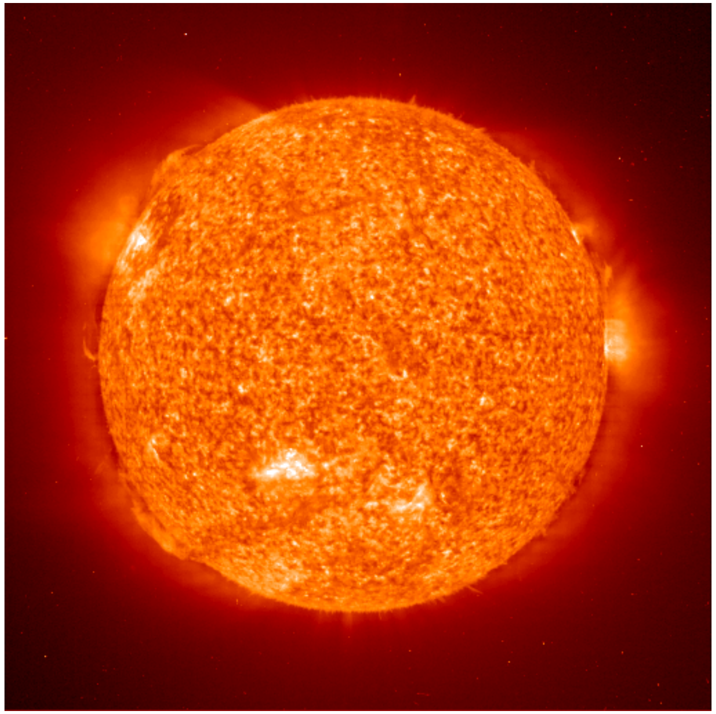
Max-Planck-Institut für Plasmaphysik

Disruptions



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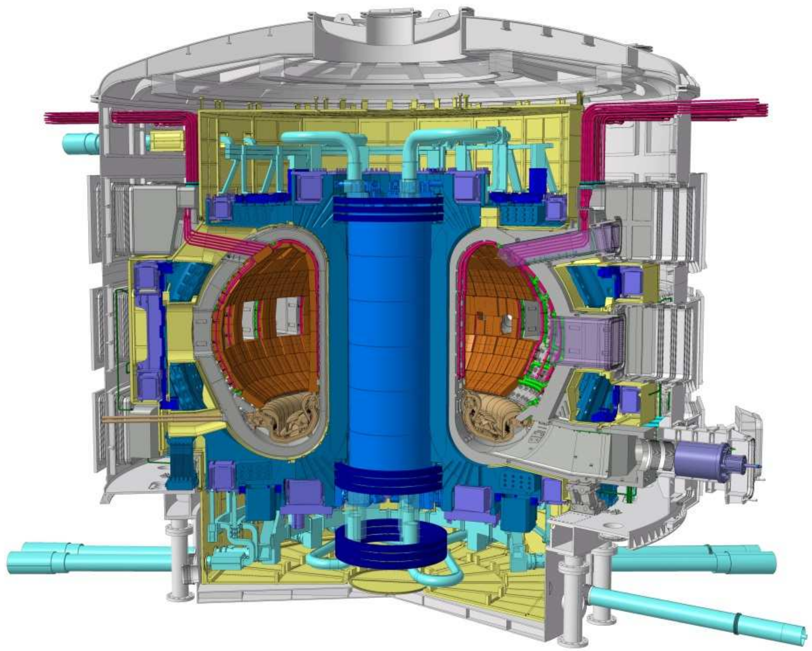


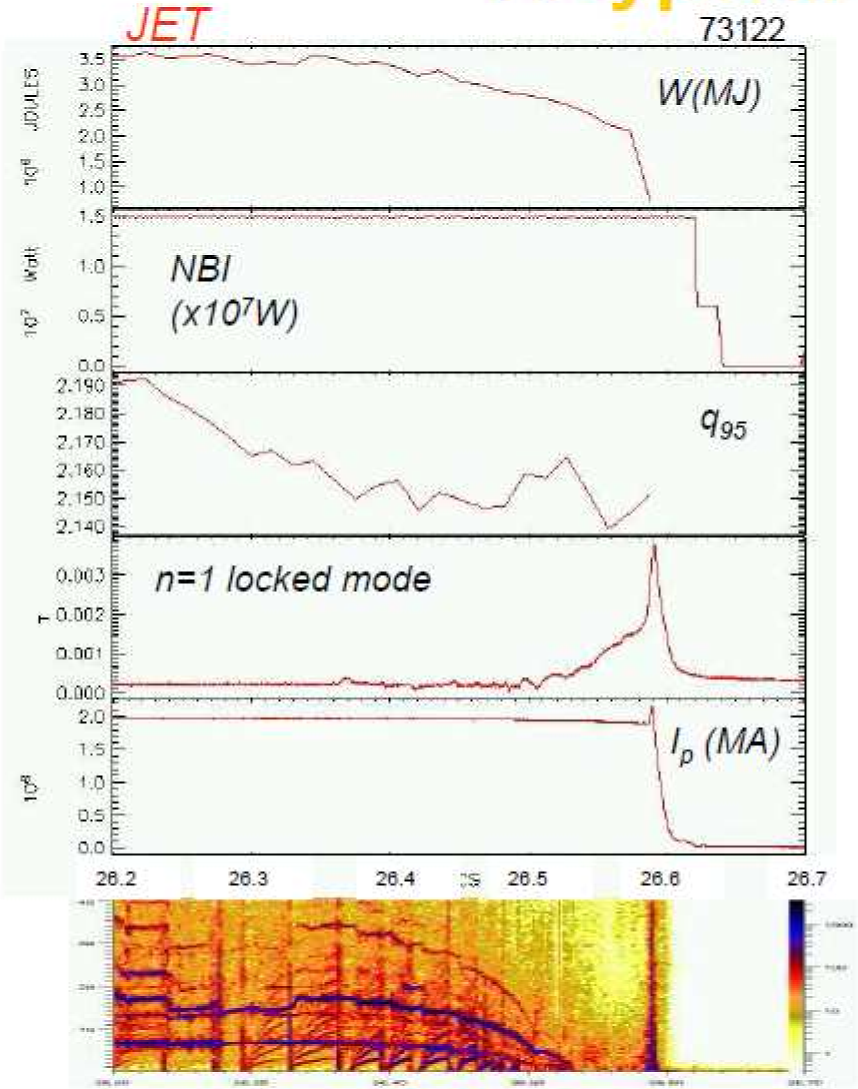
DPG Advanced Physics School
‚The Physics of ITER'
Bad Honnef, 24.09.2014

The disruptive instability

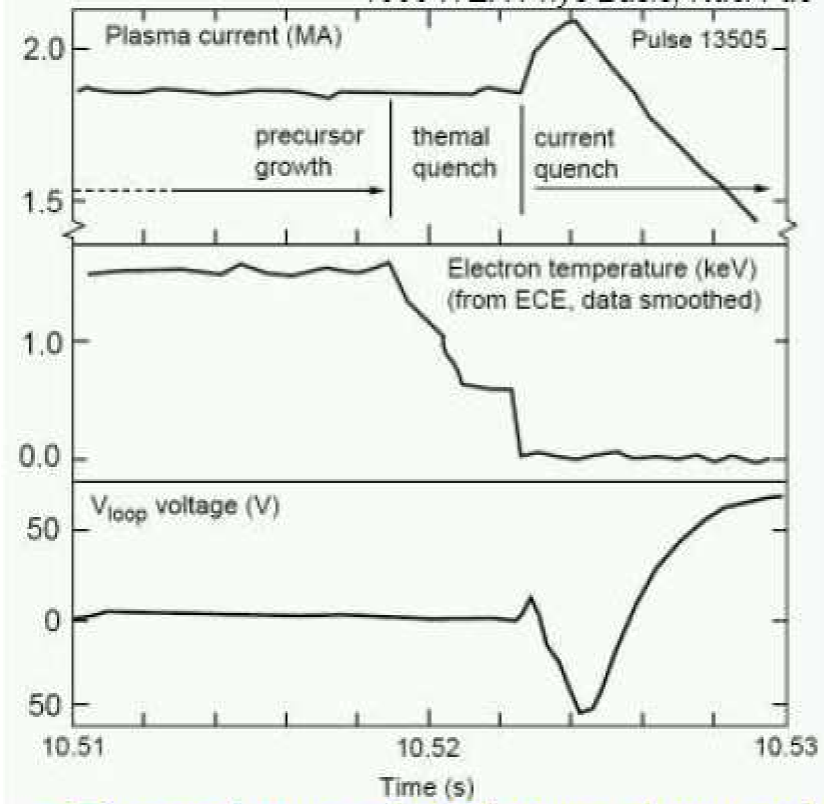
- Phenomenology and physics of disruptions
- Consequences of disruptions
- Disruption avoidance and mitigation

- **Phenomenology and physics of disruptions**
- **Consequences of disruptions**
- **Disruption avoidance and mitigation**

A typical disruption*



1999 ITER Phys Basis, Nucl Fus



- *Thermal quench and current quench*
- *Consequences heat + EM loads, VDE, halos*
- *Pre-disruption energy loss, precursors*

CCFE
CULHAM CENTRE FUSION ENERGY

**there is no such thing as a typical disruption!*

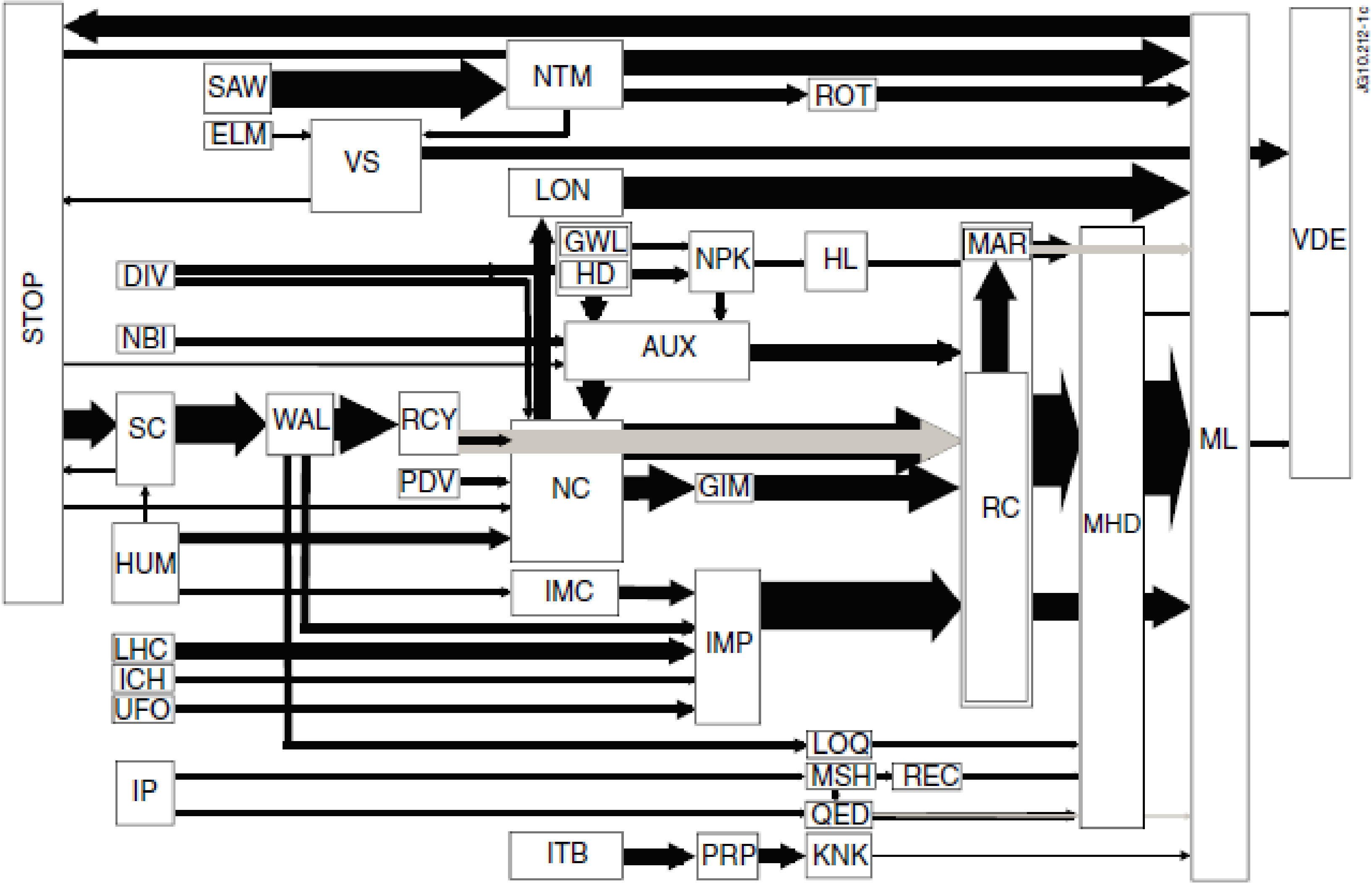
Energy

Phenomenology of disruptions

'Something goes wrong' and ultimately triggers large tearing modes

- many reasons, usually operational limit or technical fault
- in some high β scenarios, ideal mode can directly terminate discharge (!)

Disruption causes – flow chart



Phenomenology of disruptions

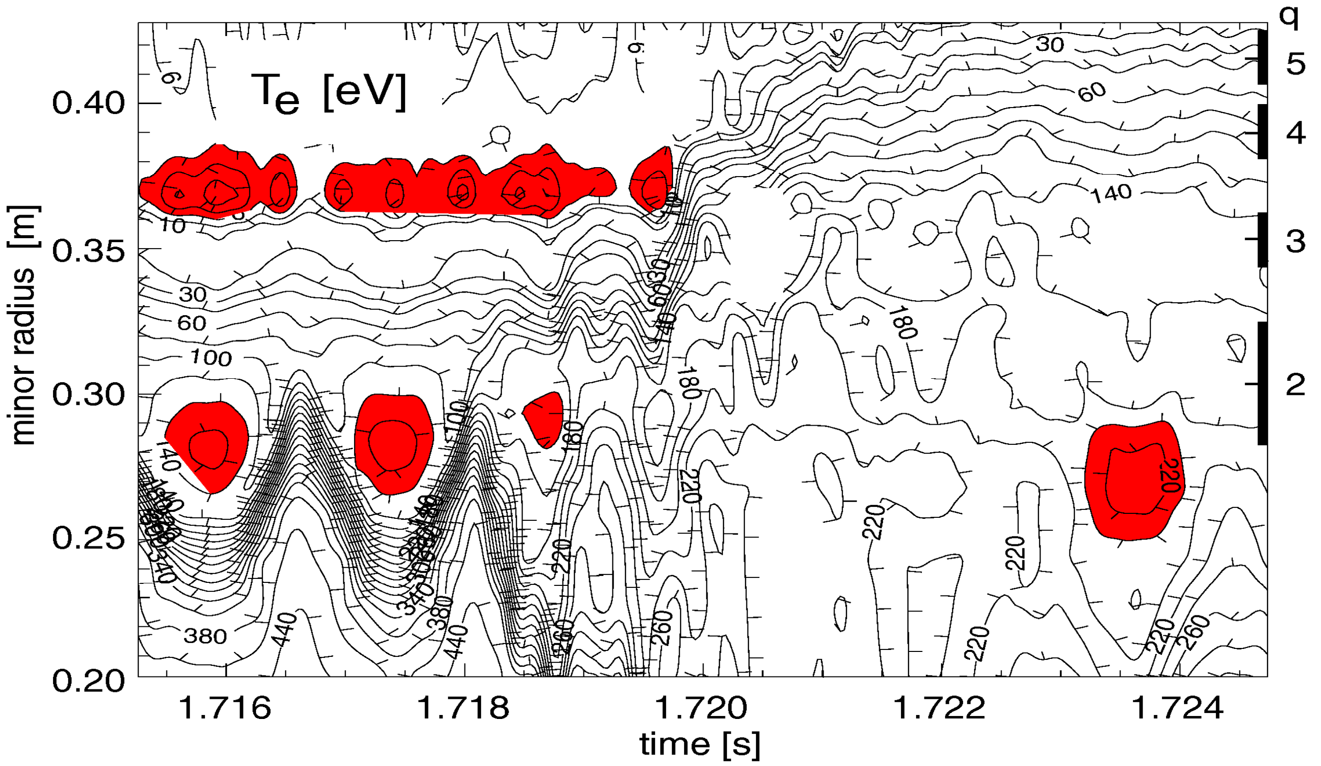
'Something goes wrong' and ultimately triggers large tearing modes

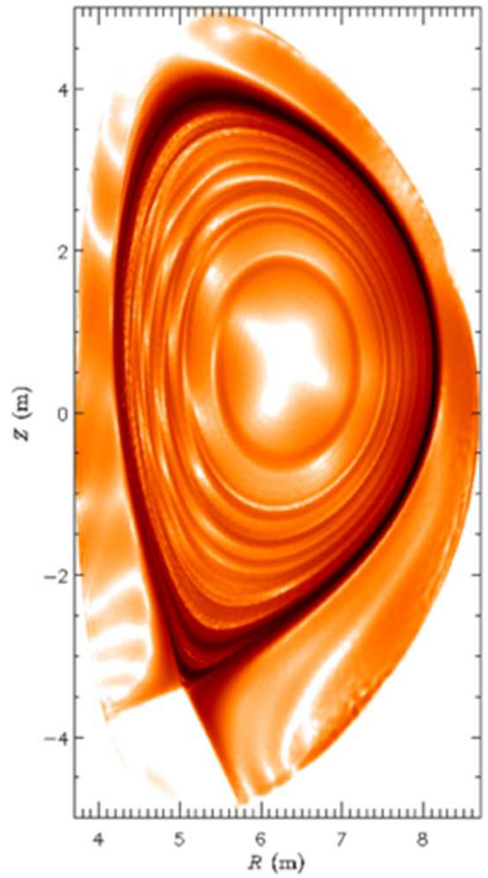
- many reasons, usually operational limit or technical fault
- in some high β scenarios, ideal mode can directly terminate discharge (!)

Coupling of tearing modes leads to fast ($\leq$ ms) thermal quench (TQ)

- temperature can drop to very low (down to 10 eV) values across radius
- indication that a mixing by ideal modes can also play a role

Thermal quench: magnetic islands & stochastisation

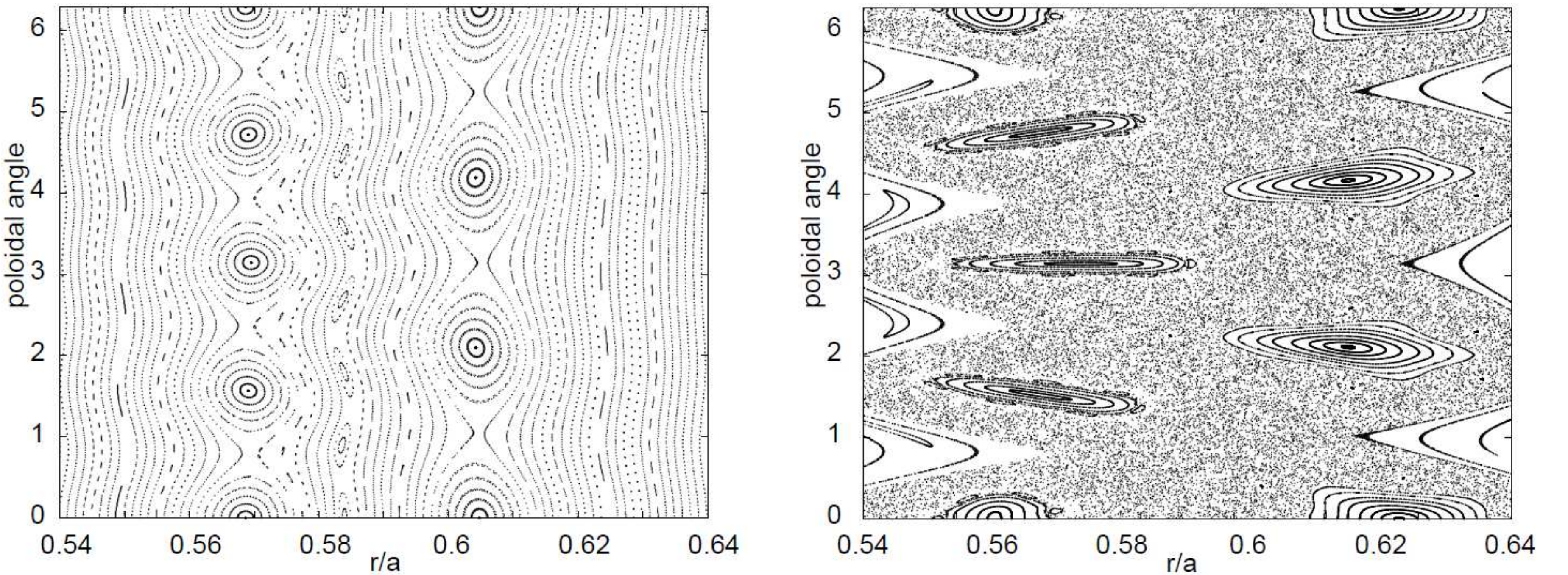




coupling between island chains (possibly stochastic regions)

⇒ sudden loss of heat insulation ('disruptive instability')

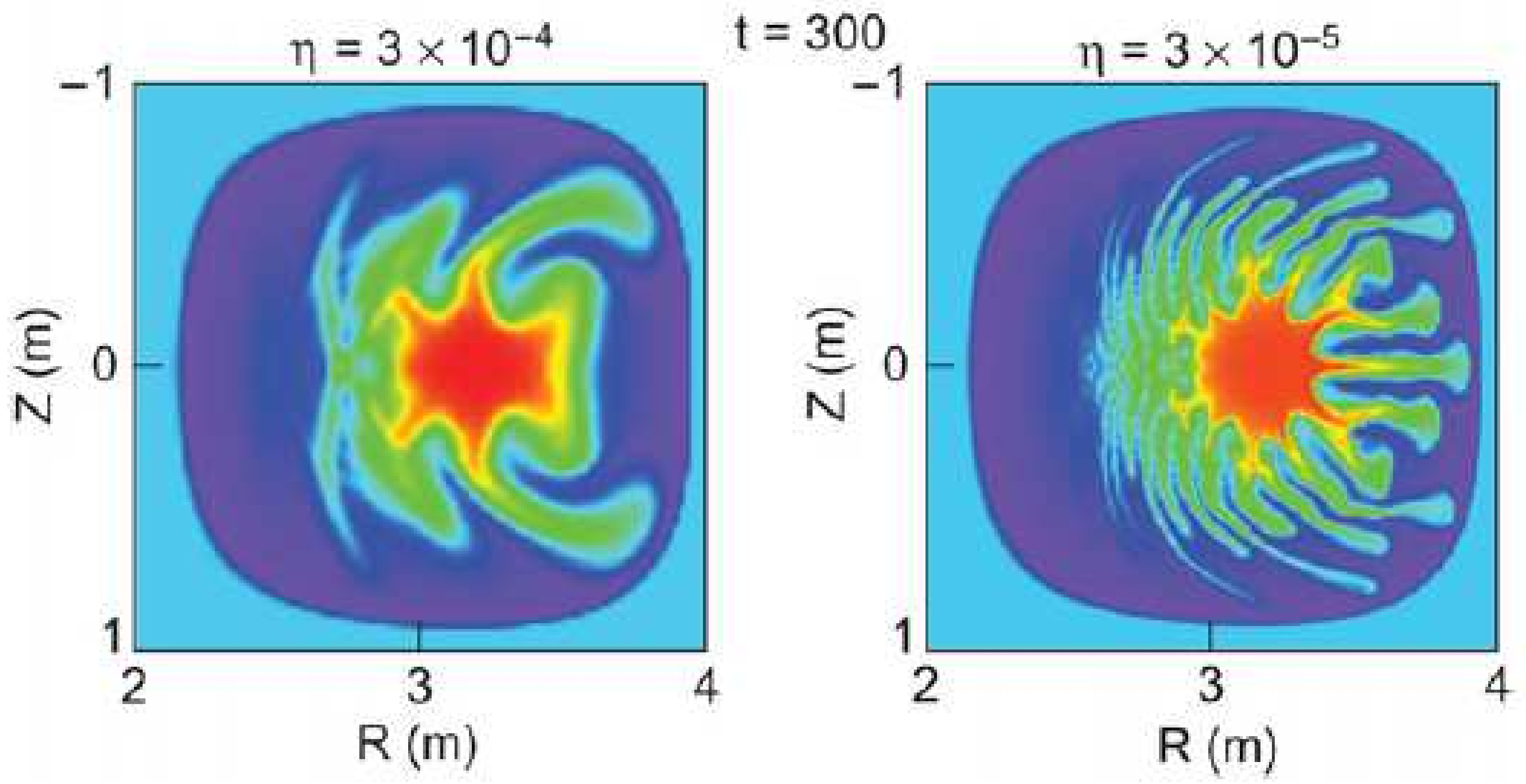
Thermal quench: magnetic islands & stochastisation



coupling between island chains (possibly stochastic regions)

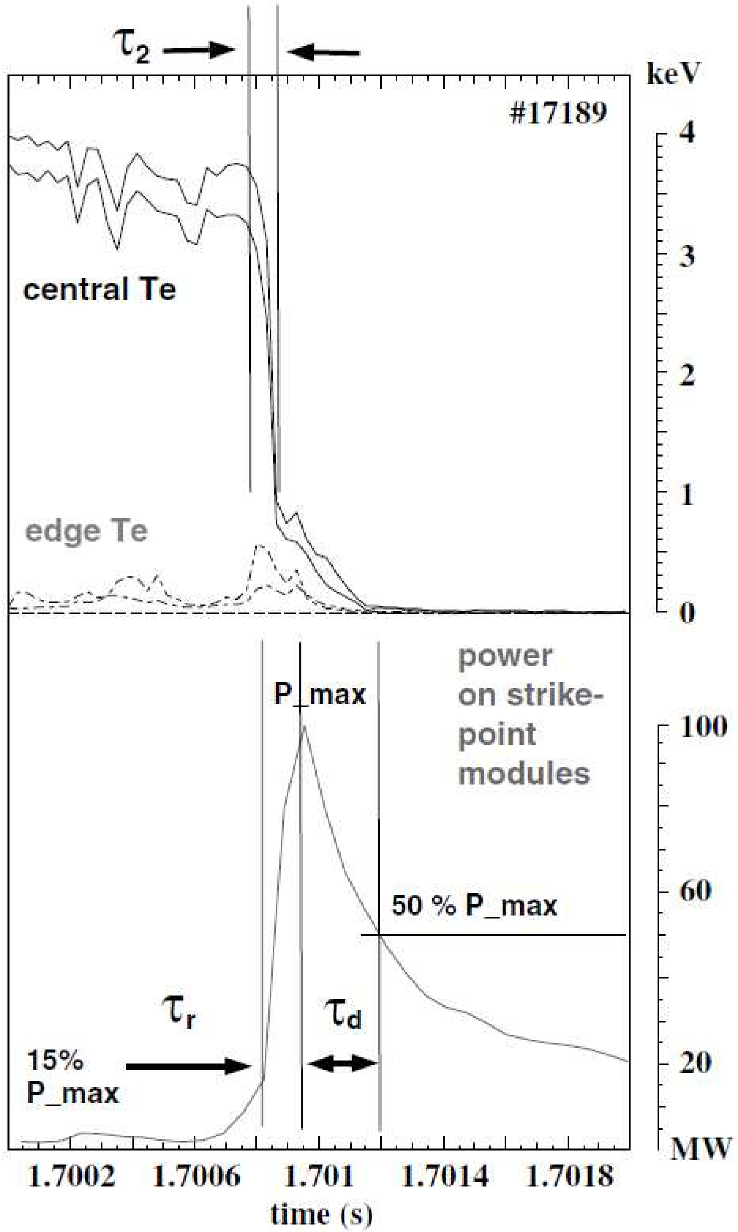
$\Rightarrow$ sudden loss of heat insulation ('disruptive instability')

Thermal quench: mixing of plasma core



Example: nonlinear ballooning modes – ‚fingers'

Disruptions: typical time scale of TQ



Typical timescale ≤ 1 ms, no clear variation with machine size, although tendency to increase…

Power on the target plates deposited during a time longer than quench time (good…)

Phenomenology of disruptions

'Something goes wrong' and ultimately triggers large tearing modes

- many reasons, usually operational limit or technical fault
- in some high β scenarios, ideal mode can directly terminate discharge (!)

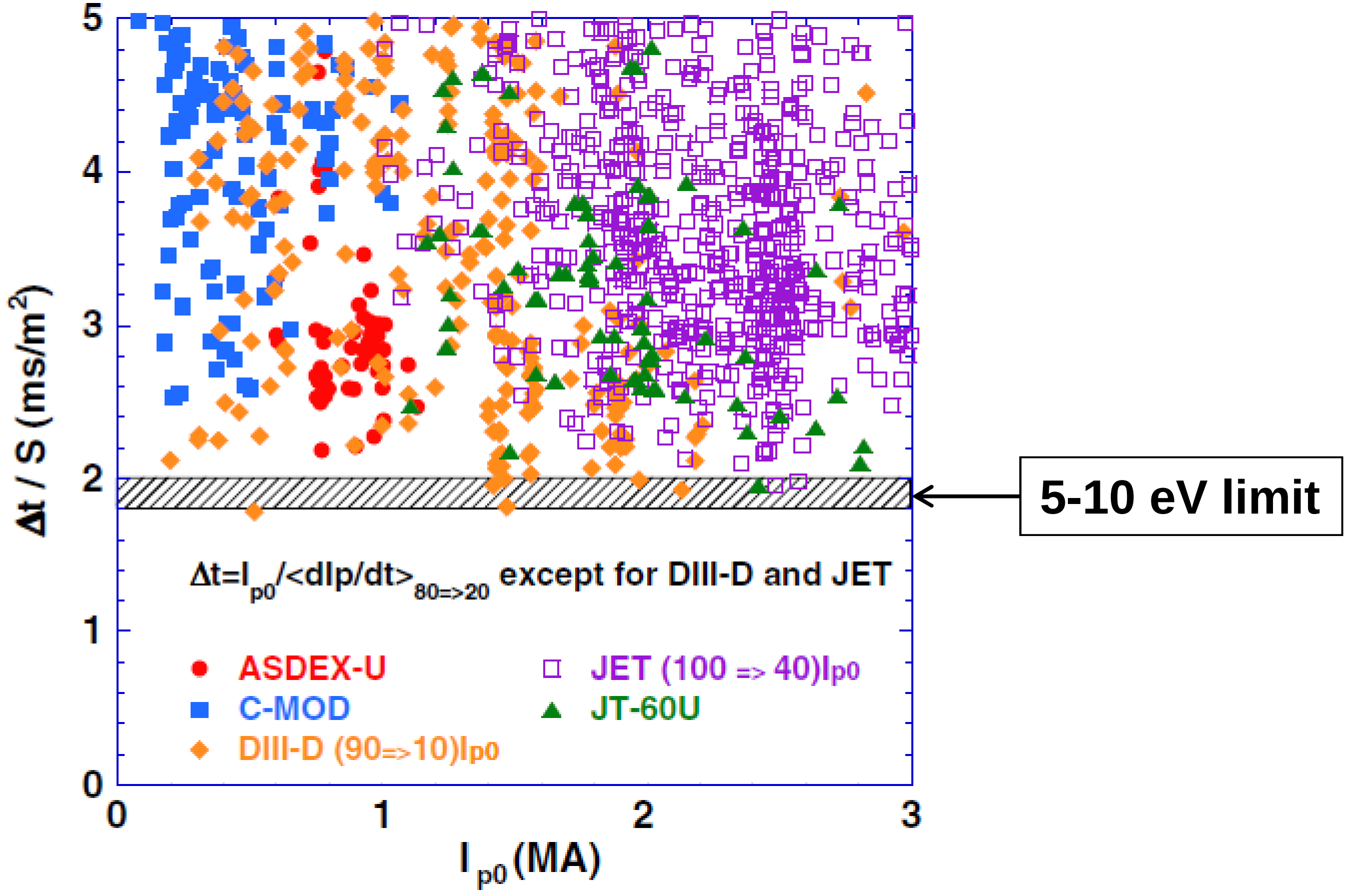
Coupling of tearing modes leads to fast ($\leq$ ms) thermal quench (TQ)

- temperature can drop to very low (down to 10 eV) values across radius
- indication that a mixing by ideal modes can also play a role

Large increase in electrical resistance $\Rightarrow$ current quench (CQ)

- drop of T_e e.g. by factor 100 means 1000 x higher loop voltage (!)
- resistive decay of current consistent with L/R time of cold plasma ring

Disruptions: typical time scale of CQ



$$\Delta t_{CQ} \propto \frac{L}{R_p} \propto \mu_0 \sigma \ell_i A_p$$

σ = electrical conductivity (~ $T^{3/2}$)

ℓ_i = inductance of plasma ring

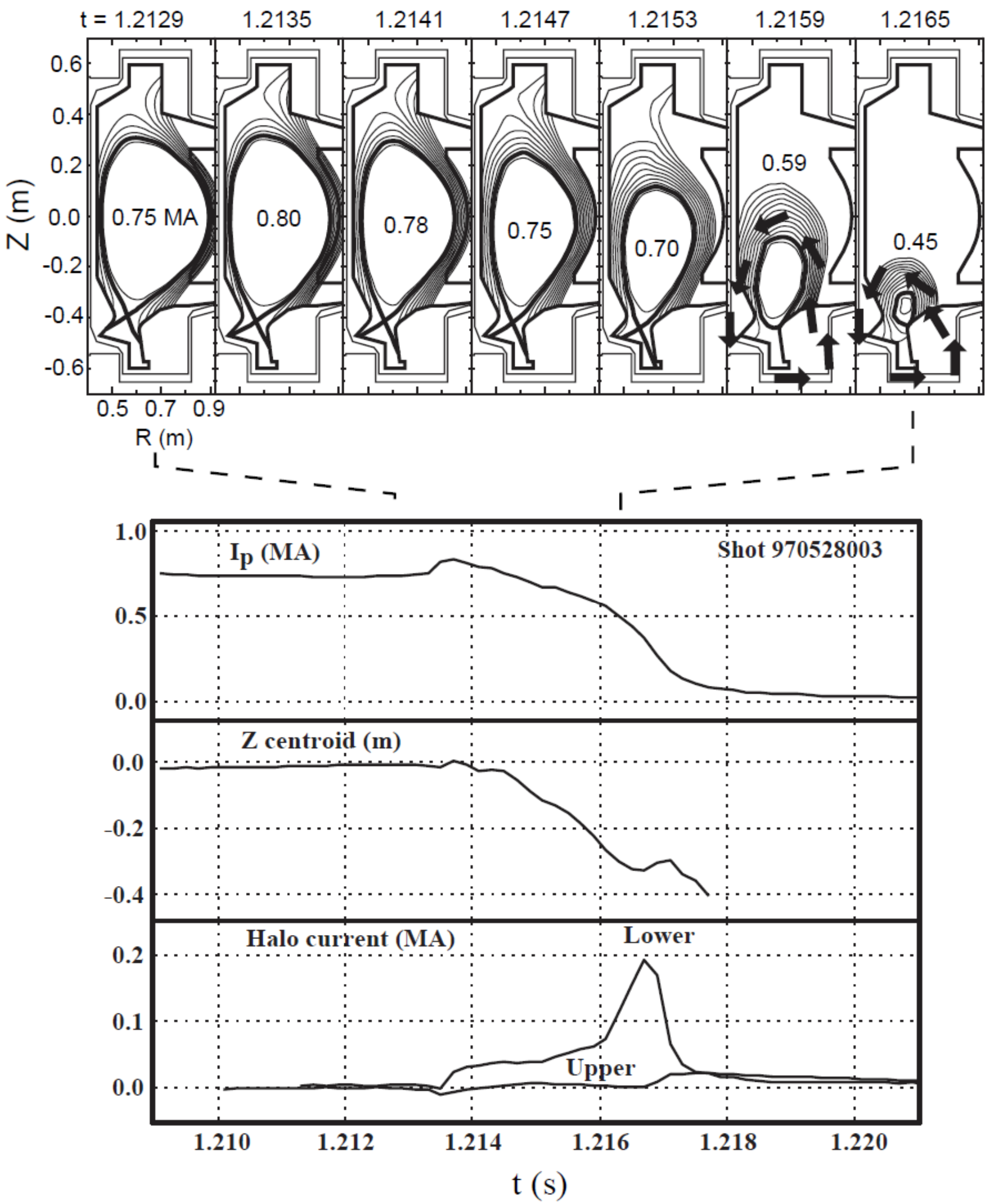
A_p = poloidal cross-section area

- Phenomenology and physics of disruptions
- **Consequences of disruptions**
- Disruption avoidance and mitigation

- Key issues to be resolved for disruptions in ITER:-
  - Forces (VDE symmetric load ~100MN, asymmetric ~40MN)
  - Heat Loads (~20MJ/m^2 ,>melt limit)
  - Runaways (~10MA at 10-20MeV)

Examples from JET

Generation of ‚halo' currents during a VDE



Elongated plasma is unstable to vertical displacement

vertical position actively stabilised in normal operation

Disruption can lead to loss of position control

vertical displacement event (VDE)

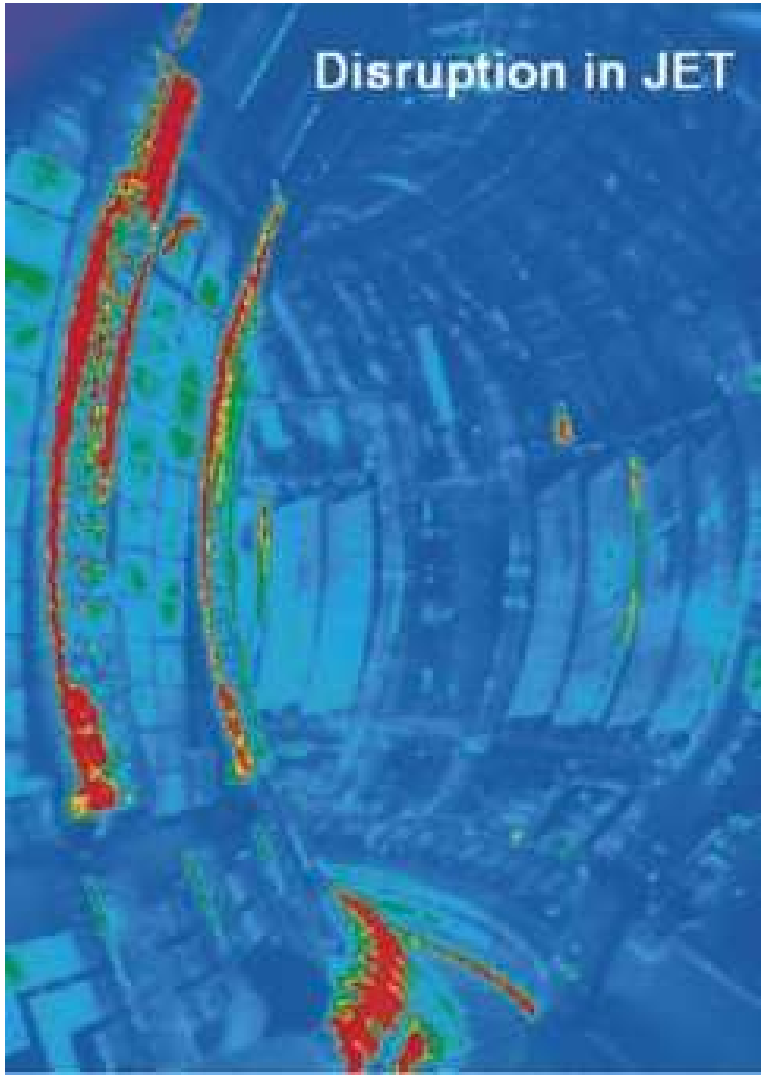
motion induces poloidal voltage

plasma in contact with wall allows poloidal current to close

‚halo current', up to 50% of I_p

huge forces (5 T x 5 MA x 1m is equivalent to 2500 t)

Thermal loads during disruptions



For large transient heat loads, ‚energy impact' matters

$$\Delta T_{component} \propto \eta = const. \frac{\Delta W}{A_c \sqrt{\Delta t}}$$

(since diffusion of heat wave into Material is proportional $\Delta t^{1/2}$)

W melt limit: η_{max} = 0.05 GW m^{-2} $s^{-1/2}$

all energy on divertor in present day device: 0.01-0.02 GW m^{-2} $s^{-1/2}$

the same in ITER: 0.45 GW m^{-2} $s^{-1/2}$

on the whole wall: 0.015 GW m^{-2} $s^{-1/2}$

Need to spread heat load over whole first wall in ITER!

Generation of Runaway electrons in a tokamak

Due to the $1/v_e^2$ dependence of collisional friction, there is a critical electric field for electrons with v_e above which they 'run away'

$$E_c(v_e) = \frac{e^3 n_e \ln \Lambda}{4\pi\epsilon_0^2 m_e v_e^2}$$

- collisional drag can no longer decelerate these electrons
- ultimate limit is energy loss by synchrotron radiation on the circular orbit

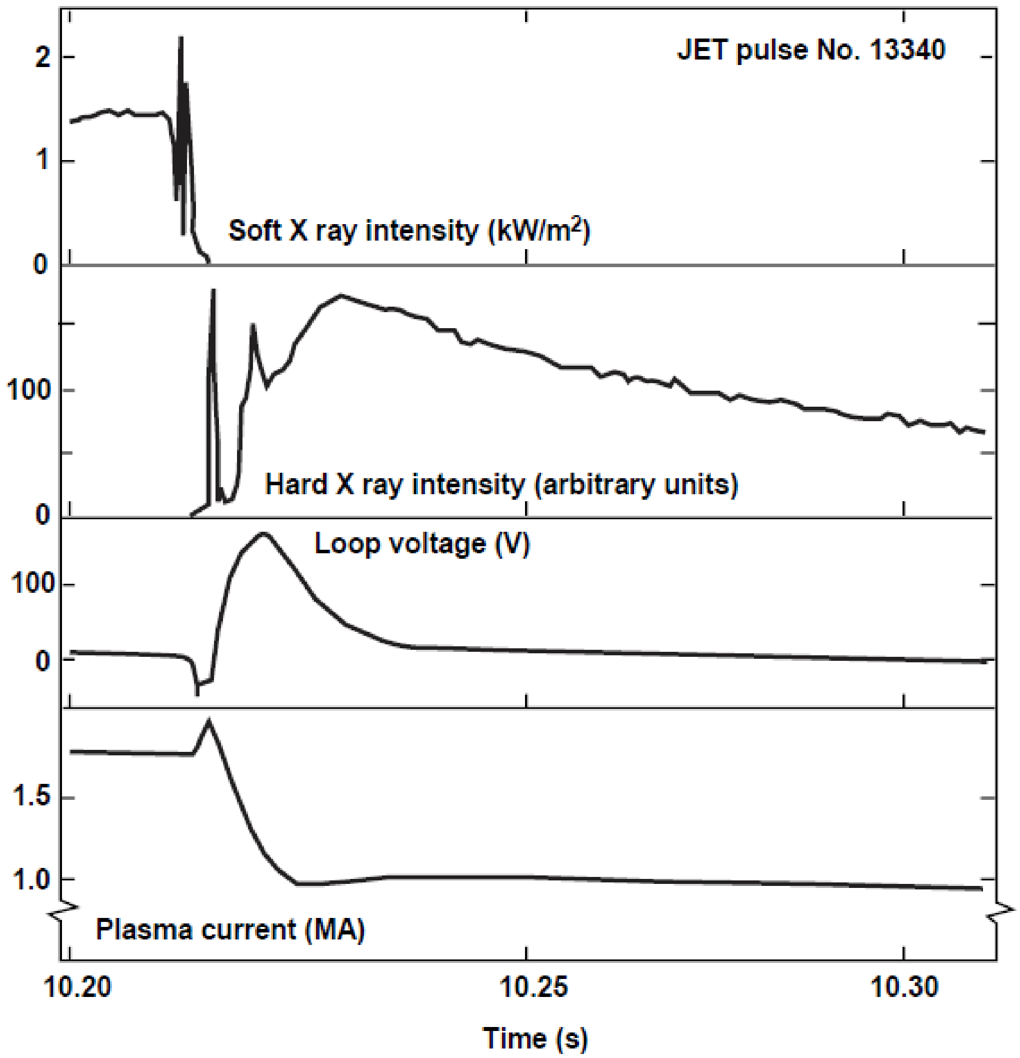
Amount of runaways generated depends on loop voltage $U_{loop}=E_{internal}\, 2\pi R$

- if $E_{internal} > E_c$ fulfilled for $v_e \sim v_{th,e} \rightarrow$ all electrons runaway
- if $E_{internal} > E_c$ fulfilled for $v_e >> v_{th,e} \rightarrow$ few electrons runaway
- if $E_{internal} > E_c$ fulfilled for $v_e \sim c \rightarrow$ no electrons runaway

$$E_{c,rel} = E_c(v_e = c) = \frac{e^3 n_e \ln \Lambda}{4\pi\epsilon_0^2 m_e c^2}$$

- relativistically, there is a remaining finite drag at $v_e=c$

Generation of Runaways during disruptions



$E_{internal}$ is high during disruption:

$$E_{internal} \approx \frac{\mu_0 \ell_i I_p}{2\pi \Delta t_{CQ}}$$

coldest plasma has largest $E_{internal}$

During disruption, large fraction of I_p can be converted into runaways

danger to vessel components…

…but only a problem at low n_e

Generation of Runaway electrons in a tokamak

However, there is a second mechanism of Runaway generation:

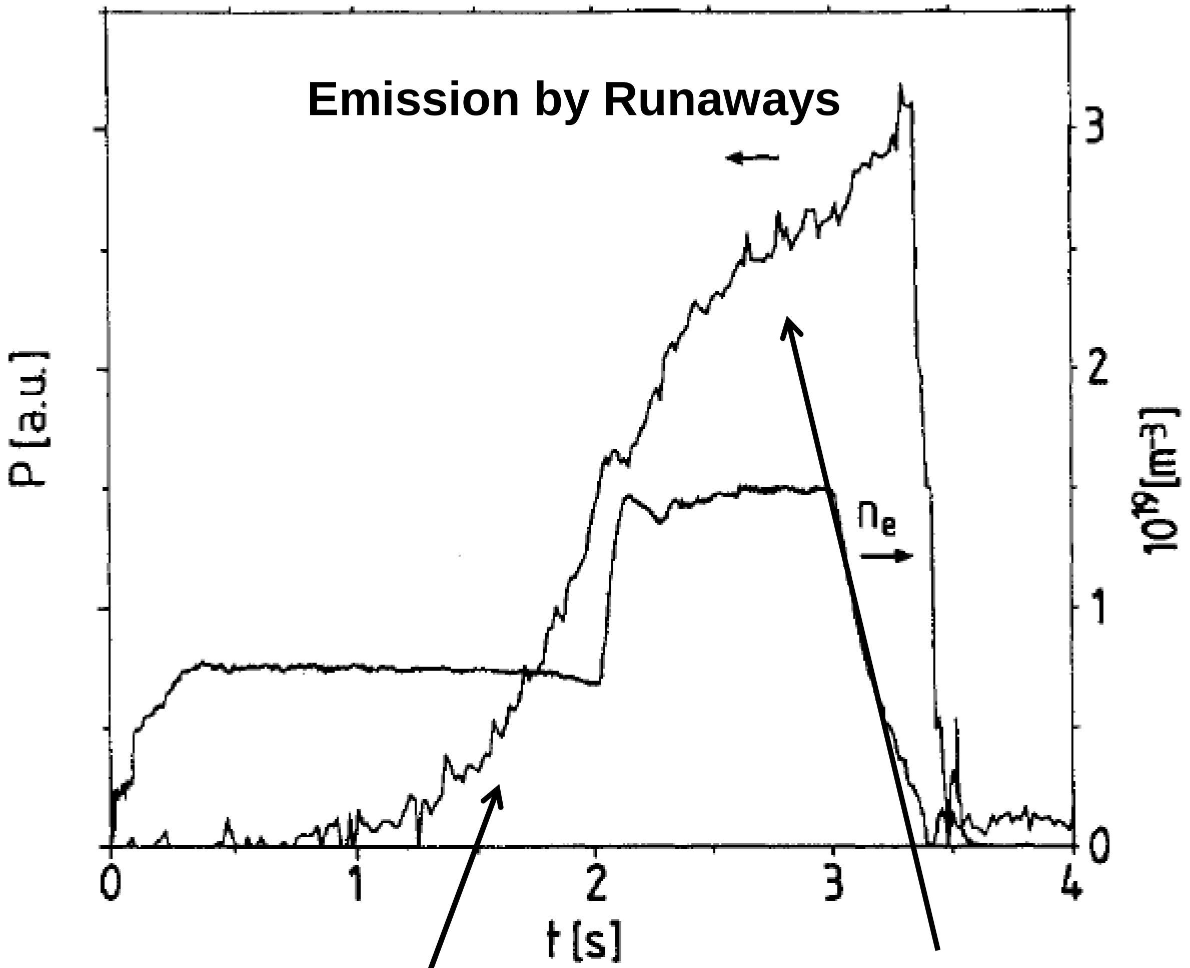
Direct knock-on can generate secondary runways

$$\frac{1}{I_{RA}}\frac{dI_{RA}}{dt} \approx \frac{eE_{c,rel}}{m_e c \ln\Lambda}\left(\frac{E_{internal}}{E_{c,rel}} - 1\right) = \frac{1}{\tau_{RA}}$$

- exponential increase (avalanche) if $E_{internal} > E_{c,rel}$
- $I_{RA} = I_{RA,0} \exp(\Delta t_{CQ}/\tau_{RA})$
- avalanche factor only depends on Ip: $\Delta t_{CQ}/\tau_{RA} = 2.4\ I_p$ [MA]
- medium sized tokamak (ASDEX Upgrade): $I_{RA}/I_{RA,0} = 10$ – no big worry
- JET: $I_{RA}/I_{RA,0} = 10^4$ – can be significant
- ITER: $I_{RA}/I_{RA,0} = 2 \times 10^{16}$ – virtually unavoidable unless $E_{internal} < E_{c,rel}$
- need to increase density such that $E_{c,rel}$ high enough

$$E_{c,rel} = E_c(v_e = c) = \frac{e^3 n_e \ln\Lambda}{4\pi\epsilon_0^2 m_e c^2}$$

Avalanche generation at low density in TEXTOR



Low density: exponential growth

High density: saturation

- Phenomenology and physics of disruptions
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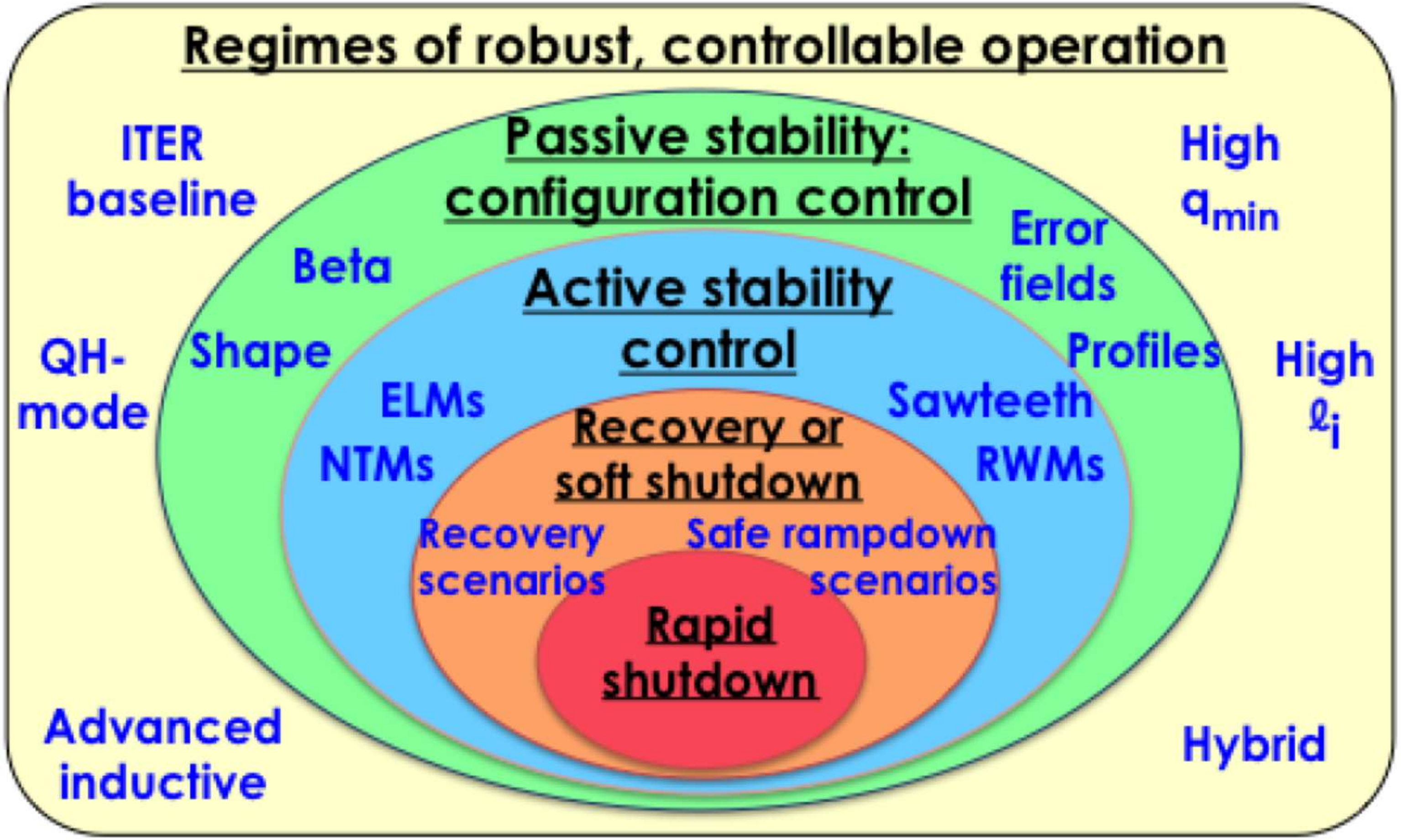
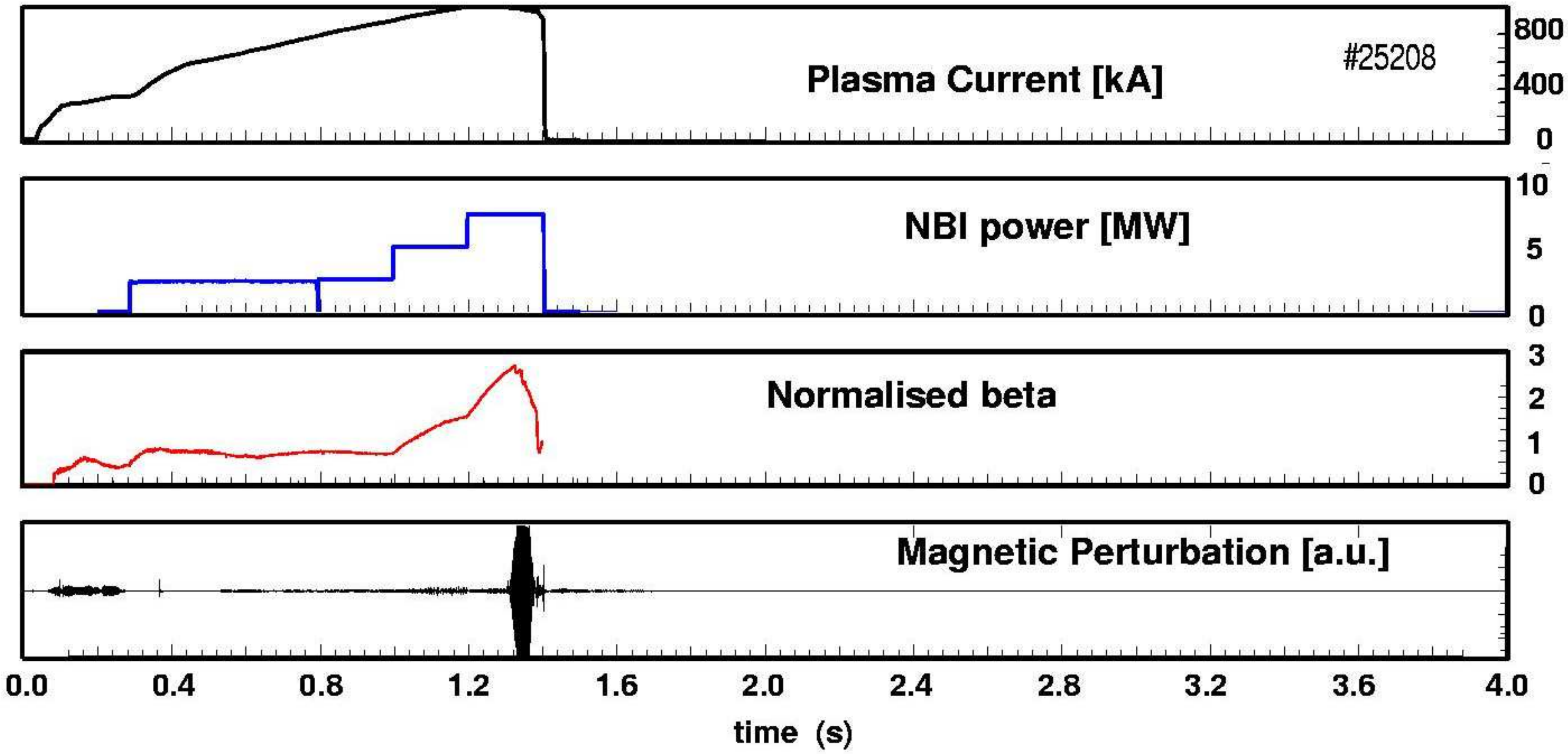
A Layered Approach to Disruption Control

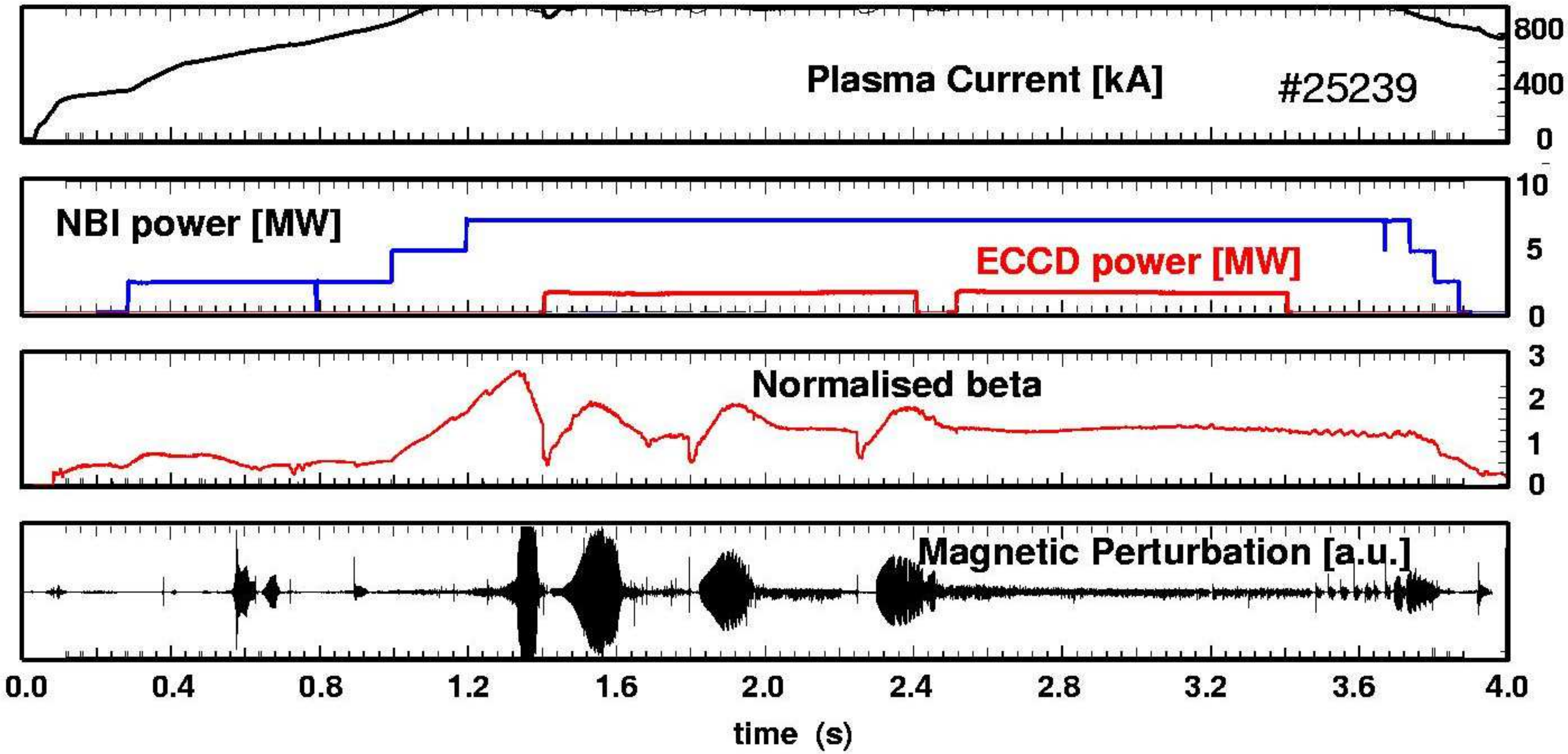


Disruption avoidance by ECRH – an example



Target: a discharge that disrupts due to an early (2,1) NTM (q = 3.9, β_N=2.6)

Disruption avoidance by ECRH – an example



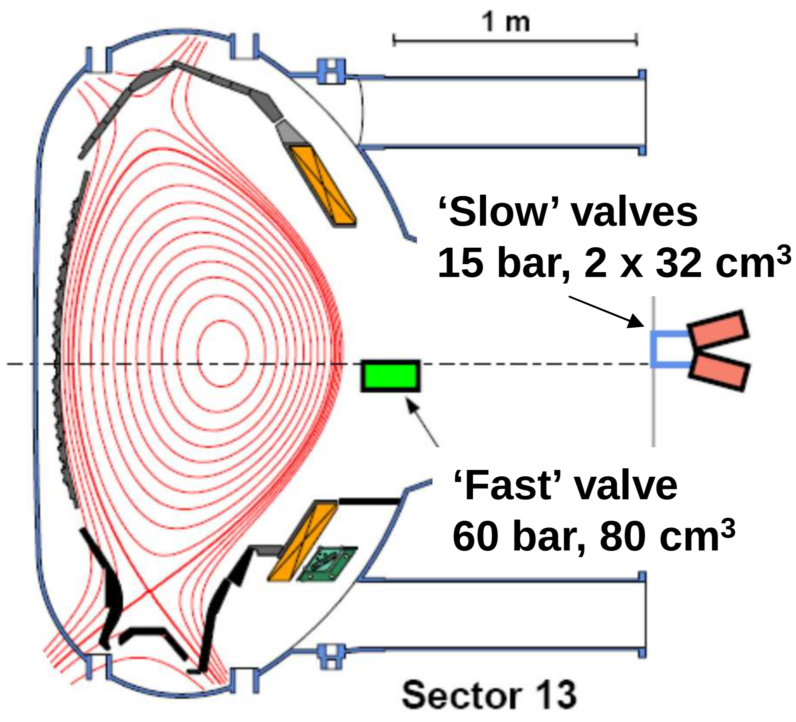
1.5 MW of ECCD sufficient to avoid disruption, prepare safe landing

- note: discharge never recovers performance – need to develop strategy
- analysis of ‘scalability’ ongoing

Disruption mitigation by high pressure gas jet

Example: ASDEX Upgrade disruption mitigation

- massive Ne puff from high pressure valve, triggered by locked mode
- on ASDEX Upgrade, main aim is to reduce halo current forces



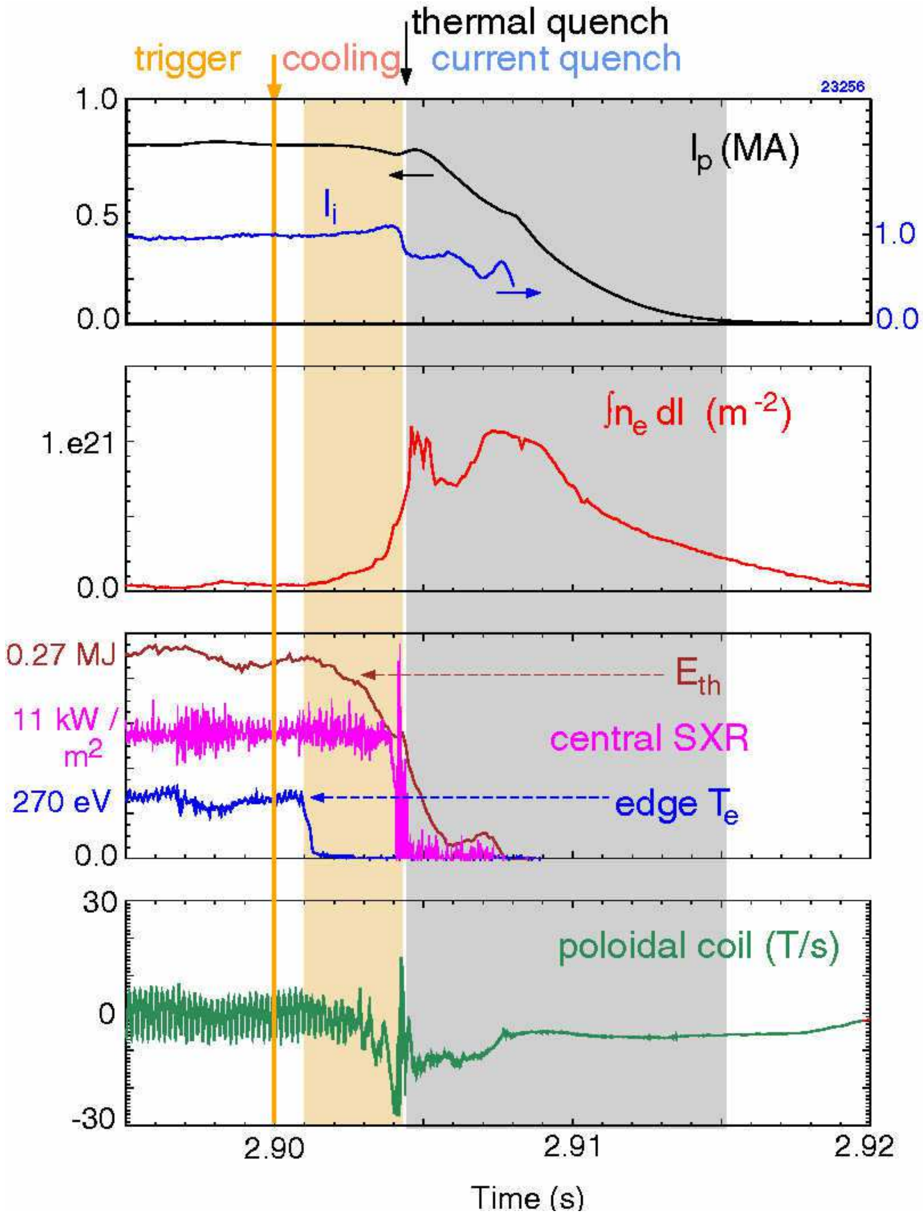
Additional research for ITER

- mitigate power load by radiation
- substantially increase density to avoid generation of runaways

Need ≥ two orders of magnitude

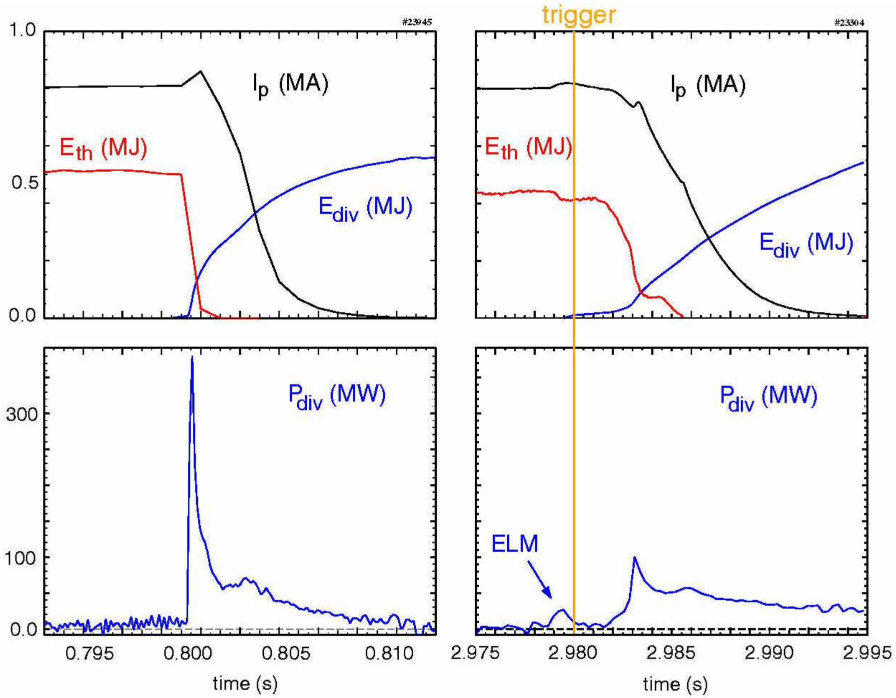
- problem of fuelling efficiency

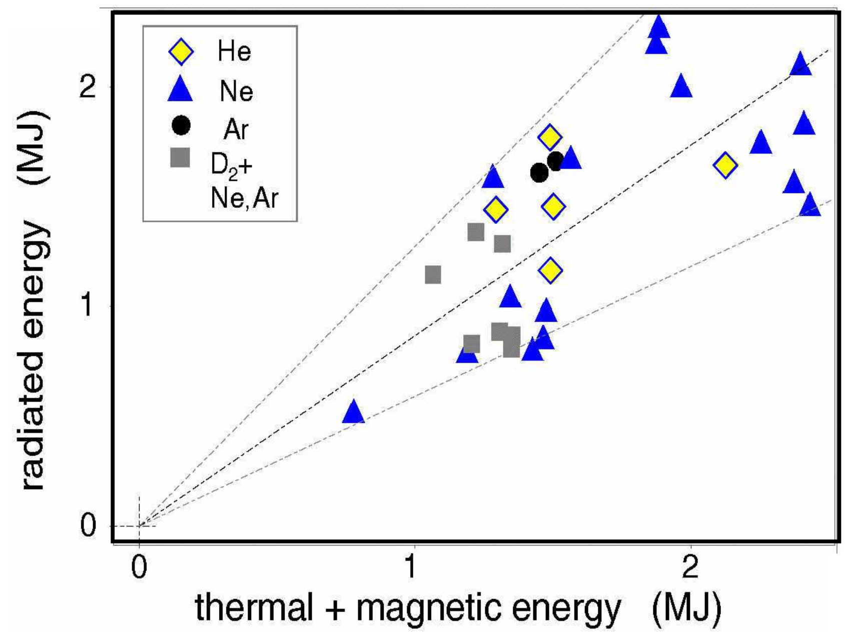
Disruption mitigation by Injection of Gas Jet



- valve open within 1 ms
  flight time ~ 0.1 ms
- density rise and plasma cooling by radiation edge -> center
- cooling of q=2 surface triggers thermal quench
- m =1 structure of SXR profile at thermal quench
- reduced spike or roll-over of plasma current starts current quench

Reduction of target load due to radiation

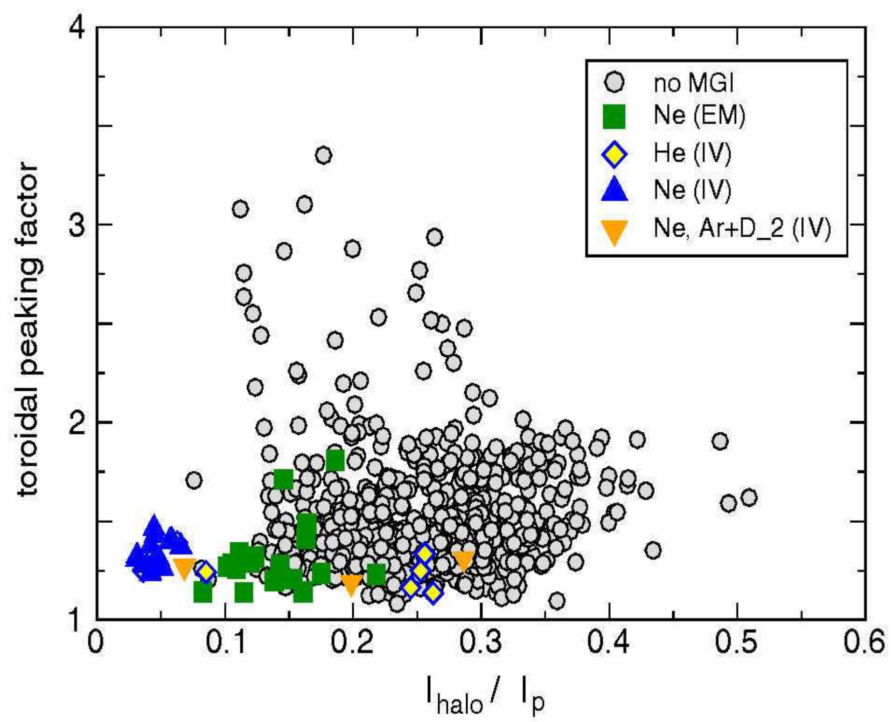


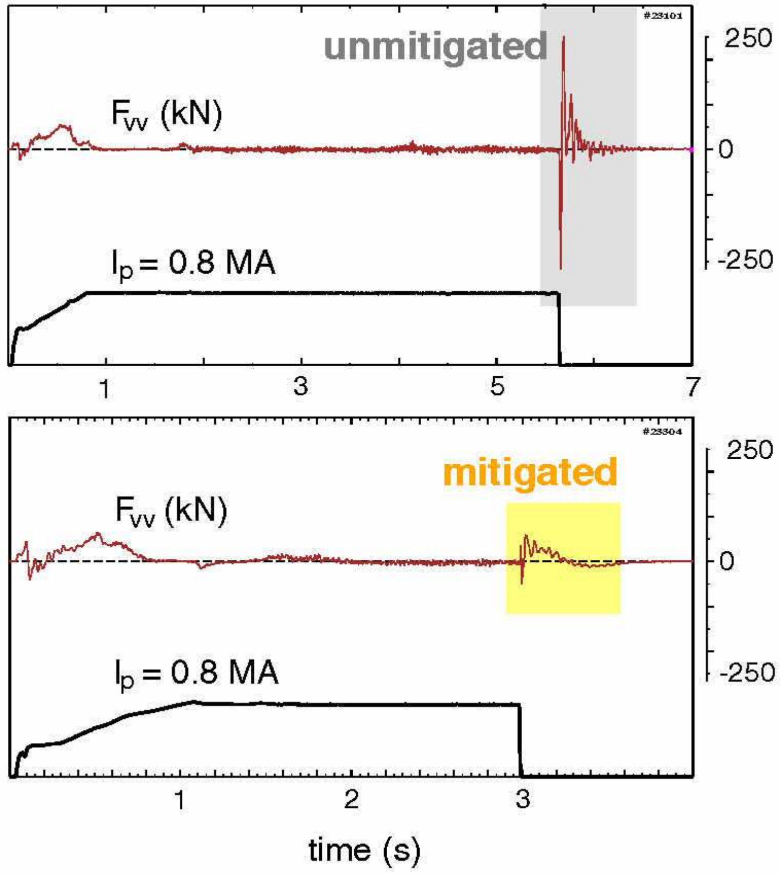


Reduction of power deposited on divertor measured by thermography

- 85 % +/- 25 % of total plasma energy measured in mitigated shut-downs
- but: large scatter indicates toroidal asymmetric distribution of radiation!

Considerable reduction of halo currents and forces

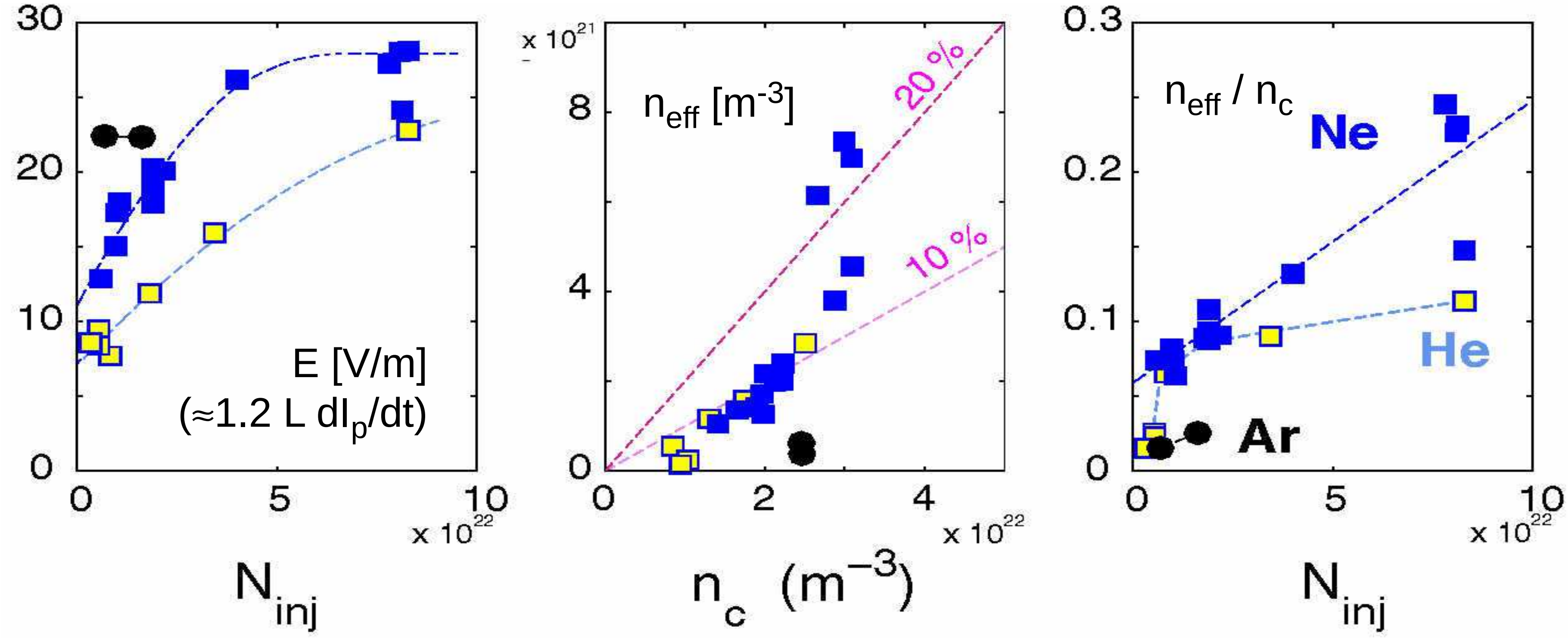




Prompt current decay and slower vertical displacement

- reduction of halo current and its toroidal asymmetry
- total vertical force on vessel reduced to value comparable to that observed during controlled ramp-up and -down

Substantial density increase towards n_c



- toroidal E field tends to asymptotic value
- n_{eff}/n_c ~ 24 % with Neon and E_{th} < 0.45 MJ, but degrades with higher stored energy - need several valves, but check linearity!
- other ideas welcome (e.g. deconfine runaways by RMPs)

Summary

Disruptions lead to a rapid loss of plasma current due to loss of energy By coupled magnetic islands

- many reasons, usually operational limit (density or β-limit)
- also triggered by technical failures (e.g. parts falling into plasma)

Consequences of disruptions are a threat to ITER and future reactors

- thermal loads may lead to melting if localised
- forces due to halo currents may exceed plastic deformation limits
- runaway electrons may lead to local damage of components

A layered approach of avoidance and mitigation needs to be in place

- massive gas injection can solve the heat load and force problem
- the runaway electron problem may need a different control approach