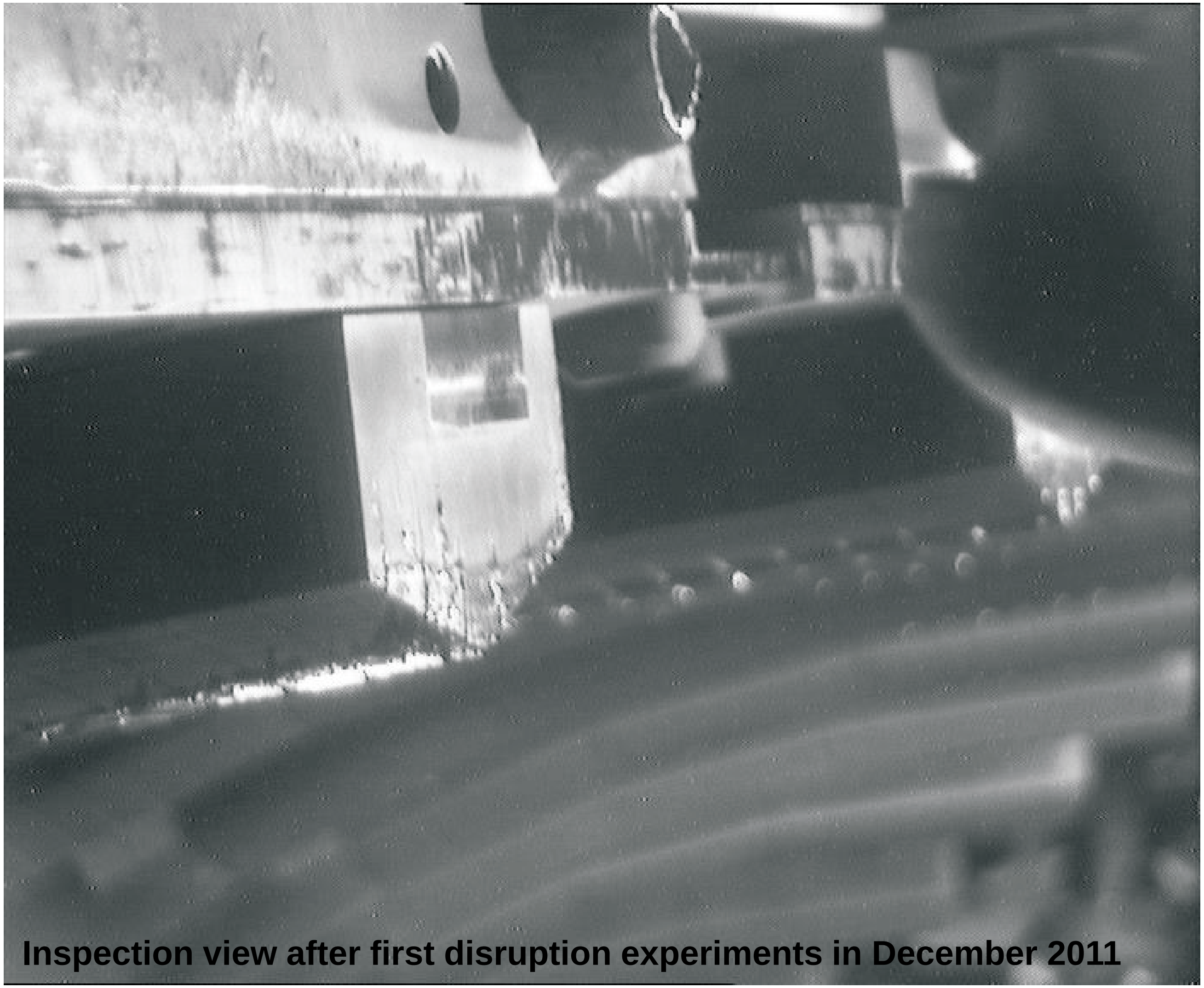
Higher ΔT_{PFC} with ILW

Less energy radiated

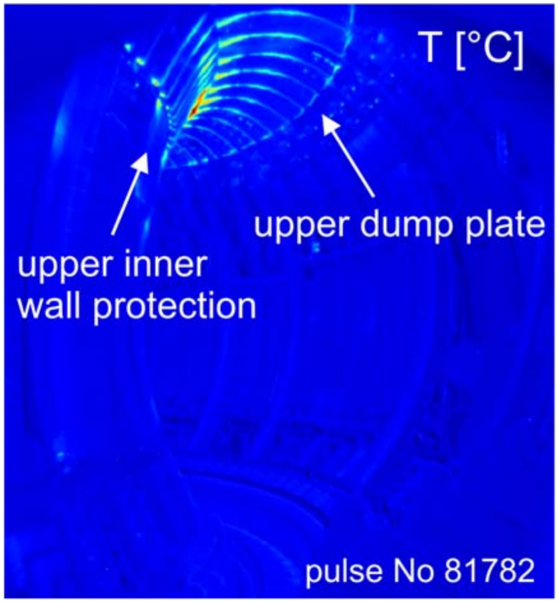
[1] M Lehnen, et al, Journ. Nucl. Mat. **438** (2013) S102

Melt damage after disruptions

- Melting associated with VDEs at low I_p=1.5MA (E_{mag}=6MJ)

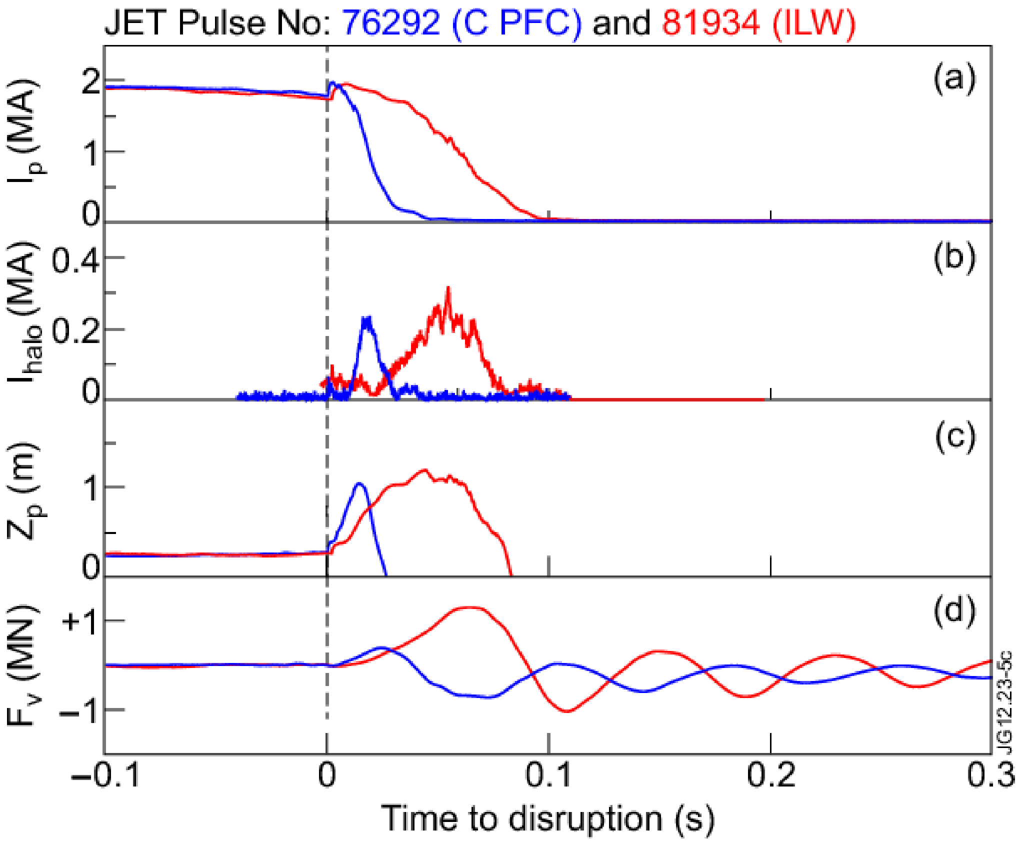


Inspection view after first disruption experiments in December 2011



Larger vessel reaction force

- The longer current quench resulted in slightly larger halo current fractions, but moreover significantly increased the swing or reaction force on the vessel[1,2]



Slightly higher I_{halo}

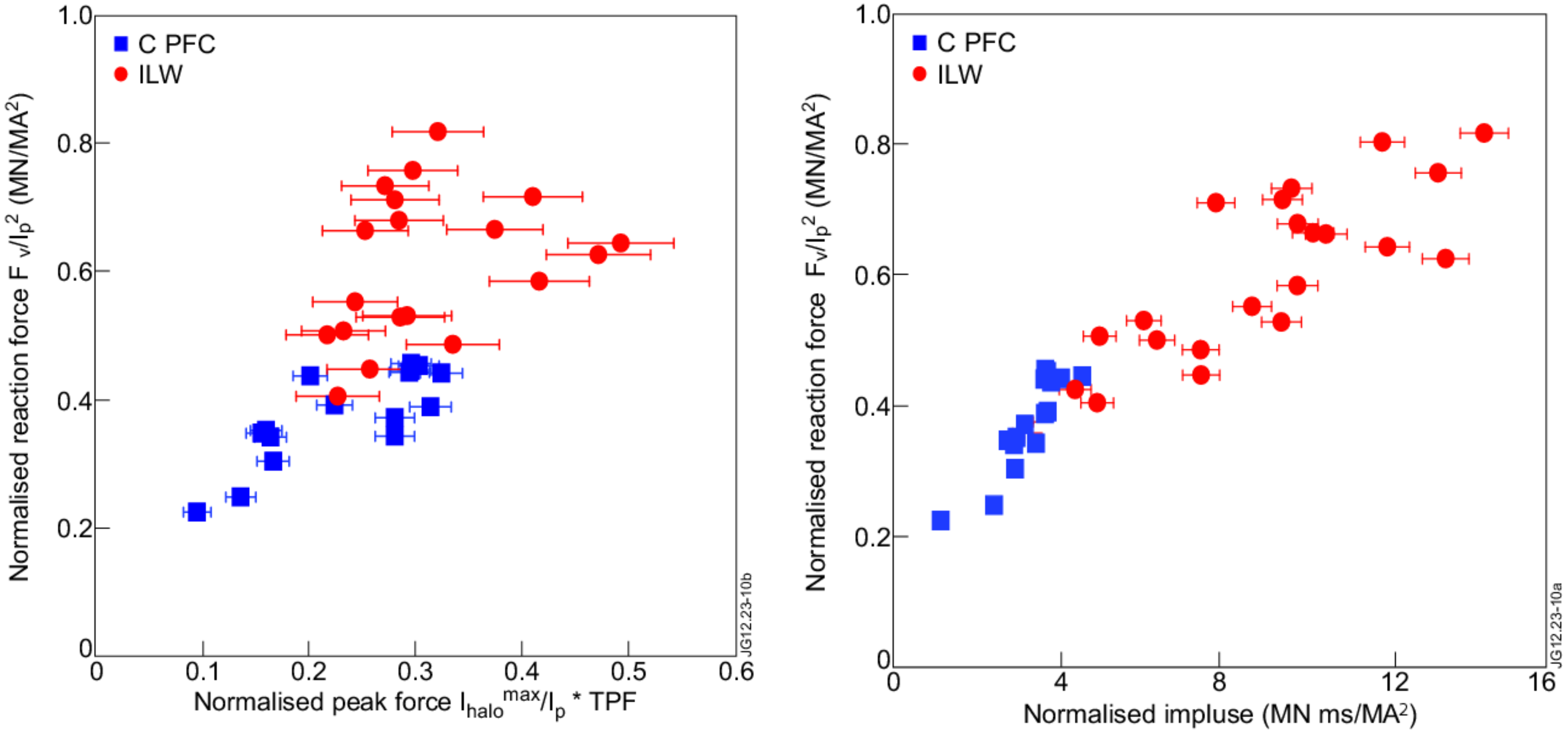
Much larger swing (F_v)

[1] P.C. de Vries, et al, Plasma Phys. Control Fusion **54** (2012) 124032

[2] M. Lehnen et al., Nucl. Fusion (2013) accepted

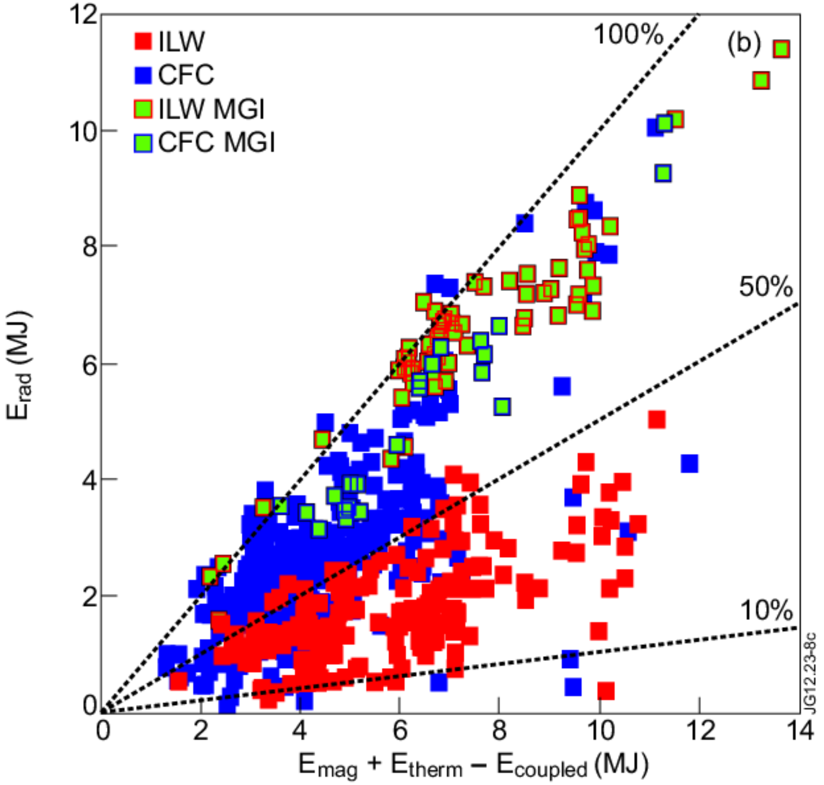
Reaction force F_v scales with impulse

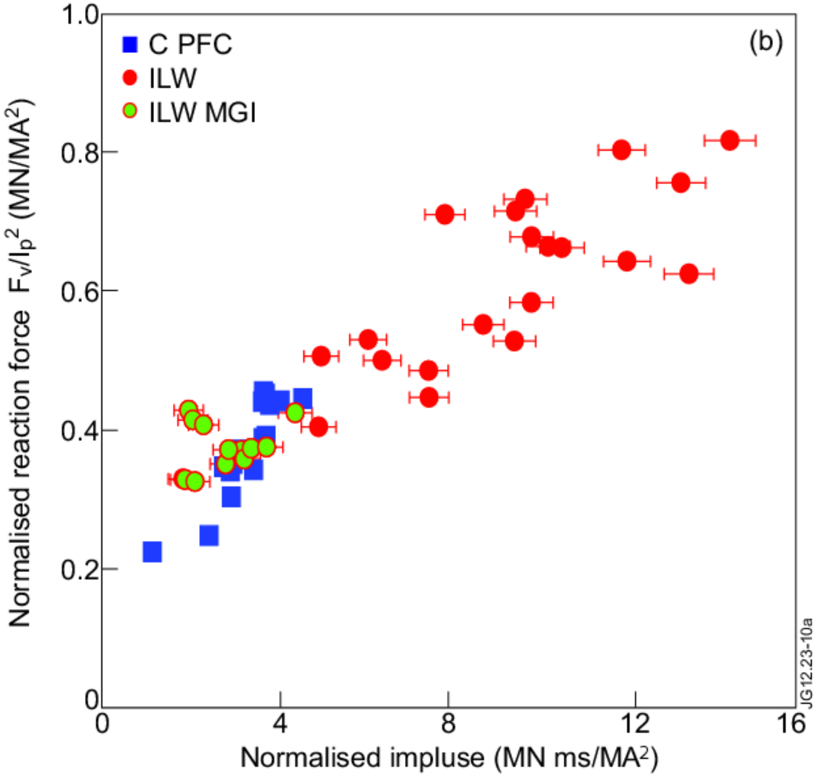
- For the same halo current fractions ➔ wide range of F_v
- But F_v scales with the time integrated halo force (impulse)



Need for mitigation with the ILW

- Low radiation fractions and high vessel reaction forces made disruption mitigation a necessity at JET (for I_p>2.5MA)
  - Massive gas injection (MGI) was used as an **active** mitigation tool at JET
  - MGI reduces current quench time, F_v and increases E_{rad} (F_{rad}>85%).





[1] M Lehnen, et al, Journ. Nucl. Mat. **438** (2013) S102

Outline of this presentation

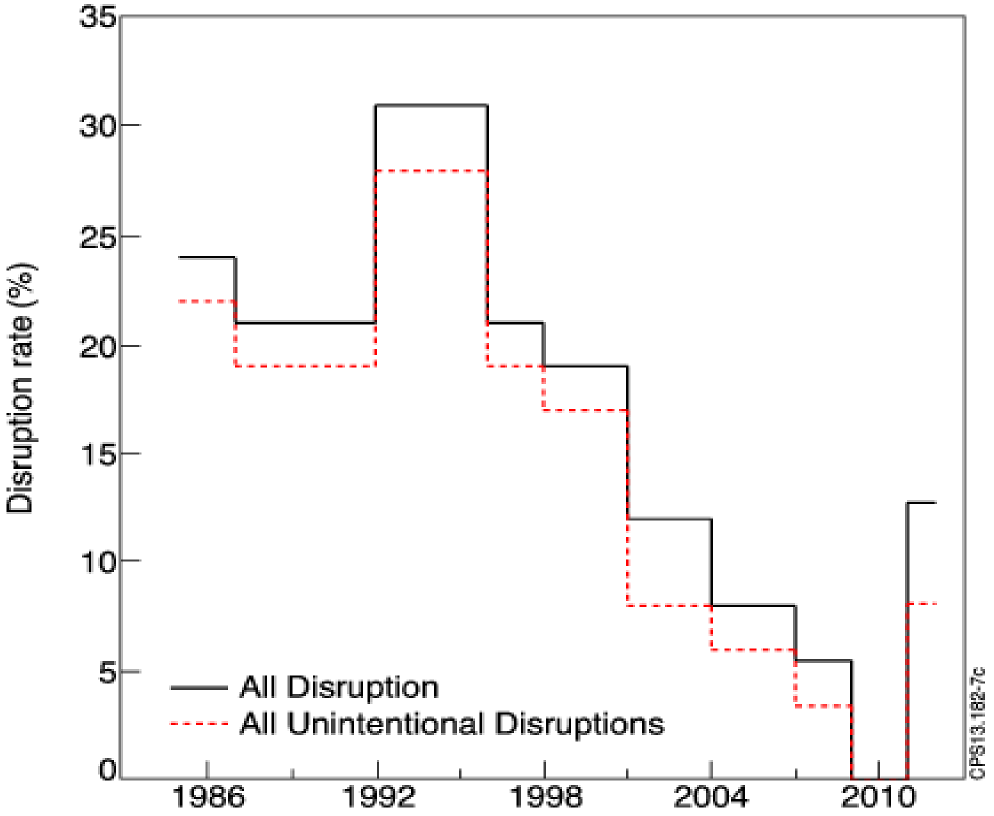
- The influence of the ILW on the disruption impact

- Disruption rate

- Disruption causes and the ILW

The JET disruption rate

- A marked decrease of the disruption rate was found over the last decade to levels as low as 3.4%[1].
  - This trend has been broken with the start of ILW operations in 2011
  - Disruptions are here defined as those events with $dI_p/dt > 5MA/s$



More intentional disruptions

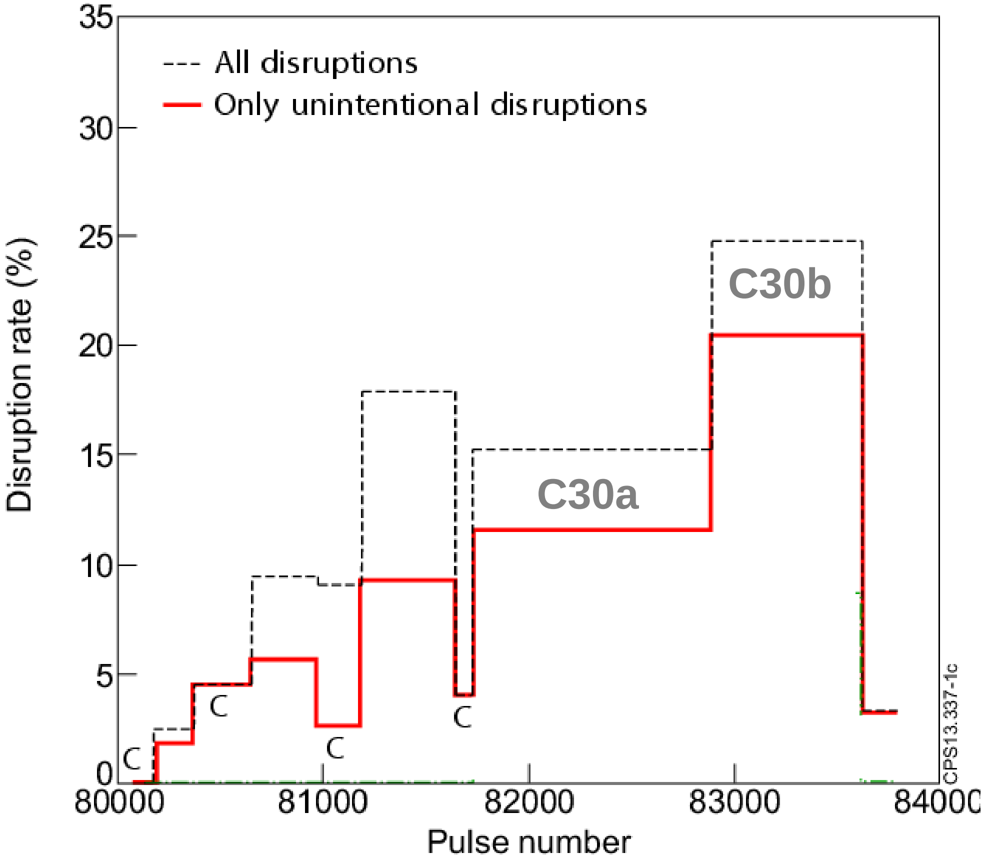
~10% with ILW

---

[1] P.C. de Vries, et al., Nucl. Fusion **51** 2011 053018

Disruption rate during first ILW operations

- Disruption rate rose during ILW campaigns
  - Only about half a year H-mode operations ➔ still building experience
  - Low disruption rate in C30c (repeat of standard ELMy H-mode)
  - Why did the disruption rate increase? ➔ disruption causes



C30c: 3.3%

C30c: Repeating 150x same H-mode discharge

Outline of this presentation

- The influence of the ILW on the disruption impact
- Disruption rate
- Disruption causes and the ILW

Density limit physics changed with ILW

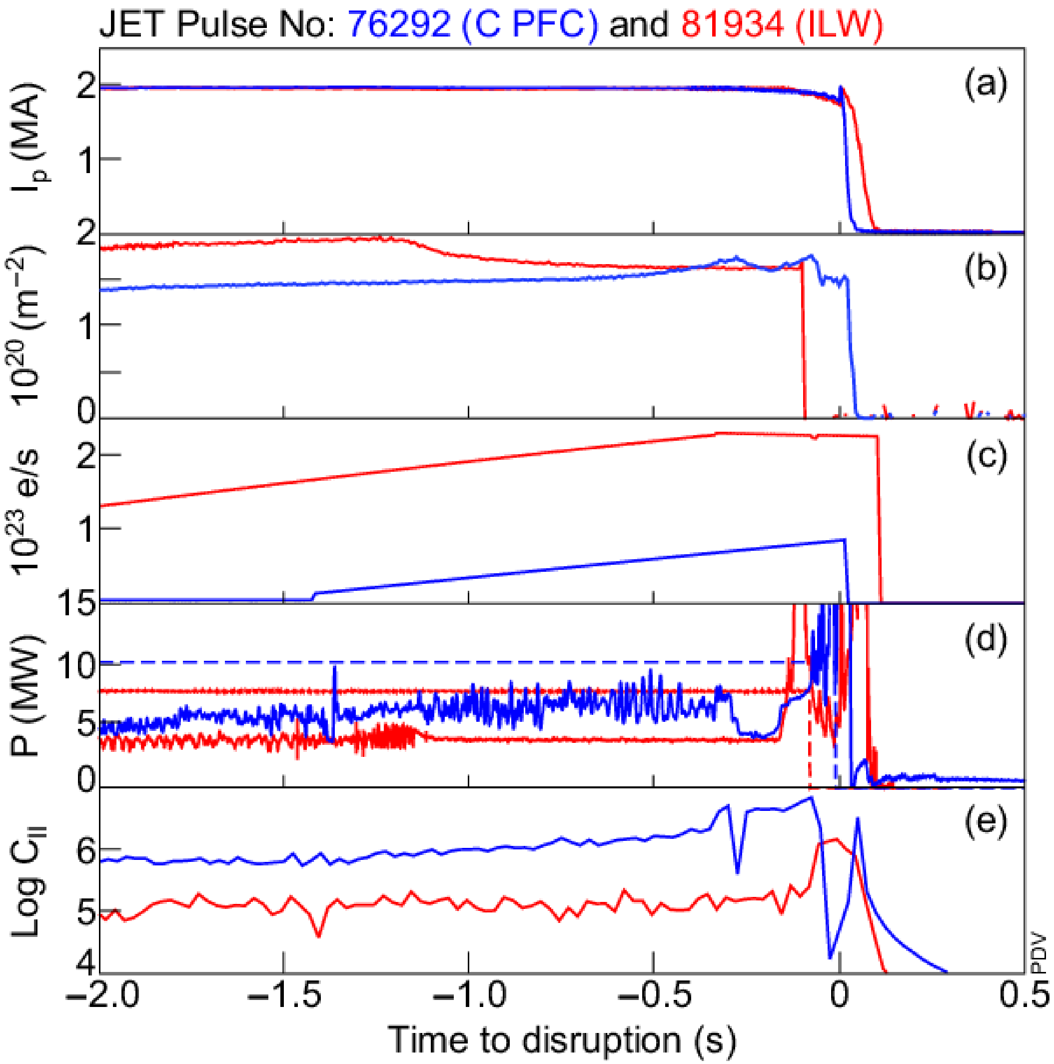
- The density limit restricts the achievable line-average density for Tokamaks,
  - The underlying physics is often related to radiation instabilities at the plasma edge.
  - Thus a change in wall material may affect the physics of this limit[1].

- Physics involved are in an H-mode density limit disruption:
  - H to L-mode back transition
  - Divertor detachment
  - Impurity radiation and recycling losses
  - Formation of X-point and inner-wall MARFEs
  - Onset of MHD activity that leads to a disruption

[1] A Huber, Journ. Nucl. Matt **438** (2013) S139

Comparing the C PFC and ILW density limit

- More gas needed to trigger a density limit disruption with ILW



Slower current quench

Earlier H-L back transition

At higher density with ILW

Development slower

More gas needed with ILW

Lower radiation with ILW

C concentration lower

[1] A Huber, Journ. Nucl. Matt **438** (2013) S139

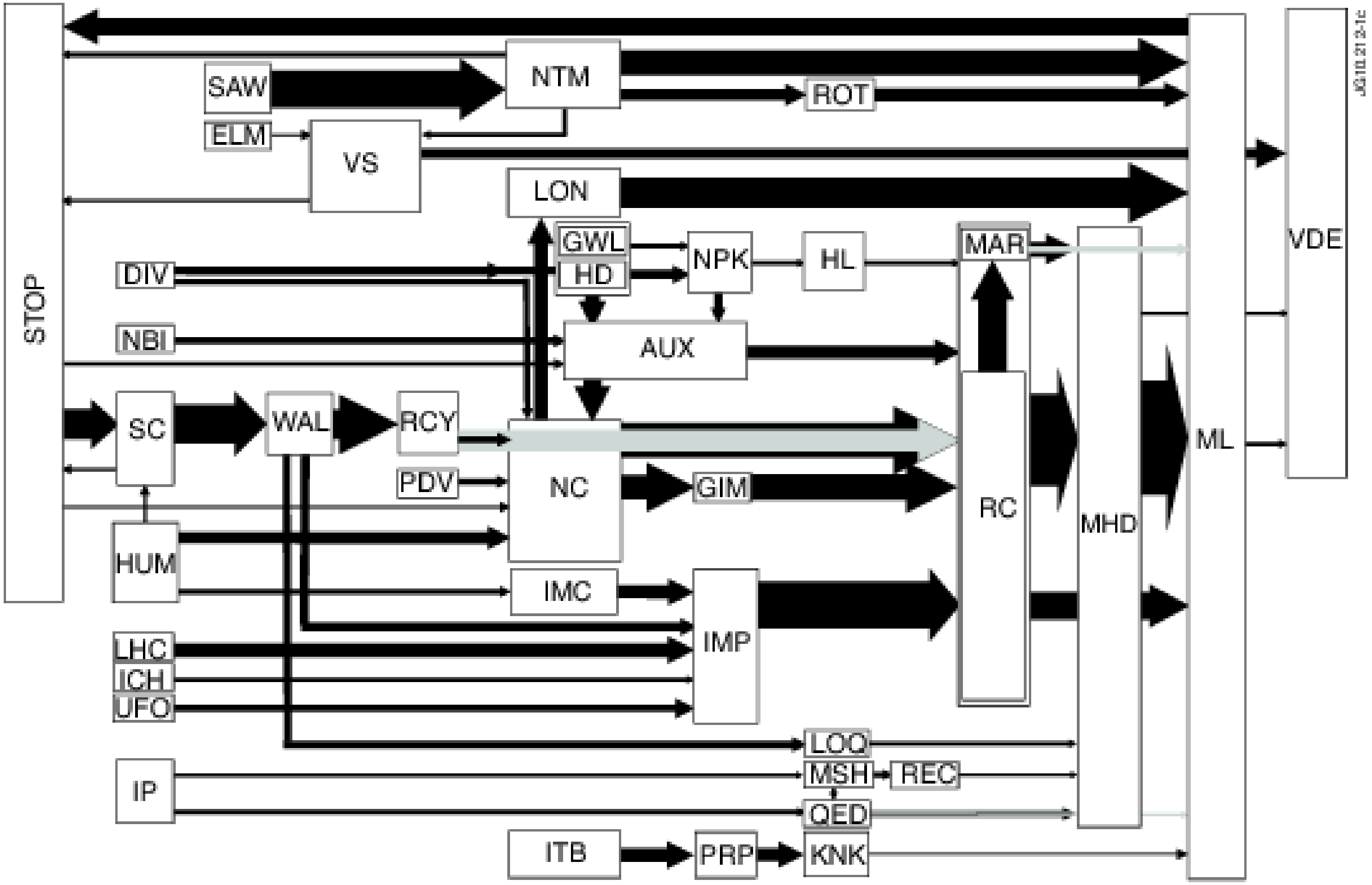
Cause analysis[1]

- Determine path of each disruption
  - Contains a number of possible steps or ‘problem nodes’
    - Multiple paths are possible but not counted here
  - Combining all disruptions gives an average disruption **flow pattern**
  - The trigger or initial node is the **root cause** of the disruption
  - Disruptions can be **classified** according to if they follow **similar paths** in the disruption scheme / flow pattern.

[1] P.C. de Vries, et al., Nucl. Fusion **51** 2011 053018

Cause analysis

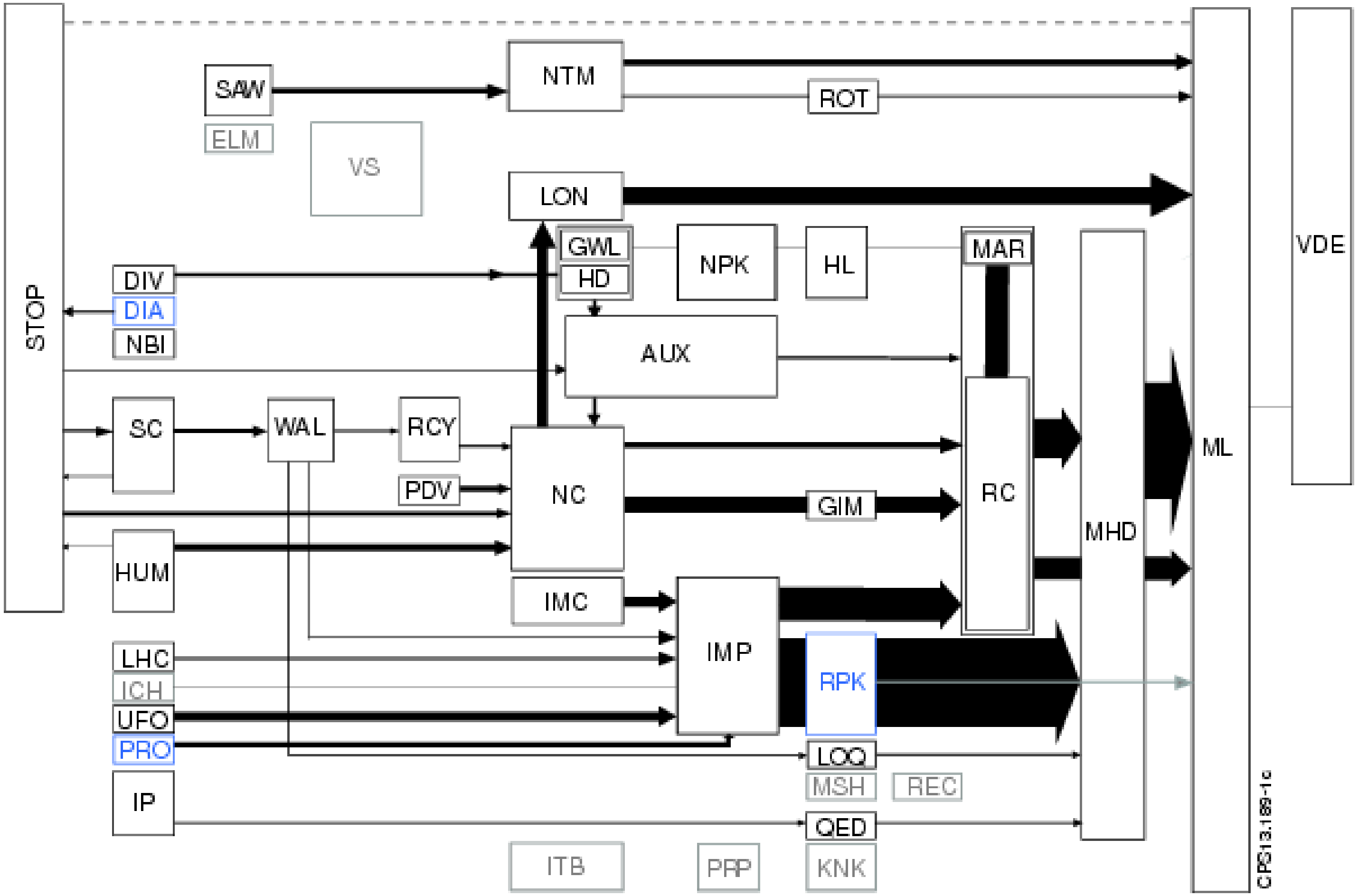
- Unintentional disruptions 2000-2010 C-wall[1]
  - Long period of 10 years and: 1654 cases



[1] P.C. de Vries, et al., Nucl. Fusion **51** 2011 053018

Cause analysis

- Unintentional disruptions 2011-2012 ITER-like-wall
  - Period of just less than 1 year: 274 cases



MHD ➔ ML kept the same width as in previous scheme

Certain nodes (grey) were not passed anymore but a few new nodes added (blue)

Cause analysis

- The comparison with recent carbon wall operations shows:

☺ Absence of disruptions due to strong ITB ← not ITBs with ILW (yet)

☺ No disruptions due to VS control issues ← VS control upgrade

☺ Reduction of problems related to wall-proximity and recycling jeopardizing the density control

☺ No disruptions during emergency shut-downs ← improved shut-down

😐 Occurrence of disruptions due to NTMs unchanged

☹ Failure of density control with ILW can quickly leads to too low density yielding error field modes

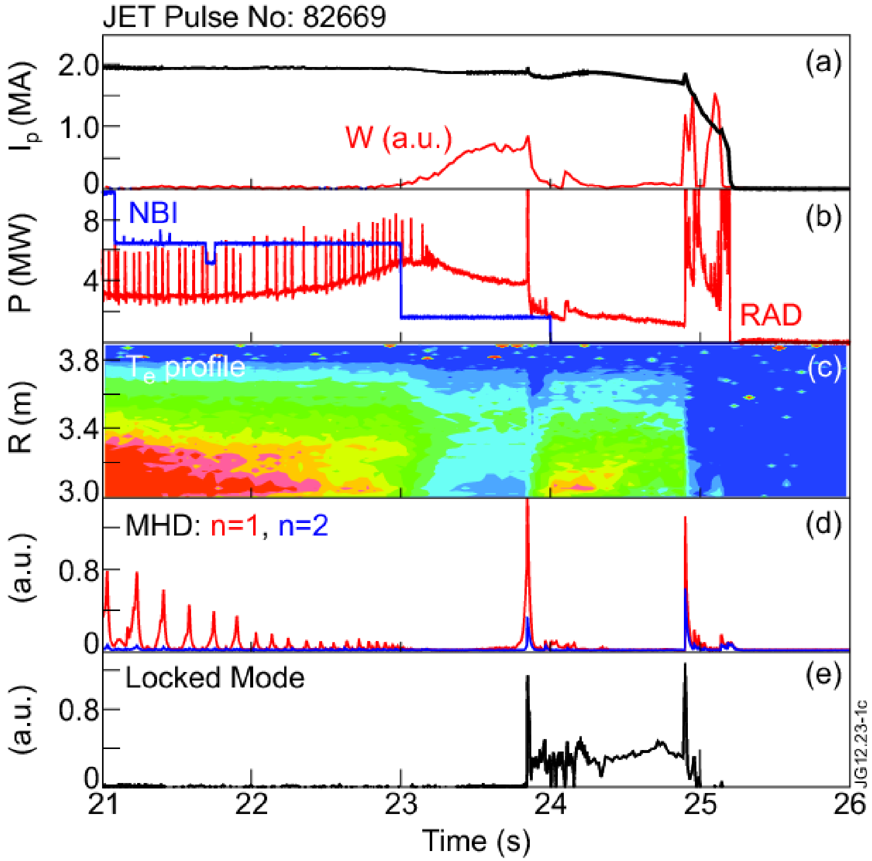
☹ Slightly more disruptions due to transient impurity influx events (=UFO's)

☹ 48% of all disruptions was due to due to too high core radiation

To reduce the disruption rate avoidance of this type of disruptions is imperative

Disruptions related to high core radiation

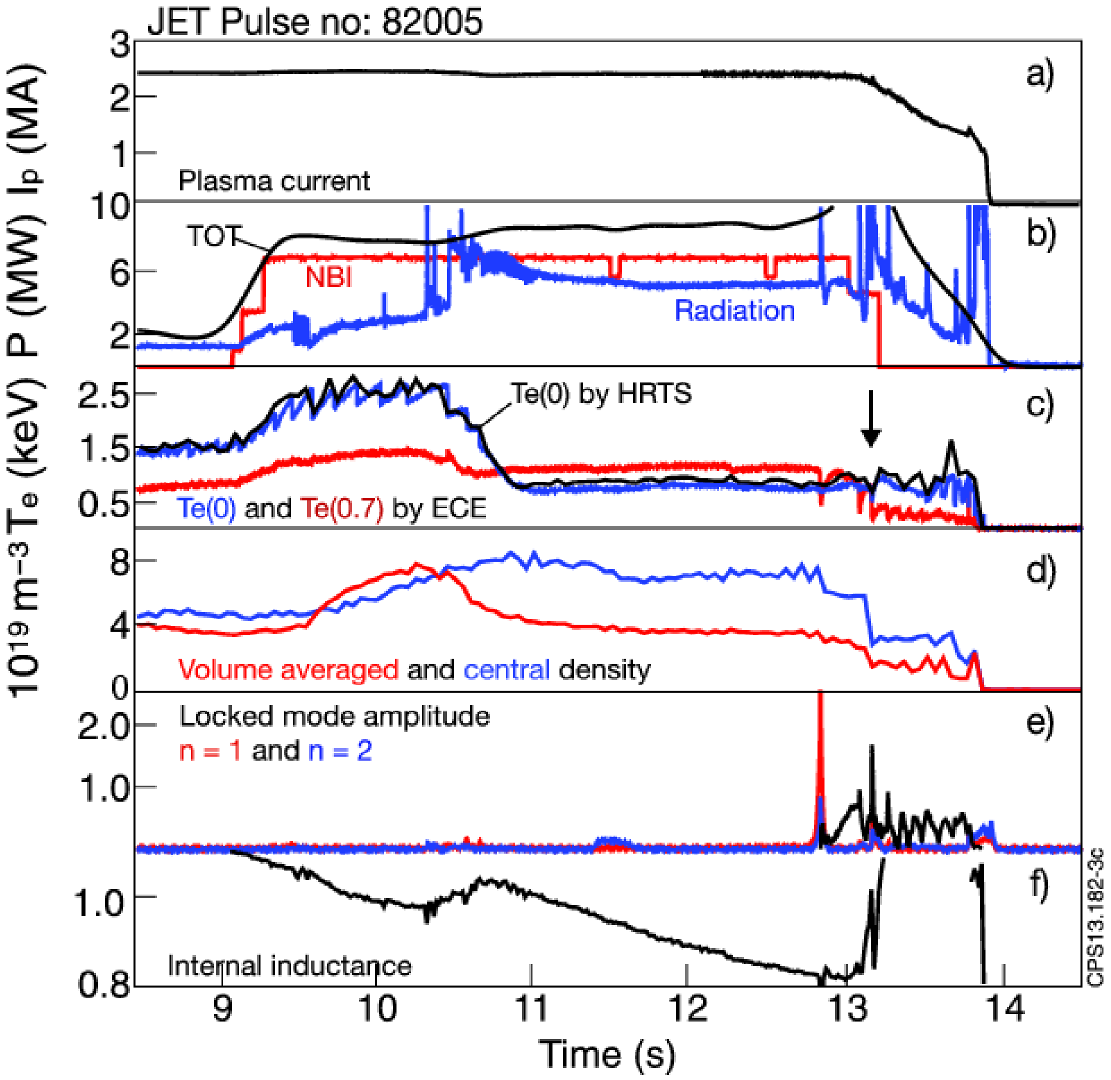
- ‘Root cause’: the radiation increases
  - Either ‘slow’, i.e. on transport time scales ➔ accumulation of W
  - Or ‘fast’ (In 30% of the cases) ➔ likely a fast influx of material
  - Not during main heating phase but radiation remains high in the termination or H-mode exit phase ➔ dominant case in C30



Example of slow increase

What happens?

- Example of ‘fast’ increase of radiation (sudden strong influx?)



P_{rad} (suddenly) increases (10.5s)

but P_{rad} remains **below** P_{tot}

Temperature profile hollow

Sawteeth disappear

Strong density peaking

But density well below n_{GW}

Strong degradation of W_{therm}

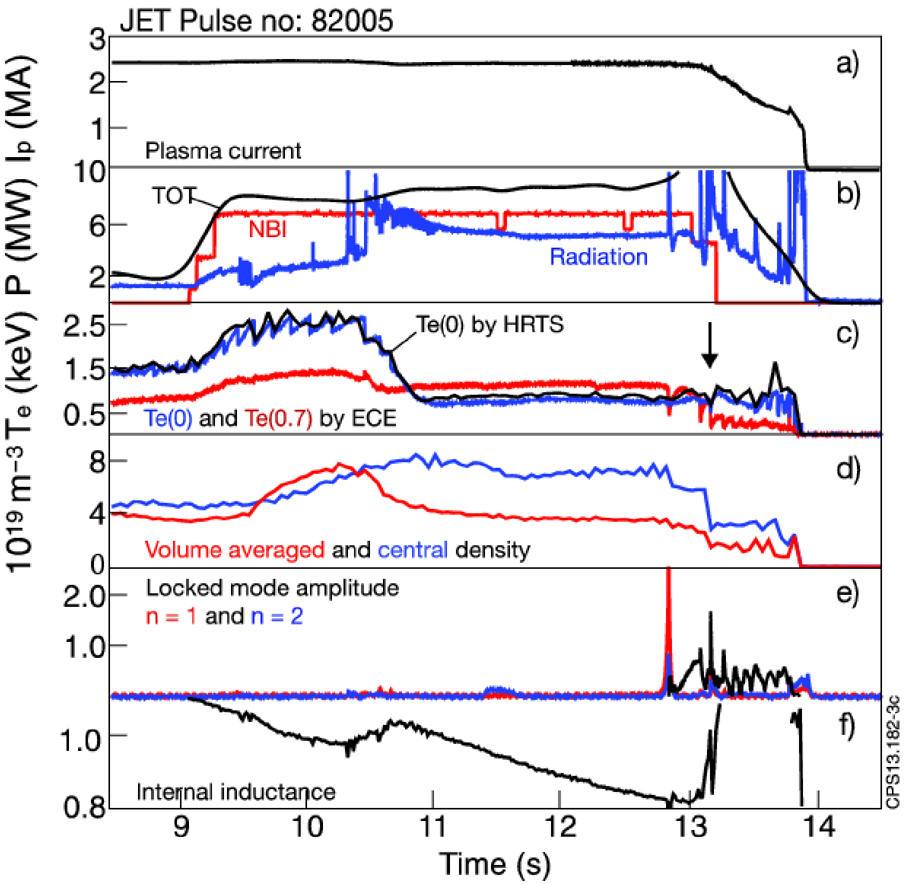
n=1,n=2 MHD activity ➔ML

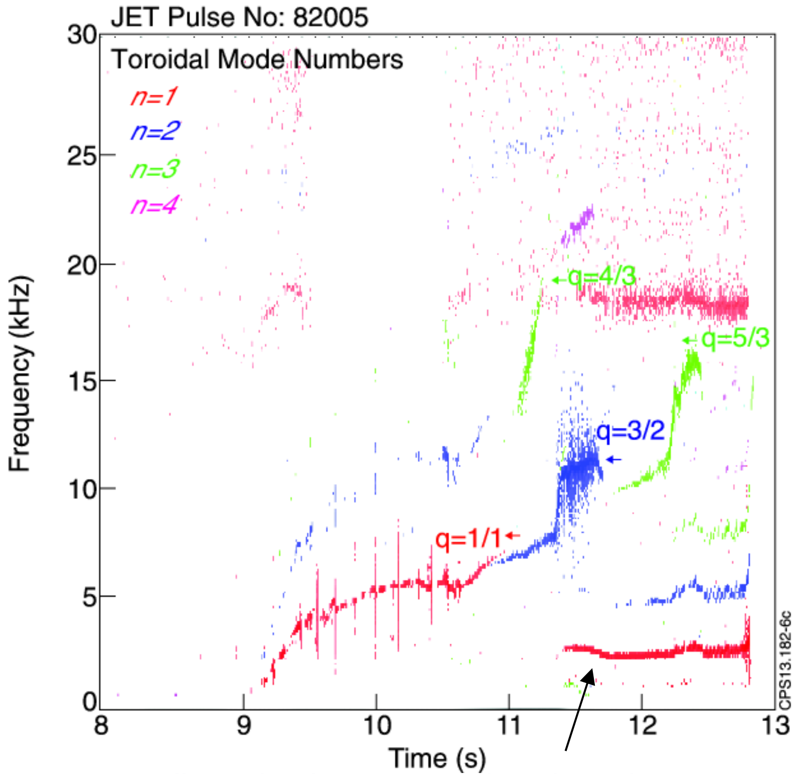
n_e and T_e profiles settle

But li and q(r) keep changing

What happens?

- Changes in T_e profile slowly changes the q profile
  - Central q increases, sometimes the profile may become hollow
  - Core MHD frequencies chirping up, but it is the appearance of low frequency (few kHz) n=1 that finally locks and causes disruptions





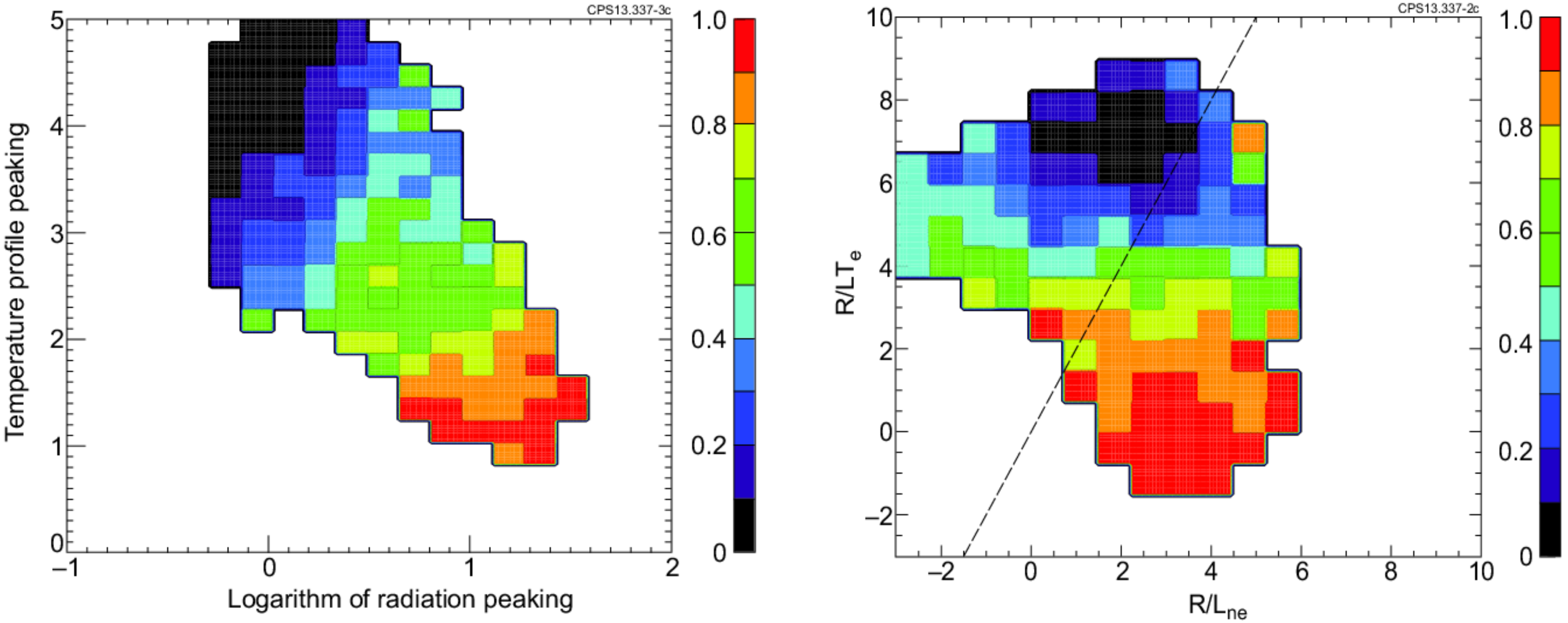
Precursor to disruption is low f n=1 (m=?) mode

Spins up just before crash (in some cases)

Low frequency and constant➔ mode located outside

When do problems appear?

- Disruptivity[1]:
  - To take very slow development into account the ‘disruptivity’ is here defined as the chance that a plasma in a specific state eventually disrupts
  - Will the plasma *always* disrupt (i.e. have a fast current quench)?



[1] P.C. de Vries, et al., Nucl. Fusion **49** 2009 055011

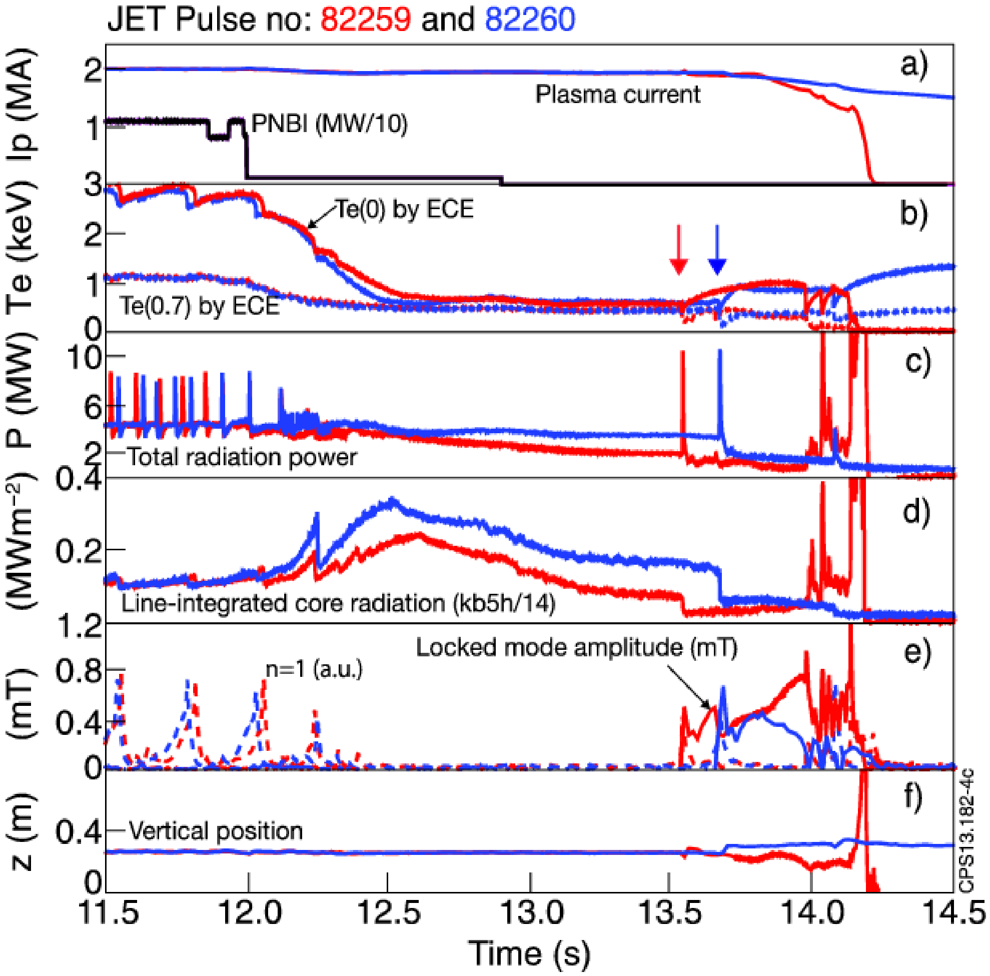
What to do about them

- Avoidance
  - The ‘root cause’ is less well understood
    - How to avoid the fast influx of material?
    - Apply central electron heating avoid accumulation ➔ AUG
    - Problems often develop during the exit from H-mode which is a very dynamic and less well controlled phase.

- Mitigation of effects
  - The development is very slow ➔ q profile modification
    - Thus ample time to detect problem and devise mitigating strategies
  - Slow-down q profile development and MHD destabilization
    - Current ramp-down to counter-act q-profile broadening
    - Apply central electron heating (which also acts on impurity transport)

Some disrupt, others not!

- Similar problems do not always result in a **real** disruption although a thermal quench mostly takes place
  - Radiation drops ➔ W ejected from core by quench ➔ T_e increases!
  - Disruptivity is determined by the post-thermal quench stability

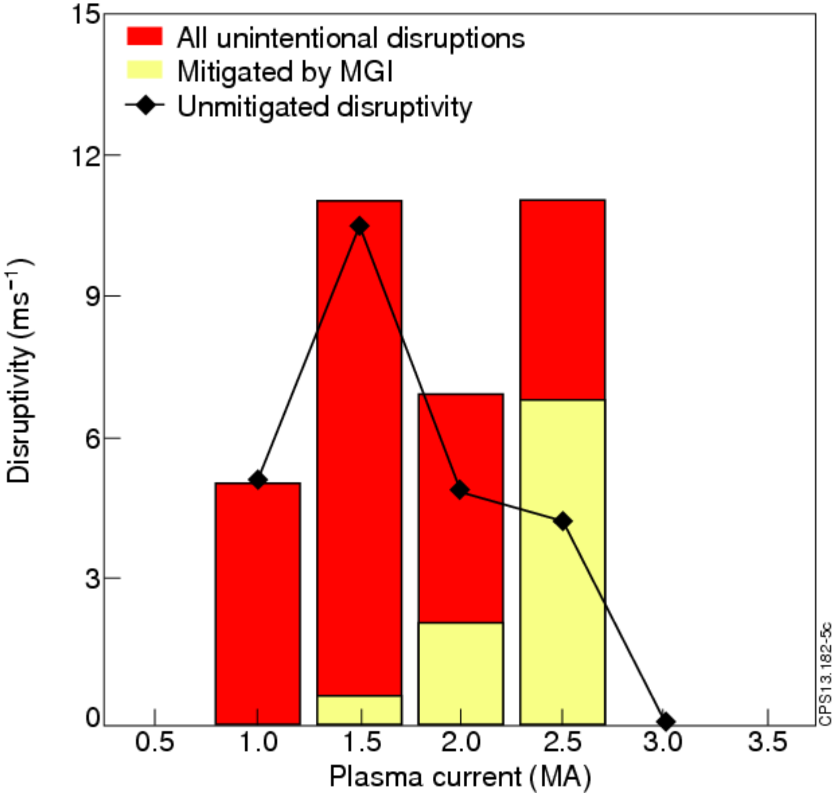


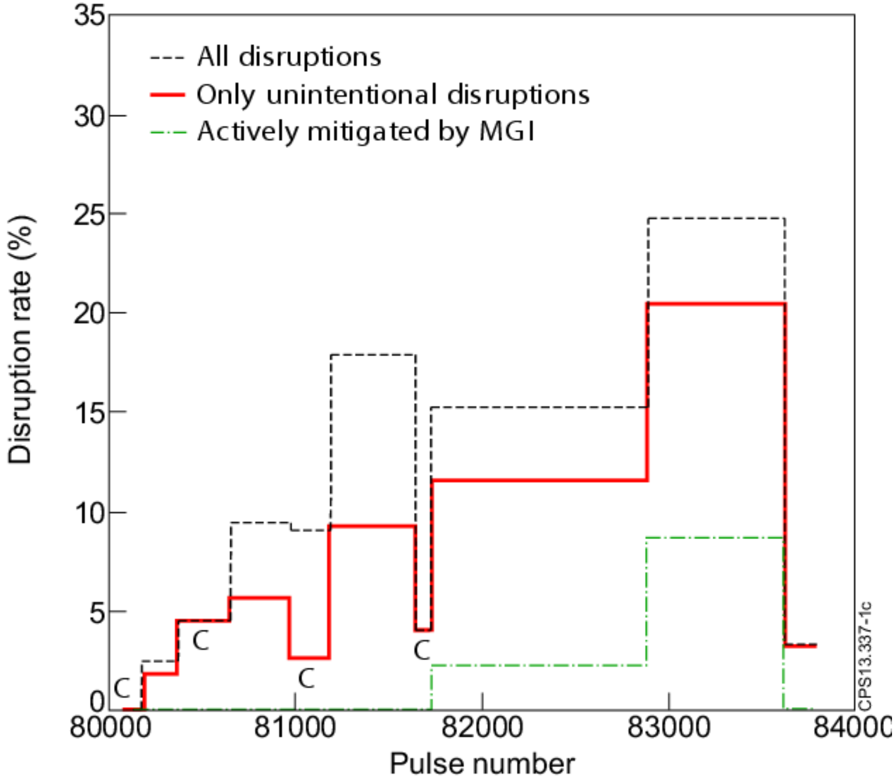
Some disrupt, others not!

- The ambiguity of the ILW disruptions complicates the calculation of the disruption rate, disruptivity or the assessment of disruption predictors.
  - What do we count as a disruption?
  - At JET those that have a fast current quench and VDE and those will impact on the PFCs and exerts forces on the vessel. Moreover, the degradation of thermal energy prior to the thermal quench makes that the later will have little impact (on heat loads)
  - If a disruption is defined as an event that has a thermal quench, higher disruption rates are found.

Impact of MGI on disruption rate

- The use of MGI as active protection against disruption impact affected the disruption rate.
  - Below I_p<2.5MA some cases do not ‘disrupt’ = a fast I_p quench
  - Above I_p>2.5MA preemptive use of MGI enforced disruptions





Conclusions (I)

- Large influence of the ILW on the disruption process it self
  - Lower radiation during the disruption
  - Higher temperatures after the thermal quench
  - Slower current quench and disruption events more ambiguous
  - Thus lower induced toroidal electric fields ➔ runaways
  - Large fractions of energy can be conducted to PFCs
  - Large vertical vessel forces

- Hence not only because tolerable heat loads on the ILW are reduced compared to the carbon wall, but also because the ILW affected the disruption process itself, active mitigation by means of MGI became necessary at JET.

Conclusions (II)

- Disruptions were more frequent during the first operations with the new ILW compared to recent carbon-wall operation.
  - The increase can be explained by the impact of the ILW on plasma behaviour requiring tuning and redevelopment of standard operation scenarios and control schemes ➔ especially impact on density control
  - Further operation is expected to reduce the number of disruptions.

- The predominant disruption cause with the ILW was high core radiation due to high-Z impurities.
  - The root cause (reason for imp. problem) is not always clearly understood
  - High Z impurity (transport) control is imperative to avoid such disruptions
  - These disruptions develop slow, yielding ample time to apply counter measures or mitigation schemes.

- The ambiguity of the disruption process with the ILW complicates the calculation of the disruptivity, disruption rate or the assessment of warning systems