Disruption

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Outline

What is the disruption?

Where disruption is probable to occurs?

What is the physical mechanism of the disruption?

How to avoid or mitigate the disruption?

What is disruption?

Disruption is a rapid loss of plasma confinement.

- The stored energy in tokamak is approximately proportional to L^5 (where L is a linear dimension of the plasma)
- The energy dissipated in the wall in this case proportional to L^3
- Conclusion: Doubling the size of the device (JET to ITER) increases energy load by one order of magnitude. If this energy is lost, we have problems….☹

PROBLEMS:

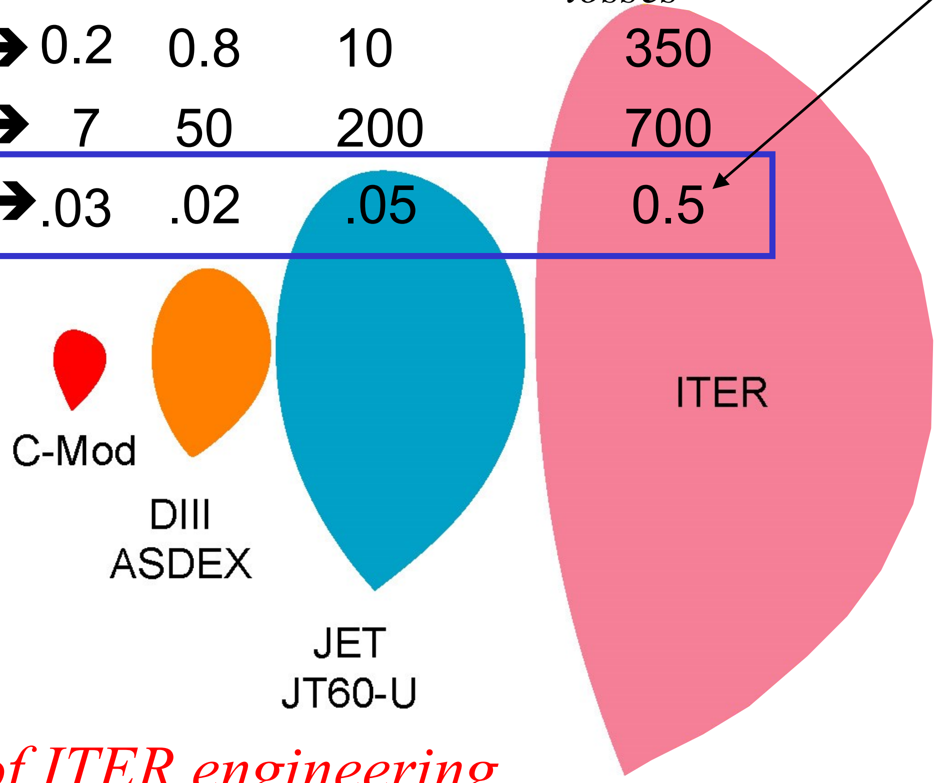
- Heat loads
- Mechanical loads

Disruptions get more severe in bigger tokamaks

In general local heat loads higher, due to conductive losses

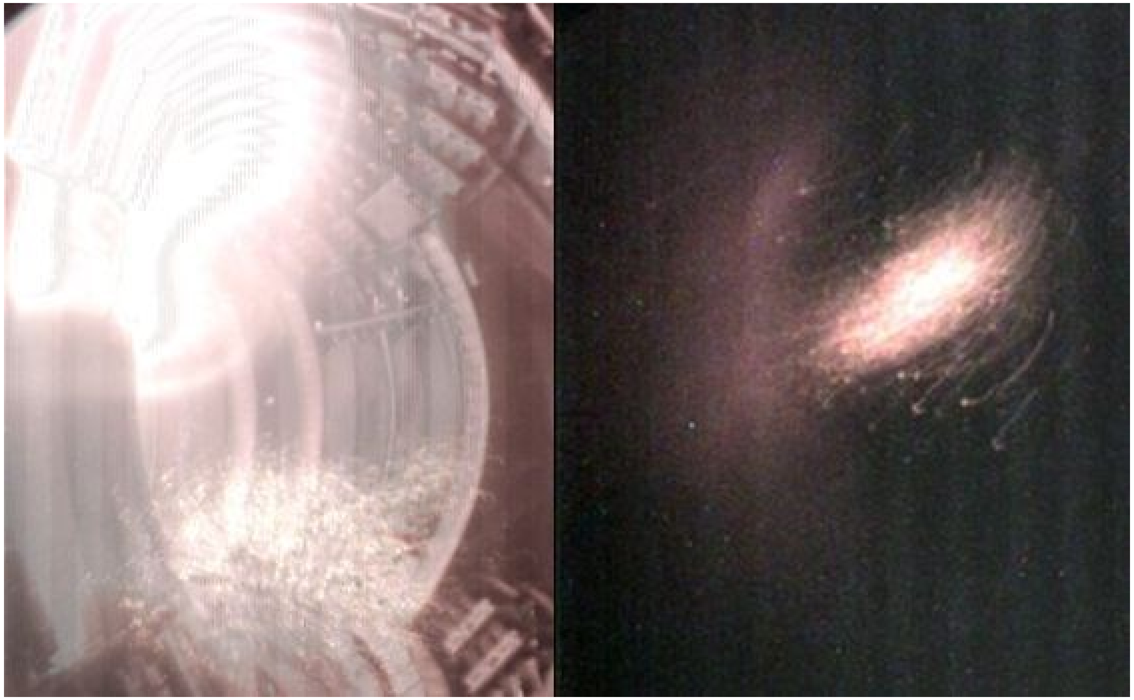
Plasma Energy W (MJ)	→	0.2	0.8	10	350
Surface Area A_{plas} (m^2)	→	7	50	200	700
W/A_{plas} (MJ/m^2)	→	.03	.02	.05	0.5

Perfect disruption mitigation



Disruptions main driver of ITER engineering

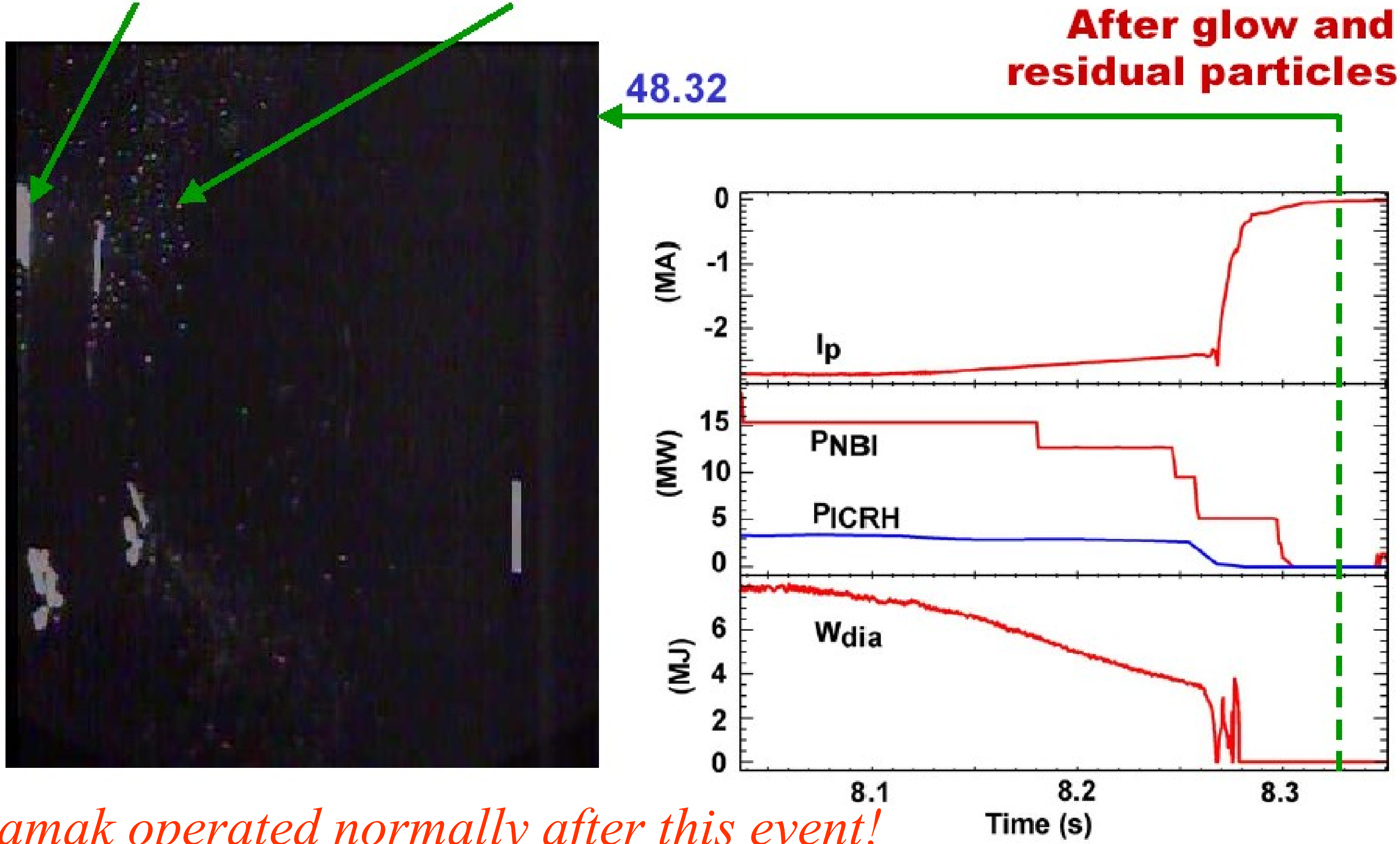
How disruption look like?



Pictures of JET during a disruption. A cloud of particles is visible in the vessel's lower half (left) and upper half (right).

It is clear that disruption is an extreme event which has to be avoided, at least in its most dangerous form.

The JET disruption



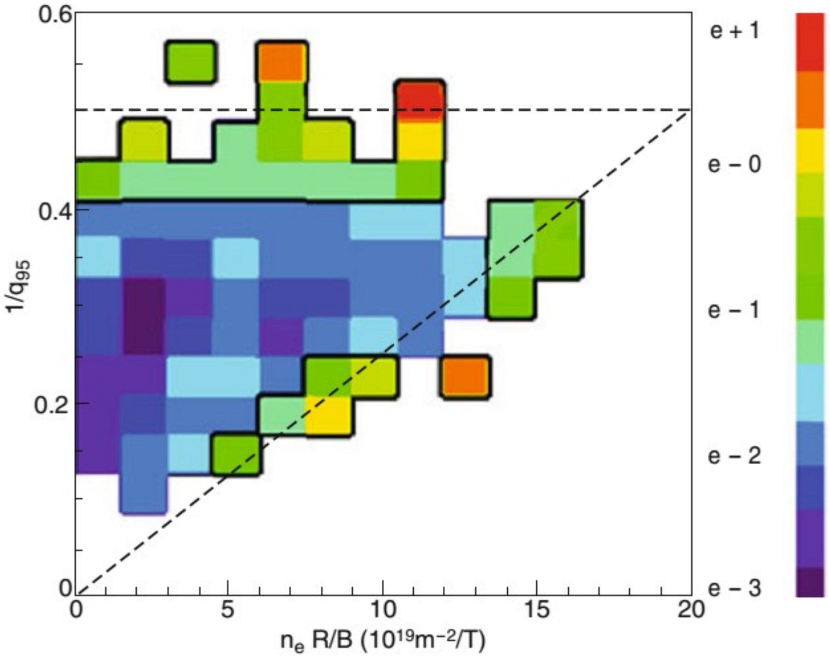
After glow and residual particles

Tokamak operated normally after this event!

Disruptions are a survivable event

- Tokamaks can be designed to withstand them
- They can be largely avoided (e.g. the shots used for D-T operation in TFTR had <1% disruptivity) and their consequences mitigated
- Most of the examples I show are deliberately induced for the purposes of studying disruption physics

Where we have the problem with disruption?



Statistics from JET for the operational period from 2000 to 2007

[P.C. de Vries et al., Statistical analysis of disruptions in JET. Nucl. Fusion49, 055011 (2009)]

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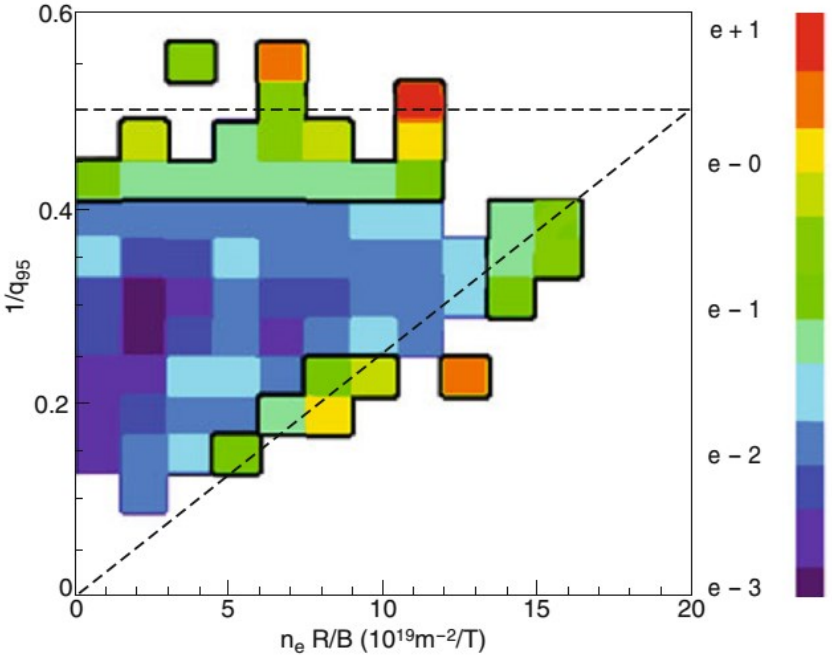

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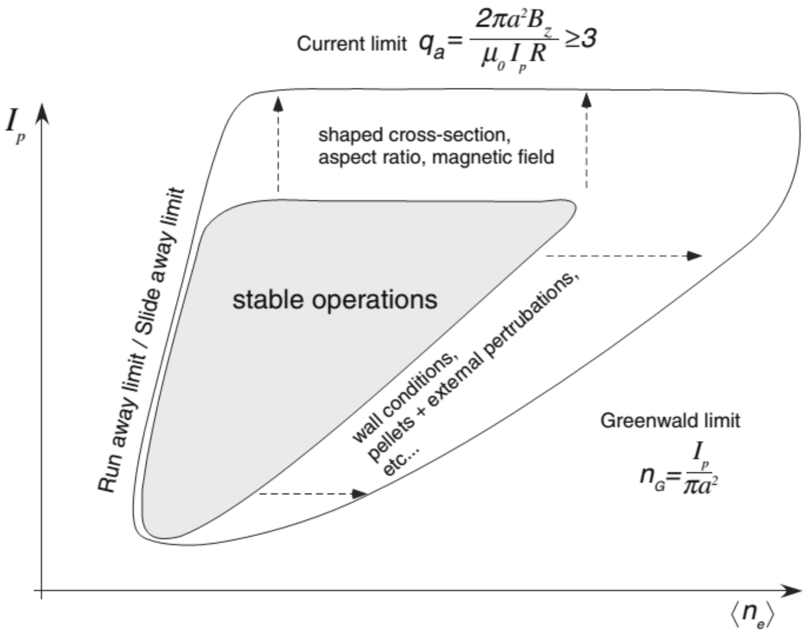

The Hugill diagram and the main limits for plasma operations

[V. Igochine, “Active Control of Magneto-hydrodynamic Instabilities in Hot Plasmas”, Springer, 2015]

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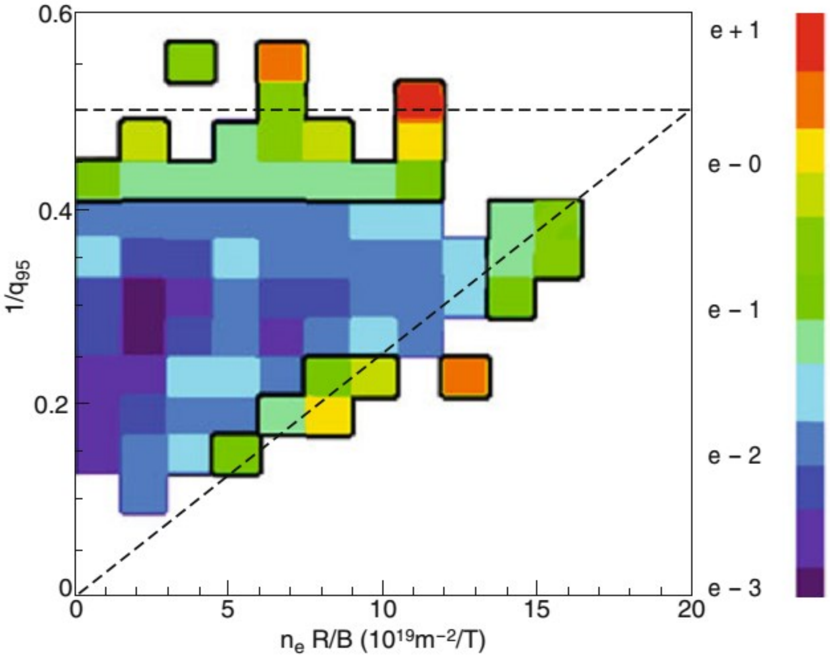

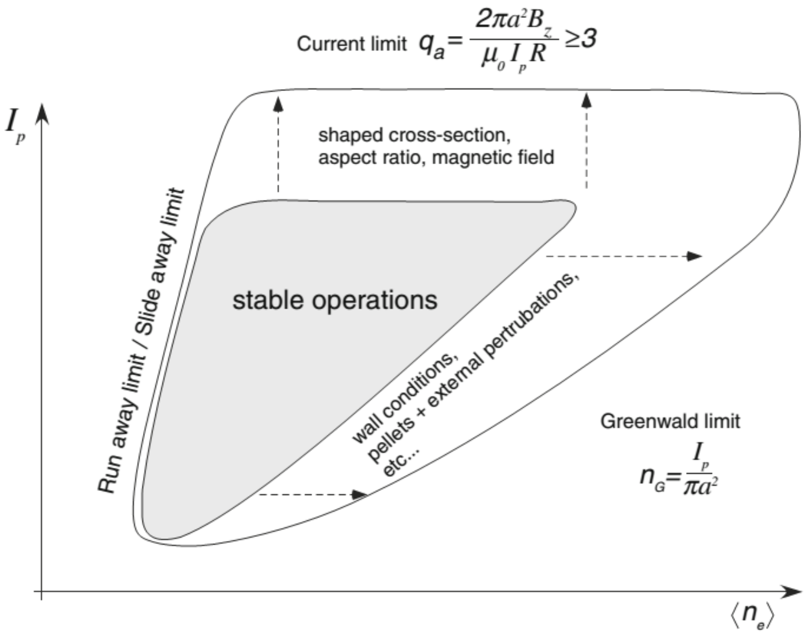

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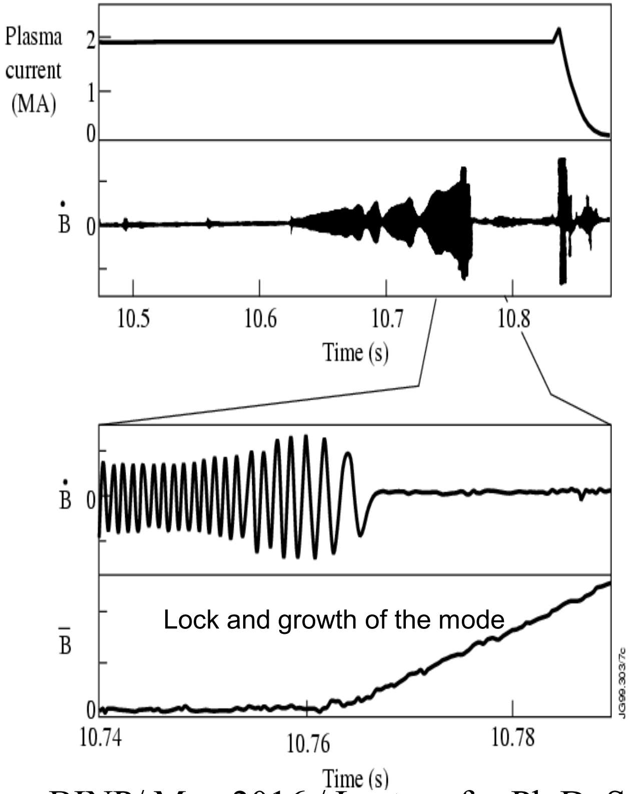
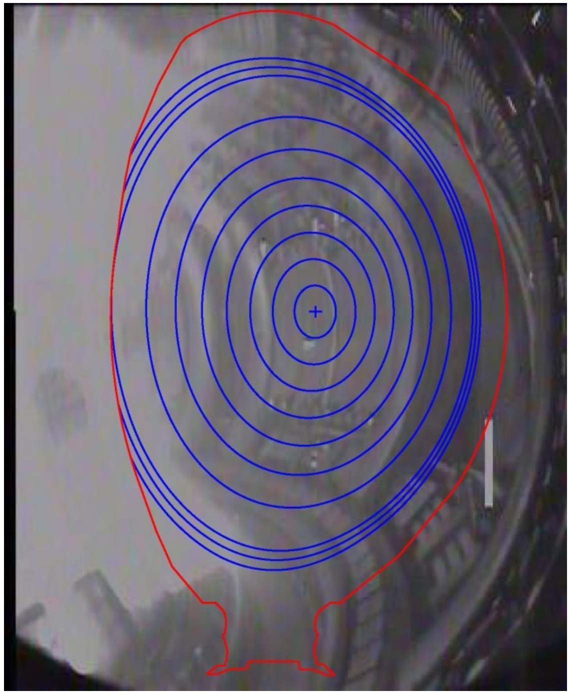
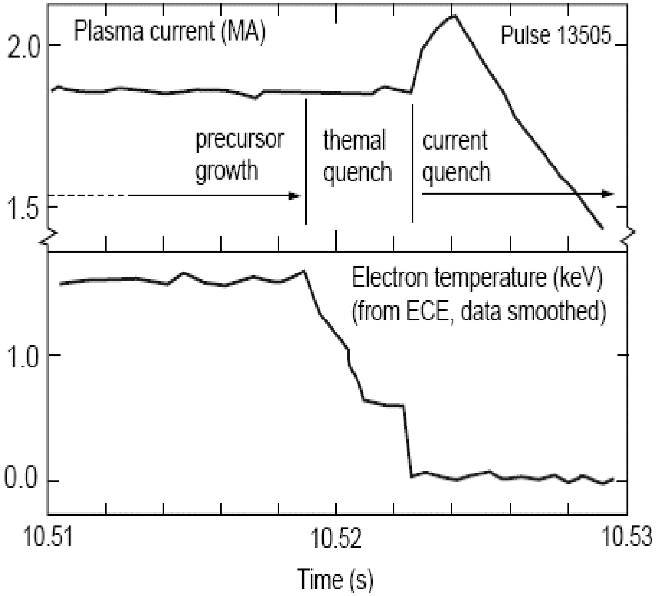
Disruption becomes much more probable close to the operation limits!

Classical disruption picture

Limit approached → Instability → Energy Loss → Plasma moves and hits wall → Impurities enter plasma → Plasma cools and highly resistive → I_p lost

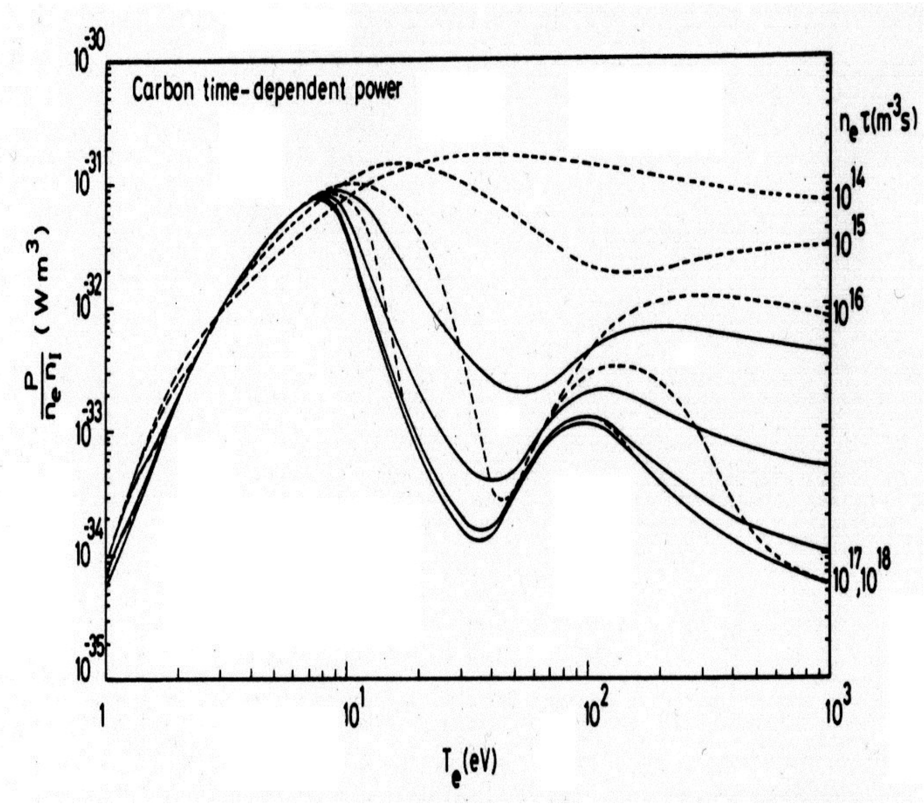




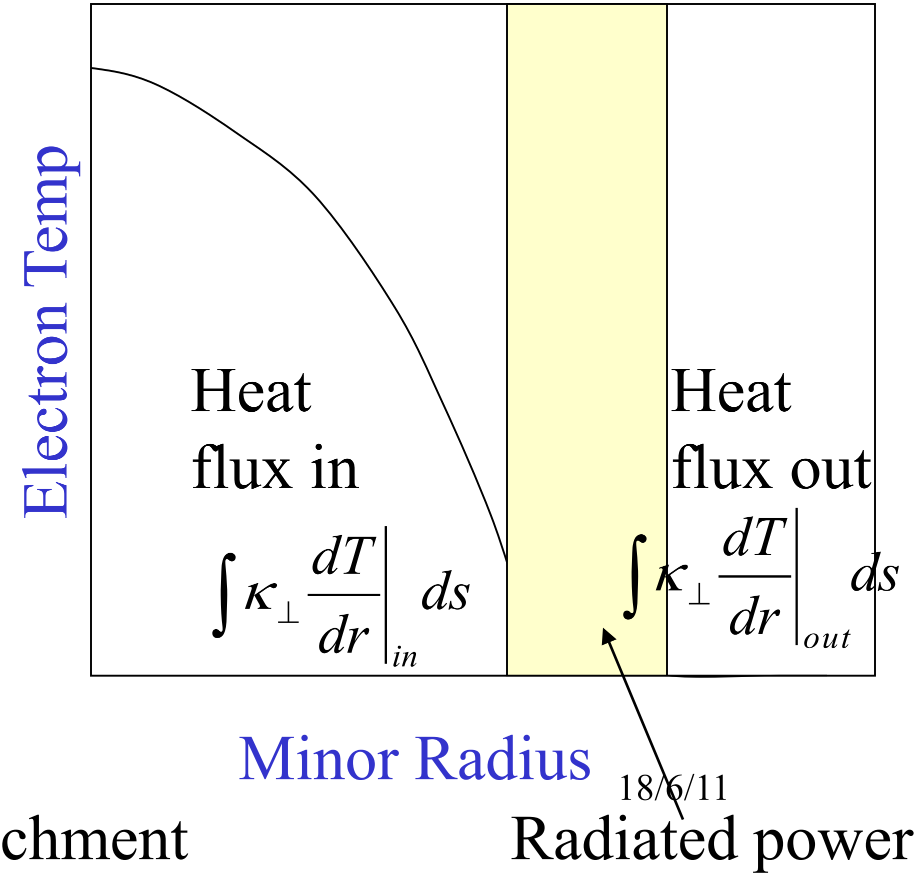


Wesson et al Nucl Fus 1989

A common limit is radiative



Carolan et al PPCF 1980



Electron Temp

Heat flux in

$$\int \kappa_\perp \left.\frac{dT}{dr}\right|_{in} ds$$

Heat flux out

$$\int \kappa_\perp \left.\frac{dT}{dr}\right|_{out} ds$$

Minor Radius

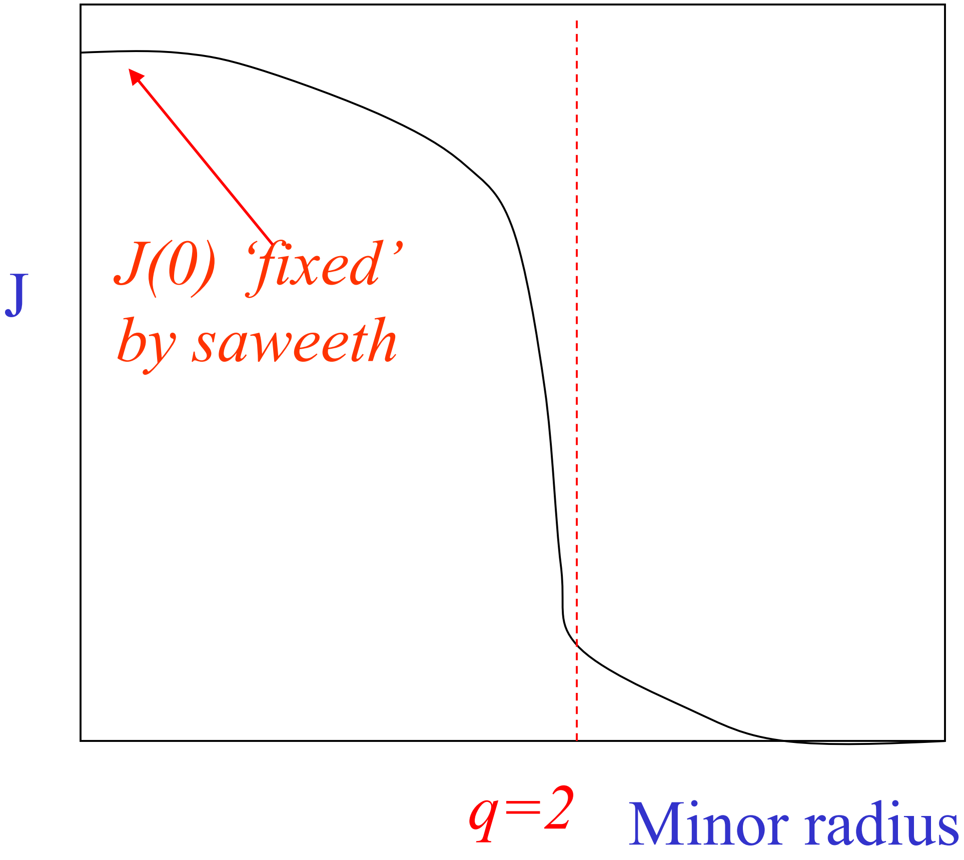
18/6/11

Radiated power

$$\int n_e n_z R(T)dV$$

- When radiated power ~100% detachment occurs (dT/dr=0) and inward contraction occurs

Radiative collapse leads to unstable J(r)



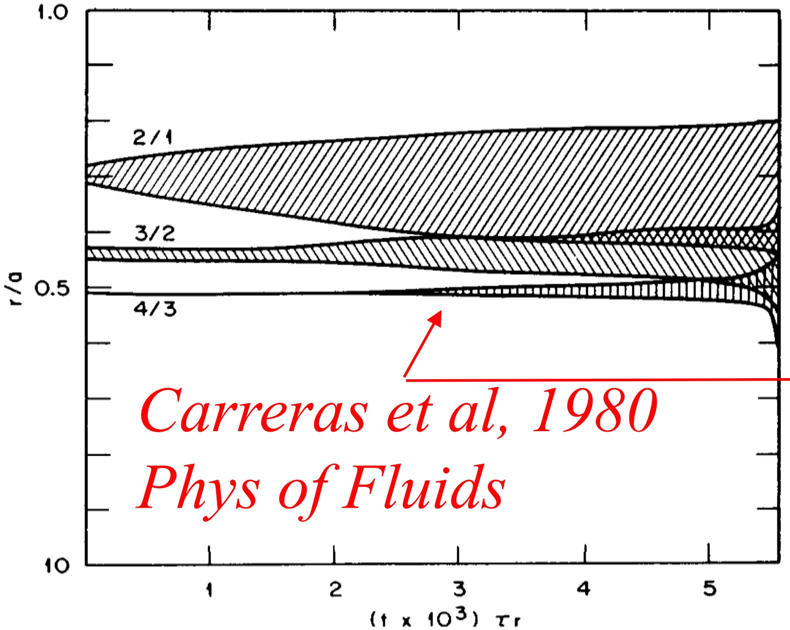
- Kink instability when effective $q_{edge}=2$

or

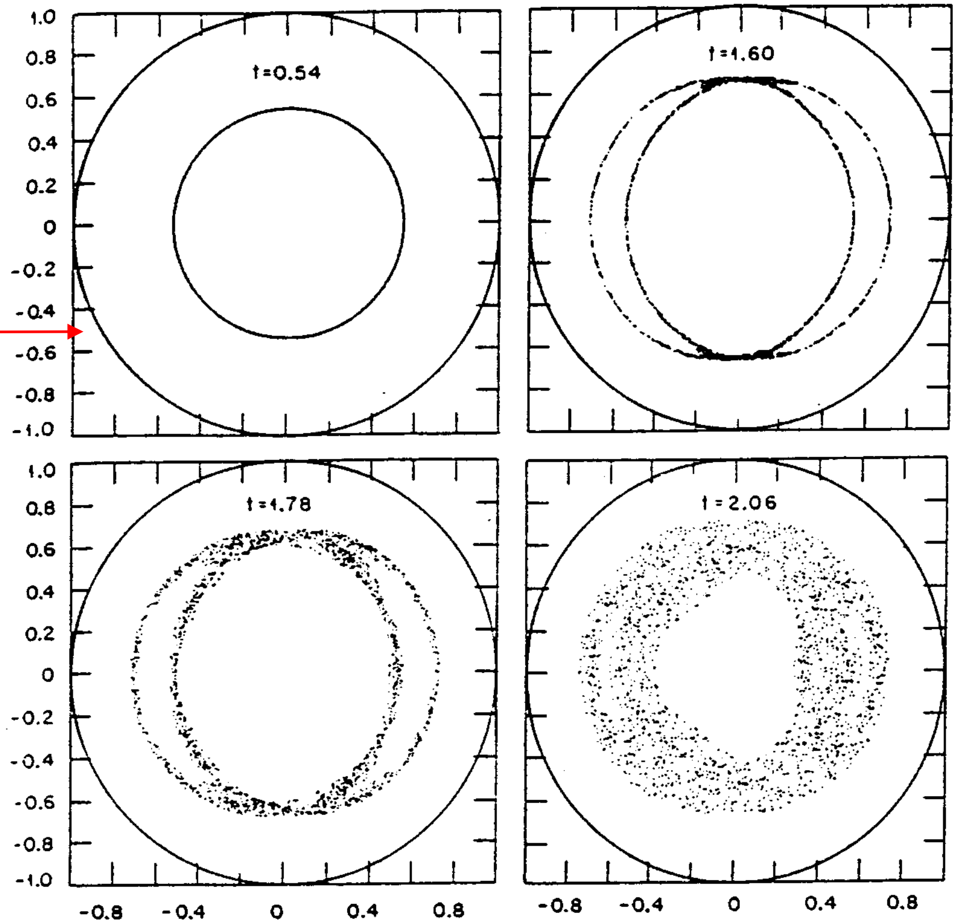
- Tearing destabilised by dJ/dr within q=2 (see NTM lecture)

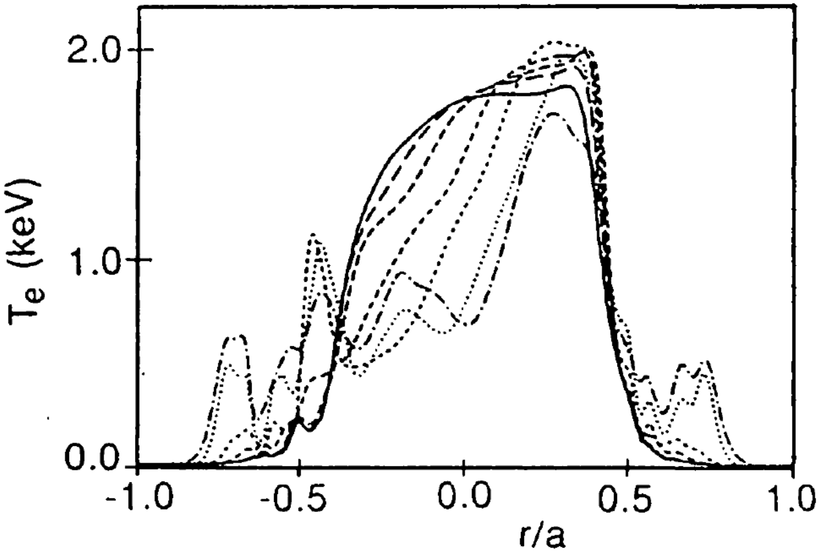
$$\frac{d^2\psi}{dr^2} - \frac{C(r)dJ/dr}{r-r_s} = 0$$

Classical picture - energy loss is stochastic



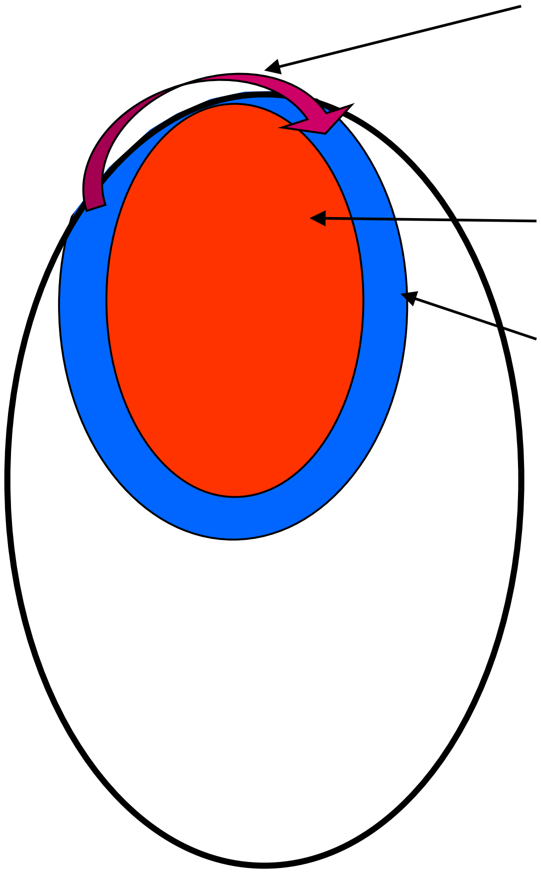
Carreras et al, 1980
Phys of Fluids





MHD simulation
Bondeson et al, NF 1991

Forces – Halo currents



Halo current flowing in vessel etc, (normally dominantly poloidal flow)

Core plasma:- shrinking and I_p decreasing

Halo region

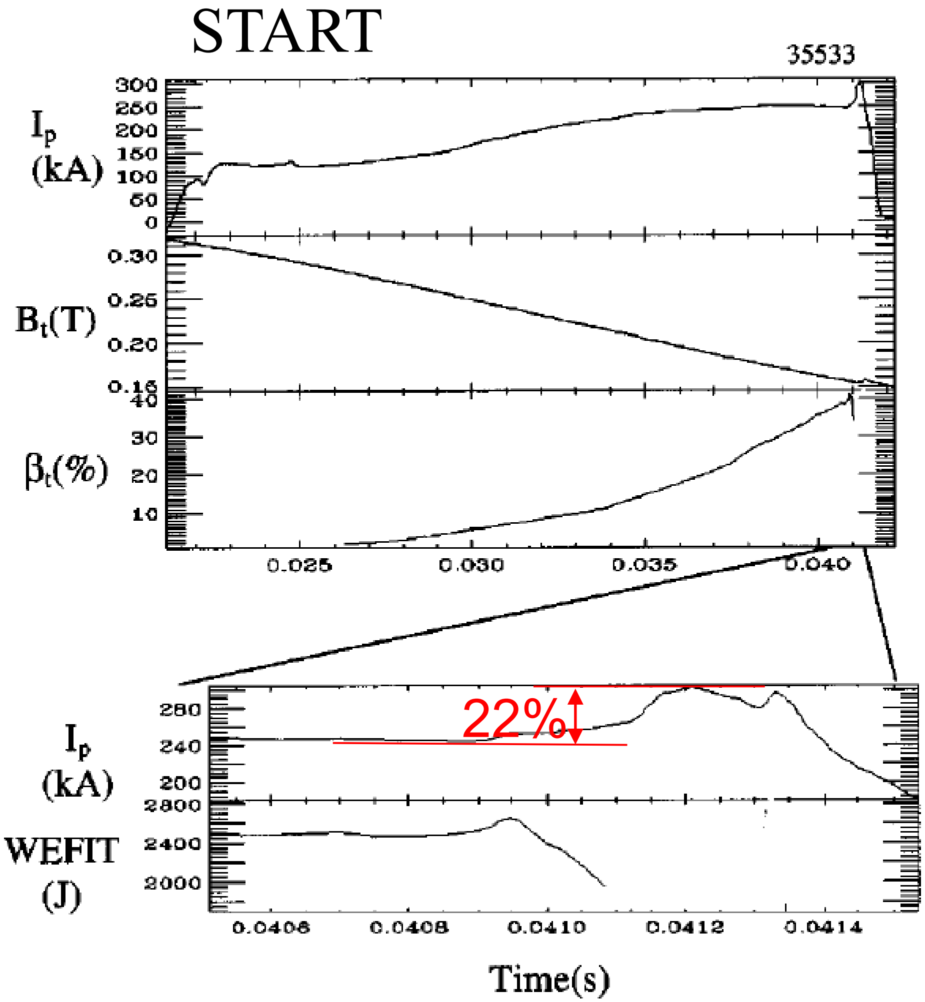
Toroidal halo current flows in I_p direction and poloidal current in direction to increase B_t

Plasma system tries to conserve toroidal and poloidal flux:-

- I_p decrease in core $\Rightarrow$ Toroidal current in plasma halo in direction of $I_p \Rightarrow$ Poloidal current in direction to increase B_t (because halo flow along field line)
- Conservation of Toroidal flux $\Rightarrow$ Poloidal current in direction to increase $B_t \Rightarrow$ Toroidal current in plasma halo in direction of I_p (because halo flow along field line)

Also decaying moving plasma drives vessel eddy currents

+ve Ip and –ve loop voltage spike



Standard explanation (Wesson):-

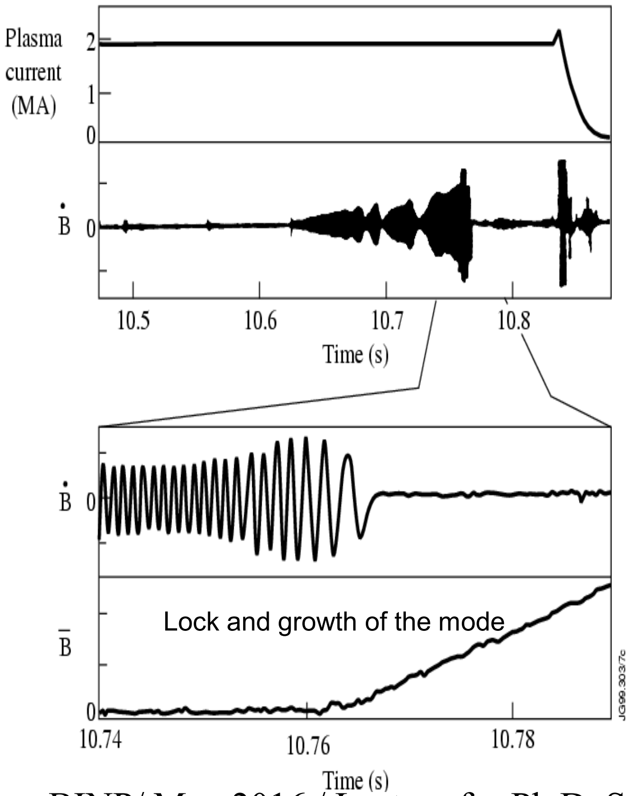
- Conservation of magnetic energy ($LI_p^2/2$) and internal inductance drop (J-flattening) $\Rightarrow$ I_p increases $\Rightarrow$ -ve V_{loop}

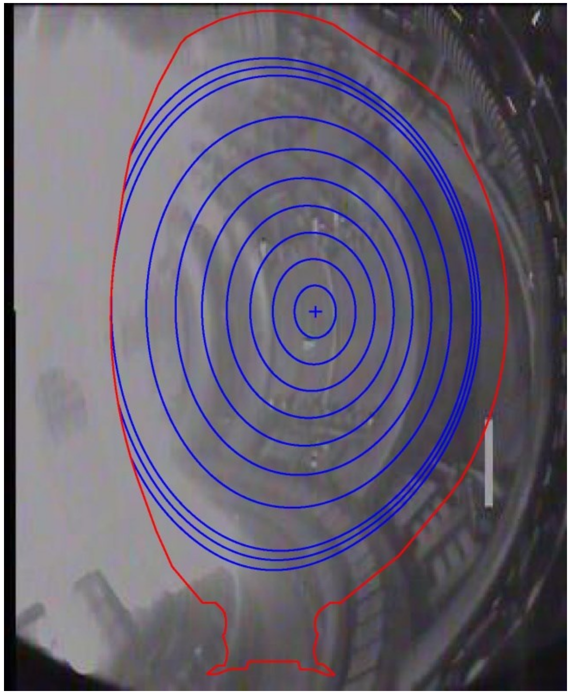
Hiro current (Zakharov NF 2010):-

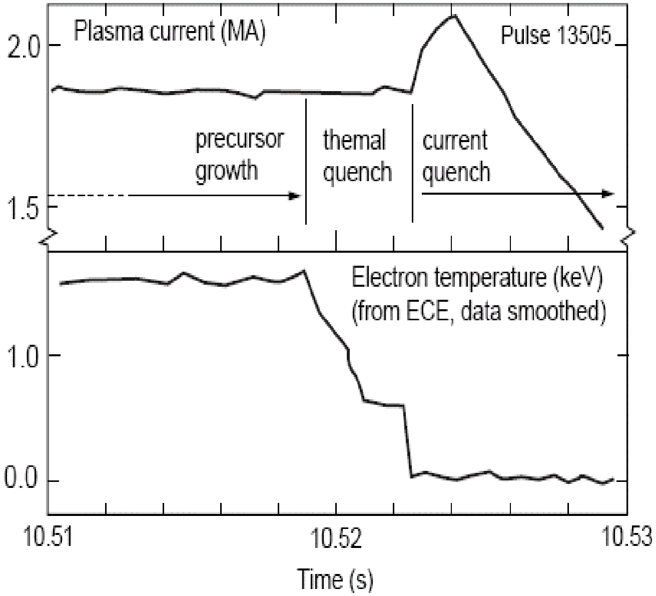
- VDE causes negative surface current, which when transferred into wall $\Rightarrow$ I_p rises

Classical disruption picture

Limit approached → Instability → Energy Loss → Plasma moves and hits wall → Impurities enter plasma → Plasma cools and highly resistive → I_p lost



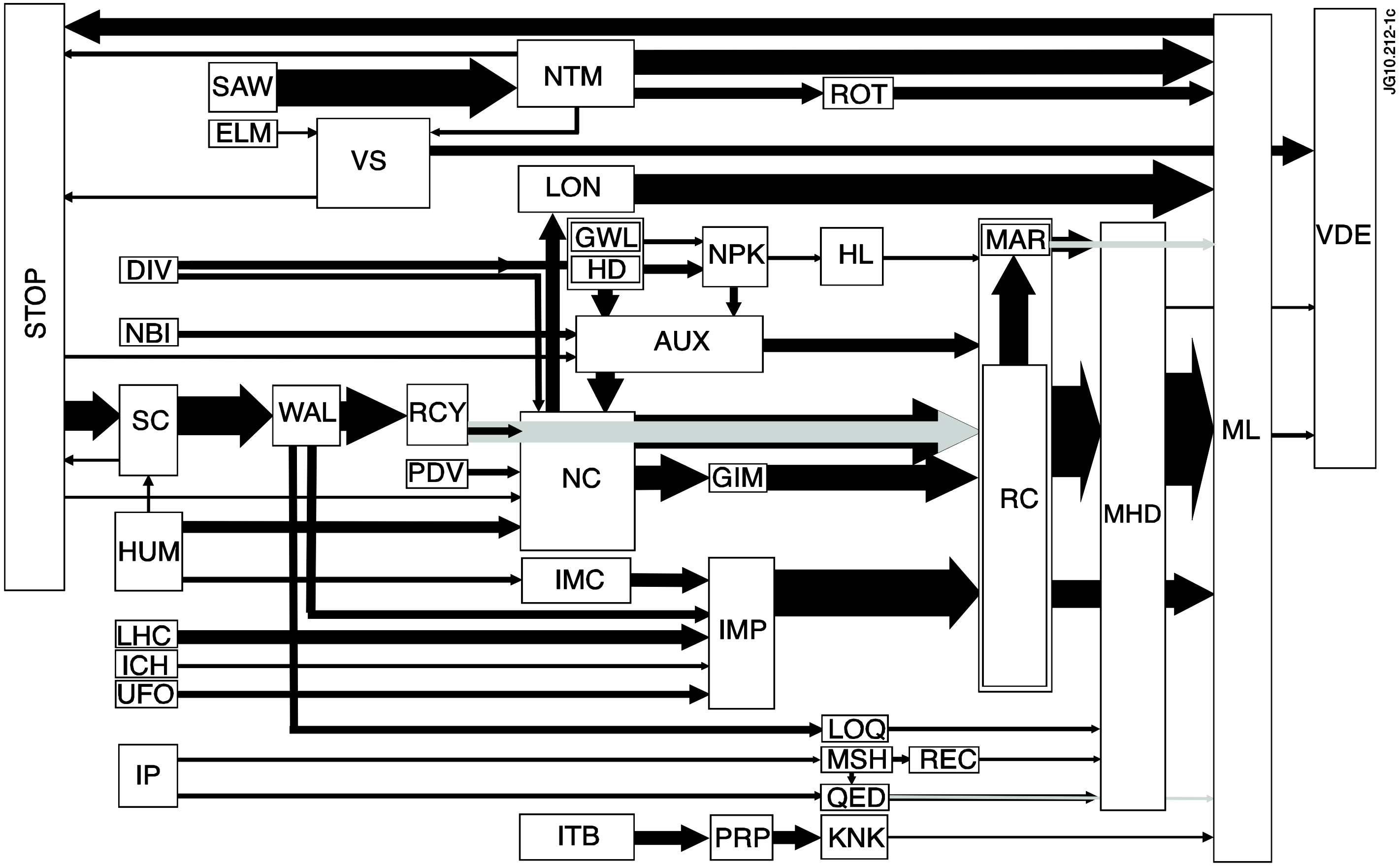




Wesson et al Nucl Fus 1989

Disruption causes – not simple!

Flow diagram* of all 1654 unintentional JET disruptions between 2000-2010$^+$

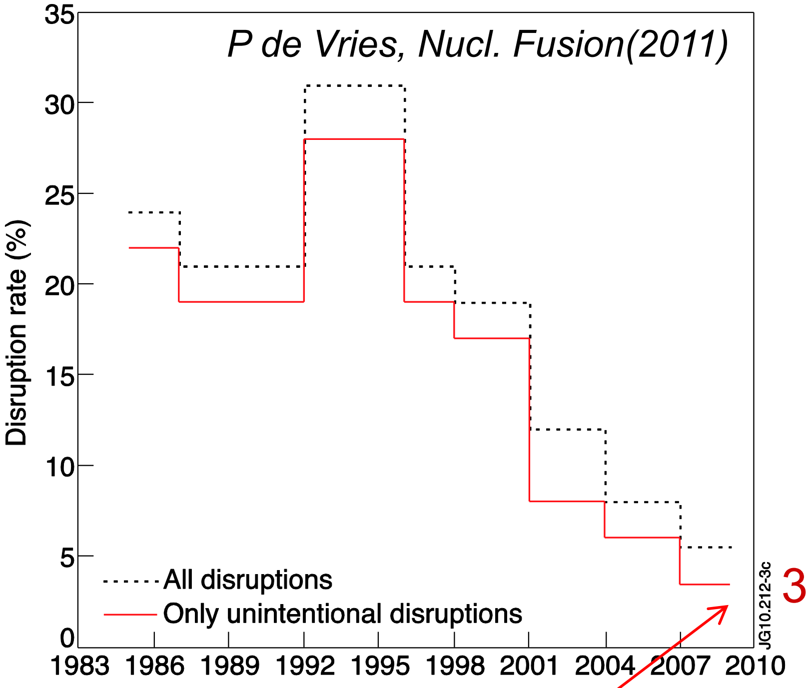


*The arrow width gives the frequency this sequence occurred in the cause database

$^+$ P.C. de Vries et al, Nucl Fus 2011

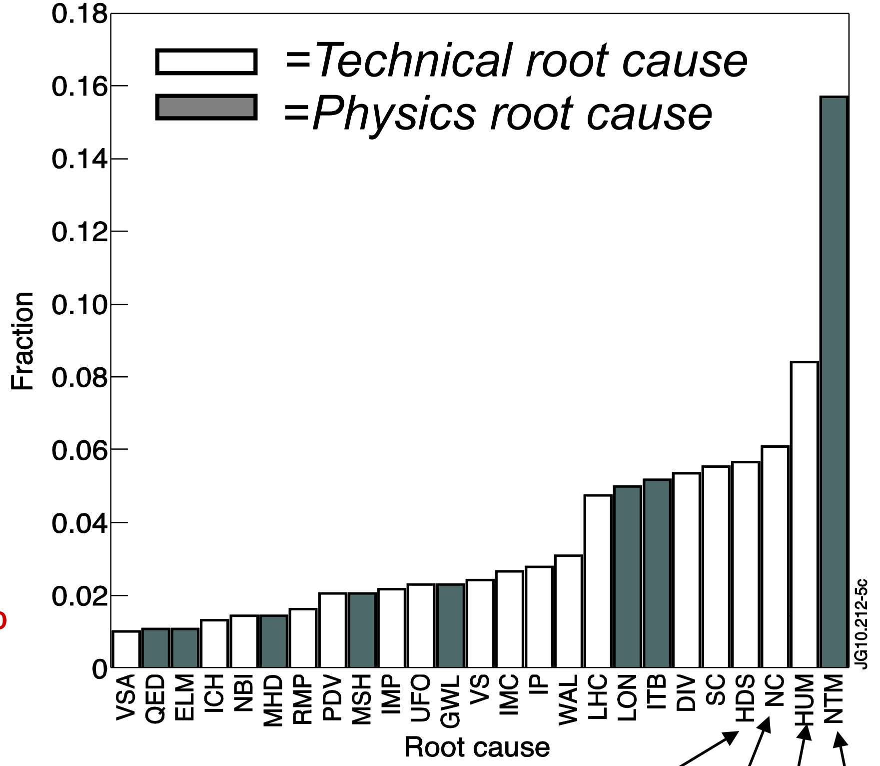
Disruption causes

- A survey of disruption causes at JET found that the most common disruption causes were neo-classical tearing modes, human error and density/impurity/shape control: >50% were caused by technical issues
- The JET disruption rate decreased significantly over the years



3.4%

The more we operate the tokamak, the less disruption probability is!



High Density

n_e control

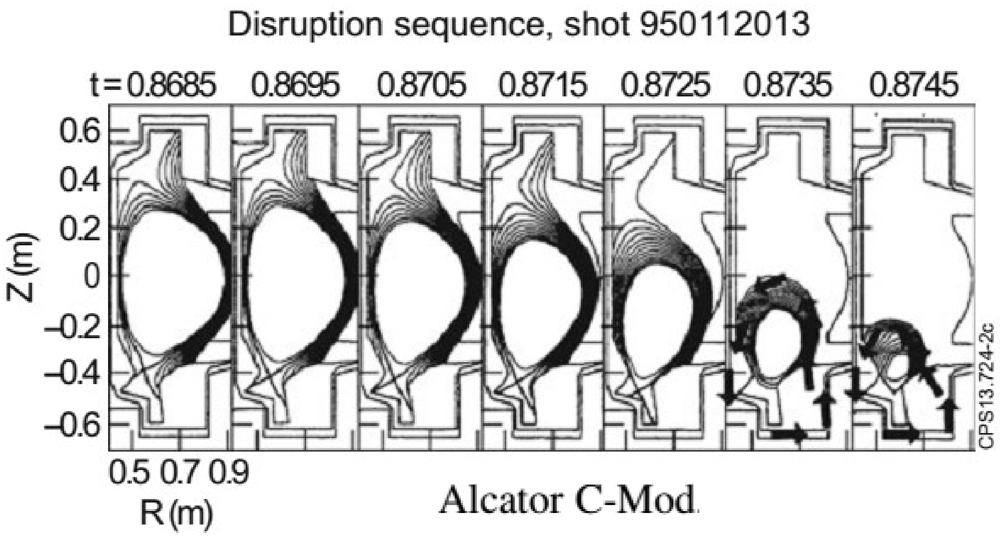
Human Error

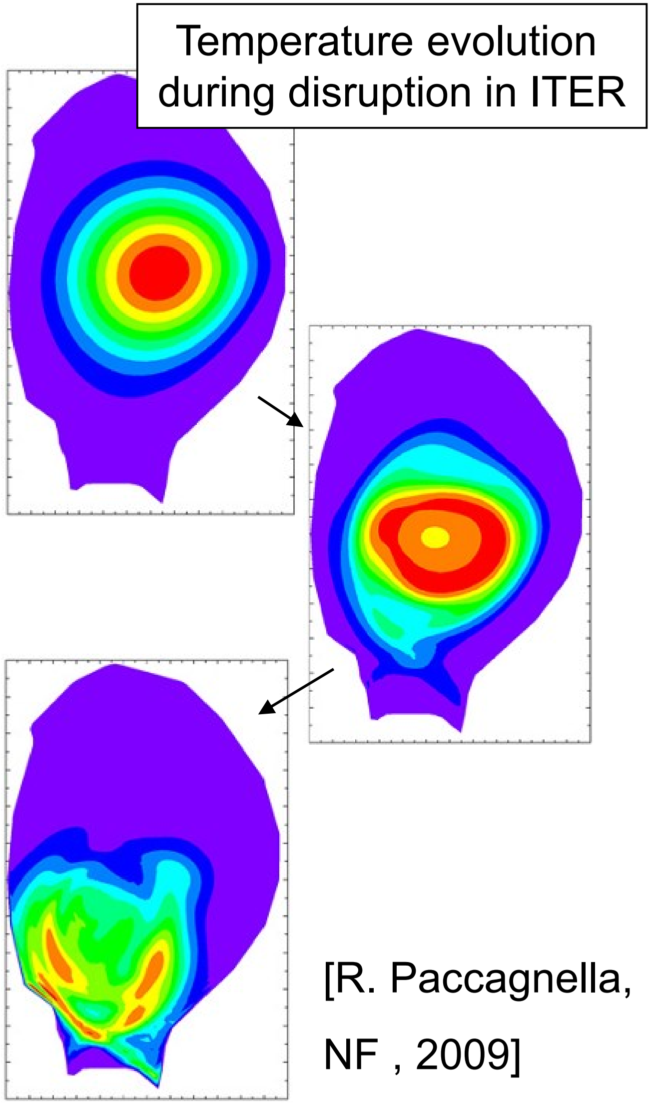
NTM

Key issues

Key issues to be resolved for disruptions:

- Forces
- Heat Loads
- Runaways
- Mitigation
- Prediction and avoidance

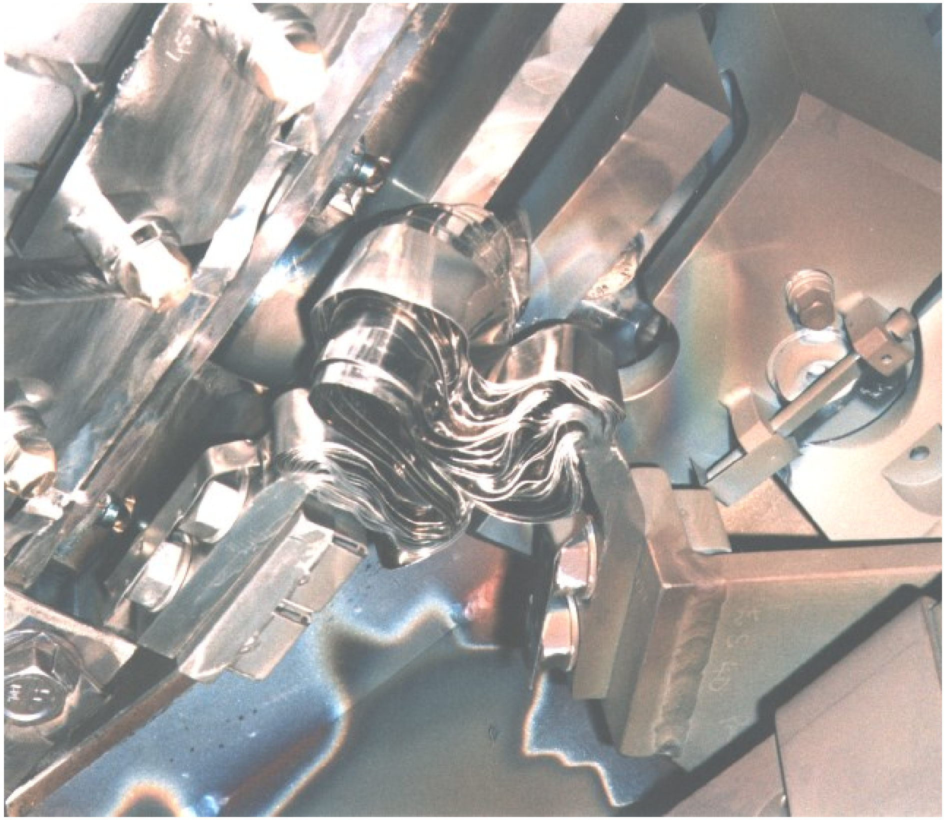



Temperature evolution during disruption in ITER

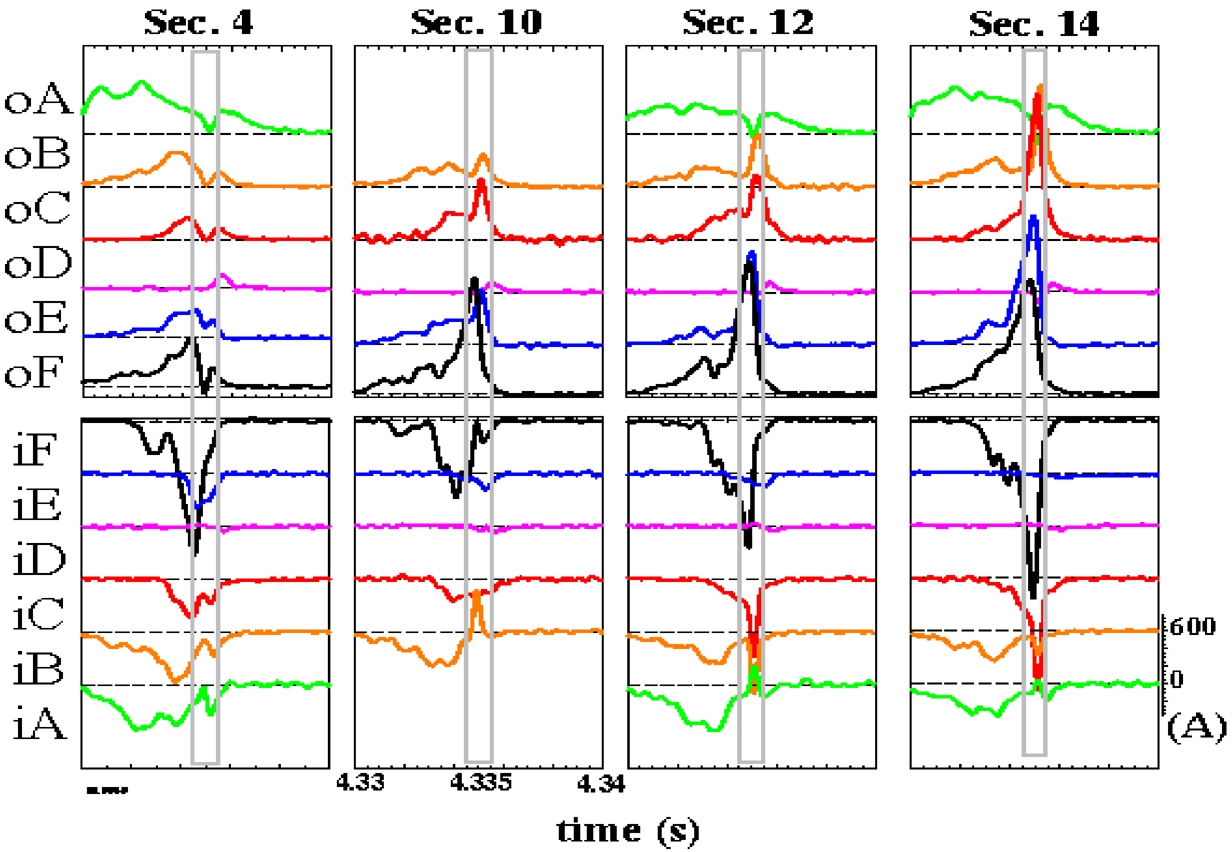
[R. Paccagnella, NF , 2009]

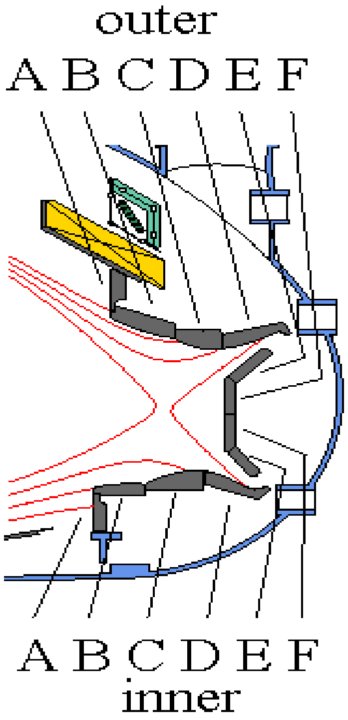
Forces

- Forces (VDE symmetric load ~100MN, asymmetric ~40MN)



Halo currents not always symmetric

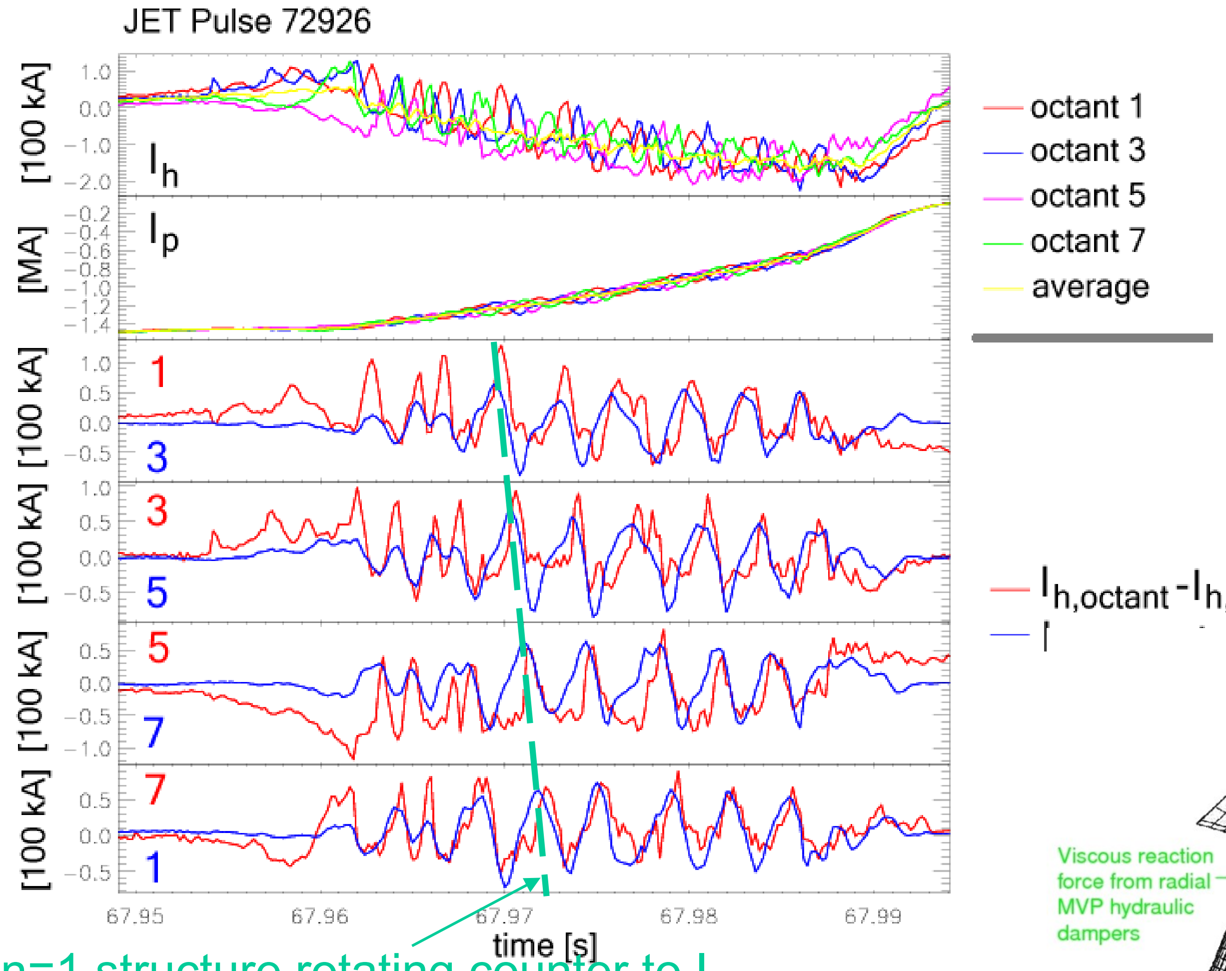




ASDEX Upgrade have cases with different currents in different sectors!

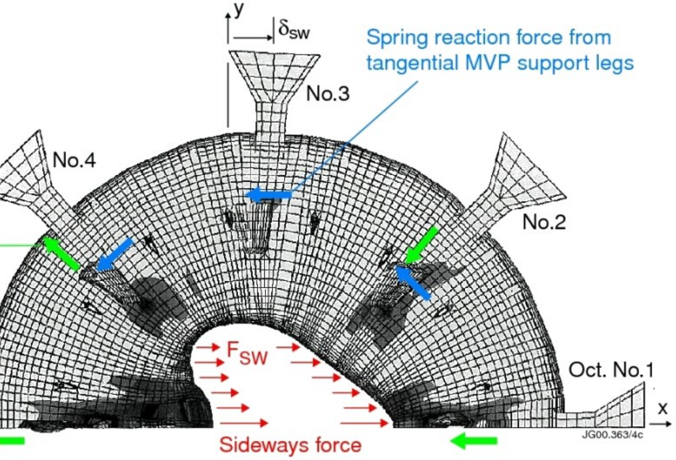
G Pautasso et al

Halo currents not always symmetric



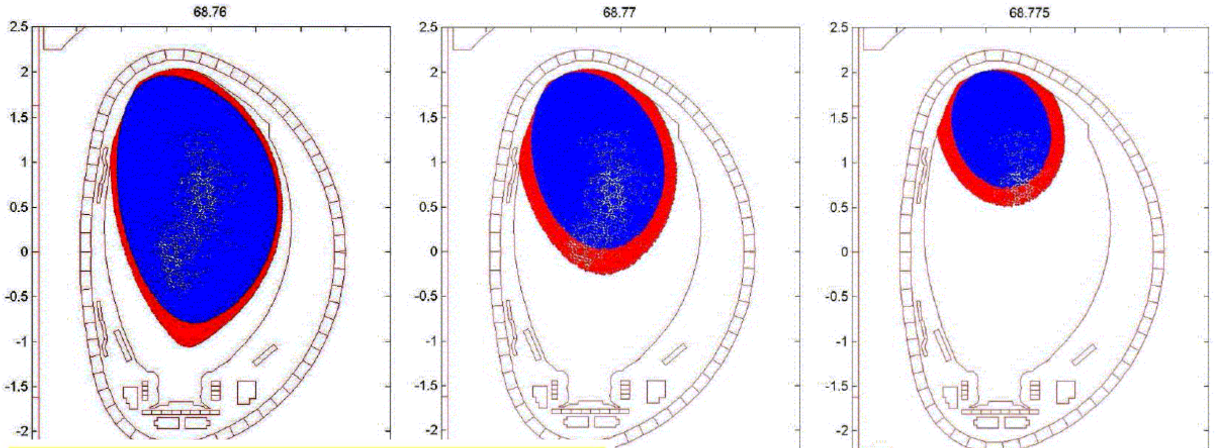
n=1 structure rotating counter to I_p

- Asymmetric currents lead to tilting and sideways vacuum vessel forces
- For JET peak sideways force ~4MN

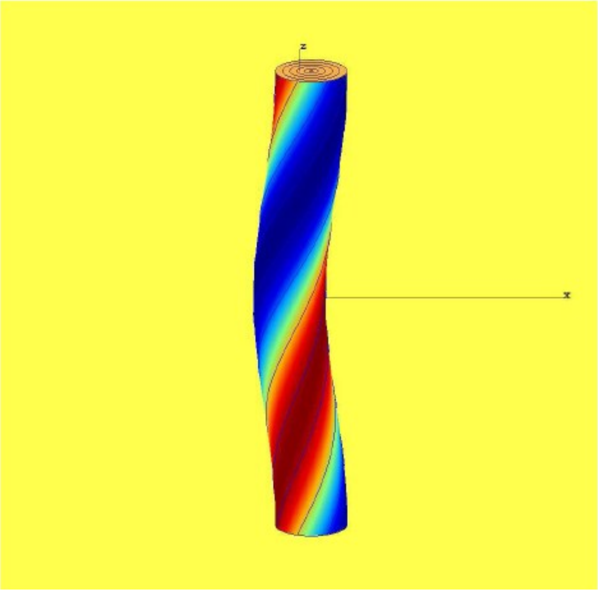


- Poloidal halo currents phase leads ΔI_p by ~90°

Current Asymmetries – wall touching kink mode



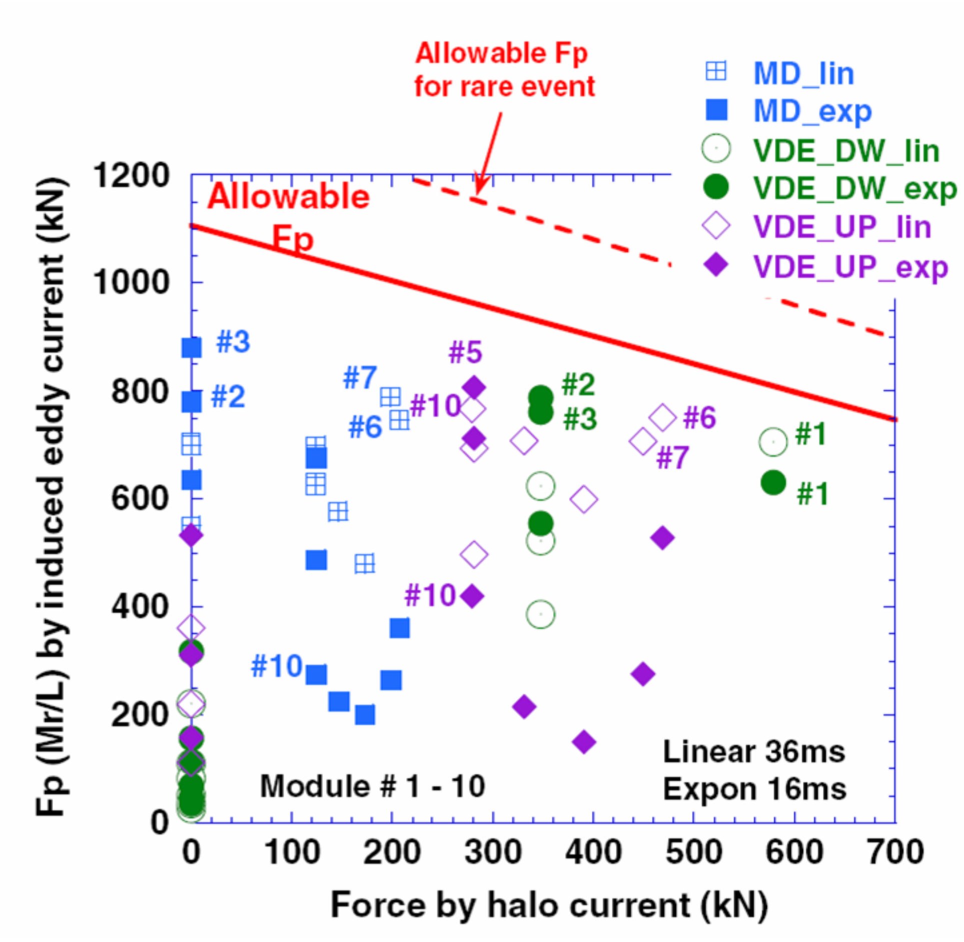
- Plasma moves up in VDE and shrinks ⇒ boundary-*q* decrease
- When $q_a=1$ external kink mode



From L Zakharov PoP 2008

- In an external kink mode a helical surface current (termed Hiro current) flows
- On the side moving towards the wall the Hiro current is against I_p

Forces – Halo and Eddy currents both important



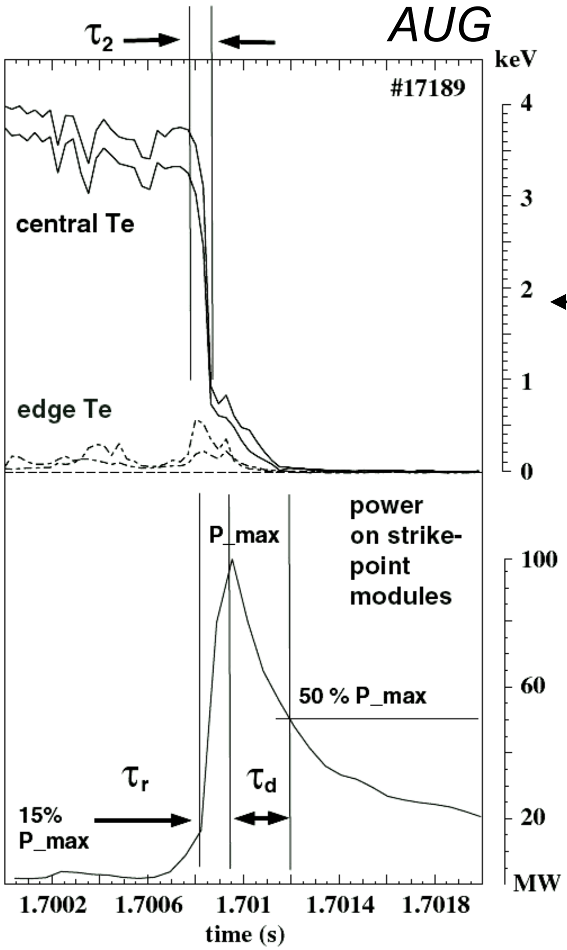
Each tokamak has its own engineering limits for maximal symmetric and asymmetric forces. This is defined already on the first design stage.

M Sugihara et al, Nucl Fusion 2007

Thermal quench and heat loads

Parameter that matters:

$$\frac{W_{dep}}{Area \times \tau^{1/2}}$$



ITER Physics Basis, Chap 3 Nucl Fus 2007

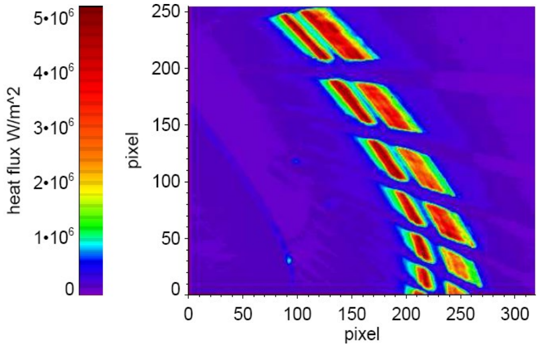
- Similar temporal broadening (3-7x) on JET

Broadening:-

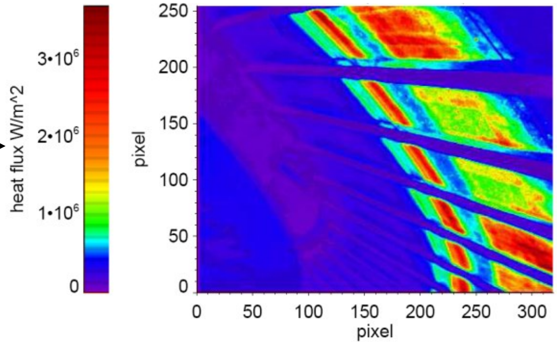
- In time
- In space of 4-10 in width
- Similar spatial broadening on JET, AUG
- But can have local hot spots

MAST

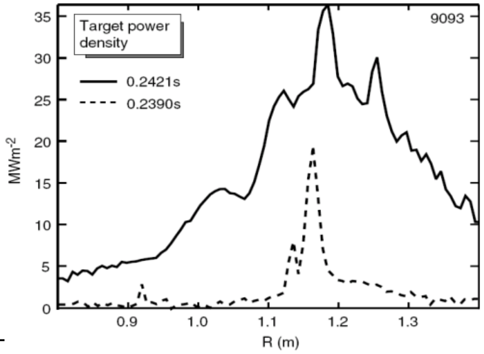
Locked mode



Locked mode disruption



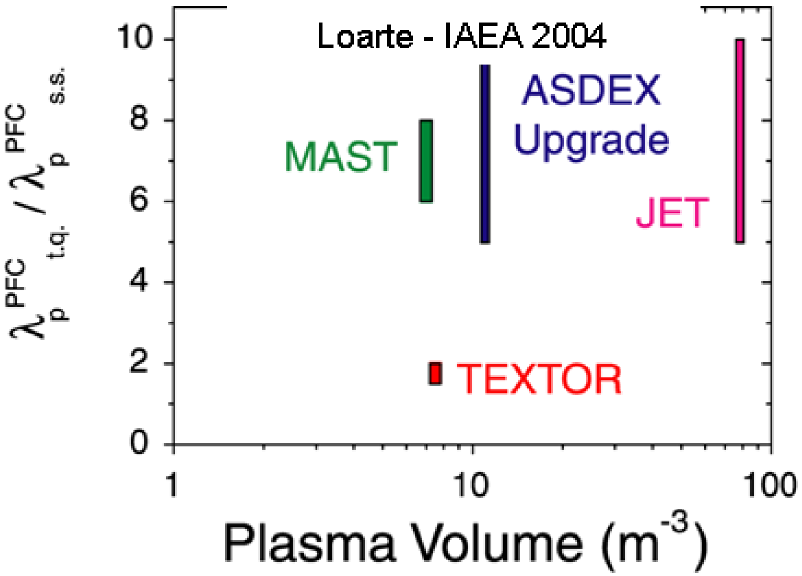
E Delchambre, Jnrl Nucl Mat 2007



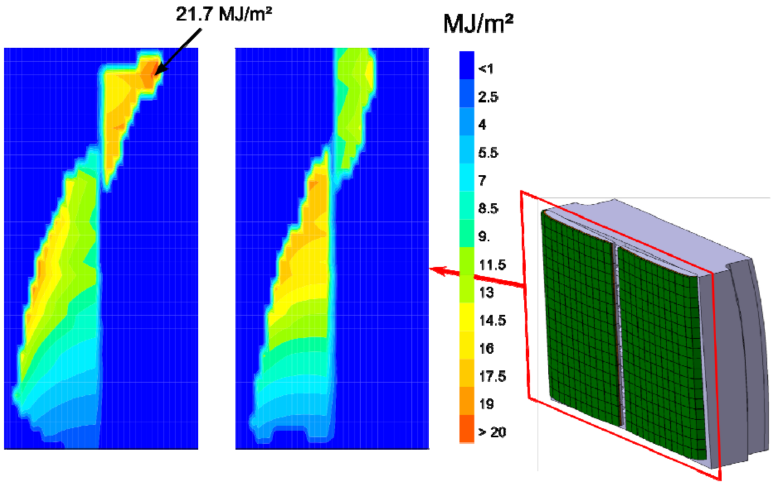
G Counsell Nucl Fus 2005

Heat Loads

Heat load in limiter config is key issue:-



(from Sugihara-san IEA workshop JET 2009)



Large areas receive >10MJ/m^2

$\Rightarrow \mathcal{E} = 180\ MJ/m^2/s^{0.5} (\Delta t = 3ms)$;

$\varepsilon_{melt} \approx 28\ MJ/m^2/s^{0.5}$

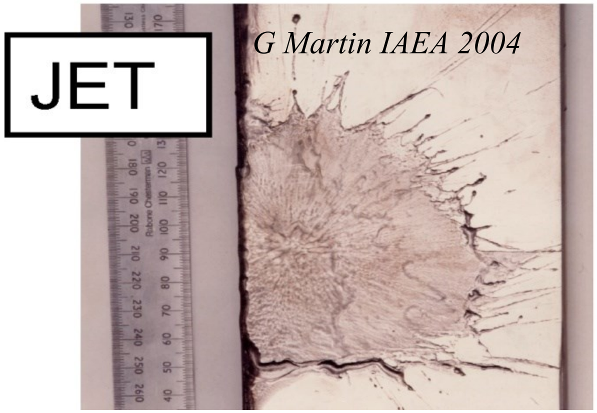
Sets targets for mitigation!

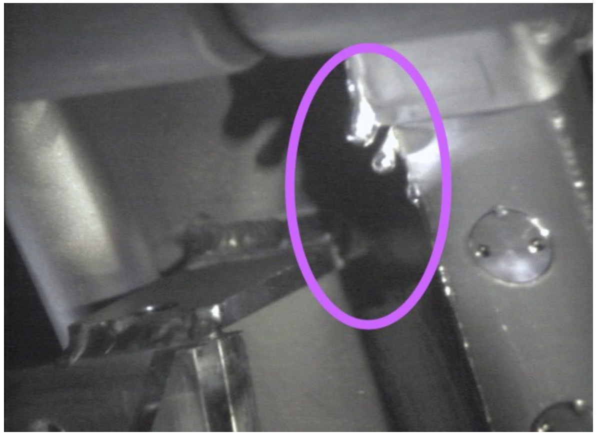
- Limiter Scrape-Off Layer expansion during disruption needs study

The term Scrape-Off Layer (SOL) refers to the plasma region characterized by open field lines.
**With limiter plasmas, this region is the region outside the Last Closed Flux Surface (LCFS).*
**With divertor plasmas, this region is the region outside the separatrix.*

Runaways

- Runaways (~10MA at 10-20MeV)

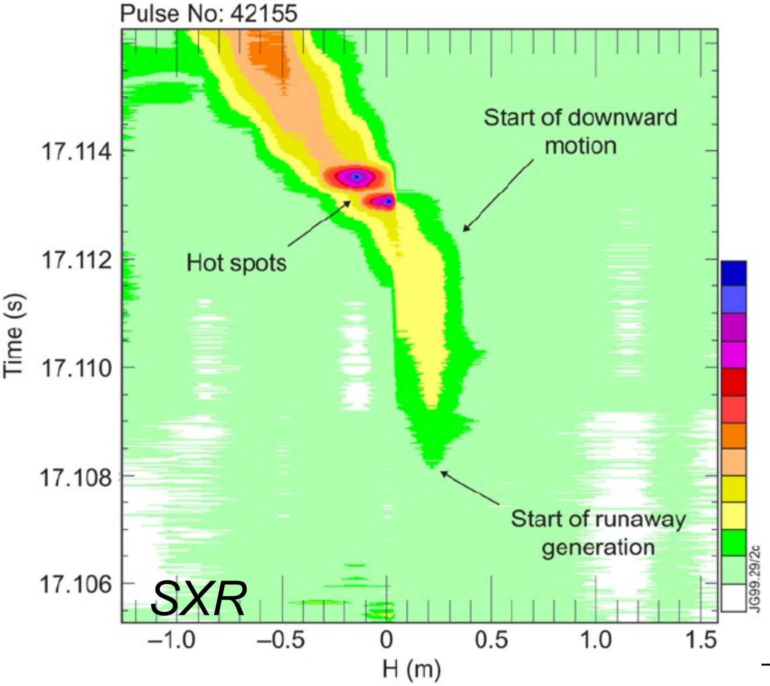


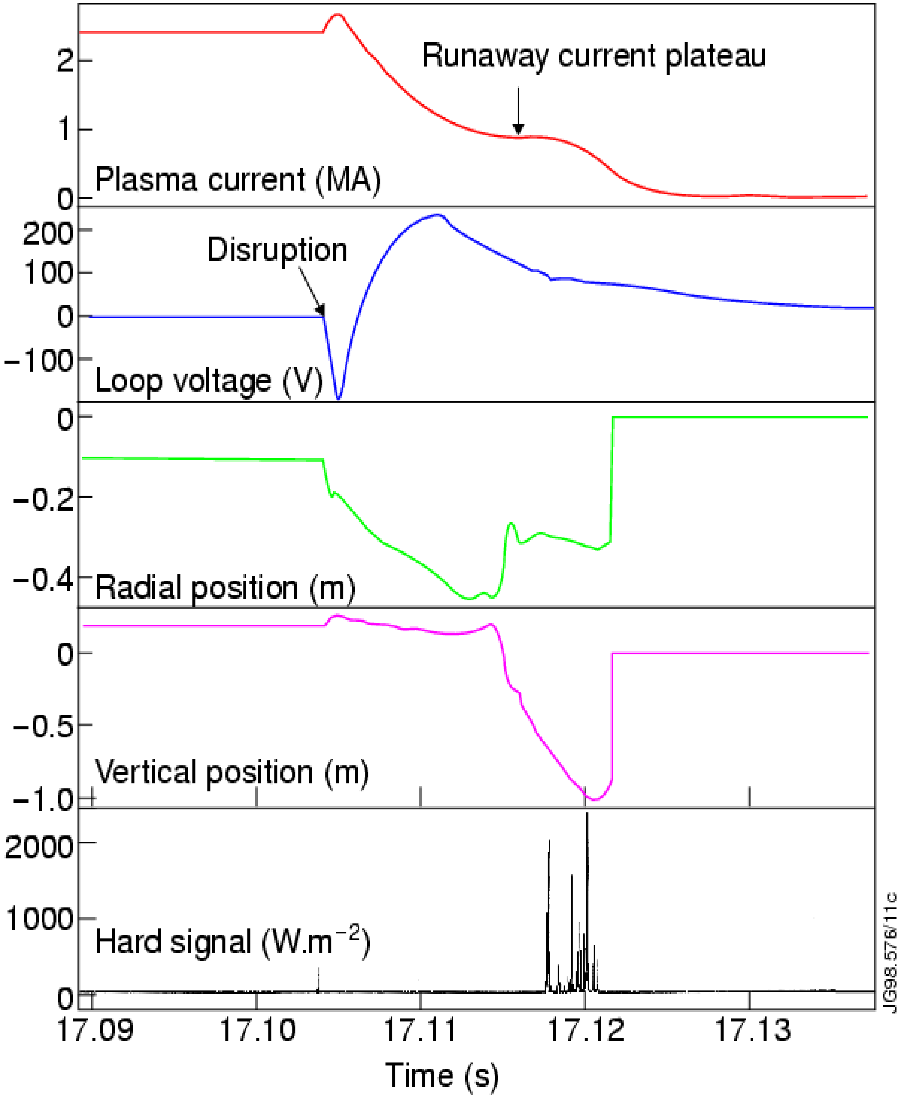


Examples from JET

Runaway electrons

- Runaway electrons are generated, which
  - are accelerated to ~ MeV range.
  - carry much of the original current.
  - usually hit the wall => hard X-rays.
  - can cause serious damage.
  - occasionally remain in the cool plasma (~ 10 eV) for several s.

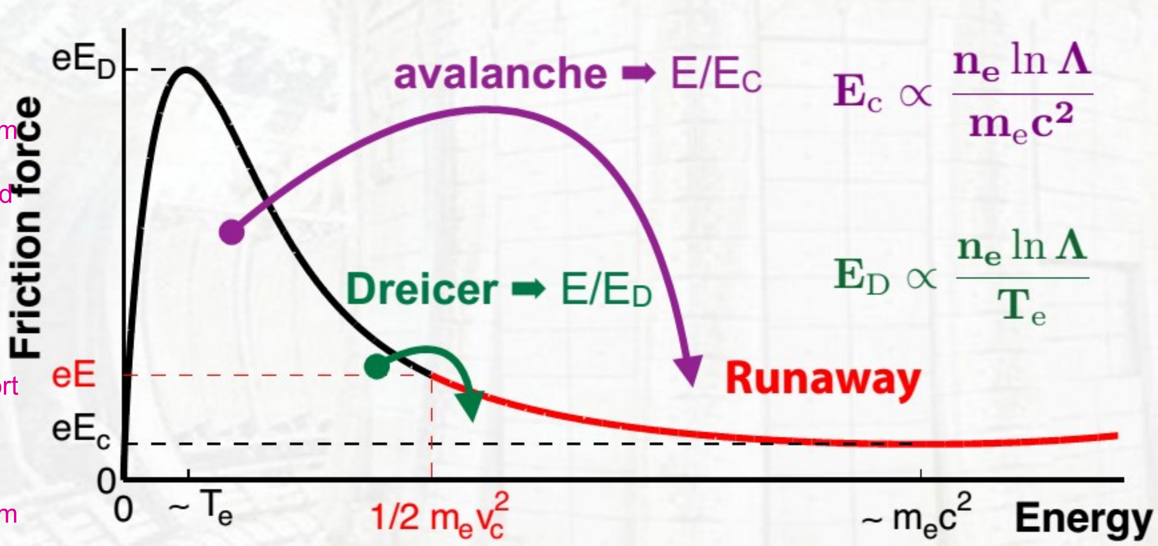




R D Gill et al, Nucl. Fusion (2000)

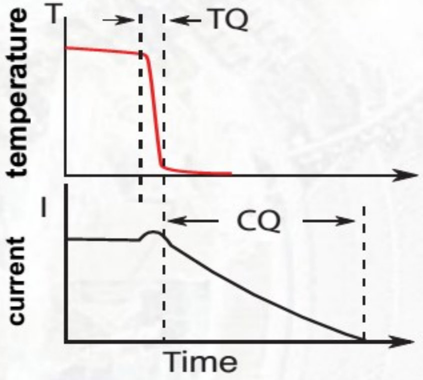
- **Disruptions:** quick cooling of the plasma (*thermal quench* - TQ)
- *Current quench* (CQ) as the resistivity is increased ($R \sim T^{-3/2}$)
  - ➡ I_p cannot drop arbitrarily fast - **toroidal electric field is induced**

knock-on collisions, where enough momentum can be transferred from existing runaways to slow electrons to transport the latter beyond a critical momentum



$$E_c \propto \frac{n_e \ln \Lambda}{m_e c^2}$$

$$E_D \propto \frac{n_e \ln \Lambda}{T_e}$$

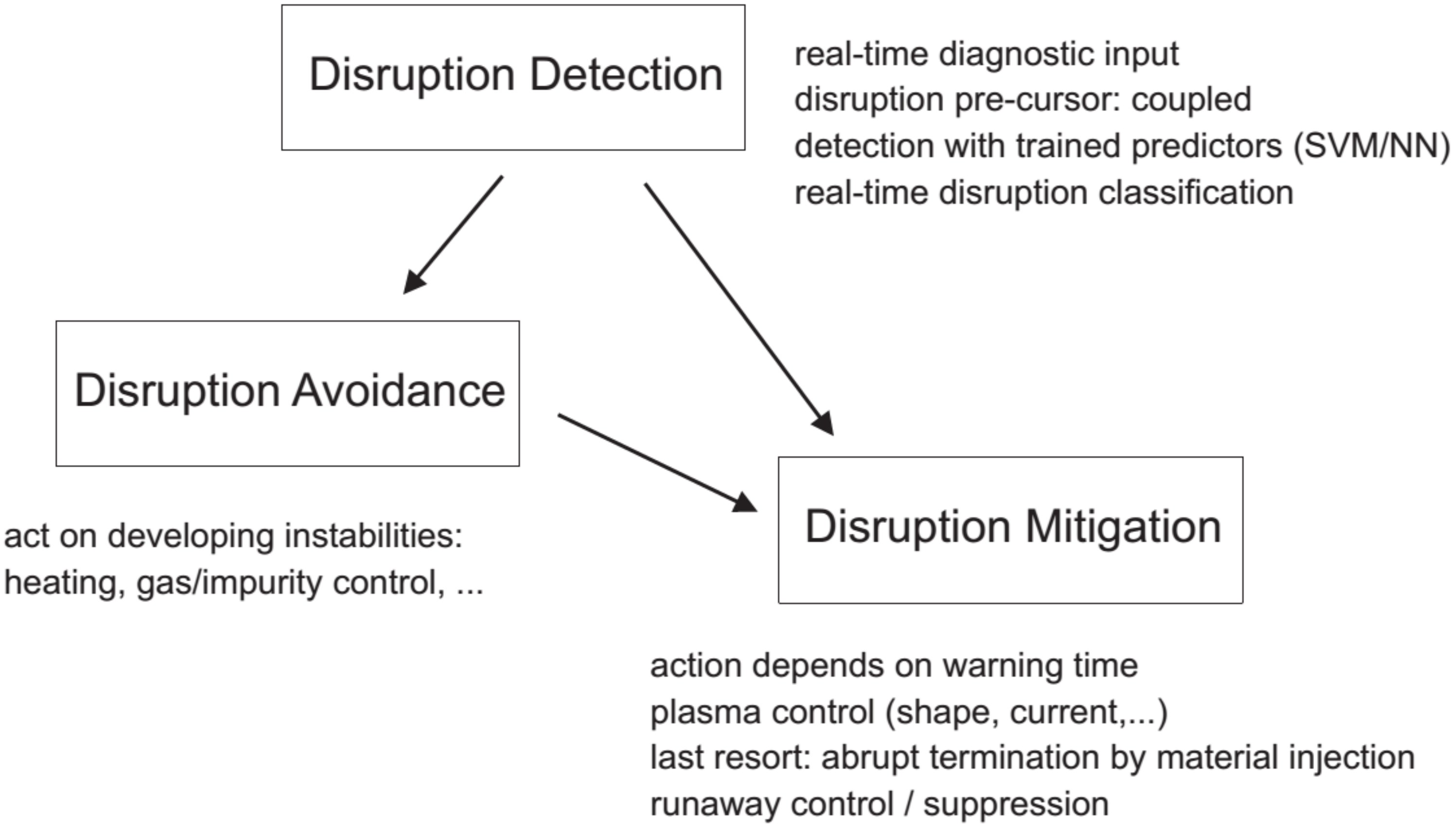


50 ms< ITER <150 ms

- **Runaway electrons (RE)** can be generated with *O*(MA) current
  - ➡ **poses a great risk to plasma facing components ➡ JET 2014**
- Runaway generation: complex dependence on E_{tor}, n_e, T_e, Z_{eff}, ...
  - ➡ **Need to understand the self-consistent evolution of all**

Disruption control

Disruption Control



Disruption Detection

real-time diagnostic input
disruption pre-cursor: coupled
detection with trained predictors (SVM/NN)
real-time disruption classification

Disruption Avoidance

act on developing instabilities:
heating, gas/impurity control, ...

Disruption Mitigation

action depends on warning time
plasma control (shape, current,...)
last resort: abrupt termination by material injection
runaway control / suppression

Michael Lehnen | Institute of Energy Research - Plasma Physics | Association EURATOM - FZJ

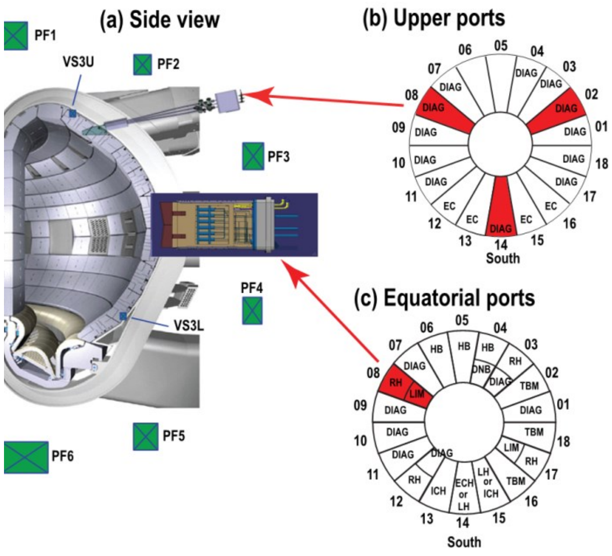
Disruption control

ITER Needs

Most demanding requirement for mitigation:
Heat loads during thermal quench and from runaway electrons

Three key elements:

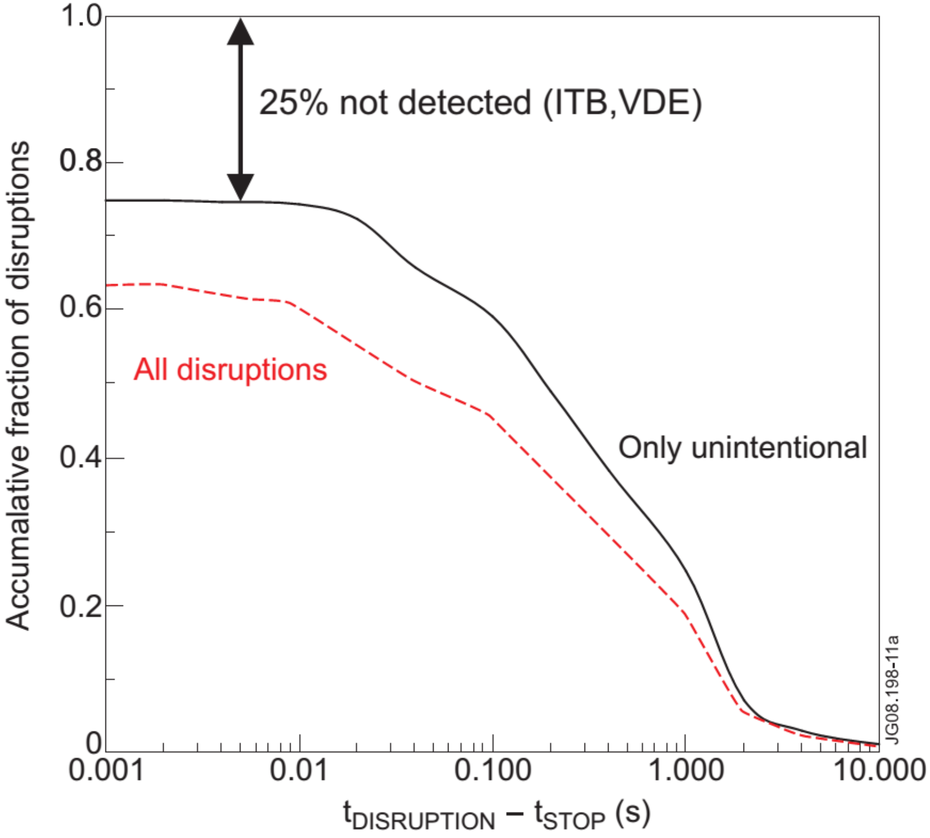
(1) Disruption rate; ≤ 3% (Avoidance)
(2) Prediction success rate; ≥ 95% (Prediction)
(3) Heat flux mitigation by DMS; ≤ 1/10 (Mitigation)



All these three target values must be satisfied simultaneously to meet the requirement for lifetime (2-3 times replacements during life)

M. Sugihara, ITPA-MDC March 2011

Detection - Example JET

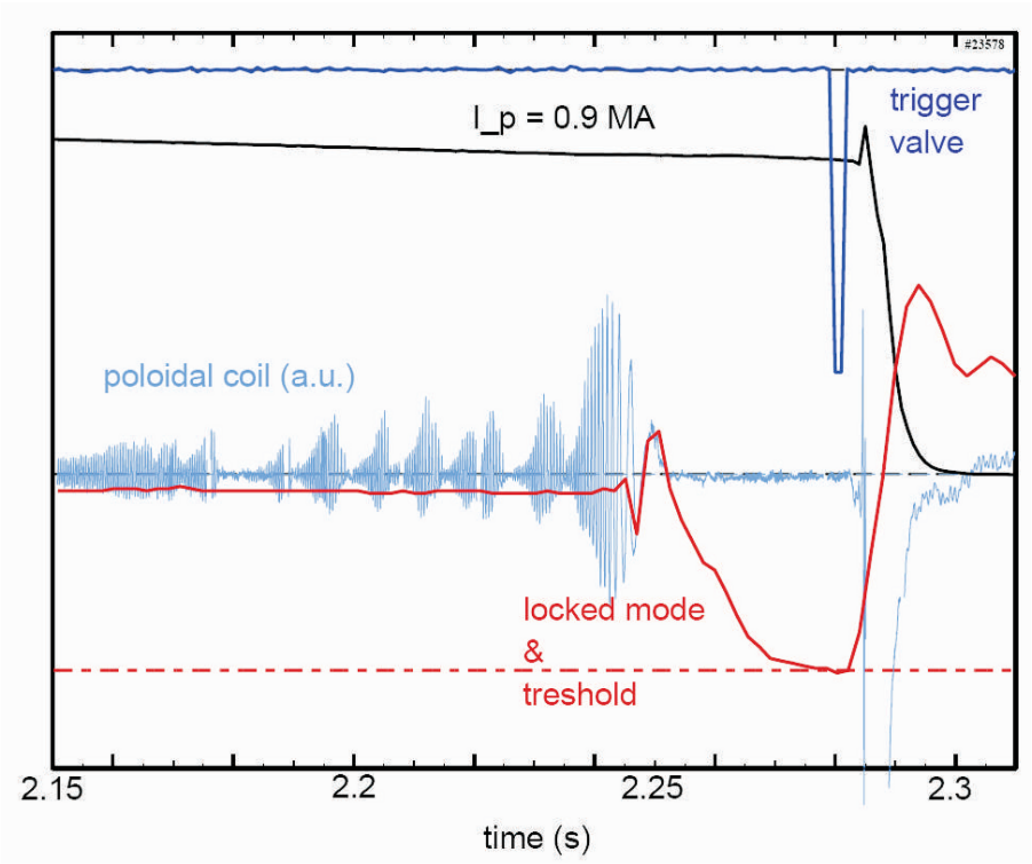


Type of shutdown	Unintentional disruptions	
Mode Lock	630	48.4%
Technical (PPCC, SC, etc.)	304	23.4%
MHD mode	40	3.1%
None	327	25.1%

only a few of the detected disruptions (~20%) have a warning time < 100ms

P. de Vries, NF 2009

Routine mitigation in AUG: locked mode detector triggers valve



But

gas injection is not always the best choice

locked mode detection does not always allow enough reaction time

in many cases other events are the root cause bringing the plasma onto the path to mode lock and eventually to disruption

detection of a single pre-cursor does not ensure safe prediction of a disruption

G. Pautasso, NF2007

Detection - Neural Networks

Neural Networks (NNs) are a family of models inspired by biological neural networks (the central nervous systems of animals, in particular the brain) which are used to estimate or approximate functions that can depend on a large number of inputs and are generally unknown. (We use it for the disruption because we do not know the exact physics!)

<u>Pro:</u> It works well
<u>Contro</u>: (1) It is almost impossible to transfer (2) It needs to be trained and we can not do disruptions for this purpouse in ITER

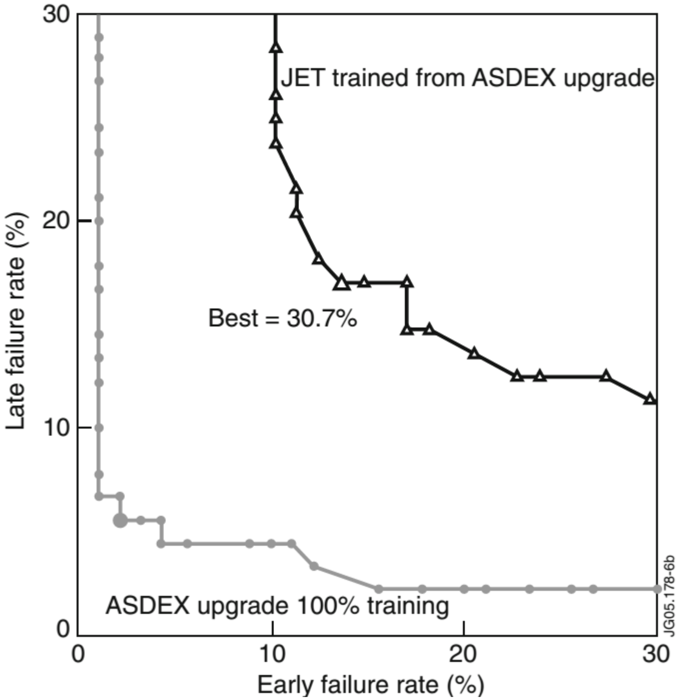


Fig. 7.11 Performance of a NN trained on ASDEX Upgrade and applied to JET. Also shown is the performance of the network on ASDEX Upgrade. From [48]

Disruption control – magnetic feedback

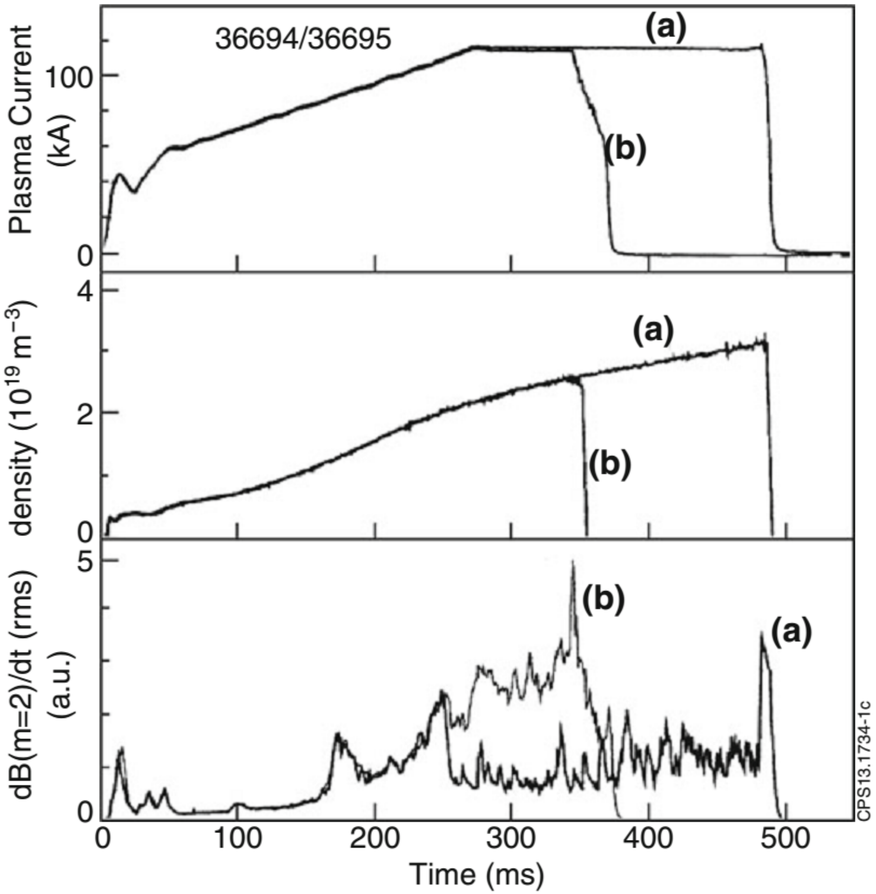
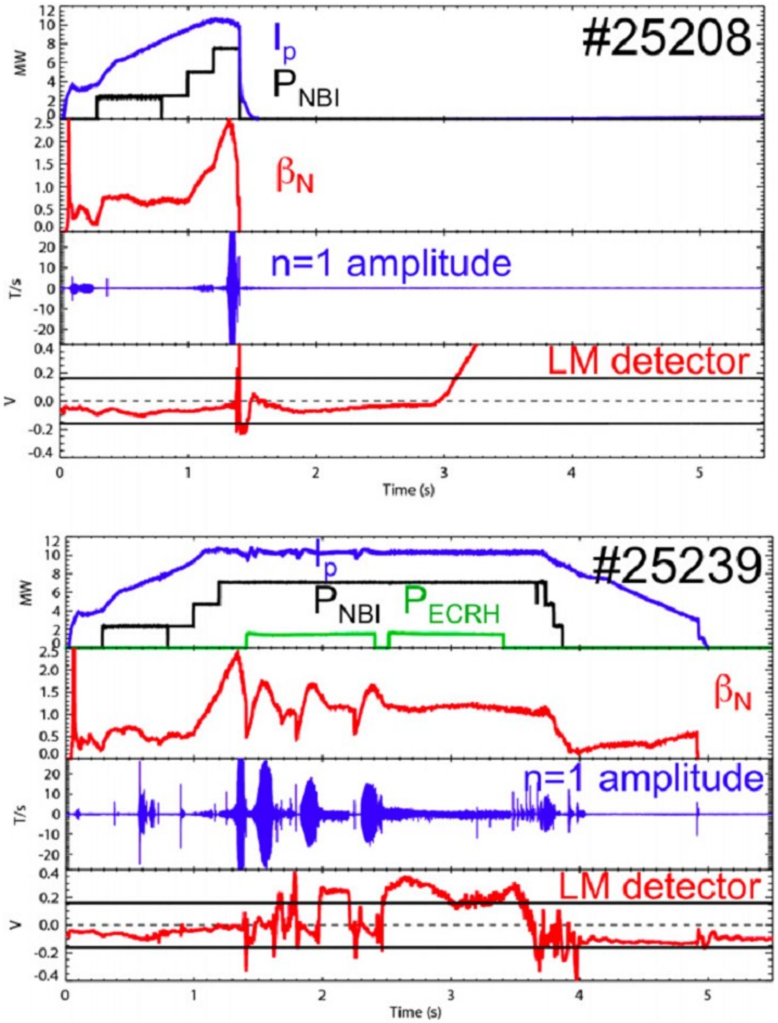


Fig. 7.12 Two nominally identical pulses with **a** magnetic feedback applied from 240 ms and **b** no feedback. The feedback lowers the magnetic fluctuation amplitude (*dB/dt*) and allows a higher density to be achieved. From [68], copyright 1990 by the American Physical Society

External coils suppress the mode.

(The same idea as for resistive wall mode control)

Disruption control - ECRH

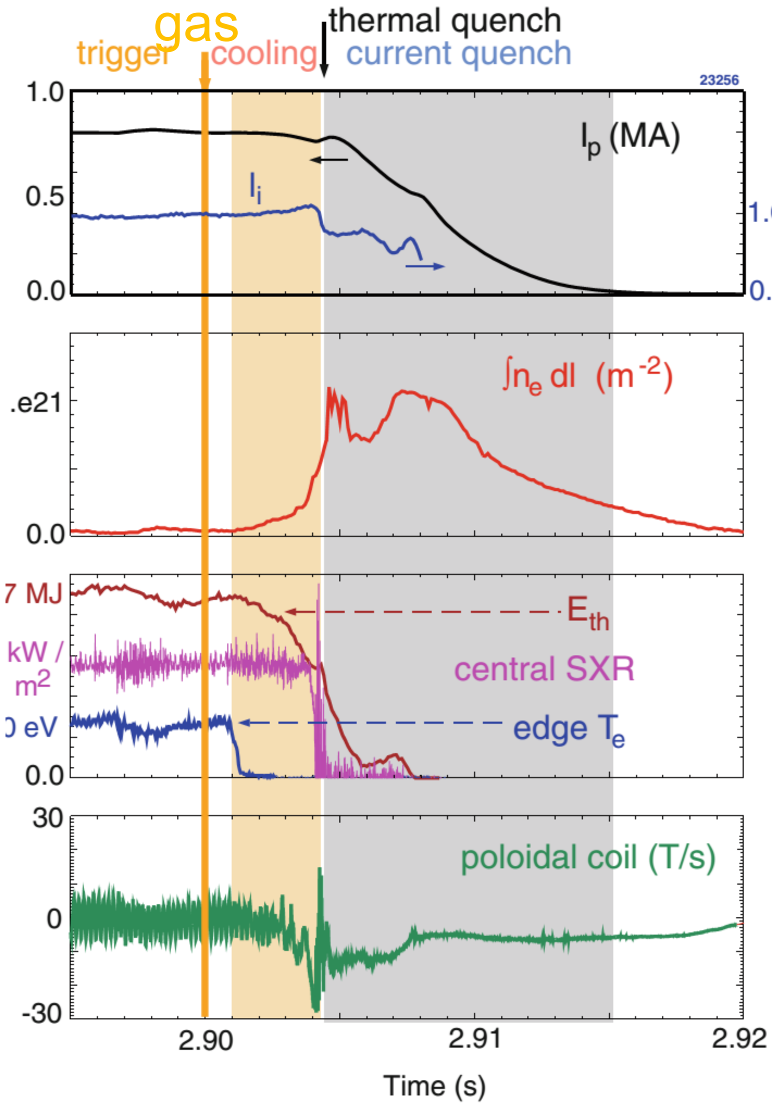


As soon as the disruption precursor signal (the locked mode detector and/or the loop voltage) reaches the preset threshold, the Electron Cyclotron Resonance Heating (ECRH) poweris triggered by real-time control and heat the island.

Figure 1. (top) Reference disruption at high β_N: time traces of I_p, P_{NBI}, P_{ECRH}, β_N, Mirnov coil signal and locked mode (LM) detector signal with its thresholds. (bottom) Same discharge repeated with injection of ECRH ($\rho_{dep} \sim 0.5$) real-time triggered by LM.

Disruption mitigation – gas puff

After a short flight time for injected gas the edge electron temperature (‘edge Te’) drops and then the outer region of the plasmas cools causing a drop in the plasma thermal energy (Eth), this is followed by a rapid loss of plasma energy (as shown by the central Soft X-ray) known as the thermal quench.



The three aims of MGI are:

- to reduce disruption heat loads to surrounding components,
- to reduce disruption EM forces
- to mitigate runaways.

Reduction of heat loads is achieved by the MGI increasing the radiated power fraction, which spreads the heat loads more uniformly.

Disruption mitigation – gas puff

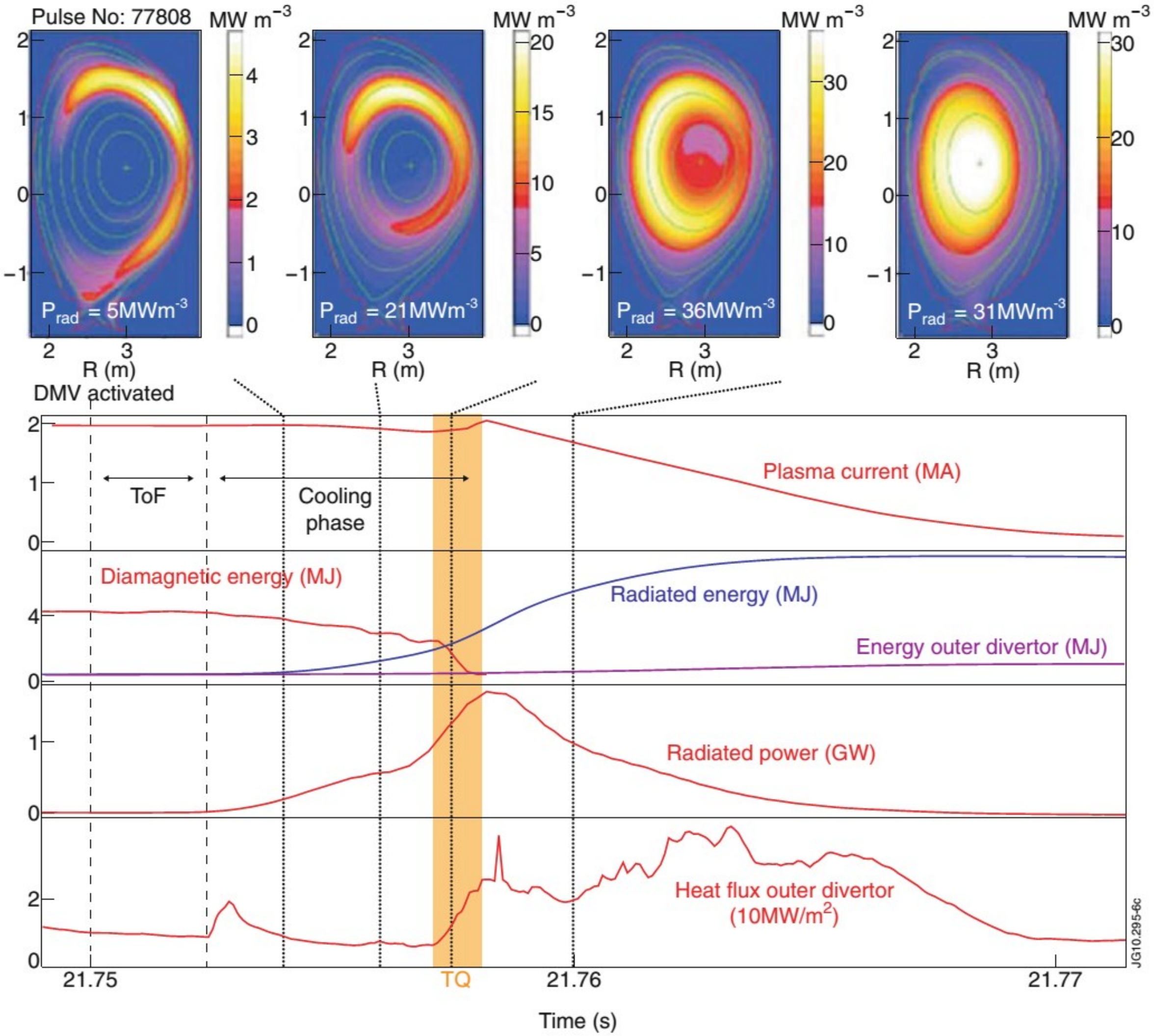
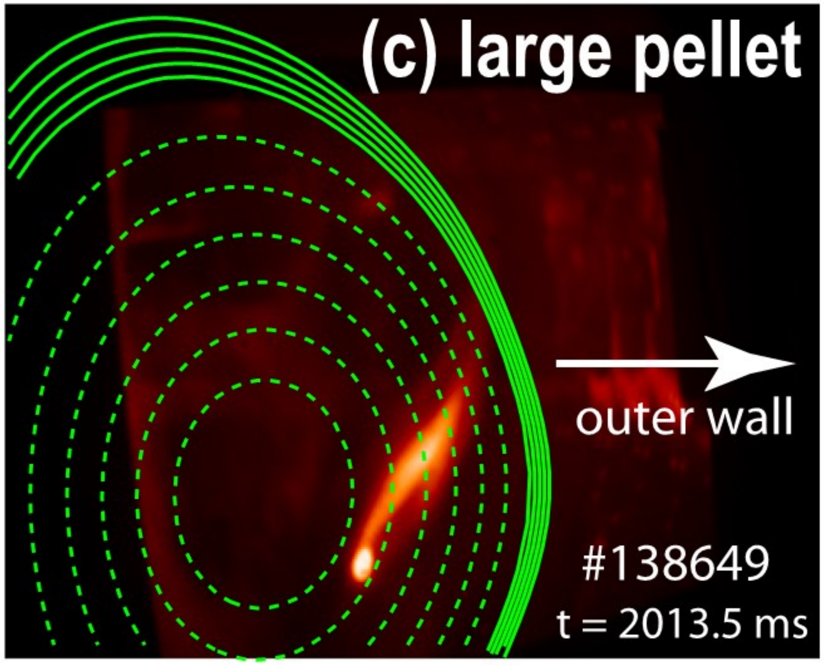


Fig. 7.16 Data from JET for an argon-deuterium MGI mixture, showing contour plots of radiated power from tomographic reconstructions, which illustrate how the core radiated power increases sharply during the thermal quench (TQ) phase. From [74]

Disruption control - Killer pellets

An alternate scheme for disruption mitigation, that pre-dates MGI, is by the injection of frozen gas killer pellets. As with Massive Gas Injection, the killer pellets were successful in mitigating heat loads and halo currents, but there was a tendency to produce runaway electrons

DIII-D



Hollmann *et al.*
Phys. Plasmas **22**, 021802 (2015)

Conclusions (1)

Disruption is …..

Disruption becomes much more probable close to ….

Typical sequences of the disruption:…

Disruption problems:

- …

Conclusions (1)

Disruption is a rapid loss of plasma confinement.

Disruption becomes much more probable close to the operation limits.

Typical sequences of the disruption: Approach the operational limit → instability → energy losses → plasma toches the wall → plasma cooling → lost of current

Disruption problems:

- Forces
- Heat Loads
- Runaways

Conclusions (2)

Disruption detection:

- …

Actions which can be done to avoid or mitigate the disruption:

- …

Conclusions (2)

Disruption detection:

- Lock mode sensor (magnetic coils)
- Neural network

Actions which can be done to avoid or mitigate the disruption:

- Magnetic control of the mode
- ECRH
- Gas puff
- Pellet