Physics of transient power loads on plasma facing components in ITER

Alberto Loarte

Fusion Science and Technology Department
ITER Organization

Outline

- ➢ Introduction
  - ✓ Plasma regimes in ITER
  - ✓ Introduction to major phenomena leading to transient power fluxes in ITER and consequences for plasma facing components (PFCs)
- ➢ Power fluxes to PFCs during ELMs and methods for ELM control/suppression
- ➢ Power fluxes to PFCs during disruptions and disruption mitigation schemes
- ➢ Summary and Conclusions

Plasmas in ITER (I)

ITER Mission : “To demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes”

- ITER major fusion performance goal

α dominated plasmas ($P_{\alpha}/P_{add} = 2 \Leftrightarrow Q_{DT} = 10$)

&

$P_{fusion} = 500$ MW

✓ Inductive operation with 300-500 s burn time

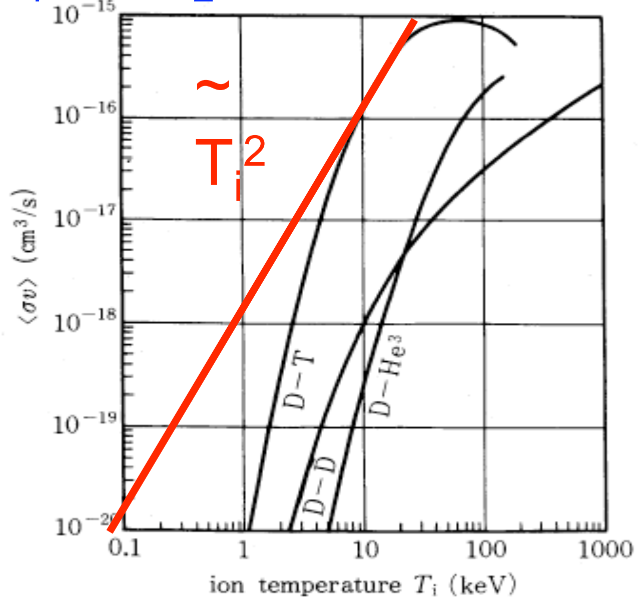
✓ H-mode energy/particle confinement H-mode

Plasmas in ITER (II)

ITER transient power fluxes ←→ ITER fusion goal

- P_{fusion} ←→ Plasma thermal energy : $W_{plasma} = 3/2 <n_e T_e + n_i T_i> V_{plasma}$

$$ {}^2_1D + {}^3_1T \rightarrow {}^4_2He\ (3.5\ \mathrm{MeV}) + {}^1_0n\ (14.1\ \mathrm{MeV}) $$



$$ P_{fusion} = E_{fusion} <n_D><n_T><\sigma v>_{DT} V_{plasma} \sim <n_{DT}>^2 <T_{DT}>^2 V_{plasma} \sim W_{plasma}^2 $$

$$ P_{fusion} = 500\ \mathrm{MW} \leftrightarrow W_{plasma} = 350\ \mathrm{MJ} $$

$$ W_{magnetic} = \frac{1}{2} L_{plasma} I_p^2 \quad with \quad L_{plasma} = \mu_0 R_0 (\ln(8\frac{R_0}{a}) - 2 + \frac{\ell_i}{4} + \frac{3}{4}\beta_p) \qquad \sim 5\ W_{plasma} $$

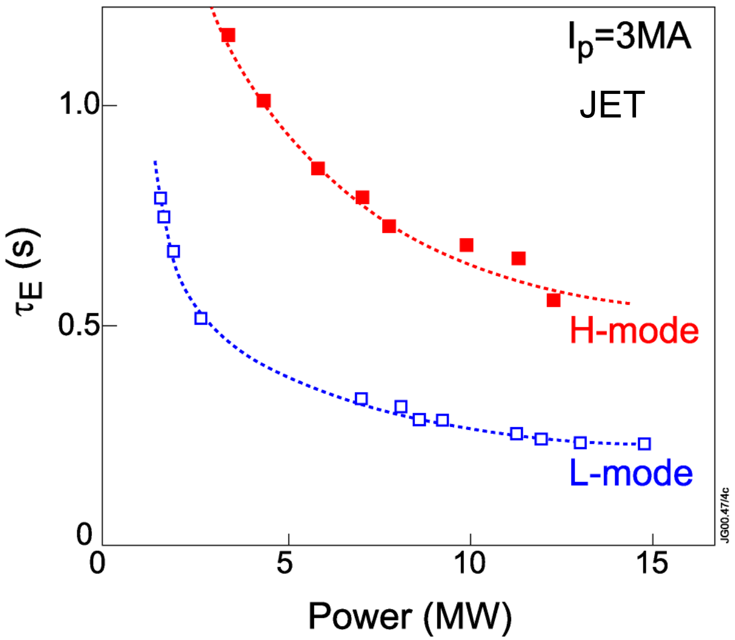
Plasmas in ITER (III)

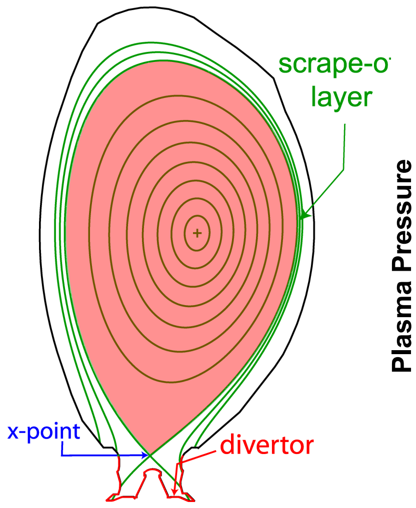
ITER transient power fluxes ←→ confinement regime

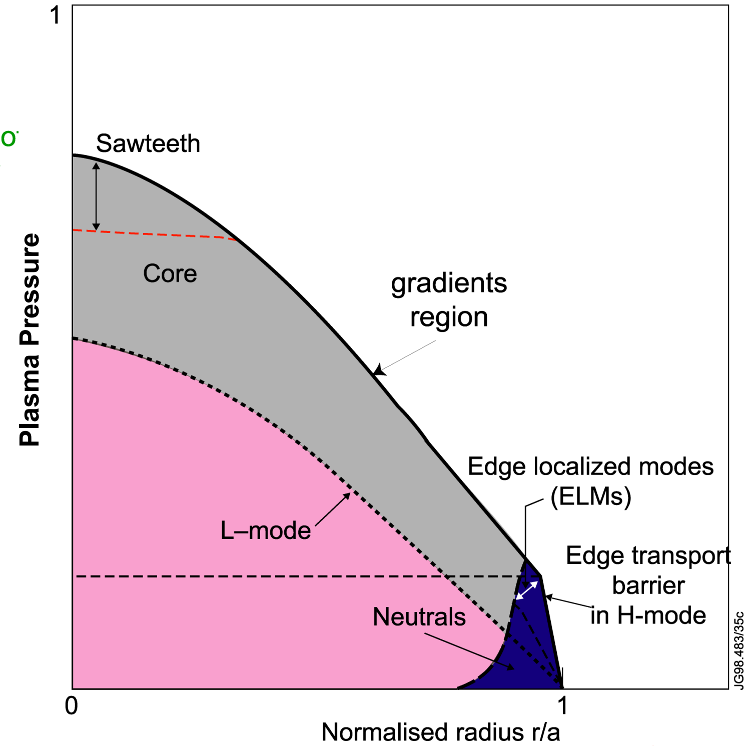
Energy Confinement in Tokamaks and Stellarators : L *(low)* and H *(high)* Confinement Modes

H-mode ←→ Edge Transport Barrier (➔ Pedestal)

In Tokamaks : $P_{INPUT} > P_{L\text{-}H}(n_e, B_t, R)$







$$\tau_E = W_{plasma}/P_{input} \rightarrow W_{plasma} \uparrow 2 \;\&\; P_{fusion} \sim W_{plasma}^2 \uparrow 4$$

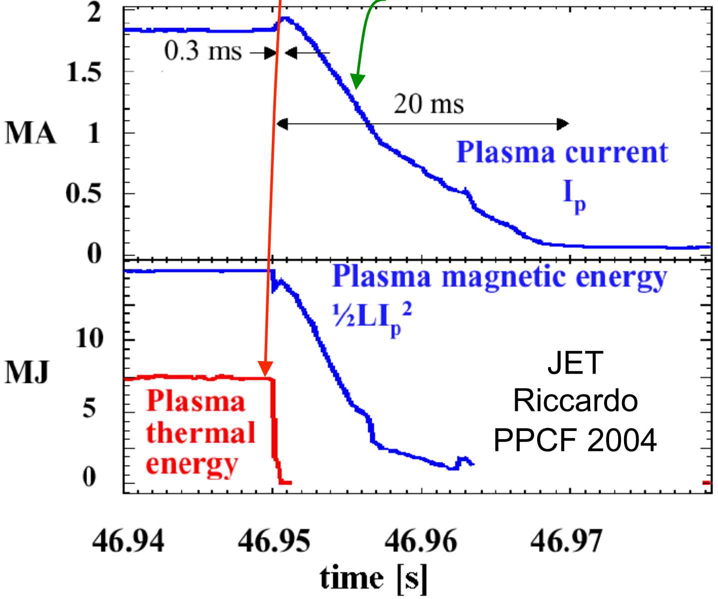
Phenomena causing transients in ITER (I)

- Largest energy transients in ITER → disruptions
  - ✓ W_{plasma} → deposited by plasma onto PFCs
  - ✓ $W_{magnetic}$ → conductors & VV + radiation/plasma onto PFCs or high E_e

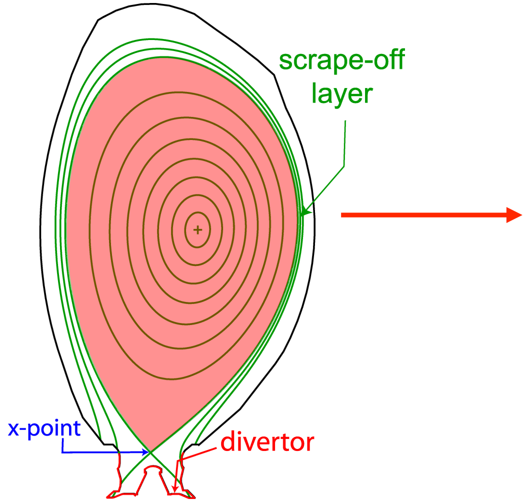
Plasma develops unstable p(r), j(r) → Large scale MHD unstable modes grow

plasma confinement is destroyed (thermal quench ~ ms) → W_{plasma}

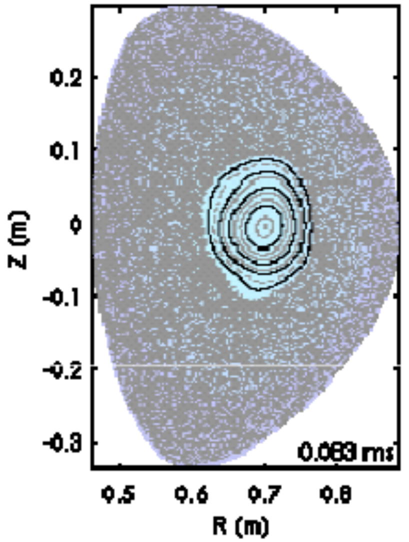
plasma current vanishes (current quench ~10s ms) → $W_{magnetic}$



JET
Riccardo
PPCF 2004



DIII-D (NIMROD) – V. Izzo NF 2007



JET-Riccardo EPS 2003

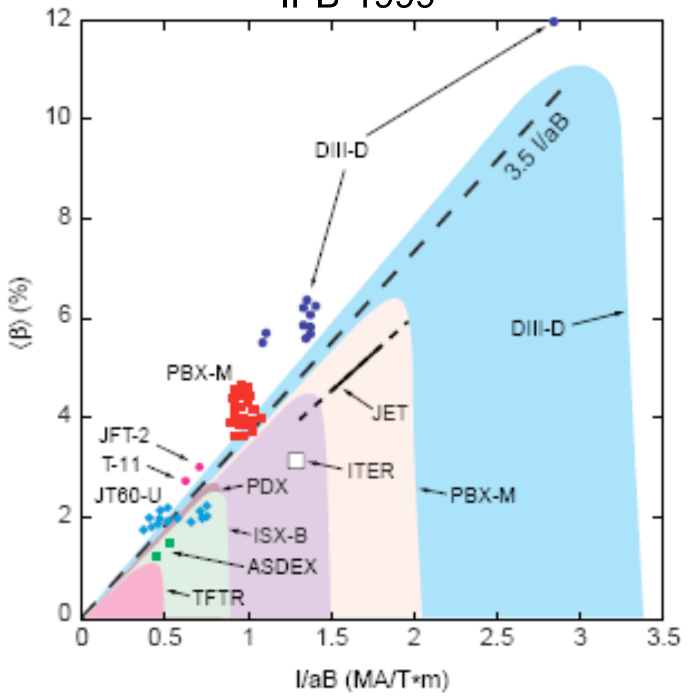
Phenomena causing transients in ITER (II)

Tokamak operation is typically disruption-limited by three limits :

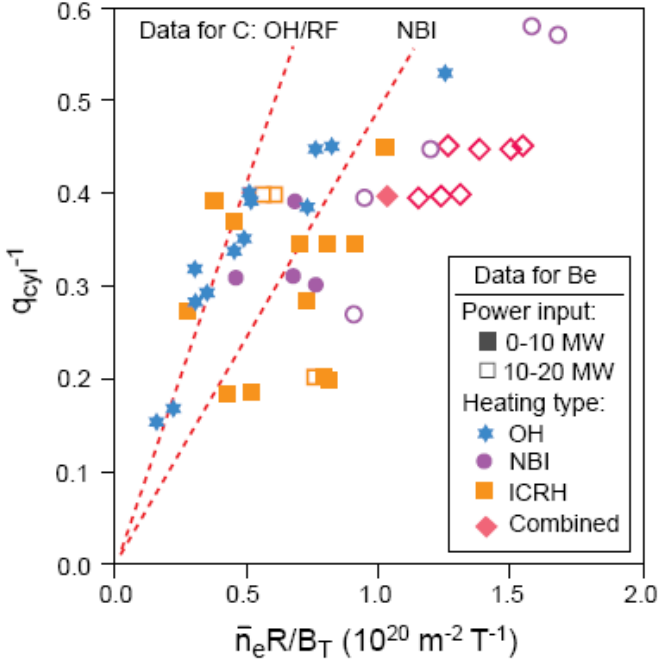
- Pressure limit → $P_{fusion} \sim \beta^2$
- Density + Radiation limit → T < 30-40 keV & stationary power flux control
- Low q limit → $q \sim B_t/I_p$

Operation of ITER (and tokamak fusion reactors) approaches these limits

IPB-1999

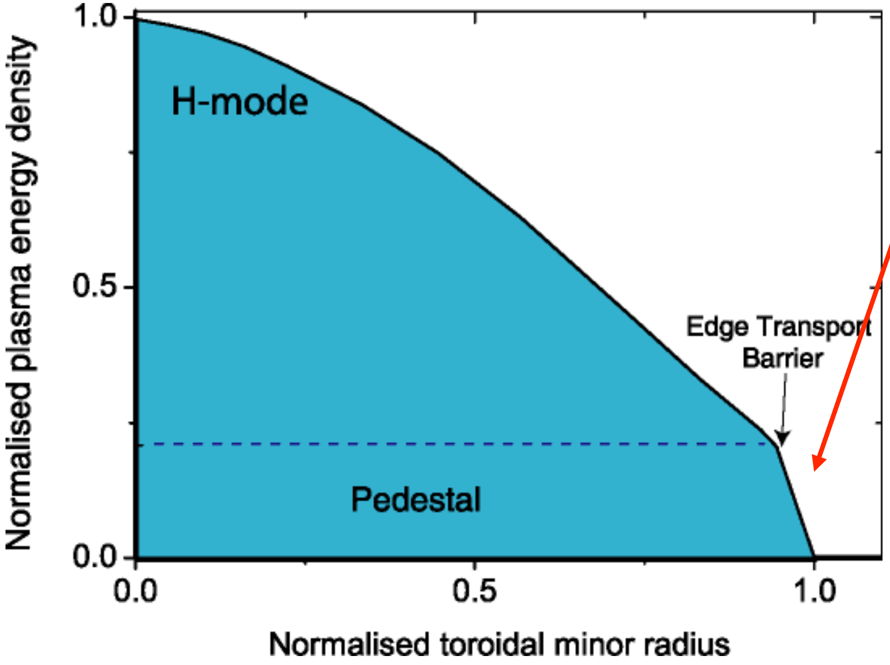


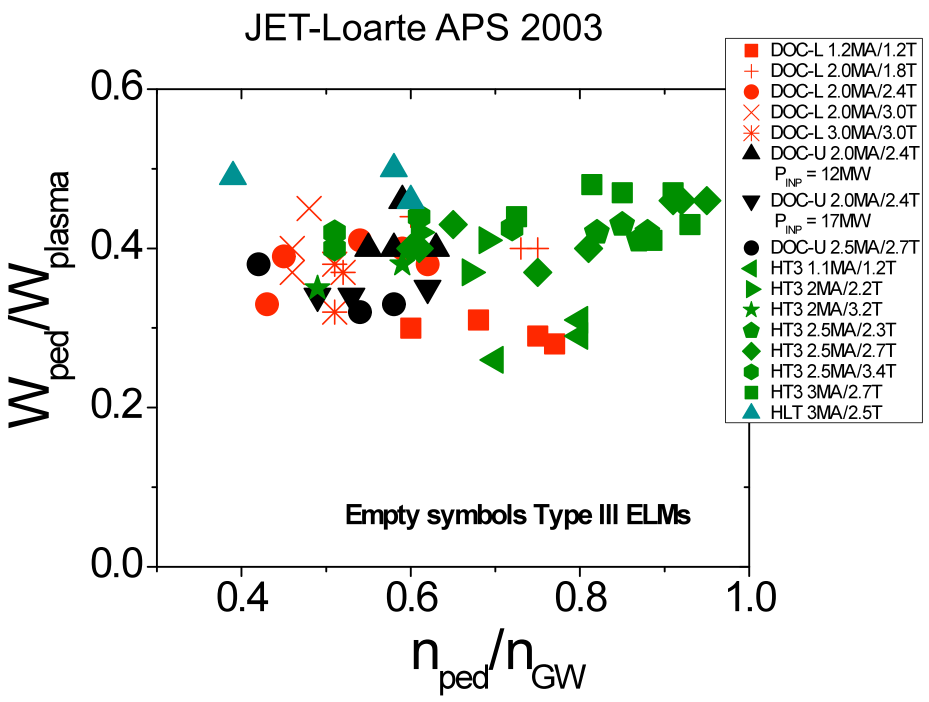
JET-Lowry APS 1990



Phenomena causing transients in ITER (III)

High W_{plasma} in H-mode associated with pedestal → large grad-p and j_{edge}





In H-mode : $W_{plasma} \sim W_{ped}$

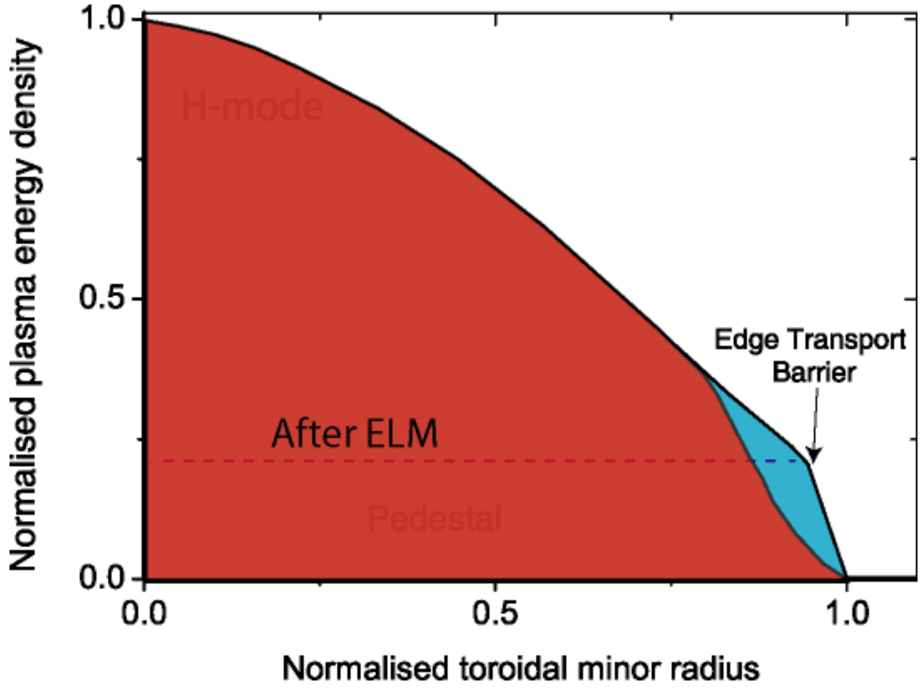
ITER : $W_{ped} \sim 100 - 140$ MJ

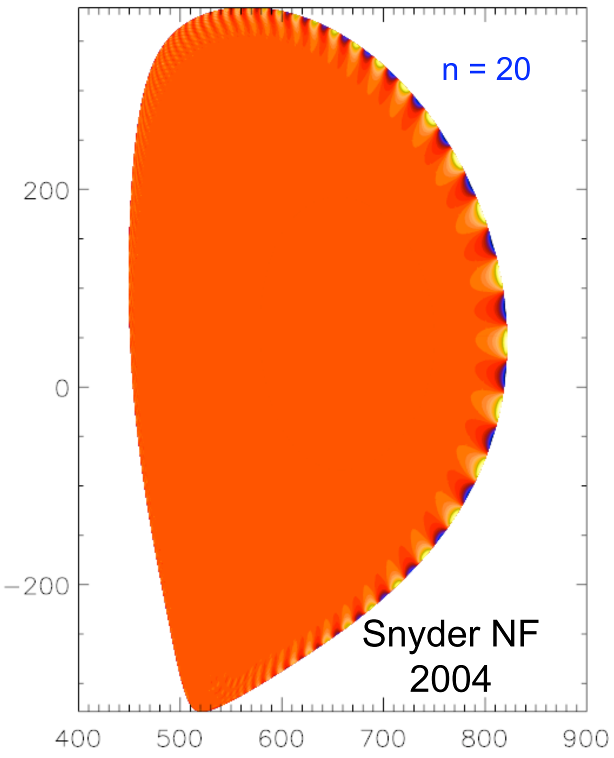
$n_{ped} = 7\text{-}9\ 10^{19}\ m^{-3}$, $T_{ped} = 3\text{-}5$ keV

$$W_{ped} = 3/2 n_{ped} (T_{e,ped} + T_{i,ped}) V_{plasma}$$

Phenomena causing transients in ITER (IV)

- Edge Transport Barrier & ELMs : large edge grad-p(r) & j(r) → edge MHD instability → quasi-periodic relaxations (ELMs) → ΔW_{ELM}
- Various Types of ELMs (grad-p, j_{edge}): highest W_{plasma} vs. n_e and "operating space" Type I ELMs → basis for ITER $Q_{DT} = P_{fus}/P_{inp} = 10$





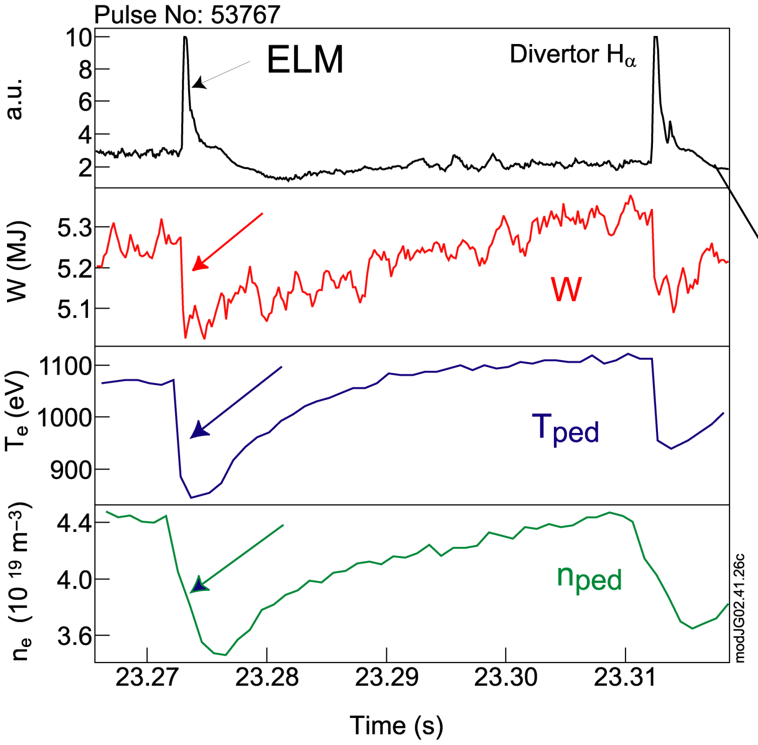
Snyder NF 2004

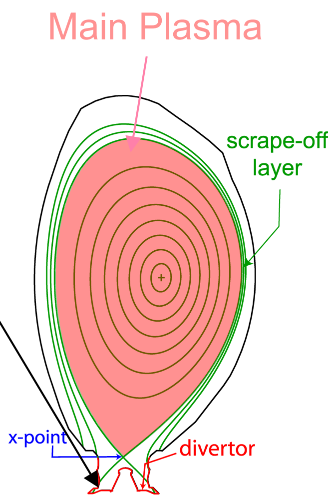
Phenomena causing transients in ITER (V)

Exterior region of plasma (r/a < 0.75) experiences quasi-periodic relaxations during ELMs

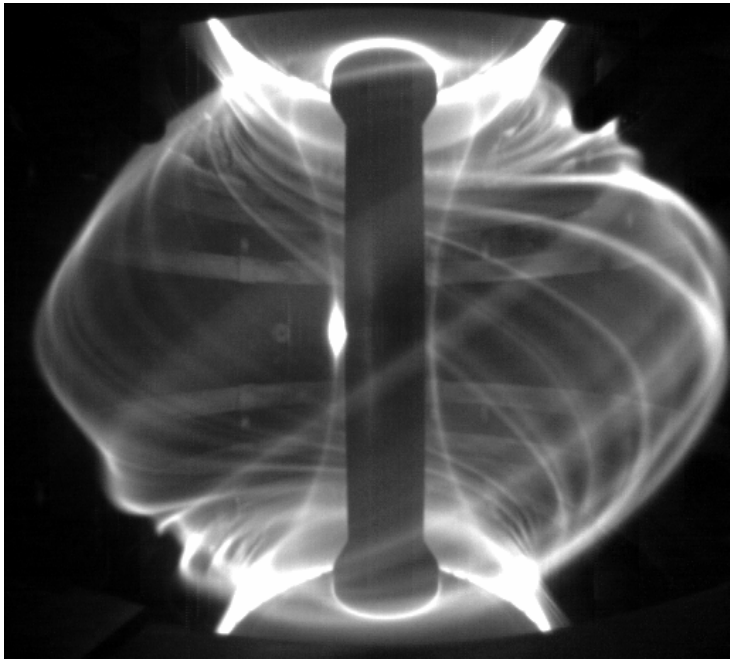
ΔW_{ELM} small Fraction of W_{plasma} (< 10 %) in ~ 200 μs → Large Energy Flux

JET – Type I ELM - Loarte PPCF 2002





MAST- Kirk, EPS'06

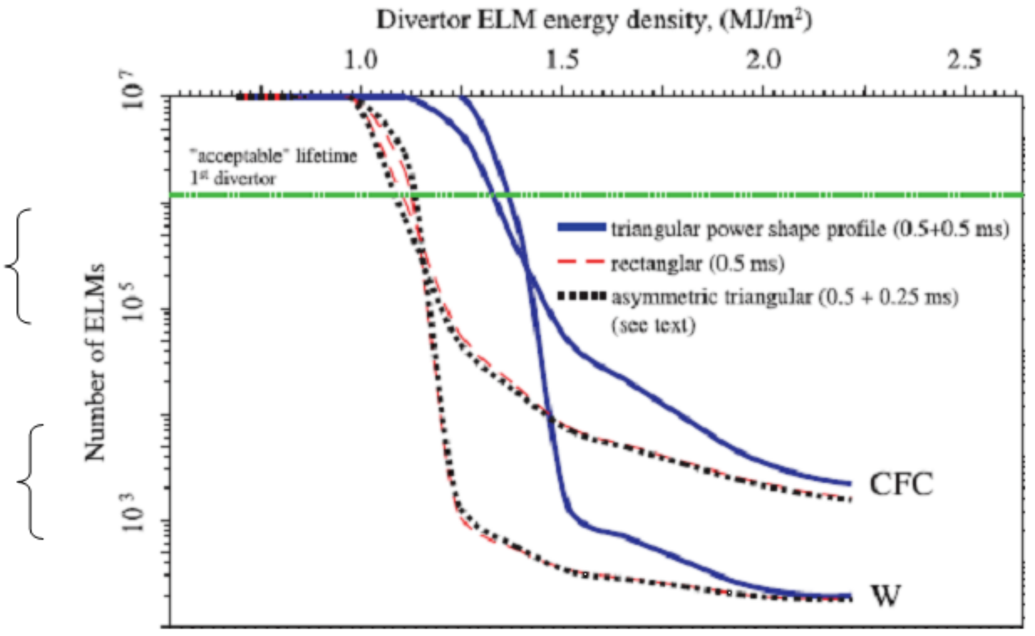


Consequences for ITER PFCs (I)

- Magnitude of transient power fluxes in ITER → Deterioration of PFCs by large erosion and deformation (W melting)
  - ✓ Reduced lifetime PFC lifetime
  - ✓ Difficulties to operation on damaged PFCs (hot spots)
  - ✓ Generation of dust, …
- For events lasting ~ 1 ms → damage threshold < 1 MJm^{-2} (CFC & W)

~ 100 Q_{DT} =10 discharge

~ 1 Q_{DT} =10 discharge

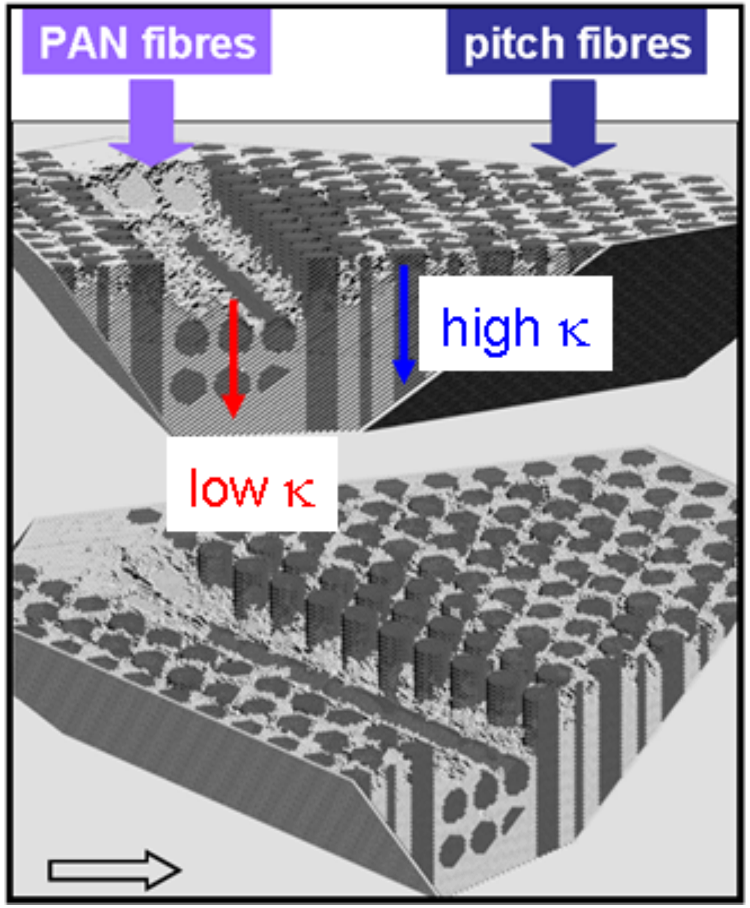


Federici PPCF 2003

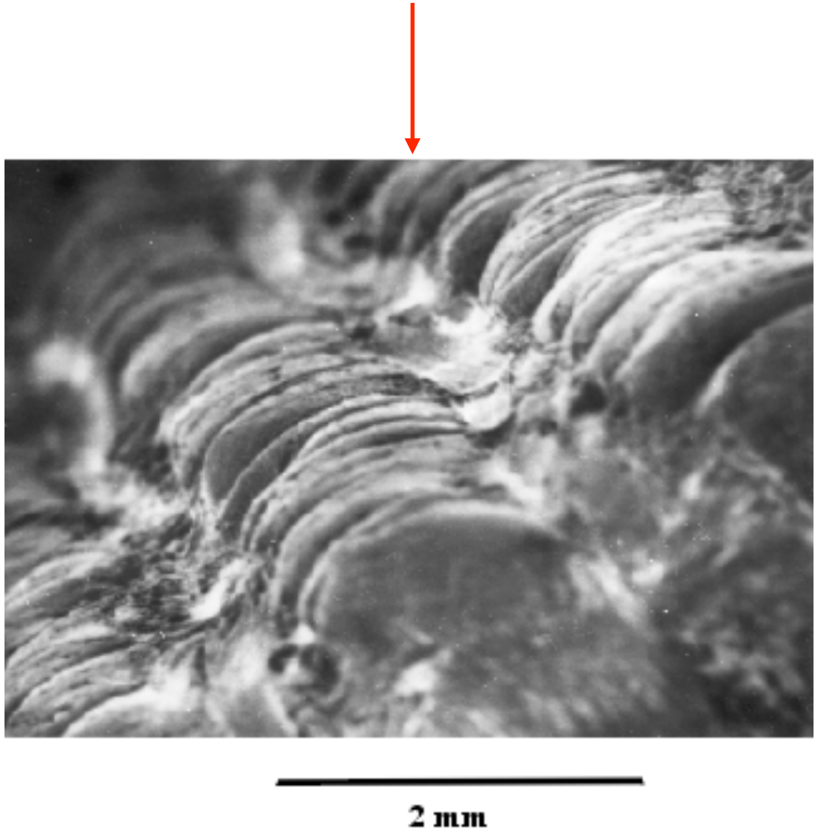
Consequences for ITER PFCs (II)

- Experimental studies of material damage under ITER-like transients

S. Pestchanyi JNM 2007



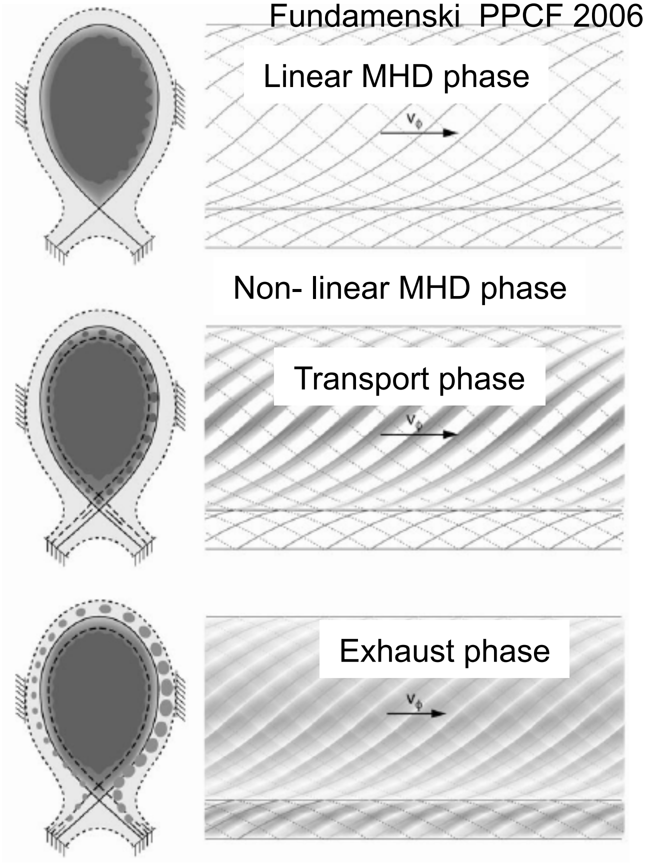
CFC target exposed to ITER-like loads in Plasma-Gun experiments



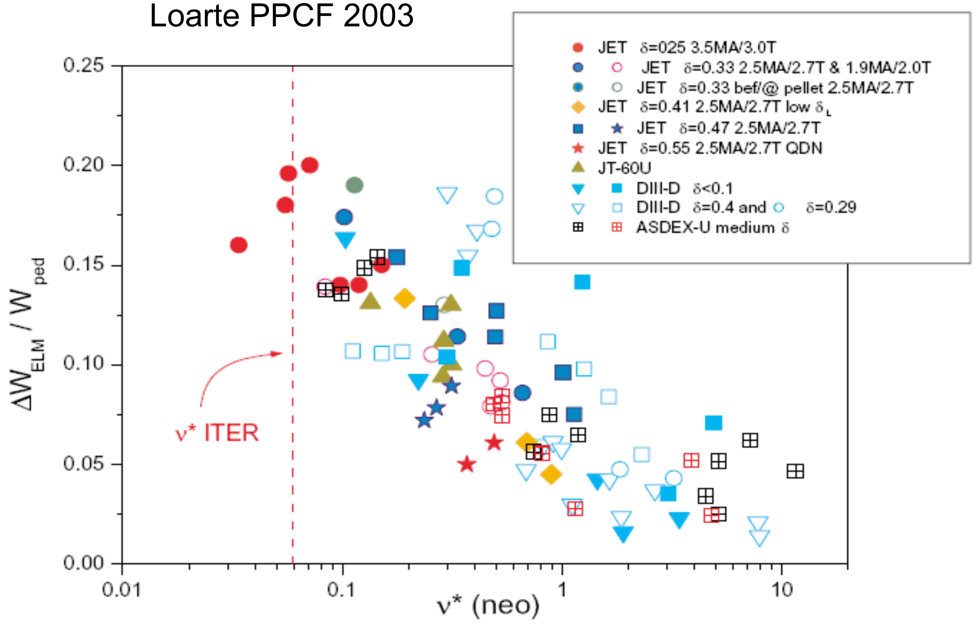
Power fluxes to PFCs during ELMs (I)

- Basic physics picture of processes leading to energy loss by ELMs (ΔW_{ELM}) well developed
- Quantitative modelling/prediction of ΔW_{ELM} outstanding → empirical extrapolation to ITER

Fundamenski PPCF 2006



Loarte PPCF 2003



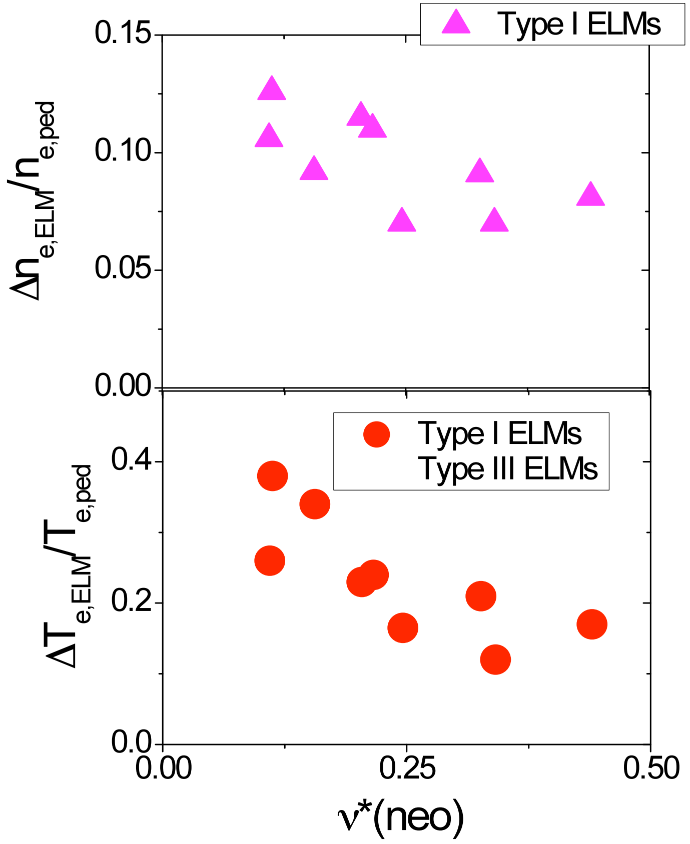
$\nu^* \sim Rn_e/T_e^2$

ITER : W_{ped} ~ 100-140 MJ → ΔW_{ELM} > 20 MJ

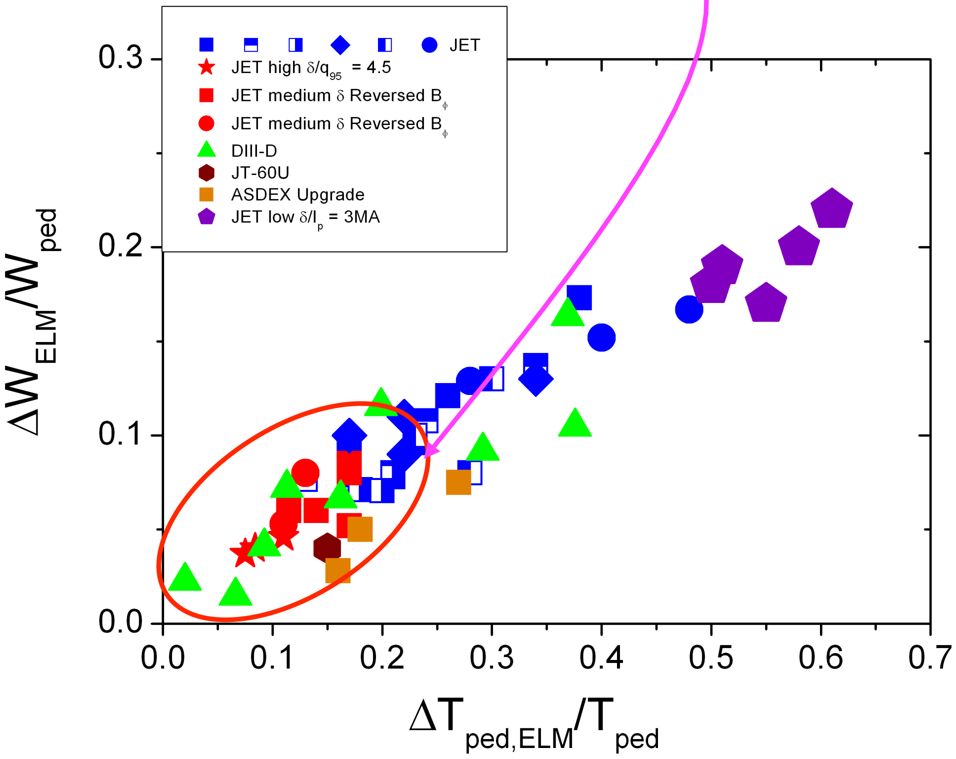
Power fluxes to PFCs during ELMs (II)

$$\Delta W_{ELM} = (3 < n_{ped} > \Delta T_{ped,ELM} + 3 < T_{ped} > \Delta n_{ped,ELM})V_{ELM}$$

Loarte-PoP 2004



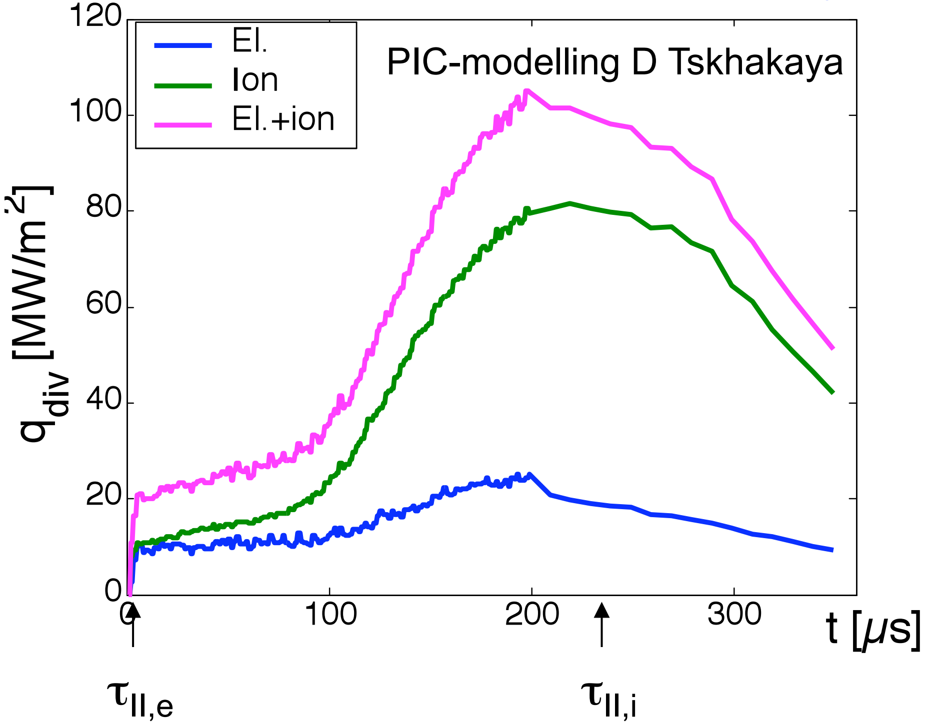
Loarte-IAEA 2006



➢ Reduction of $\Delta W_{ELM}/W_{ped}$ mainly by reduction of $\Delta T_{ELM}/T_{ped}$ → decrease of conductive ELM losses → R&D decrease of conductive losses compatible with ITER requirements

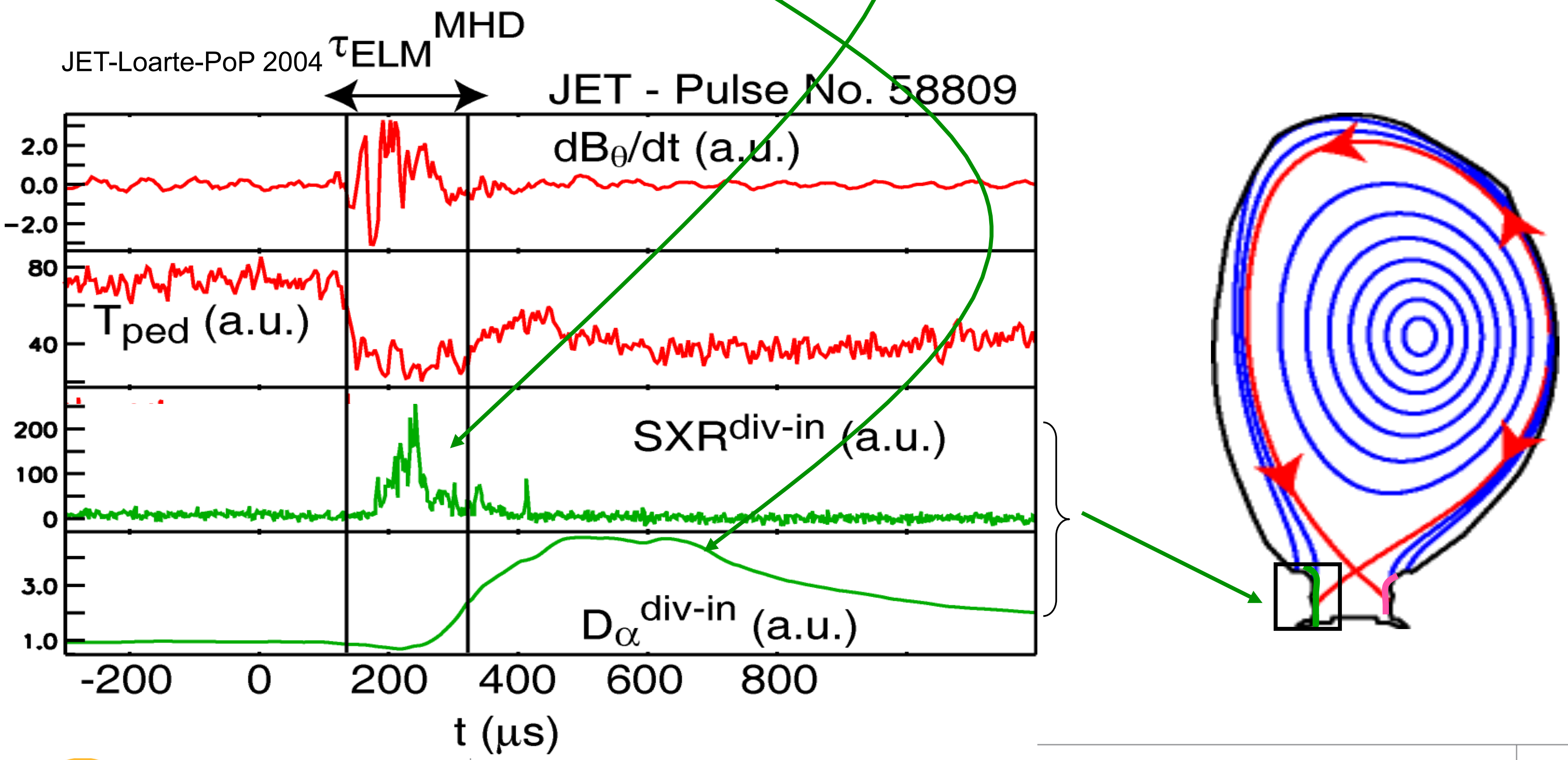
Power fluxes to PFCs during ELMs (III)

- In non-linear MHD phase plasma with $n \sim n_{ped}$, $T \sim T_{ped}$ connects to PFC along open field lines
  - ✓ Hot electrons arrive at the divertor target $v_e/v_i \sim (m_i/m_e)^{1/2} \sim 60$ ($\tau \sim \mu s$)
  - ✓ Formation of sheath with $T \sim T_{ped}$ → acceleration of ions
  - ✓ Ions arrive at target in timescale of τ_{II} (~ 100's of μs)
  - ✓ ELM power pulse dynamics dominated by ion $q_{div}^{ELM}(t) \sim q_{ion}^{ELM}(t)$



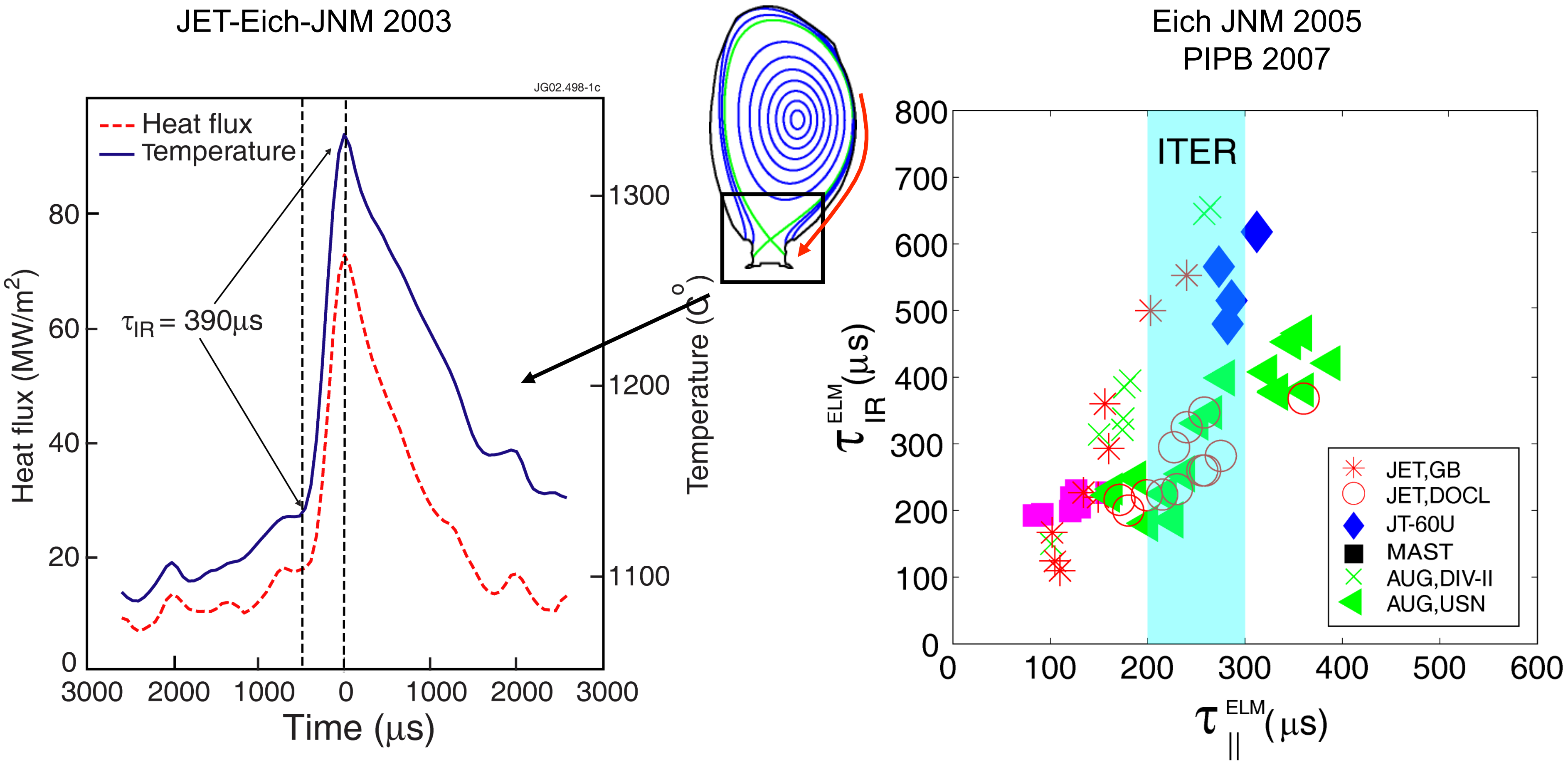
Power fluxes to PFCs during ELMs (IV)

- Basic ELM power flux physics picture experimental confirmation
  - ✓ Hot electrons soft X-ray emission
  - ✓ Delayed ion arrival (D_α)



Power fluxes to PFCs during ELMs (V)

- Time scale of divertor ELM energy flux rise correlated with $\tau_{II,i} \sim L/v_i(T_{ped})$


JET-Eich-JNM 2003

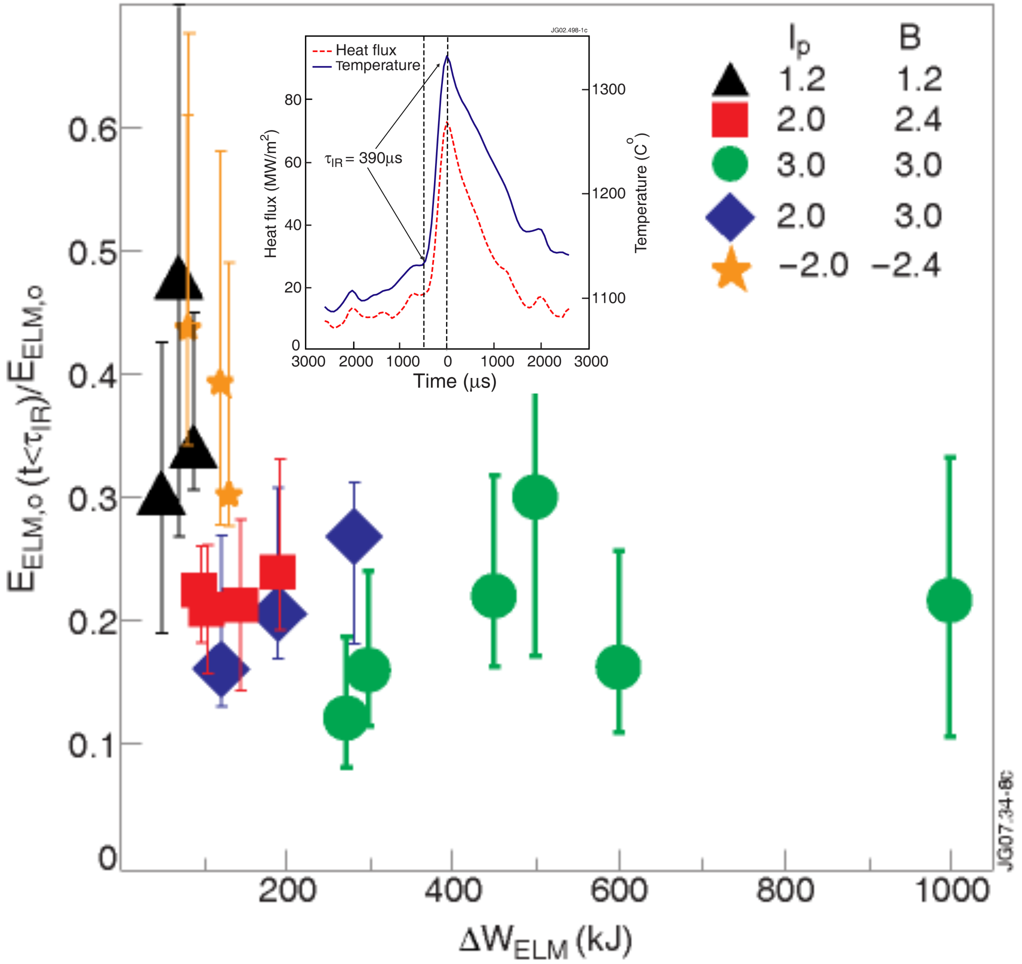
Eich JNM 2005
PIPB 2007

Physics basis for ELM power flux duration in ITER through plasma conditions (n_{ped}, T_{ped}) & R → R&D $\tau_{ELM}^{IR} \sim \tau_{II}$ relation (pre-ELM divertor plasma, etc.)

Power fluxes to PFCs during ELMs (VI)

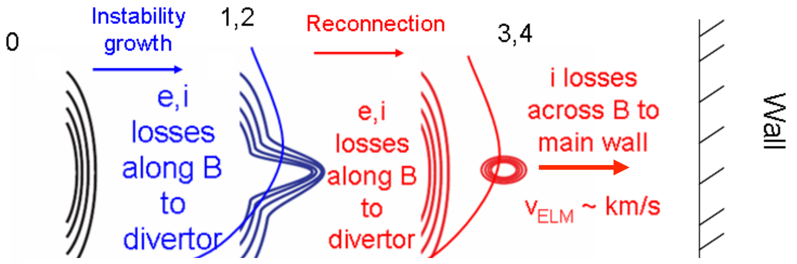
- Because of sheath formation → large proportion of ΔW_{ELM} arrives after τ_{IR} → smaller ΔT_{surf} for given ΔW_{ELM}

JET-Eich-JNM 2005, PItts-IAEA 2006

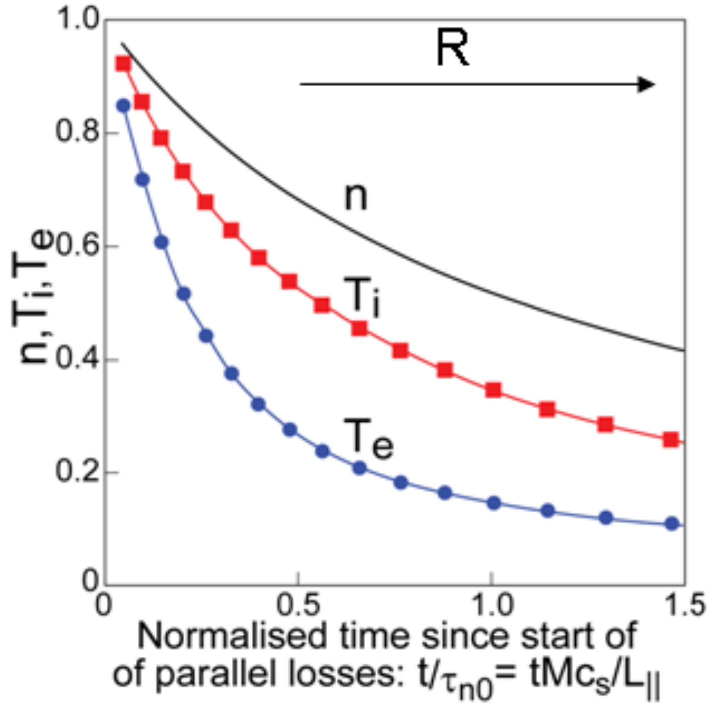


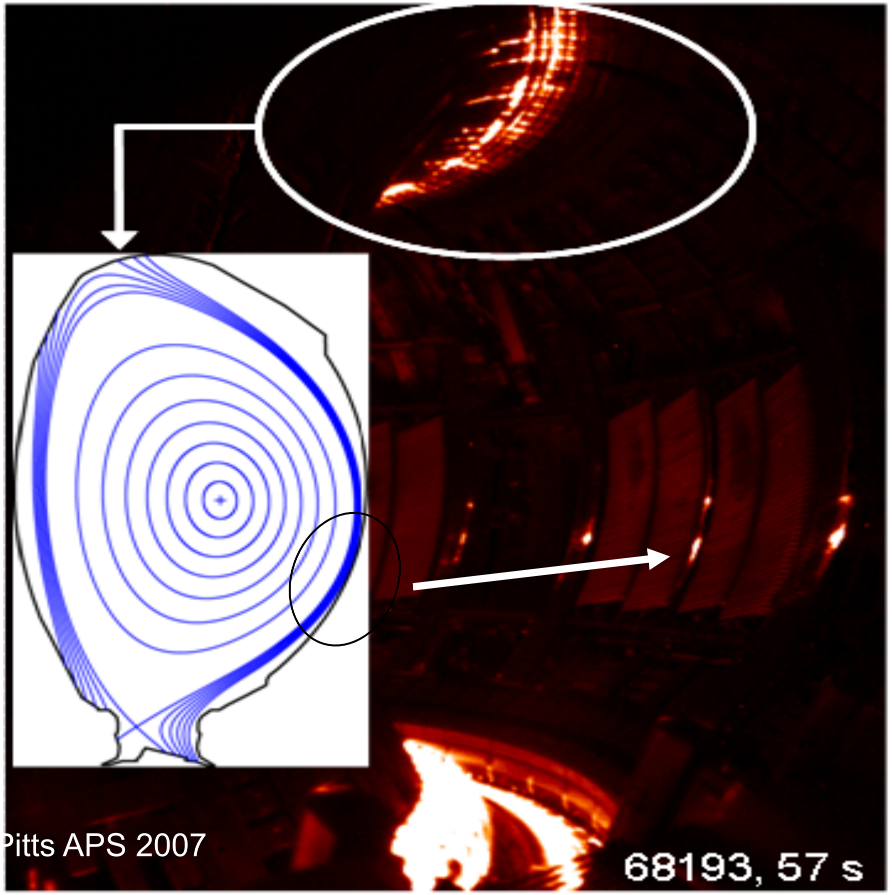
Power fluxes to PFCs during ELMs (VII)

- ELM energy transport and MHD origin determine areas for deposition of power and power sharing between PFCs : e + i near separatrix & i



Fundamenski - PPCF 2006



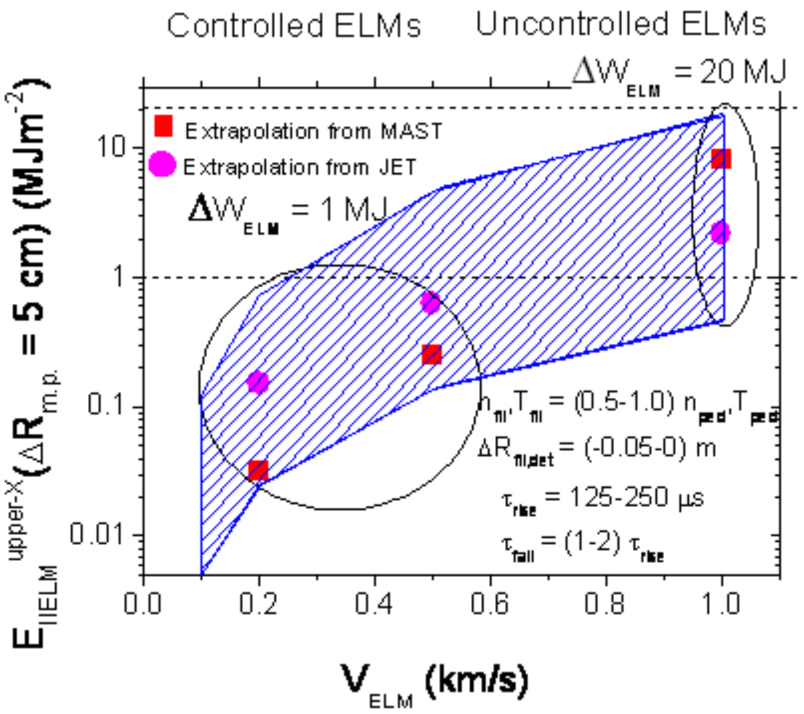


Pitts APS 2007

Power fluxes to PFCs during ELMs (VIII)

- Physics model and physics based extrapolations applied to determine ELM power fluxes to divertor and wall in ITER (R&D on-going)

ELM Type	ΔW_{ELM} (MJ)	$E_{\|\|,max}^{div-in}$ (MJm^{-2})	E_{max}^{div-in} (MJm^{-2})	$E_{\|\|,max}^{div-out}$ (MJm^{-2})	$E_{max}^{div-out}$ (MJm^{-2})	τ_{ELM}^{rise} (μs)
uncontrolled	20	300	17	180	8.5	250-500



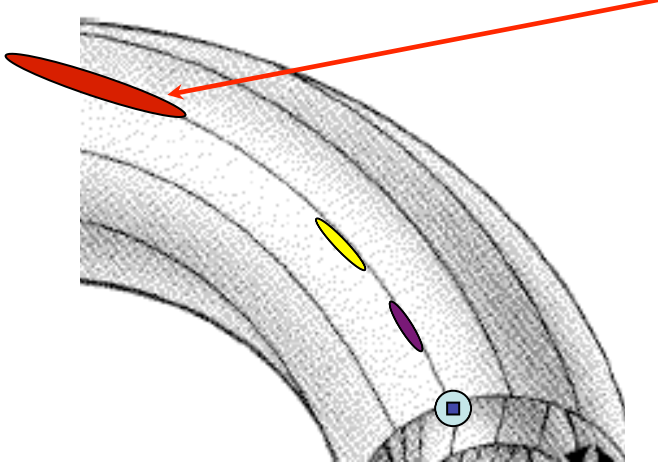
- Uncontrolled ELMs in ITER → energy fluxes exceed by large factors (~> 10) material damage thresholds → damage to PFC and lifetime reduction
- Control of ELM power fluxes is mandatory for reliable ITER operation

Active control of ELMs (I)

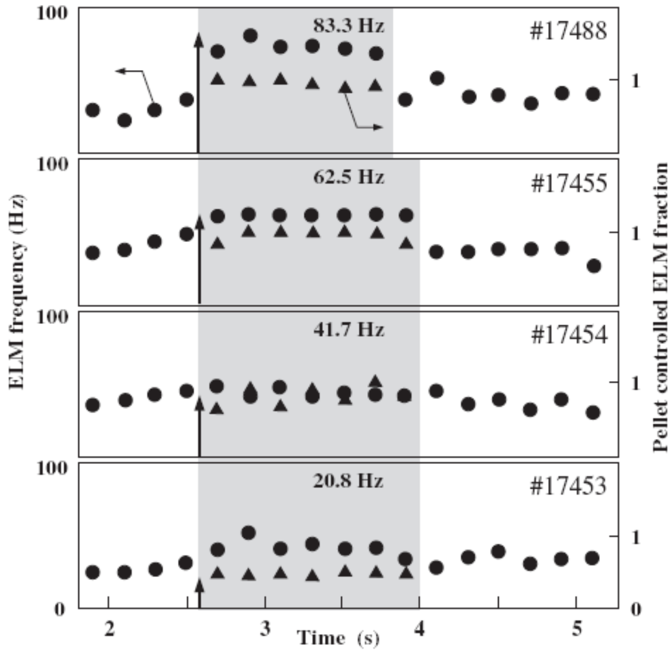
Two methods considered for ELM control in ITER → injection of frozen pellets & perturbation of edge magnetic field

- Injection of frozen pellets → frozen hydrogen vaporizes leading to local n_e increase & (after thermalisation) pressure increase
- Local pellet perturbation → MHD instability & ELM

→ f_{pellet} = f_{ELM} & ΔW_{ELM} decreases in controlled way



ASDEX-Upgrade – P. Lang NF'04

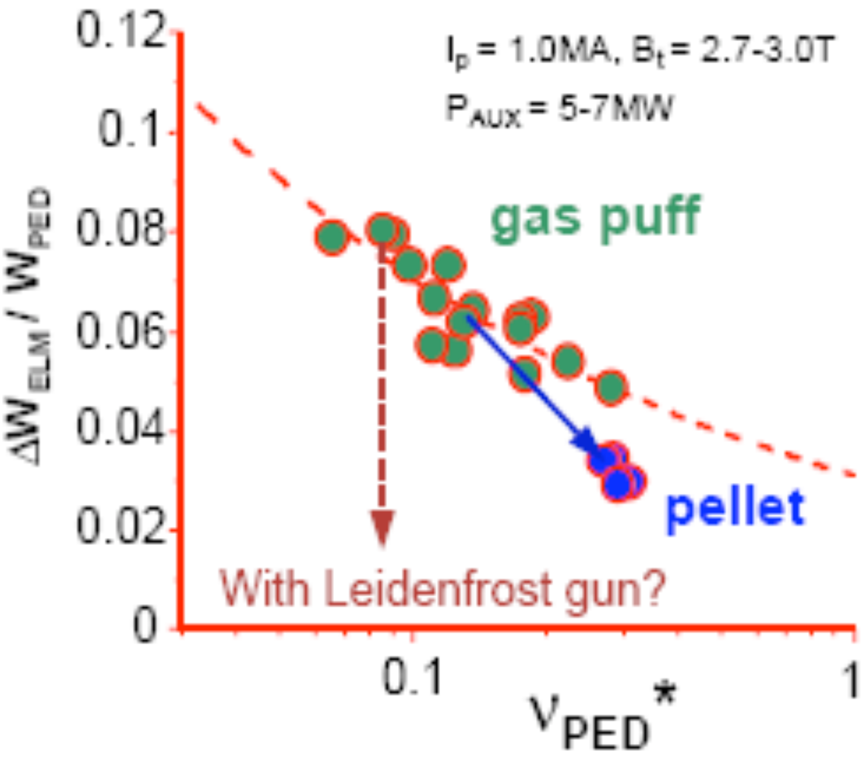


Active control of ELMs (II)

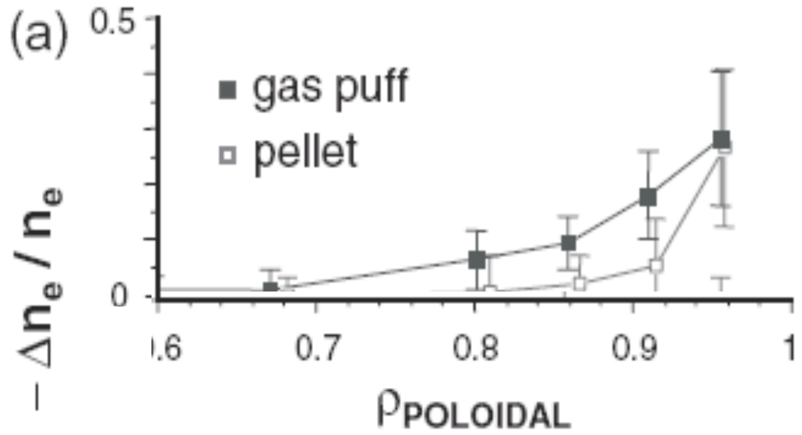
Injection of frozen D pellets allows control of ELM trigger and ΔW_{ELM} (ASDEX Upgrade – P. Lang)

Main effect associated with reduction of particle losses for pellet triggered ELMs

ASDEX-Upgrade – P. Lang



ASDEX Upgrade - Urano PPCF 2004



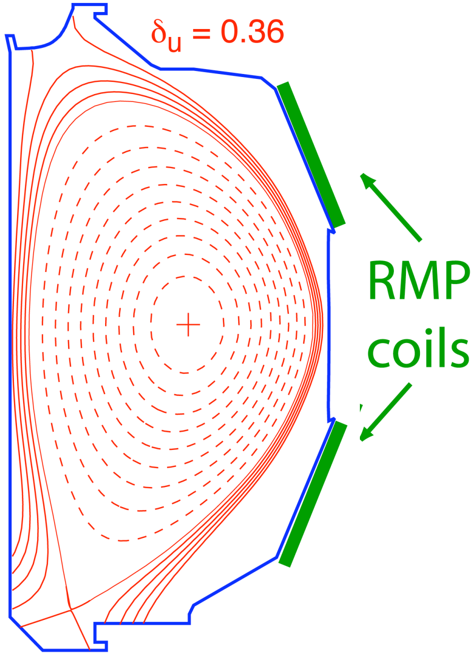
Present results far from ITER requirements (by factor of ~10) → R&D with specially designed pellet injection systems/ experiments on going

Active control of ELMs (III)

- Applying an external magnetic perturbation of edge B_θ allows complete control and/or suppression of ELMs
- Edge field lines are ergodised and edge plasma energy transport is affected

DIII-D- T. Evans NF'08

126006 3500 ms

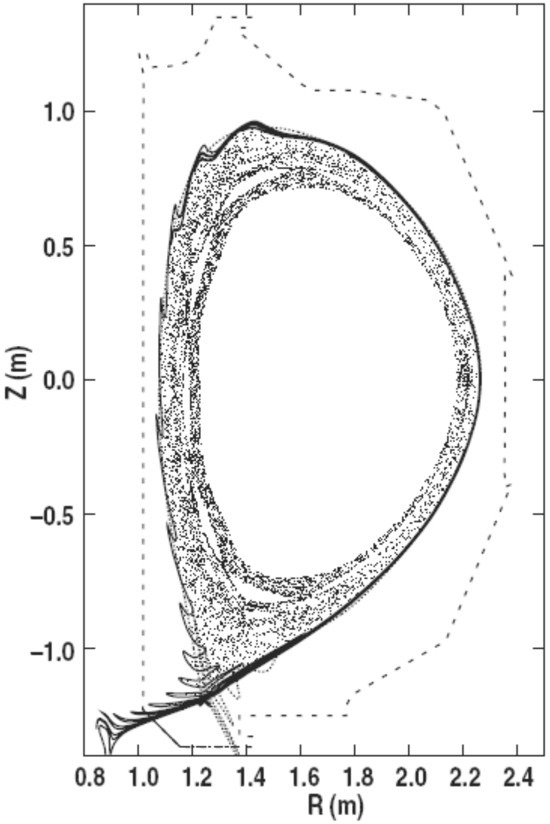


$\delta_{low} = 0.70$

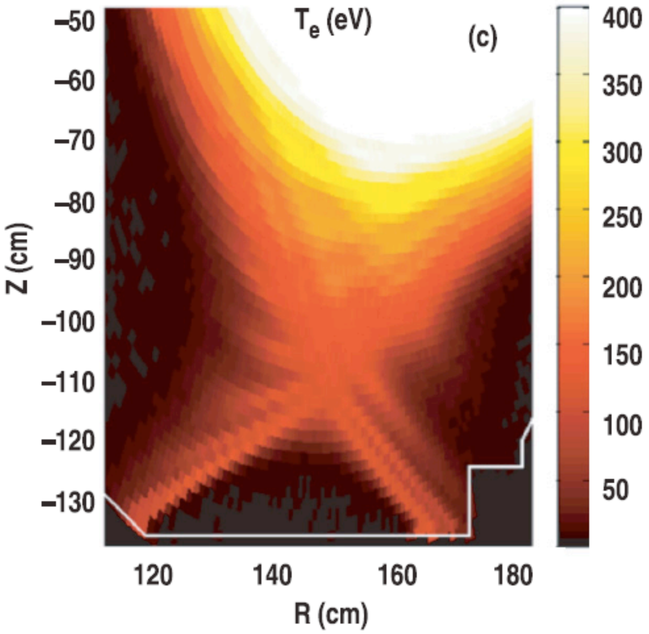
2006 ITER

Similar Shape

Wingen-PoP 2009

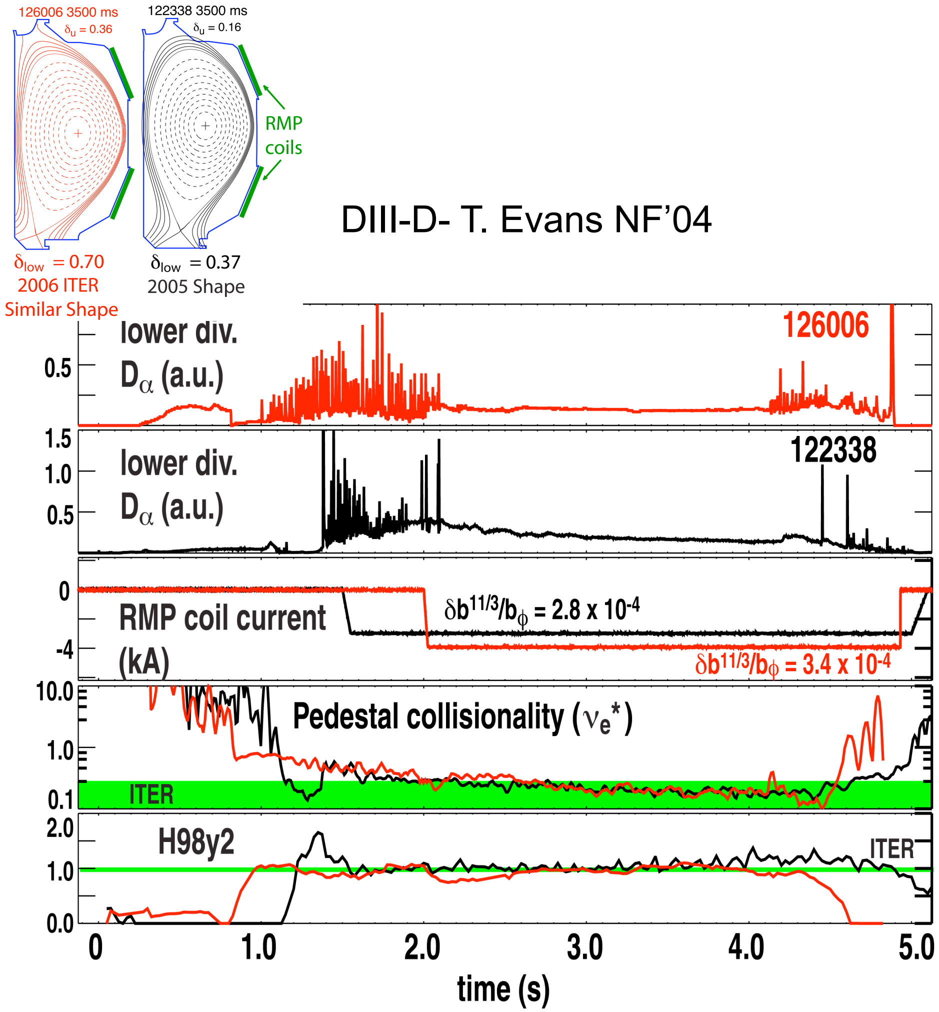


Joseph-NF 2008

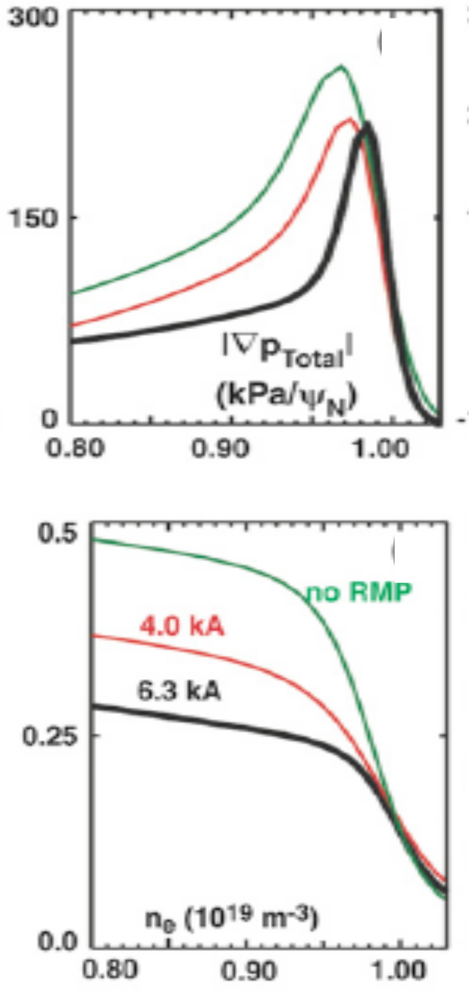


Active control of ELMs (IV)

- With large enough B_θ perturbation → edge grad-p decreases & ELMs suppressed
- Major effect is n_e reduction not T_e → experimental and theoretical R&D

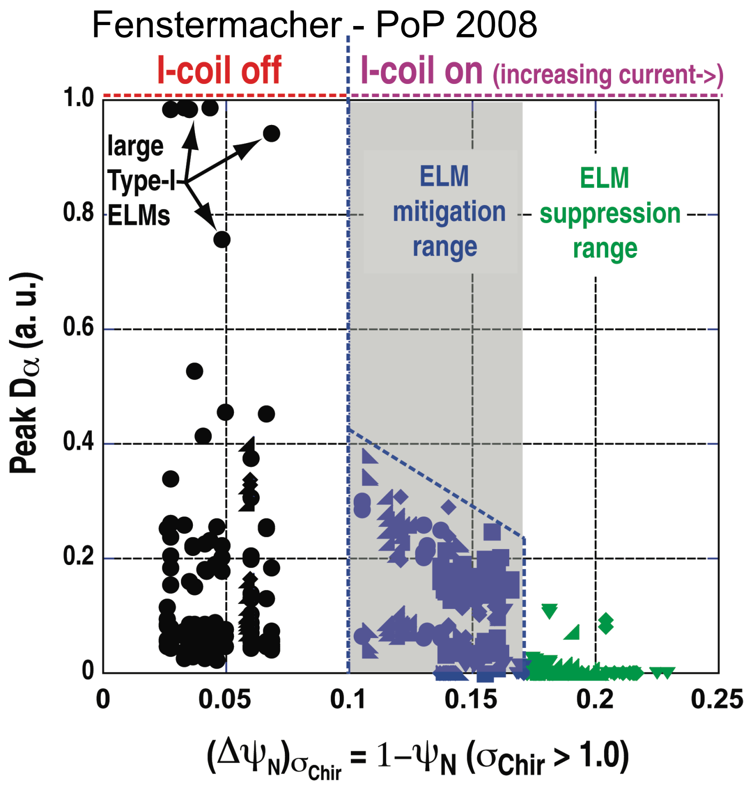


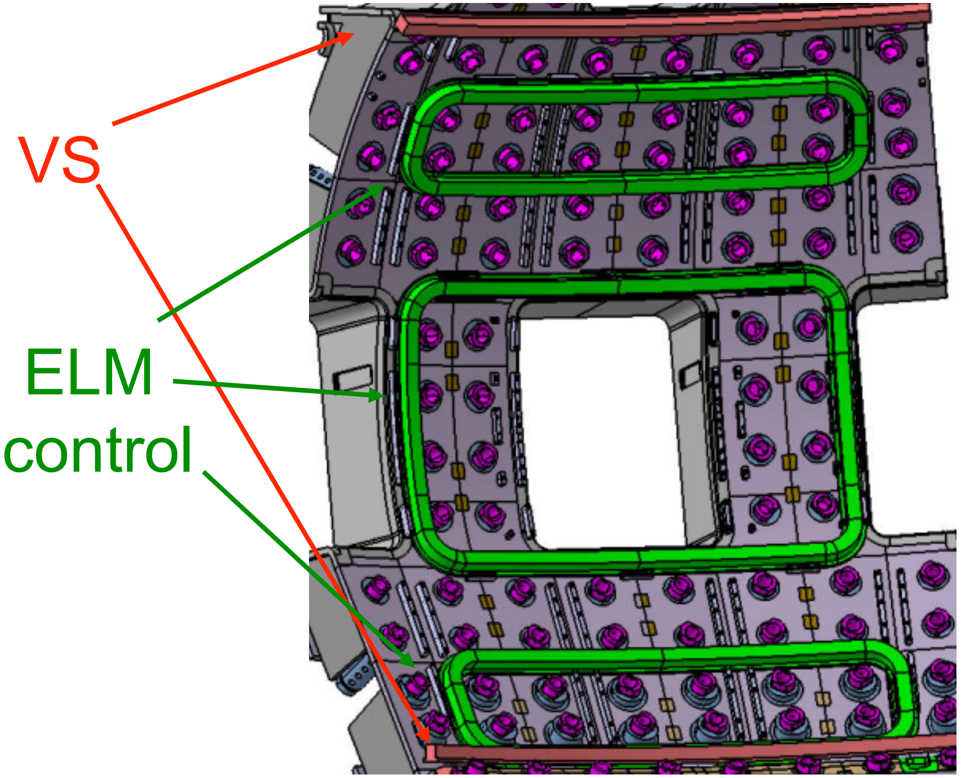
DIII-D- T. Evans NF’04



Active control of ELMs (V)

- ➢ ELM control coils for ITER designed on DIII-D based criterion for ELM suppression (~ 90-100 kAt, including 20% margin)
- ➢ Flexible system → all coils powered independently
- ➢ Technology R&D work ongoing to define coil conductor/insulation design
- ➢ Integration with other ITER components being finalised to fix interfaces


Fenstermacher - PoP 2008



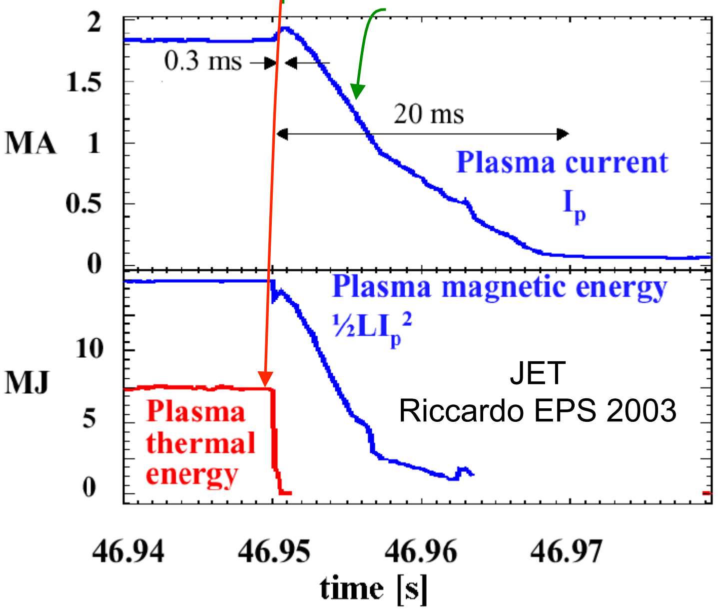
Phenomena causing transients in ITER (I)

- Largest energy transients in ITER → disruptions
  - ✓ W_{plasma} → deposited by plasma o
  - ✓ $W_{magnetic}$ → conductors & VV + ra

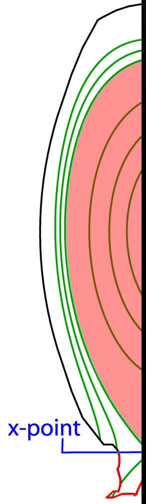
Plasma develops unstable p(r), j(r) → L

plasma confinement is destroyed (t

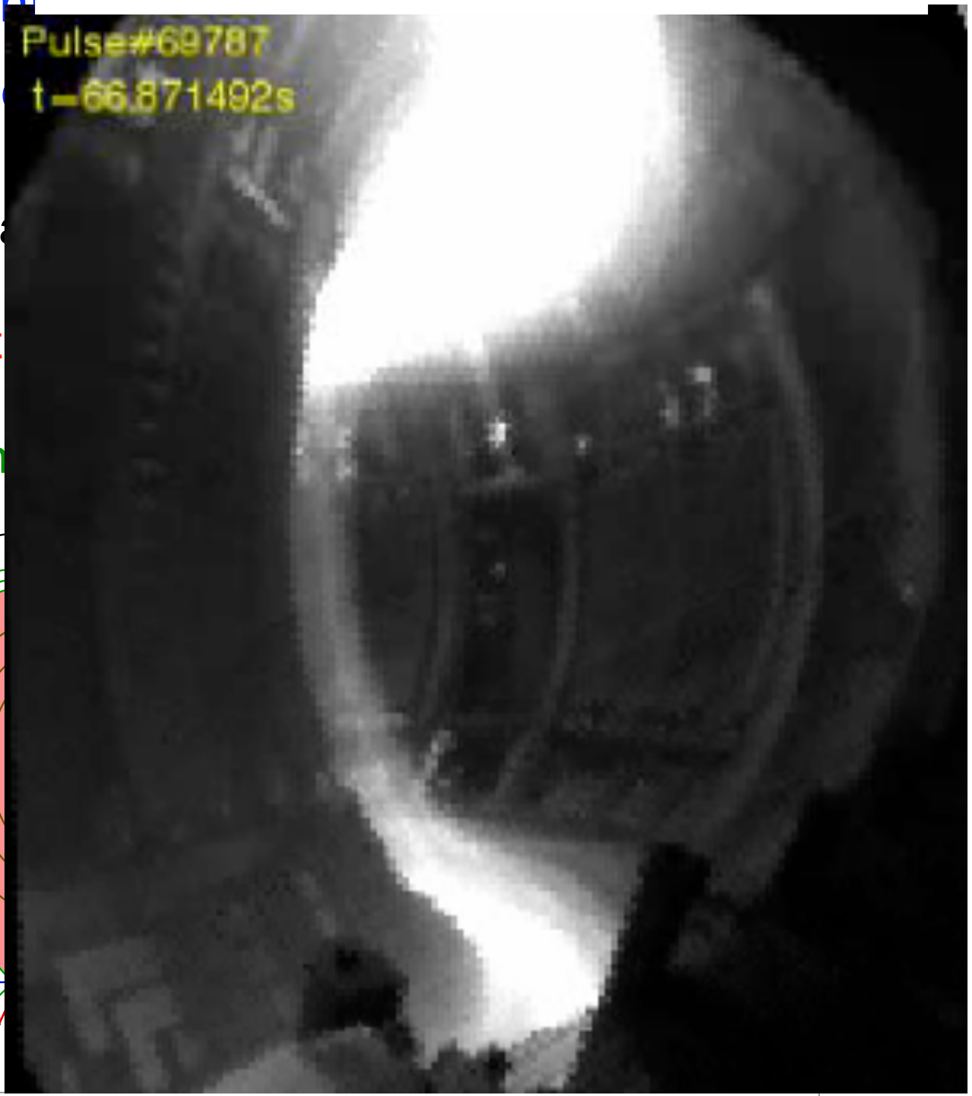
plasma current vanishes (curren



JET
Riccardo EPS 2003



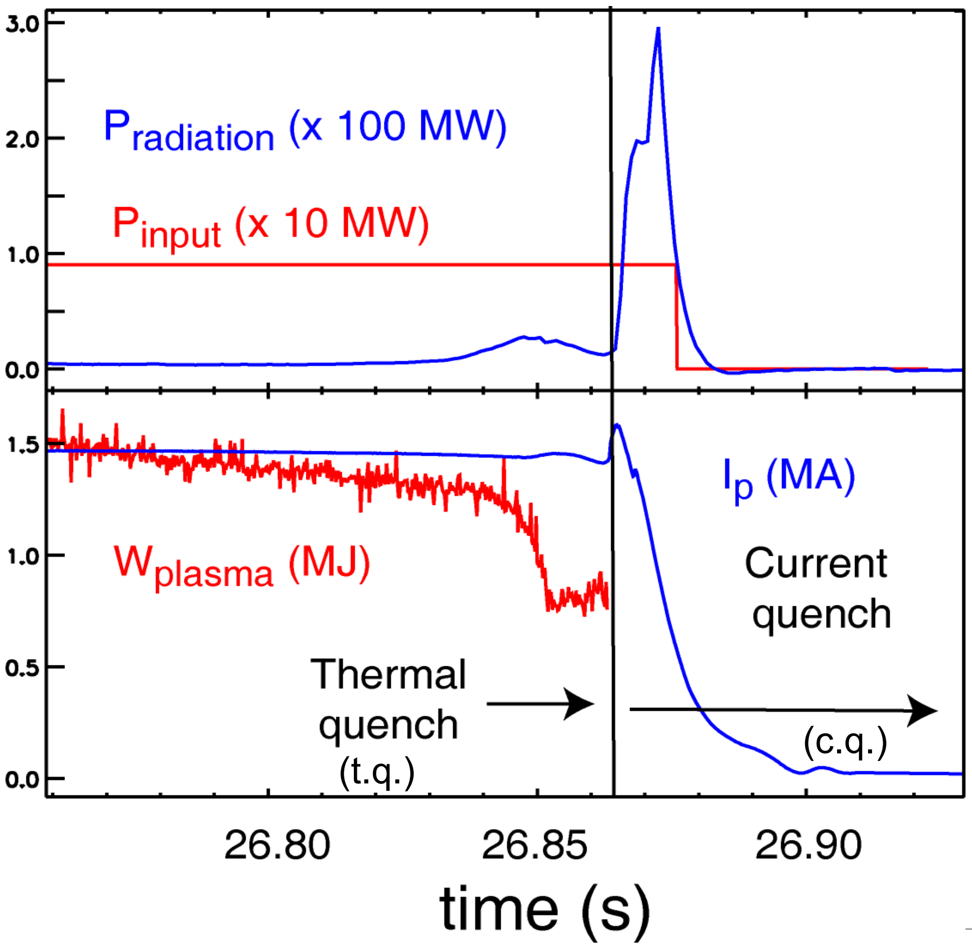
JET- .A. Alonso



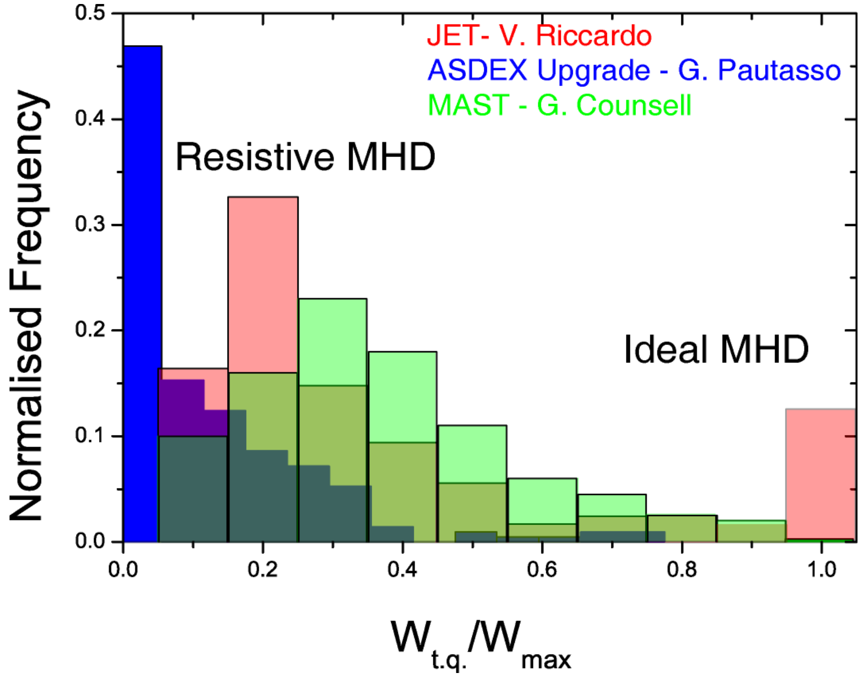
Power fluxes to PFCs during disruptions (I)

- Thermal quench leads to largest disruptive power fluxes because of W_{plasma} and short timescale (excluding runaway electrons)
- τ_E deteriorates in advance of disruption → $W_{t.q.} \sim 0.3\ W_{plasma}^{H\text{-mode}}$

JET-Pulse No. 69787

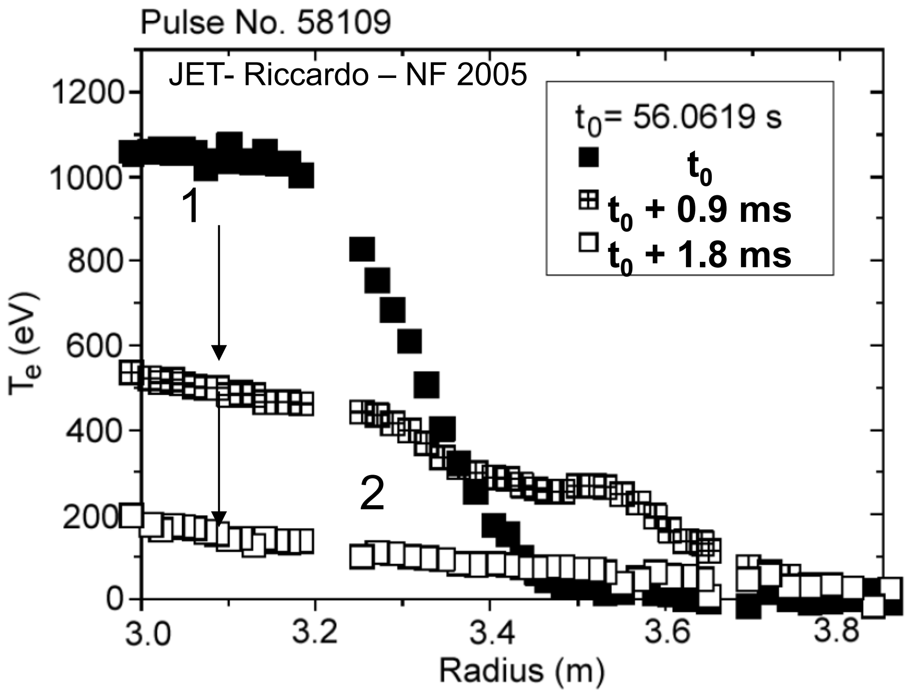


A. Loarte - EPS 2007

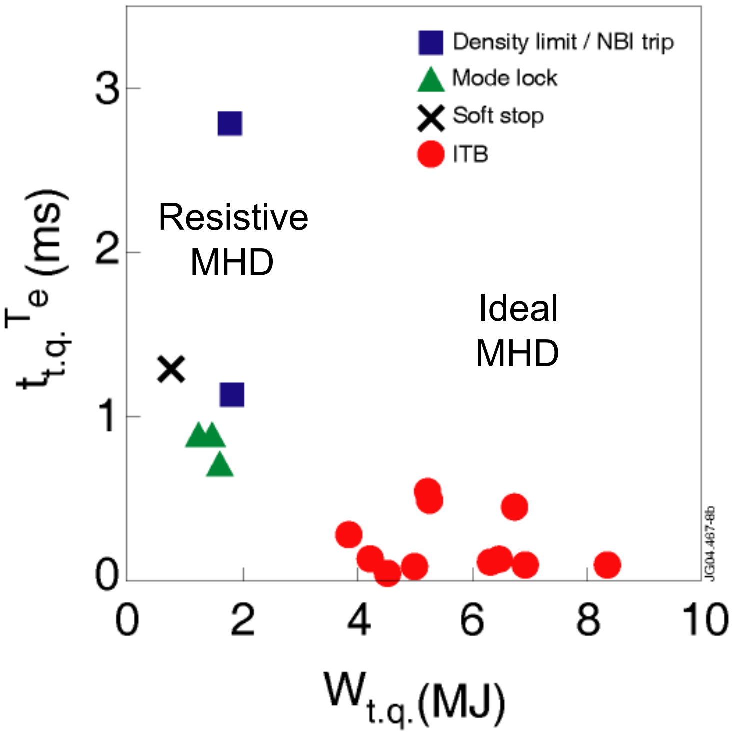


Power fluxes to PFCs during disruptions (II)

- Power fluxes during thermal quench show large variability → complex processes leading to final plasma thermal energy collapse
- A. Disruptions (resistive MHD) :
  1. Enhanced transport in plasma core
  2. Loss of remaining plasma energy → flattening of current profile
- B. Disruptions (ideal limit) → plasma collapse by explosive growth of modes



JET- Riccardo – NF 2005

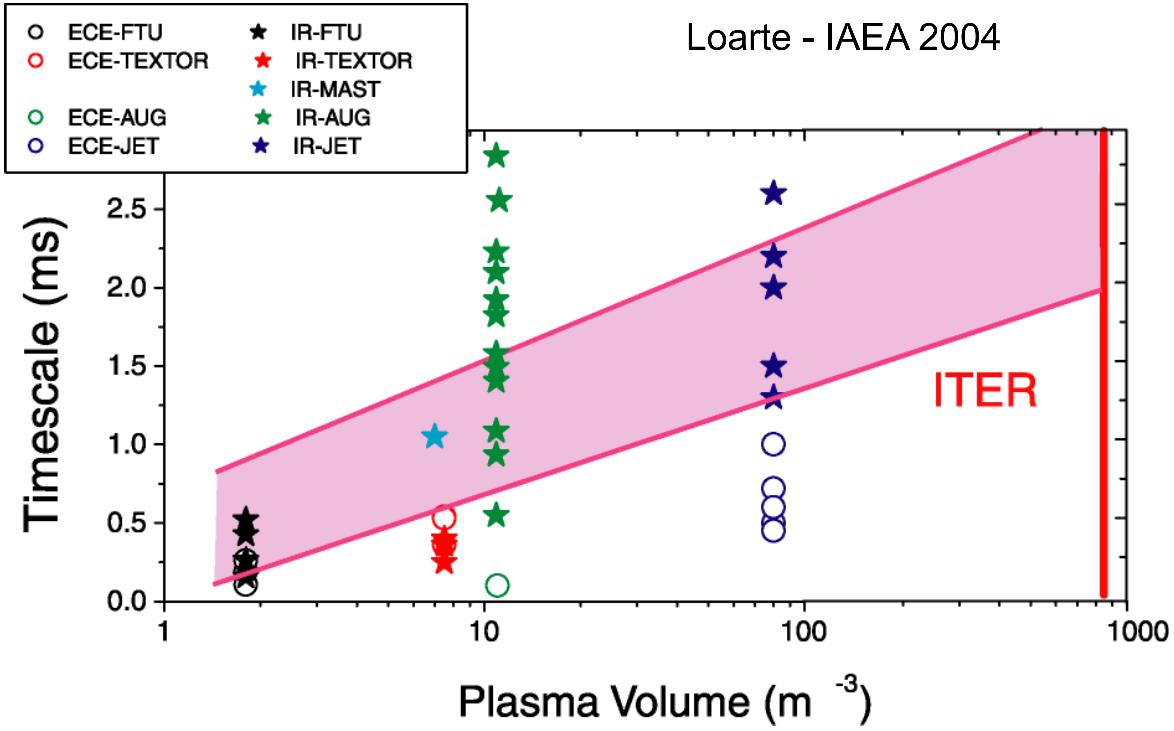


Resistive MHD plasma collapse →Longer timescales than ideal MHD collapse

Power fluxes to PFCs during disruptions (III)

➢ Contrary to ELMs power flux timescales gets longer with size of device not inconsistent with energy diffusion in a strongly perturbed field

- ✓ $t_{t.q.} \sim R^2/\chi_{R\text{-}R}$
- ✓ $\chi_{R\text{-}R} \sim v_e\, L_c\, (\delta B_r/B)^2$ with $L_c \sim R$ & $v_e \sim T_e^{1/2} \sim R^{\alpha}$ $(\alpha < 1)$

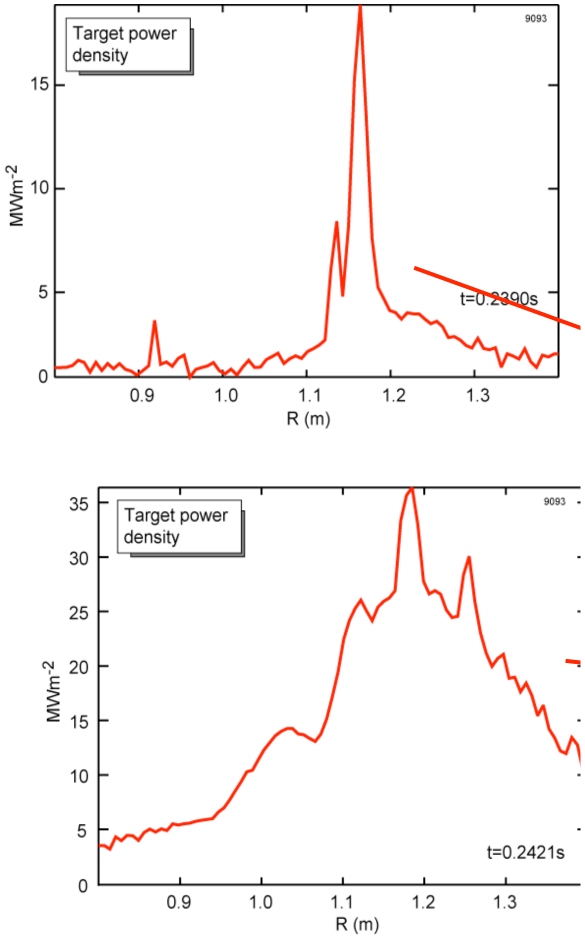


Loarte - IAEA 2004

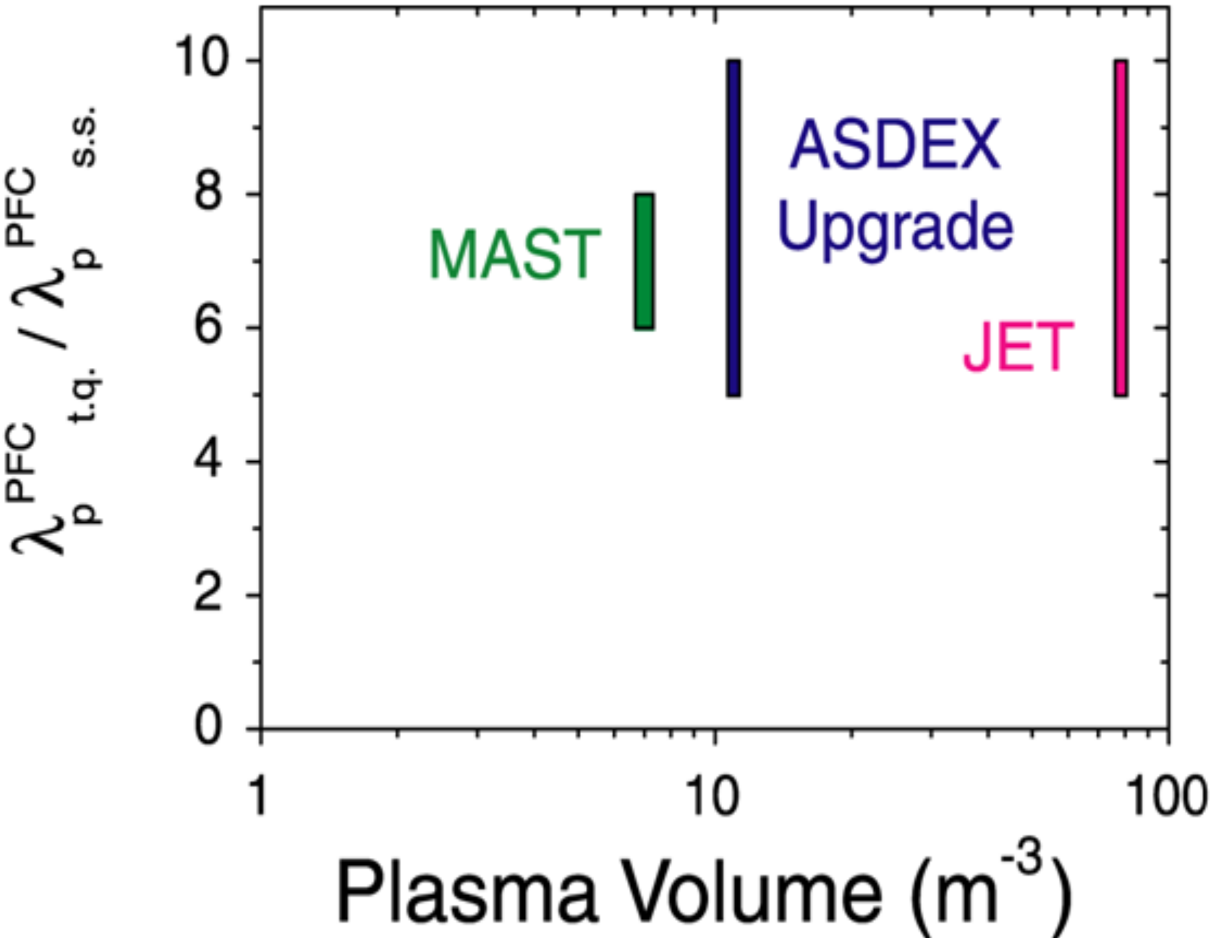
But large variability within a single experiment due to complex plasma dynamics during disruptions → no correlation with n_e,T_e before thermal quench

Power fluxes to PFCs during disruptions (IV)

- Large broadening of the power flux footprint on PFCs (divertor targets) at thermal quench in divertor tokamaks → large ⊥B transport (ergodisation of flux surfaces)

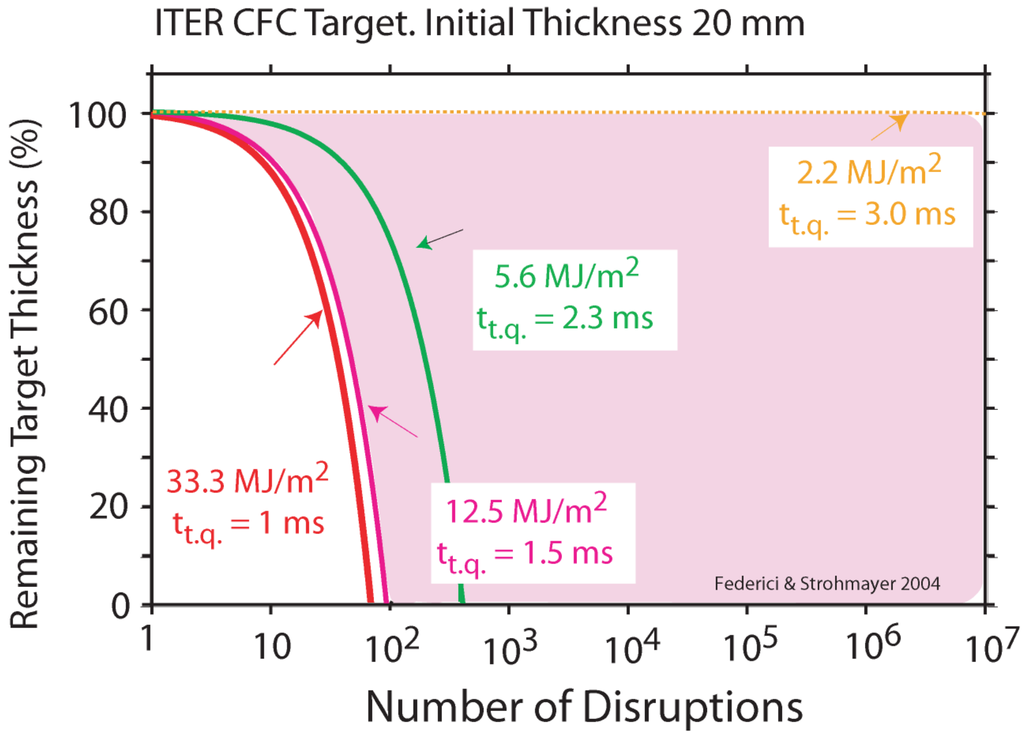


Loarte - IAEA 2004



Power fluxes to PFCs during disruptions (V)

- Physics model and physics based extrapolations applied to determine disruption power fluxes to divertor and wall for thermal quench in ITER (R&D on-going)
- Expected maximum values similar to uncontrolled ELMs (~ 20 MJm^{-2}) but over much large area of PFCs (5 -10 with respect to ELMs)



Federici & Strohmayer 2004

100 disruptions → ~ 100 μm/disruption

$1 m^2$ erosion → 200 g of C

ITER DT Plasma mass = 0.4 g

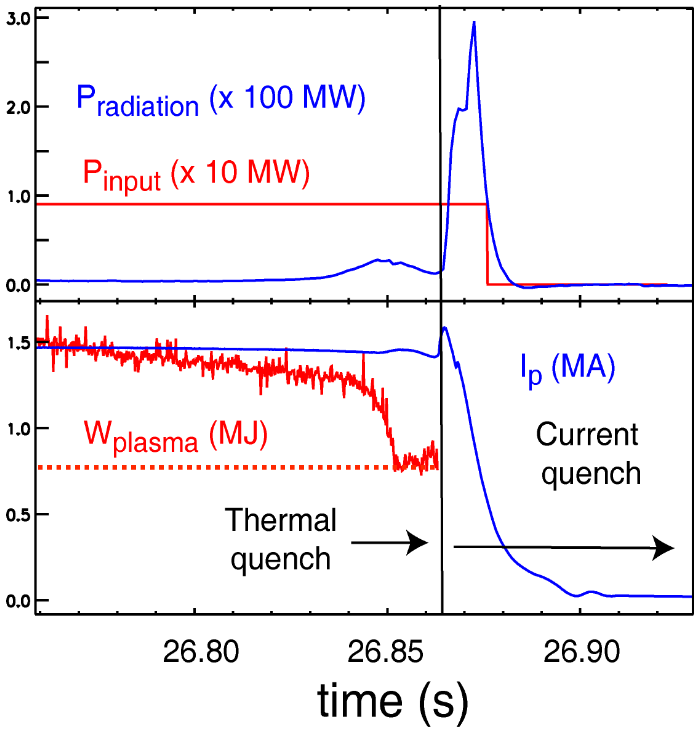
- Divertor lifetime ~ 100s high energy disruptions → control of power fluxes during disruptions required for high performance ITER operation

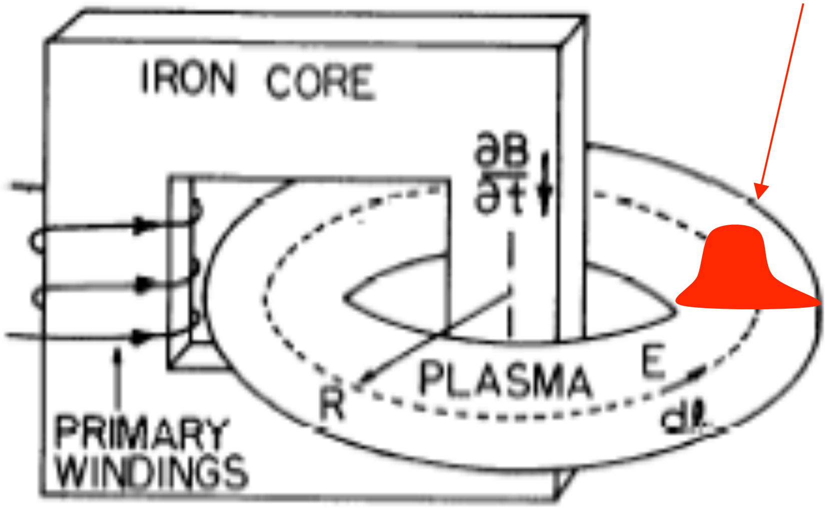
Power fluxes to PFCs during disruptions (VI)

- At thermal quench T_{plasma} ~ 10s eV → plasma becomes resistive $\eta \sim T^{-3/2}$
- V transformer small → I_p decays (current quench)
- Internal magnetic energy → Joule heating → radiation by partly ionised impurity ions from thermal quench

JET-Pulse No. 69787

$$W_{magnetic} = \frac{1}{2} L_{plasma} I_p^2 \quad with \quad L_{plasma} = \mu_0 R_0 \underbrace{(\ln(8\frac{R_0}{a})}_{\text{external}} \underbrace{-2+\frac{\ell_i}{2})}_{\text{internal}}$$

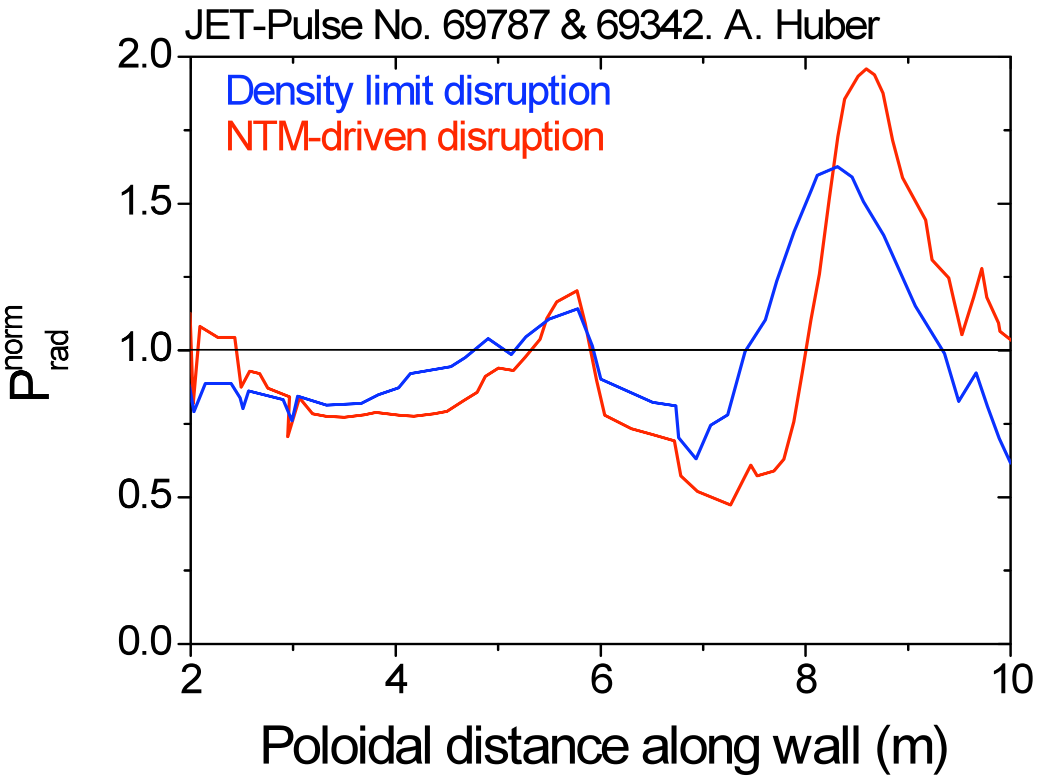


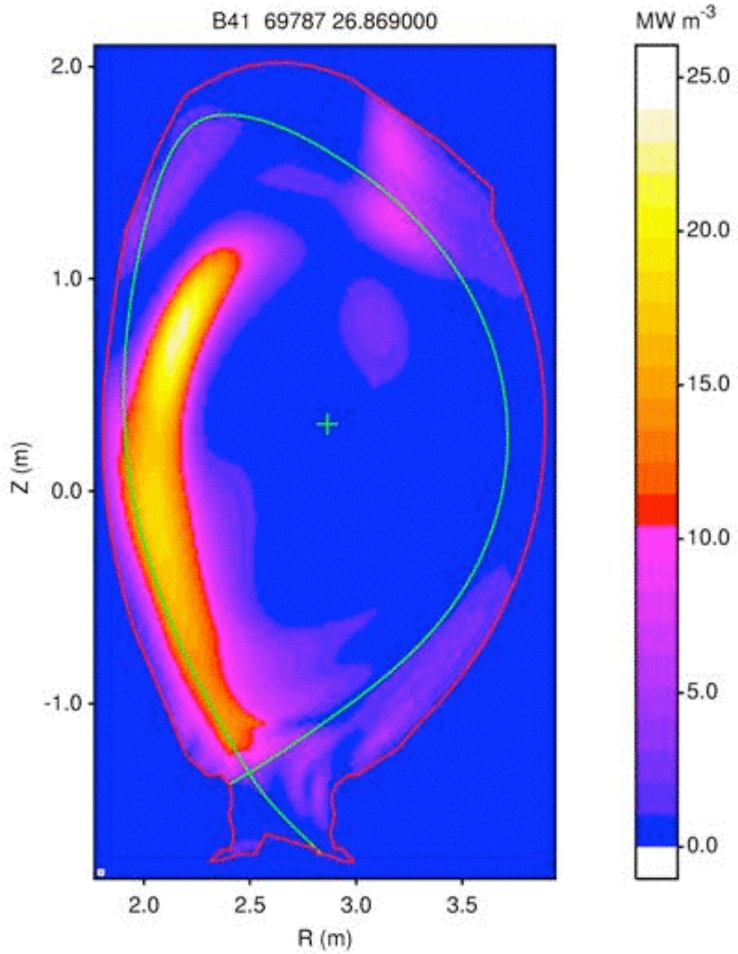


- Most external magnetic energy coupled back to external conductors by induction

Power fluxes to PFCs during disruptions (VII)

- $W_{ohmic} = W_{mag} - W_{conductors}$ → plasma heating and radiation
- Radiation to distributed power flux (from magnetic energy loss) during current quench

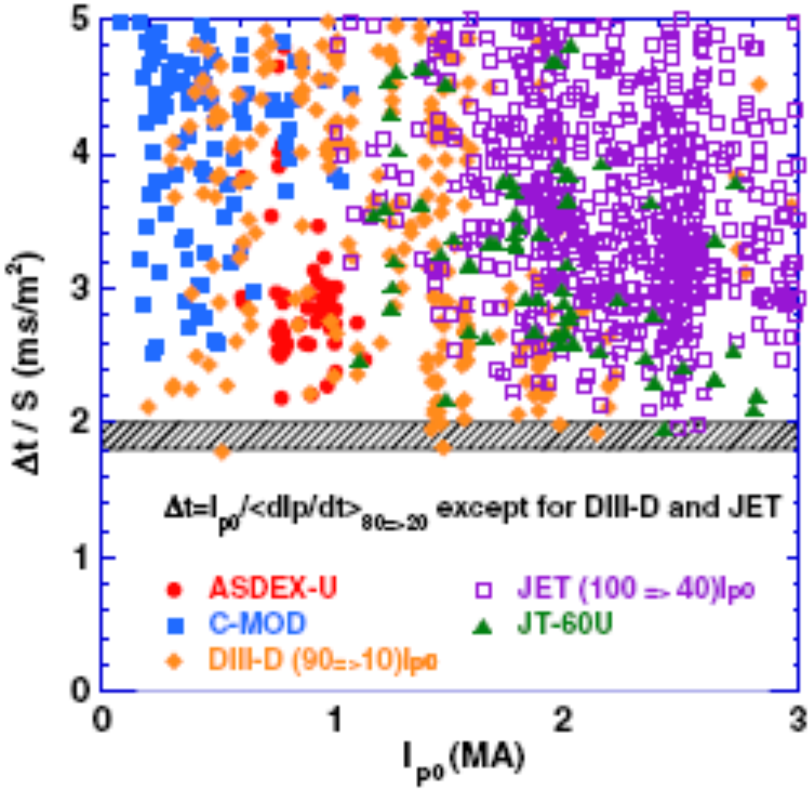


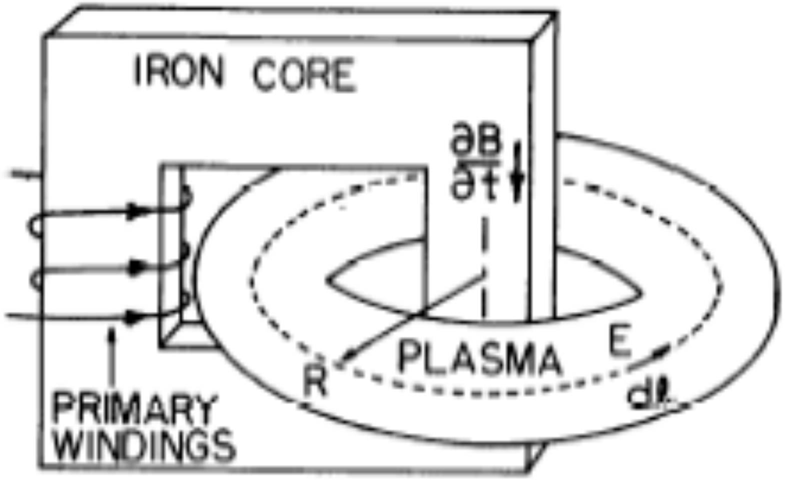


Power fluxes to PFCs during disruptions (VIII)

- Timescale of current quench scales with device size → 20 – 40 ms in ITER
- Long time scale and distribution of power by radiation → relatively low energy flux on PFCs during current quench
- Large induced E → runaway electrons

PIPB – NF 2007





$$\Phi_{magnetic} = L_{plasma} I_p$$

$$\frac{d\Phi_{magnetic}}{dt} = L_{plasma} \frac{dI_p}{dt}$$

$$\oint_{\partial S} \mathbf{E} \cdot \mathrm{d}\mathbf{l} = -\frac{\partial \Phi_{B,S}}{\partial t}$$

Power fluxes to PFCs during disruptions (IX)

- Electric field induced in plasma during current quench

$$E_{\parallel} 2\pi R_0 = \frac{1}{2}\mu_0 R_0 \ell_i \frac{dI_p}{dt} \sim \frac{1}{2}\mu_0 R_0 \ell_i \frac{I_p}{CS_{plasma}}$$

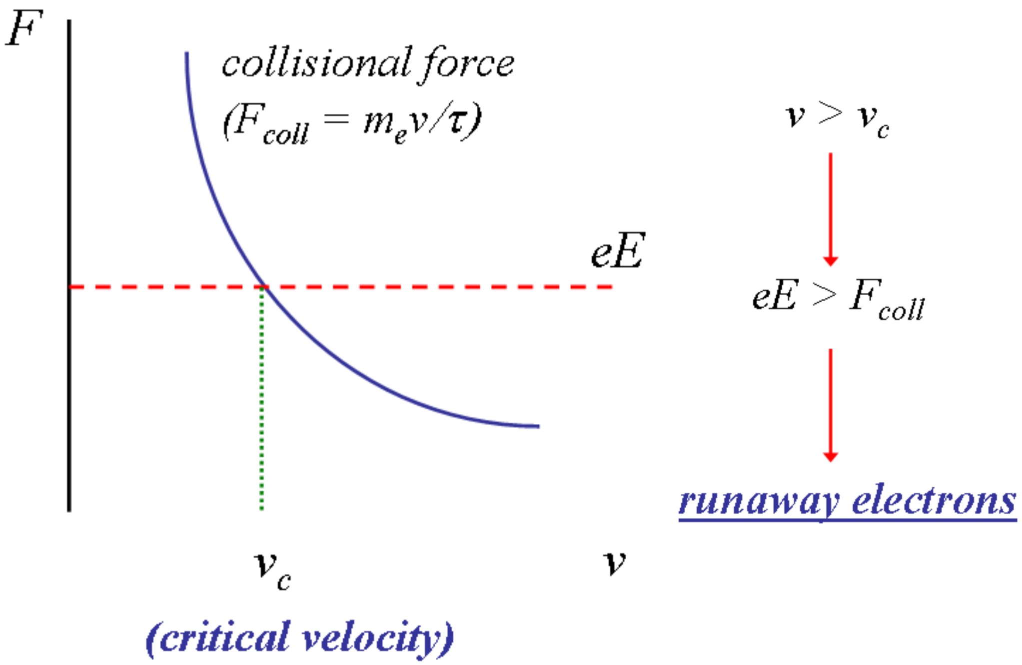
- If field large enough → some electrons accelerated to v_e ~ c (runaway e^-)

  e^- in plasmas subject to acceleration (by E) and deceleration by collisions

$$F_a = eE$$

$$F_d = m_e \frac{v_e}{\tau_s} \longrightarrow F_d = m_e \frac{v_e}{\tau_s} \propto \frac{1}{v_e^2}$$

$$\tau_s = \left(\frac{4\pi\varepsilon_0^2 m_e^2}{(Z^2+2)ne^4 \ln\Lambda} \right) * v_e^3 \propto v_e^3$$



Power fluxes to PFCs during disruptions (IX)

- Formation of sizeable runaway current limited by diffusion in velocity space Dreicer mechanism →critical electric field dependent only on plasma density

$$E > \frac{ne^3 \ln \Lambda}{4\pi\varepsilon_0^2 m_e c^2}$$

→ Runaway electron generation in current quench

(no runaways if n sufficiently high)

- Collisions between runaways and thermal electrons can also create secondary runaways (avalanche)

Generation rate

$$R_f = \frac{1}{\tau_R} \qquad \tau_R = 3 \ln \Lambda \frac{m_e c}{eE}$$

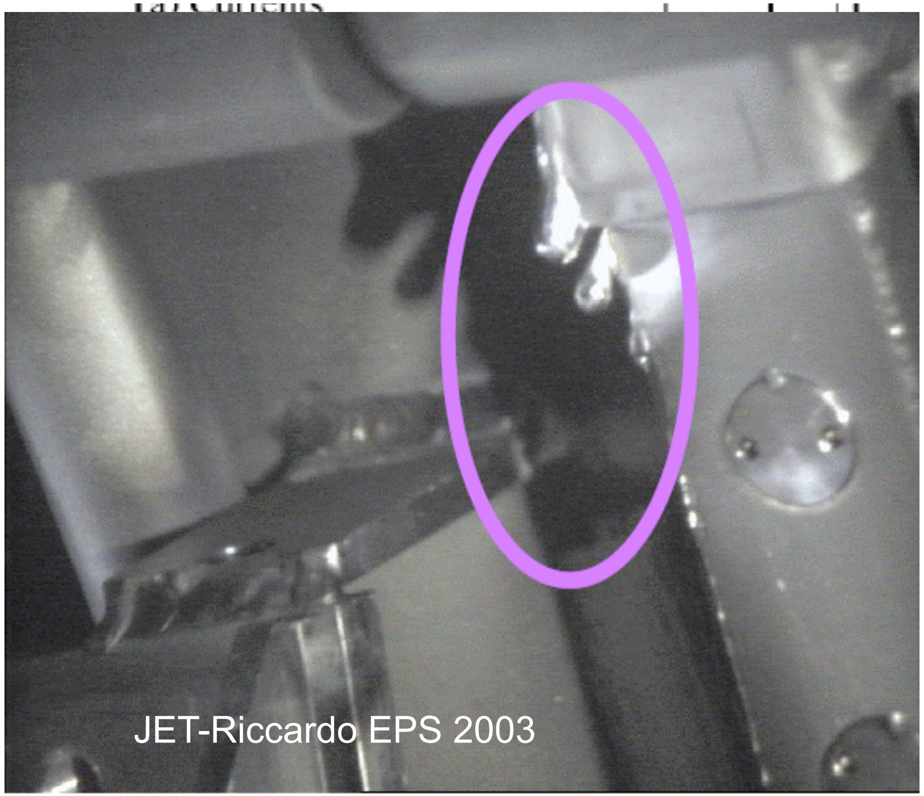
$$I_r = I_0 e^{t/\tau_r} \approx I_0 e^{2.5 I_p(MA)}$$

→ For ITER (I_p = 15 MA) I_r ~ I_p before thermal quench with E_e ~ 10s MeV

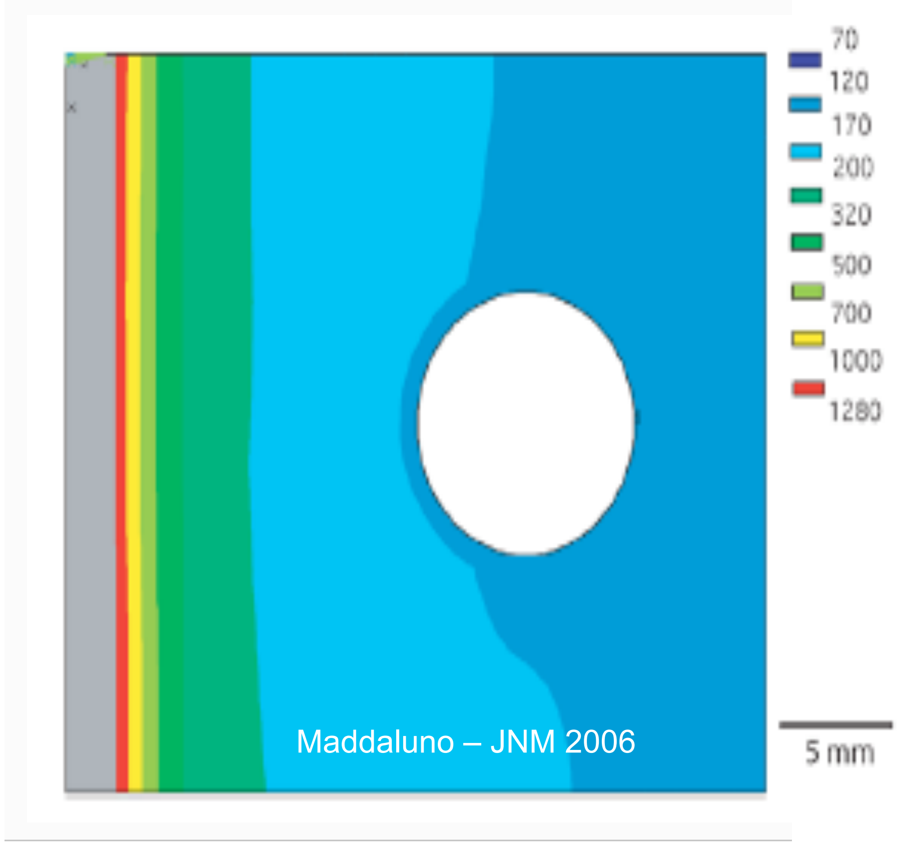
Power fluxes to PFCs during disruptions (X)

- Runaway electron discharges become vertically unstable and deposit their energy on localised areas of the first wall
- Deep melting (~ mm) expected in ITER (seen already in present generation of tokamaks) → problems for water cooled components (< 1 cm thick PFM)

Runaway electron damage in JET



JET-Riccardo EPS 2003



Maddaluno – JNM 2006

runaway formation avoidance and/or controlled energy deposition required for ITER

Mitigation of disruptions (I)

Disruption mitigation schemes aim at reducing consequences of disruptions in ITER

1. High power fluxes onto PFCs
2. Large forces on VV caused by plasma displacement before disruption
3. Formation and localised impact of runaways

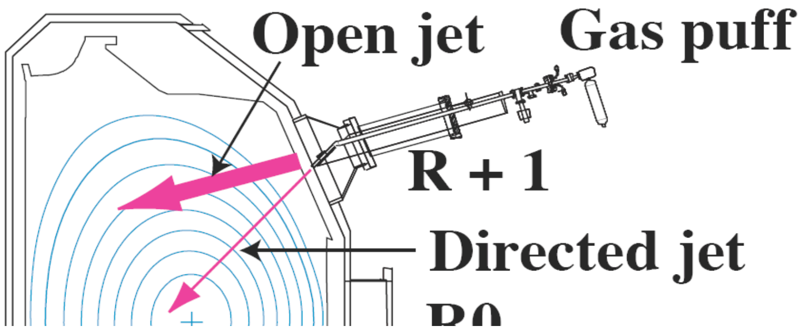
Schemes foreseen rely on present experimental results

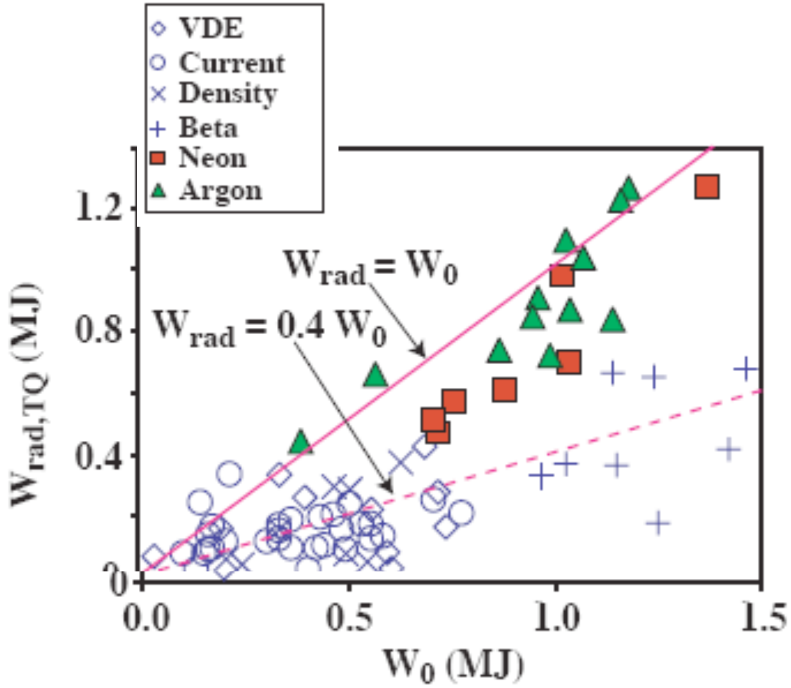
- Injection of large amount of material before disruption (OK for 1, 2 and possibly 3)
- Application of schemes for soft landing of runaway electron discharges (for 3)

Mitigation of disruptions (II)

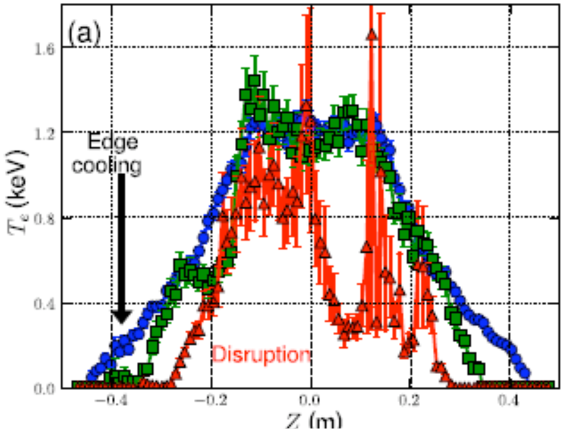
- Injection of large amount of impurities before disruption can radiate plasma energy at thermal quench → more distributed power load on PFCs

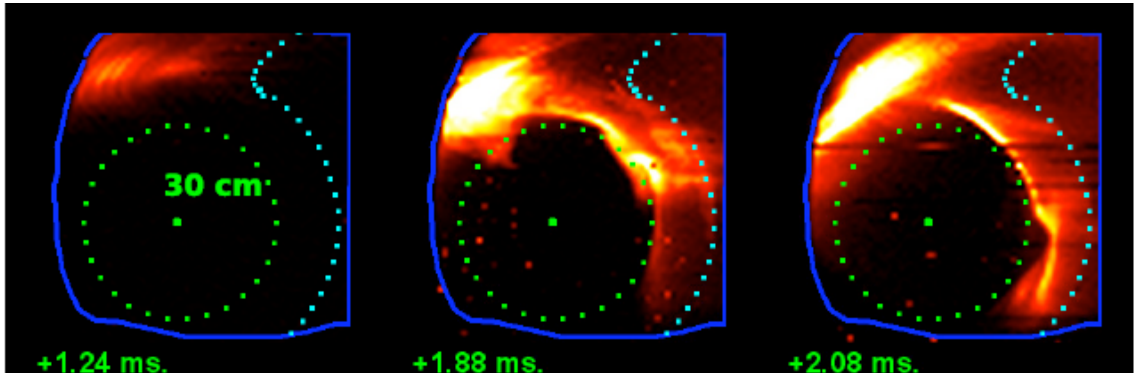
DIII-D Whyte NF 2005





Bozhenkov TEXTOR PPCF 2008

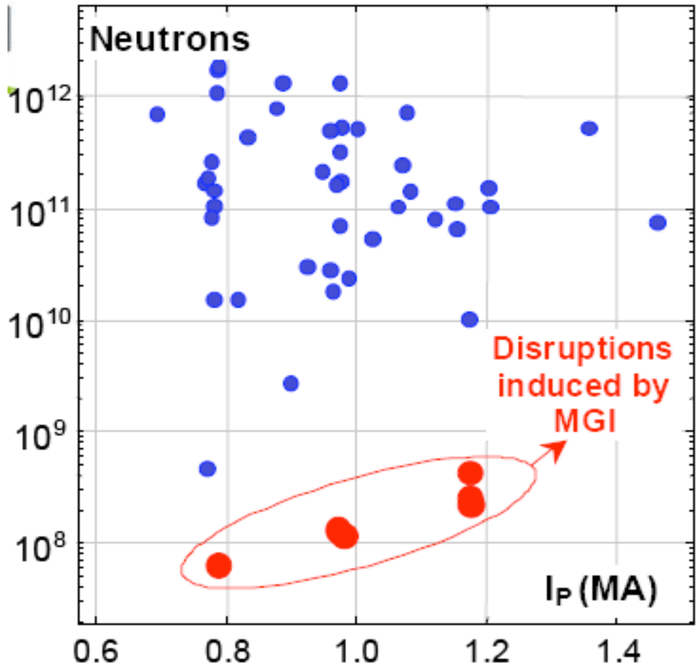




Mitigation of disruptions (III)

- Injection of large amount of gas is effective in also effective in suppressing runaway electrons formed during current quench in present experiments

Tore-Supra-F. Saint-Laurent

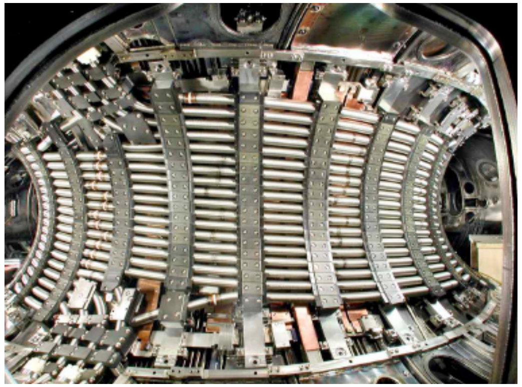


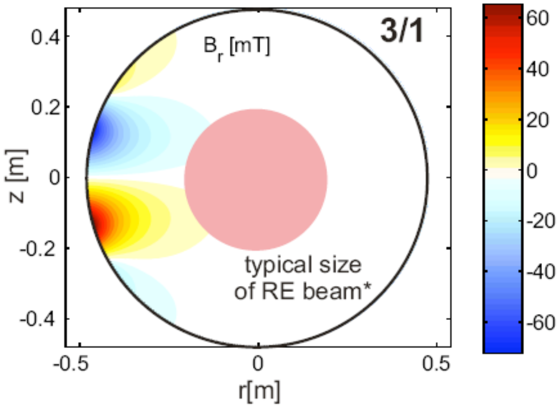
- Suppression of avalanche mechanism in ITER requires $n_e \sim 5\ 10^{22}\ m^{-3}$ → 100's g of material injected in few ms
  - ✓ Complex technology
  - ✓ Complications in restoring high vacuum after mitigation

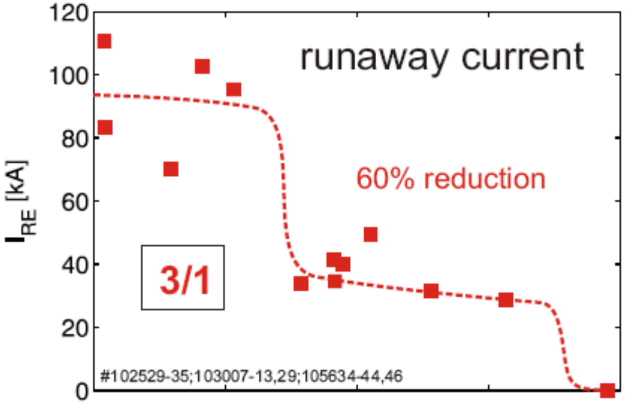
Mitigation of disruptions (IV)

- Solution investigated → combination of massive material injection & enhanced runaway loss by perturbed magnetic field (Lehnen PRL'08)

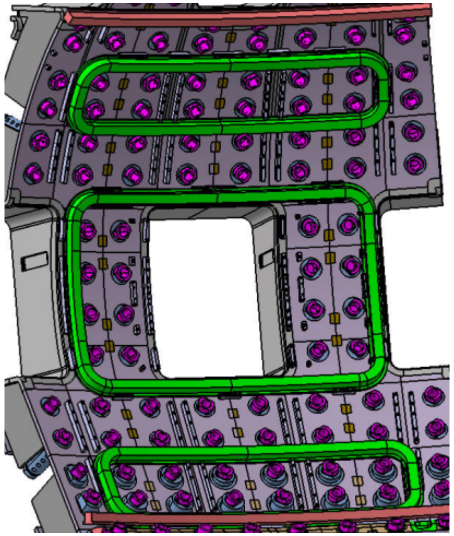
TEXTOR



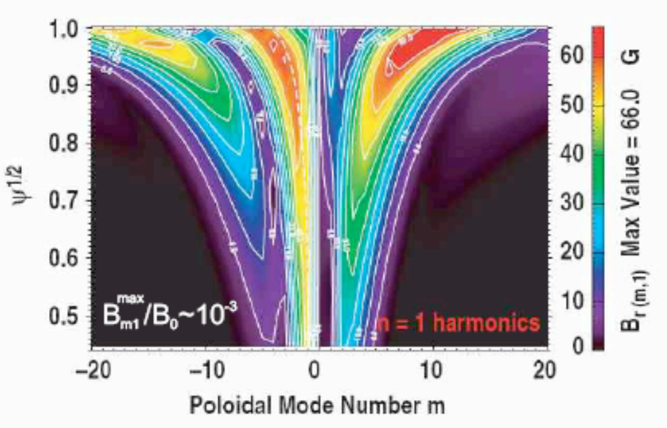




ITER



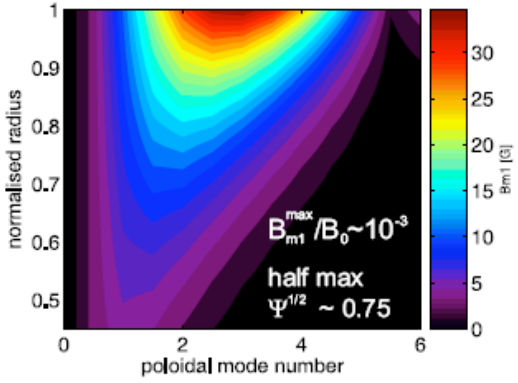
ITER study for n=1 mitigation



M.J. Schaffer et al, Nucl. Fusion 48 (2008) 024004

TEXTOR n=1

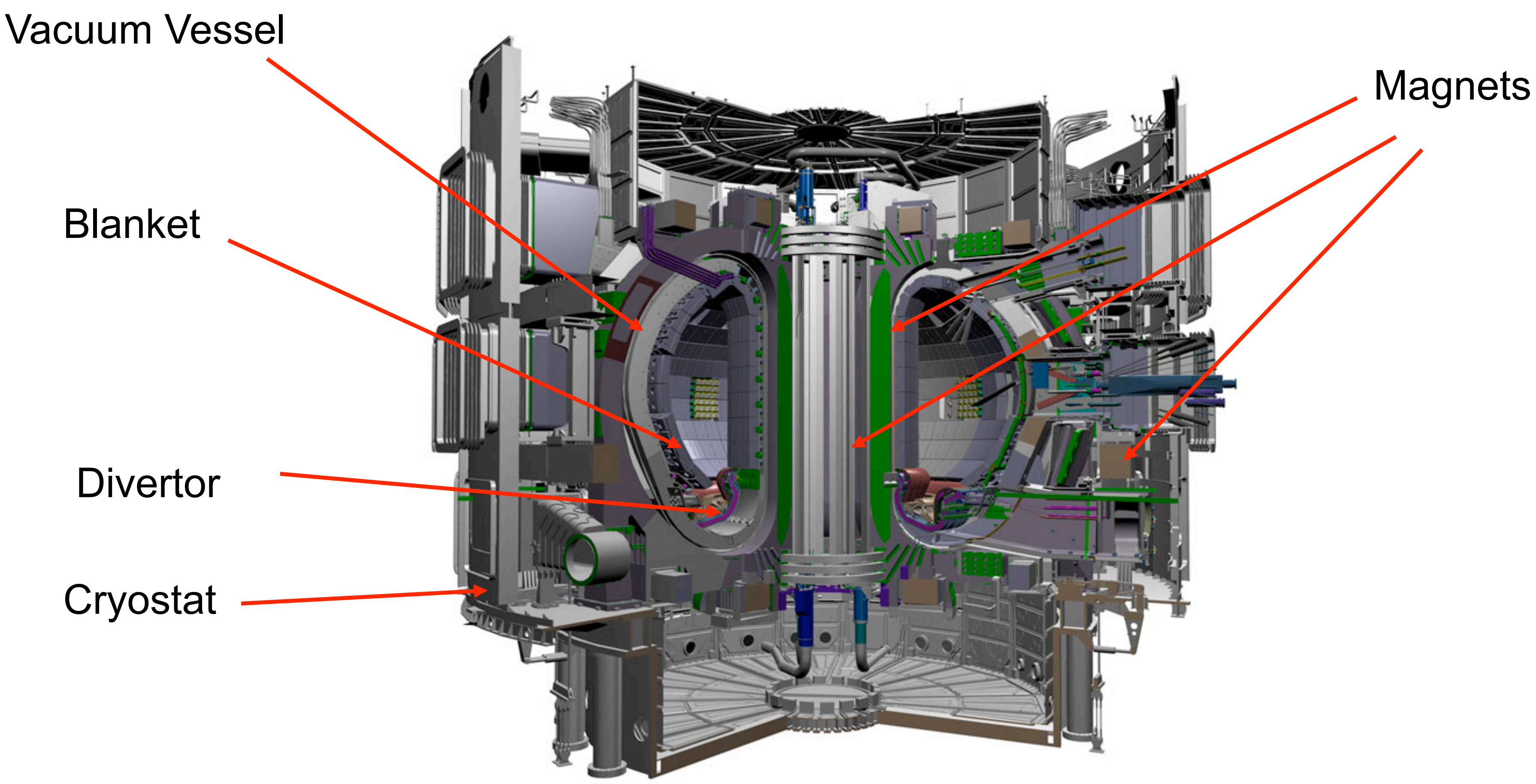
I_{DED} = 1.4kA (RE threshold)



Summary and Conclusions

- Physics of power transients in ITER involves large range of physical processes not fully understood
  - Confined plasma MHD
  - Transport of energy and particles along distorted magnetic surfaces
  - Interaction of hot plasmas (~ keV) with material surfaces
  - Formation of high energy electron plasmas (~ MeV) and their interaction with material surfaces
- Understanding physics of power transients is required for their control and mitigation
- Reliable ITER operation as required to achieve ITER's goals is synonymous of reliable control and mitigation of transients

Plasmas in ITER (II)



Diagnostics and H&CD systems (33 MW NNBI, 20 MW ICRH, 20 MW ECRH)

- Machine mass: 23350 t (Cryostat + VV + Magnets)
- Inductive operation: R = 6.2 m, a = 2.0 m, κ_{sep}= 1.85, δ_{sep}= 0.48, I_p = 15 MA, B_t = 5.3T

Power fluxes to PFCs during ELMs (III)

- Physics of energy flow from plasma to PFCs → competition of parallel and perpendicular transport after linear MHD phase