Fusion Reactor Technology I
(459.760, 3 Credits)

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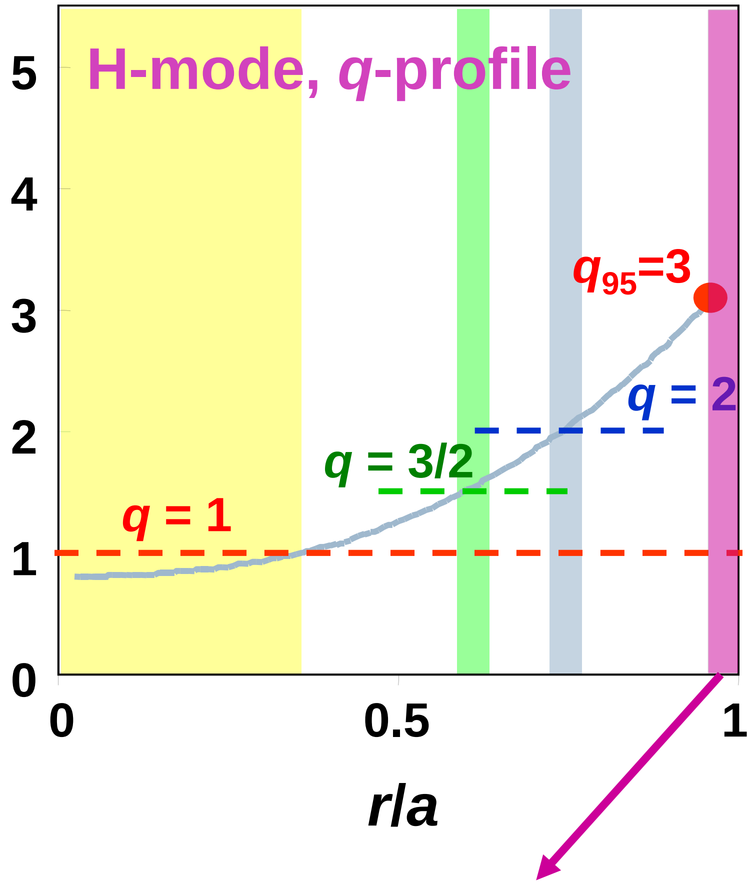
Contents

Contents

H–modes: Limitations

Stability of H-mode plasmas related safety factor profile: $q(r)$



Periodic collapses of the ETB (ELMs)

$q_0 < 1$: Sawtooth instability, periodic flattening of the pressure in the core

$q = 3/2$ and $q = 2$:

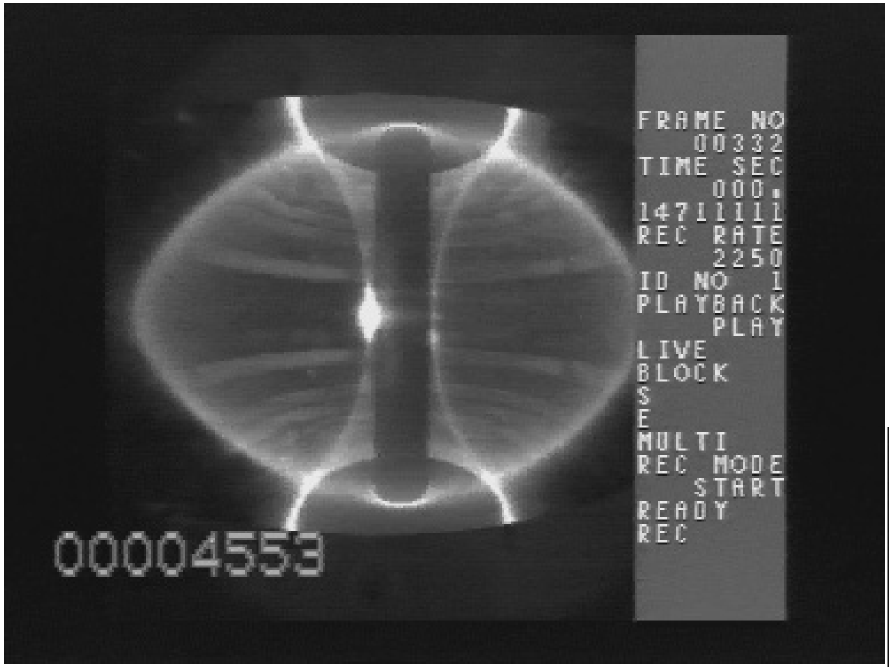
Neoclassical Tearing Modes (NTMs):

- limit the achievable $\beta \equiv 2\mu_0 p/B^2$
- degrade confinement (+ disruptions)
- often triggered by sawteeth.

- ITER work point is chosen conservatively: $\beta_N \leq 1.8$!

q_{95} ($\propto 1/I_p$) = 3: Safe operation at max. I_P

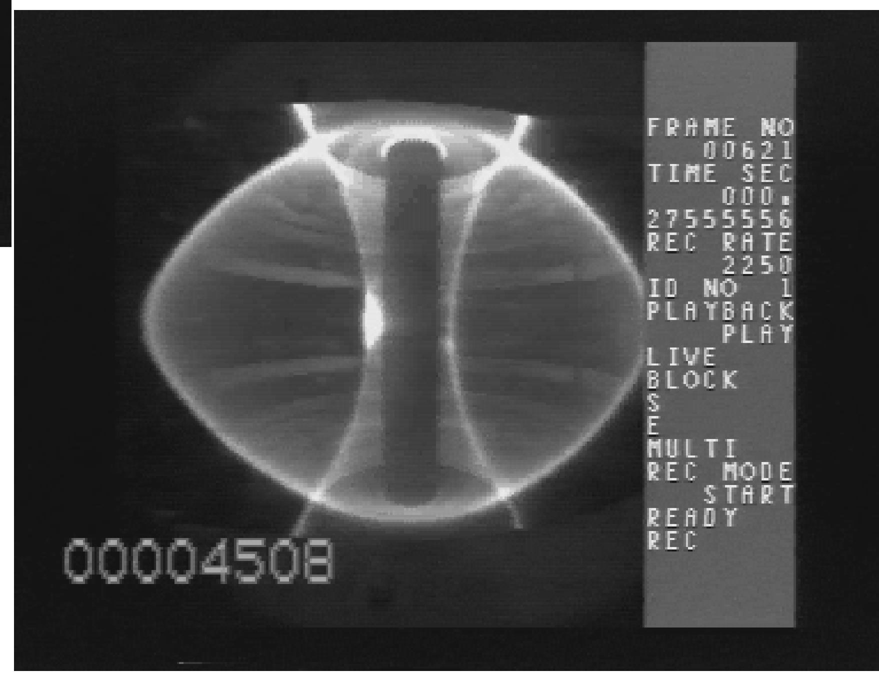
Edge Localised Mode (ELM)



Edge Localised Mode

MAST
MEGA-AMPERE SPHERICAL TOKAMAK

ELM-induced disruption

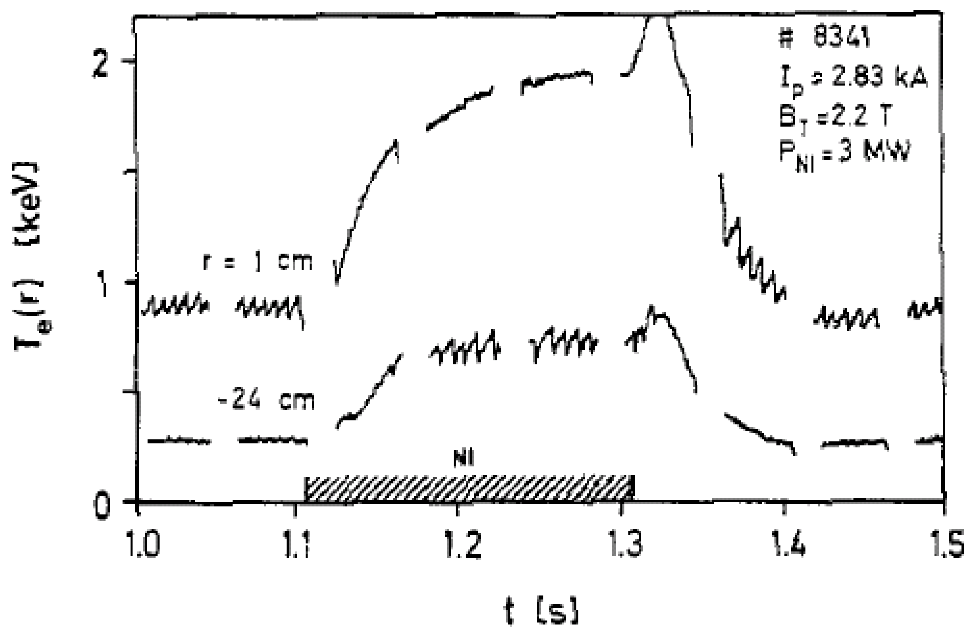


Edge Localised Mode (ELM)

Plasma Physics and Controlled Fusion Vol.26 No.1A pp.49-63, 1984 0032-1028/84$3.00+ .00
Printed in Great Britain

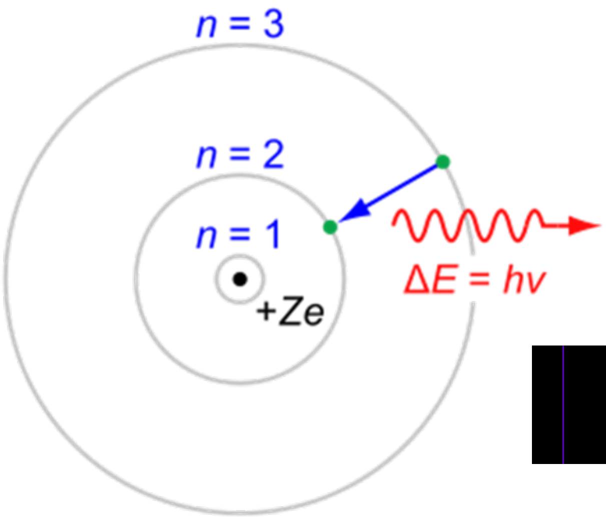
8. Edge Localized Modes

As already discussed in Sec. 2 and in the previous section, the H-phase is repeatedly interrupted by a new MHD phenomenon which severely limits the plasma temperatures and ß values attainable during this high-confinement mode. (The existence of this mode was already reported in ref. /1/.). Since the location of this MHD-phenomenon - as we will see - is at the plasma periphery, we call it the edge localized mode (ELM).



The charac ... or
high (H)-c ... a wide
range of o ... onfine-
ment after ... igh $ß_p$
values com ... eter
for transi ... f ~600 eV
only a few ... easured.
This requi ... he H-re-
gime in li ... al of
H-mode pla ... diffusivity by a factor of typically
2 over the entire plasma. H-mode energy confinement times are found to scale linearly with current, but to have little dependence on plasma density and absorbed beam power ($P_{NI} \leq 3.4$ MW). The confinement is degraded by a fast growing mode localized at the plasma edge that may be identified as a kink or tearing mode driven unstable by the high current densities at the edge.

Edge Localised Mode (ELM)



- H-alpha (H_α) is a specific red visible spectral line created by hydrogen with a wavelength of 656.28 nm, which occurs when a hydrogen electron falls from its third to second lowest energy level.
- It is difficult for humans to see H-alpha at night, but due to the abundance of hydrogen in space, H-alpha is often the brightest wavelength of visible light in stellar astronomy.

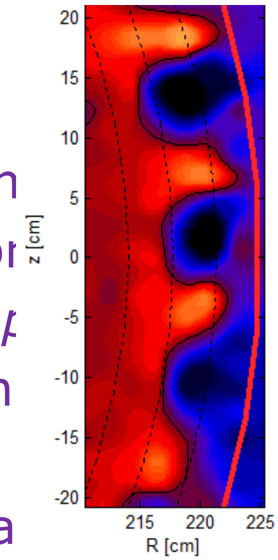
http://en.wikipedia.org/wiki/H-alpha

Edge Localised Mode (ELM)

- **Edge Localised Modes (ELMs)**

- First observed upon discovery of the H-mode in auxiliary heated divertor plasmas in ASDEX (1984)
- Subsequently universally observed in all divertor tokamaks and also in limiter tokamaks in certain operational regimes
- localized in the plasma edge region (defined roughly as comprising the last 5% of the closed flux surfaces) of a tokamak
- MHD instability in the plasma edge occurs when the edge ∇p exceeds a critical threshold $\rightarrow$ loss of edge confinement $\rightarrow$ temporary reduction of the ∇p $\rightarrow$ eventual recovery of the ∇p $\rightarrow$ recurrence of the ELM
- This cycle, which continues indefinitely in a sustained H-mode discharge is a ubiquitous feature of such long pulse H-mode plasmas: ELMing (or ELMy) H-mode.

Edge Localised Mode (ELM)

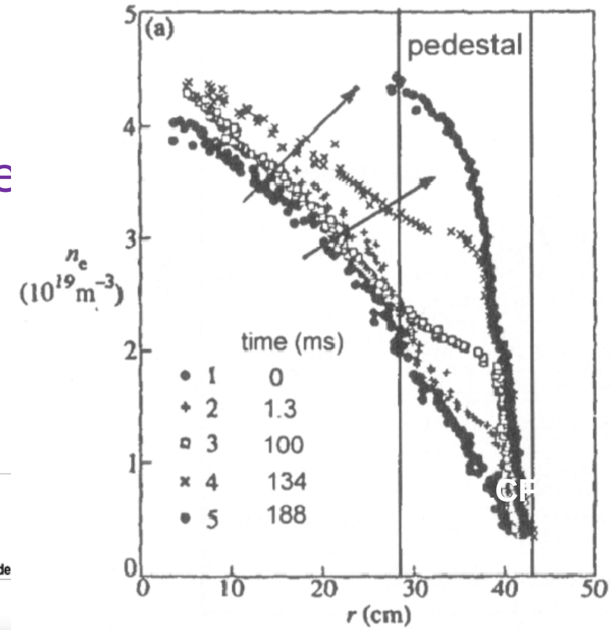


- **Edge Localised Modes (ELMs)**

- Characteristic sharp periodic increases in D_α (or H_α) en n
  the divertor or limiter region caused by a temporary br of
  the H-mode edge confinement barrier (reduction of ∇p

→ Plasma particles and energy are expelled, and the en
  recycling increases D_α emission.

- ELMs also accompanied by various edge region fluctua
  (both magnetic and kinetic) and localized
  bursts of MHD activity, including magnetic
  precursors (e.g. directly observable change
  in the edge region plasma temperature
  and density profiles and energy content)

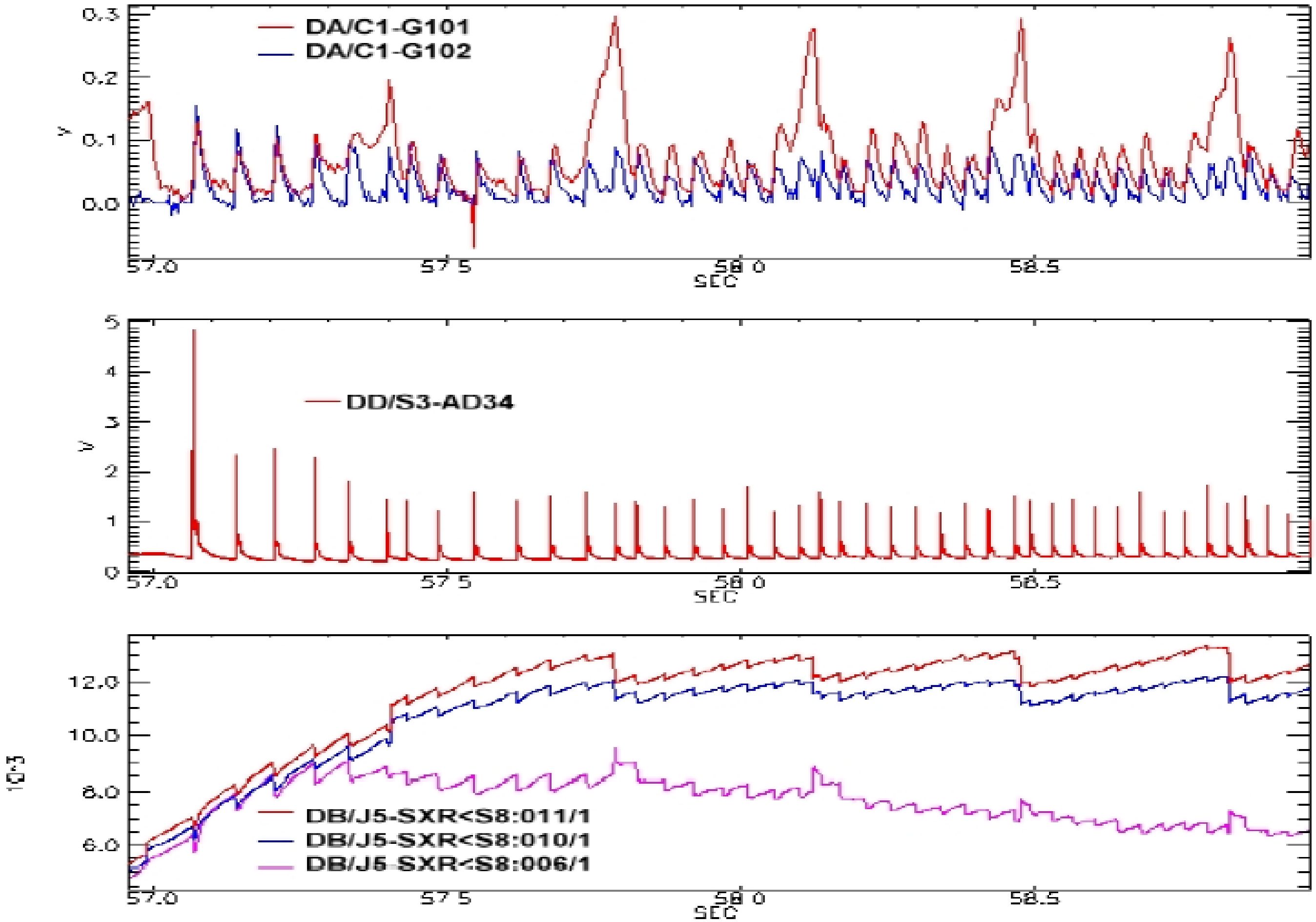


POSTECH
PDS²O
ASDEX Upgrade

Edge Localised Mode (ELM)

- **Example of sawteeth and ELMs**

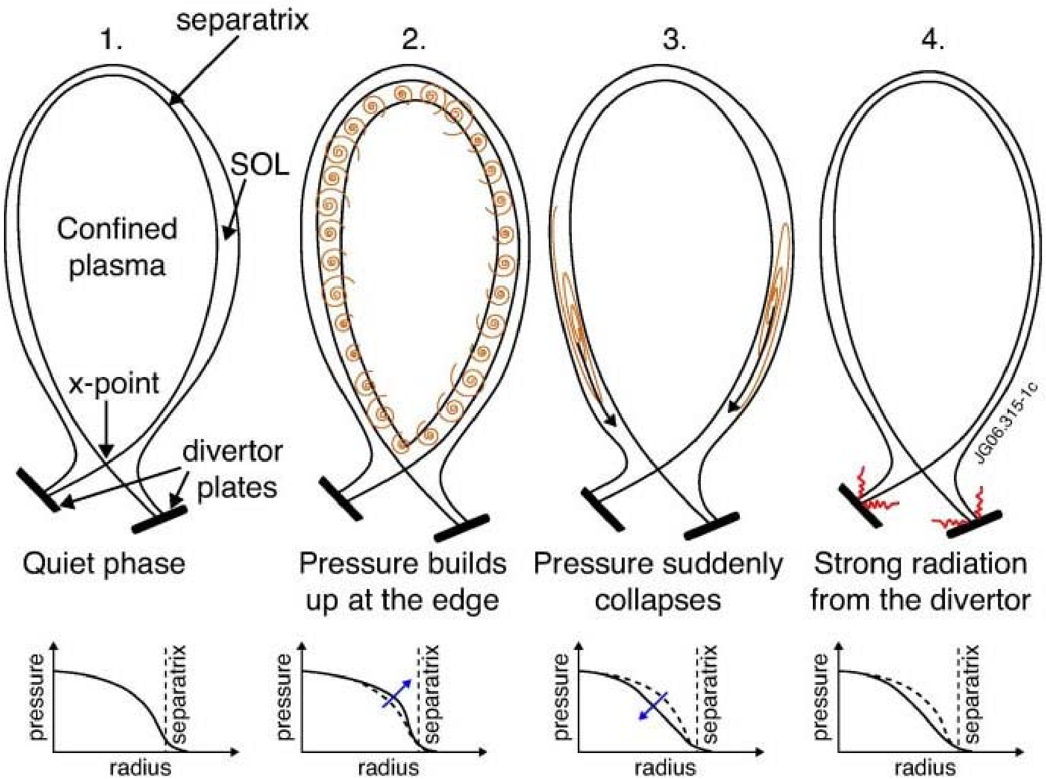
JET, Pulse 52022

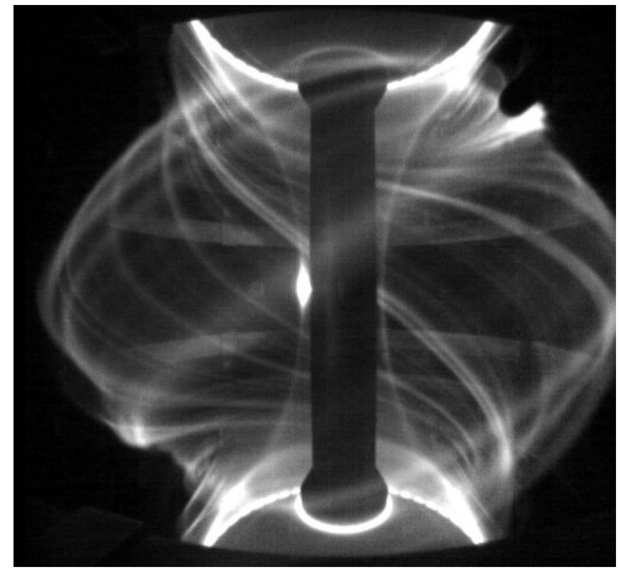


EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET

Edge Localised Mode (ELM)





- Fast cameras in MAST allow identifying the filaments detaching form plasma at high speed (~several km/s)

Edge Localised Mode (ELM)

- **ELM Oscillations**

- Current driven (peeling mode) and pressure driven (ballooning mode) combined instability

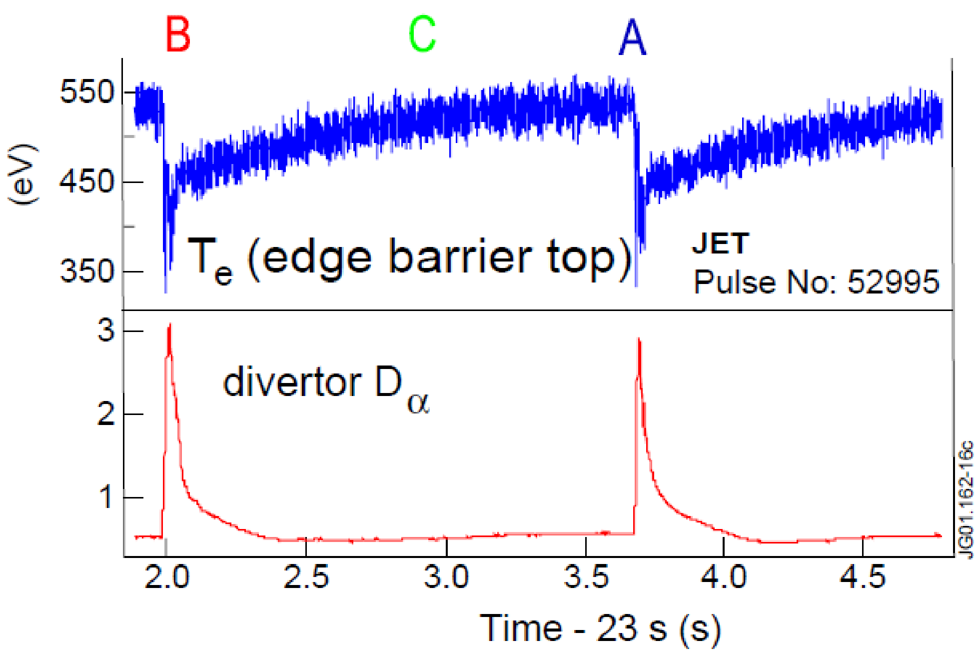
Edge Localised Mode (ELM)

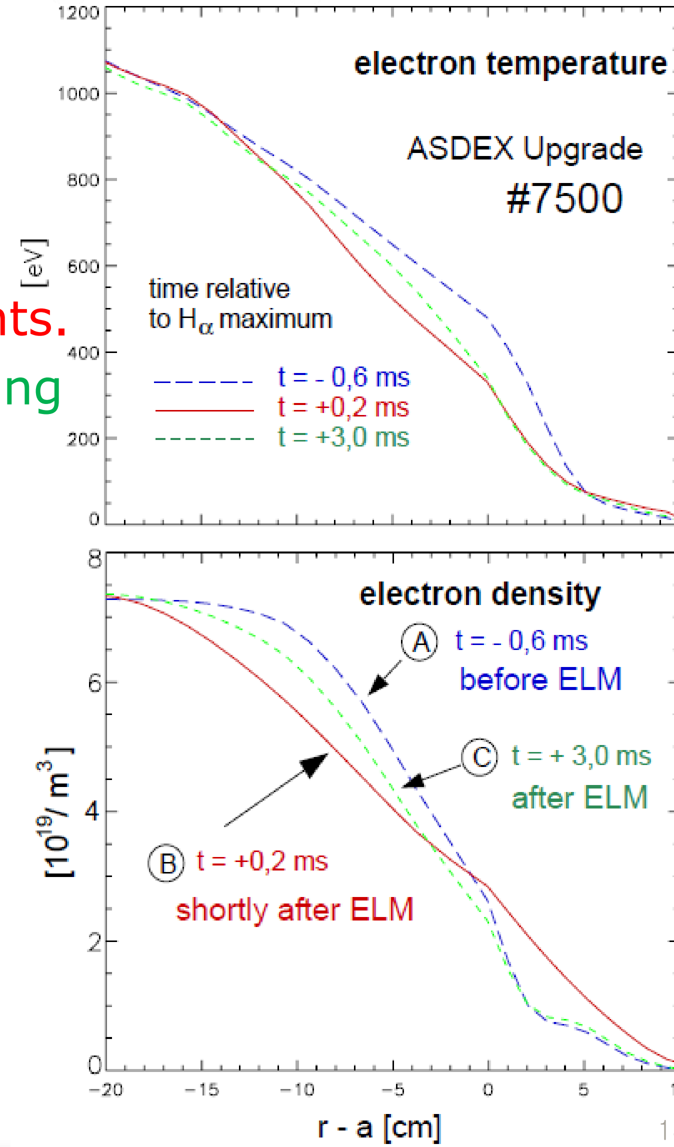
- **ELM Oscillations**

A. Critical ∇p in ETB region reached
→ short unstable phase (ELM event)

B. Energy and particle loss reduces gradients.

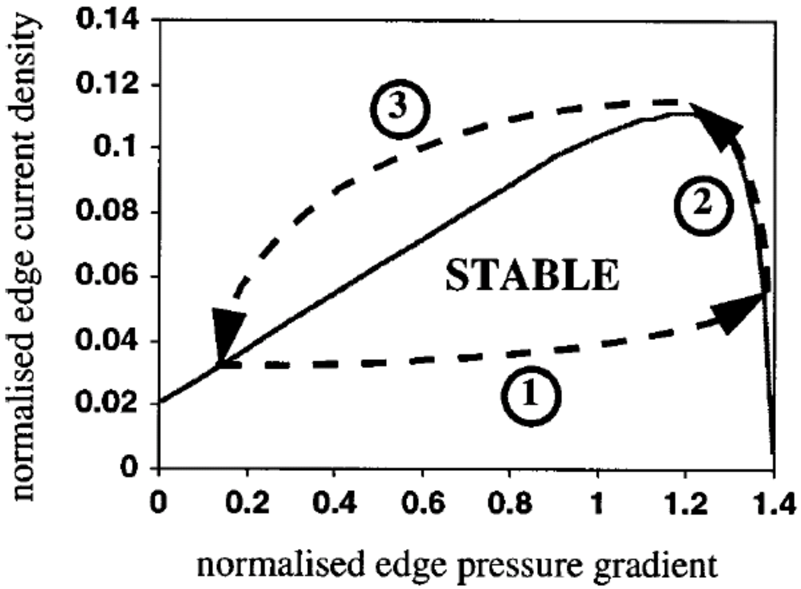
C. Gradients build up during reheat/refuelling phase.





Edge Localised Mode (ELM)

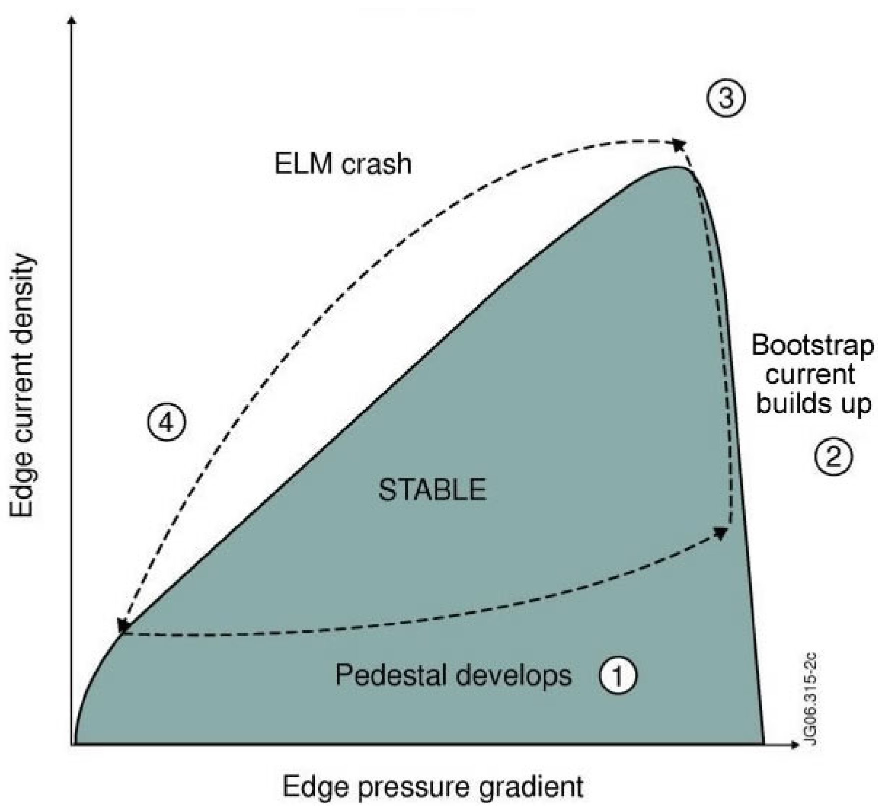
- **Peeling-Ballooning model for ELM cycle**



J. W. Connor et al, Physics of Plasmas ***5*** *2687 (1998)*

Edge Localised Mode (ELM)

- **Peeling-Ballooning model for ELM cycle**

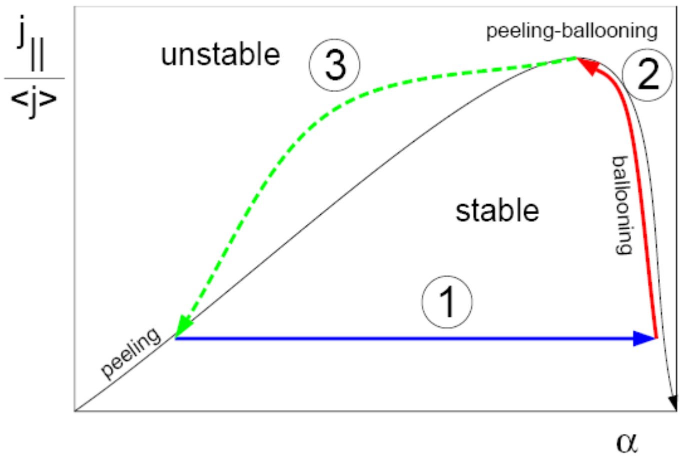


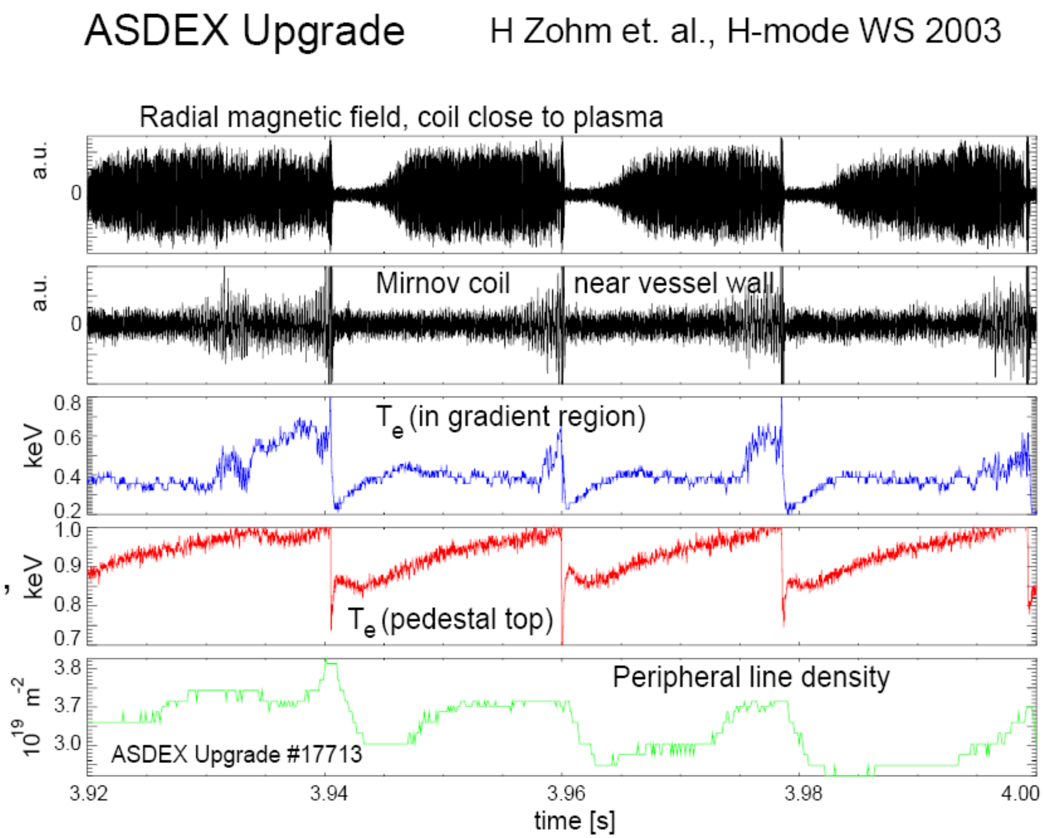
- The ELM cycle starts with a low pressure gradient as a result of the previous ELM crash that has removed the edge pressure "pedestal".
- Due to the edge transport barrier, the edge pressure pedestal develops quickly (1).
- The growth of the pedestal stops at the so called "ballooning stability" limit (2).
- Due to the pressure pedestal, the bootstrap current – which is proportional to the pressure and temperature gradients – starts to grow. Eventually, the bootstrap current destabilizes an effect known as "ideal peeling" which leads to an ELM crash (3) and the loss of the edge pressure pedestal (4).
- The cycle then restarts from the beginning.

Edge Localised Mode (ELM)

- **Peeling-Ballooning model for ELM cycle**

ASDEX Upgrade





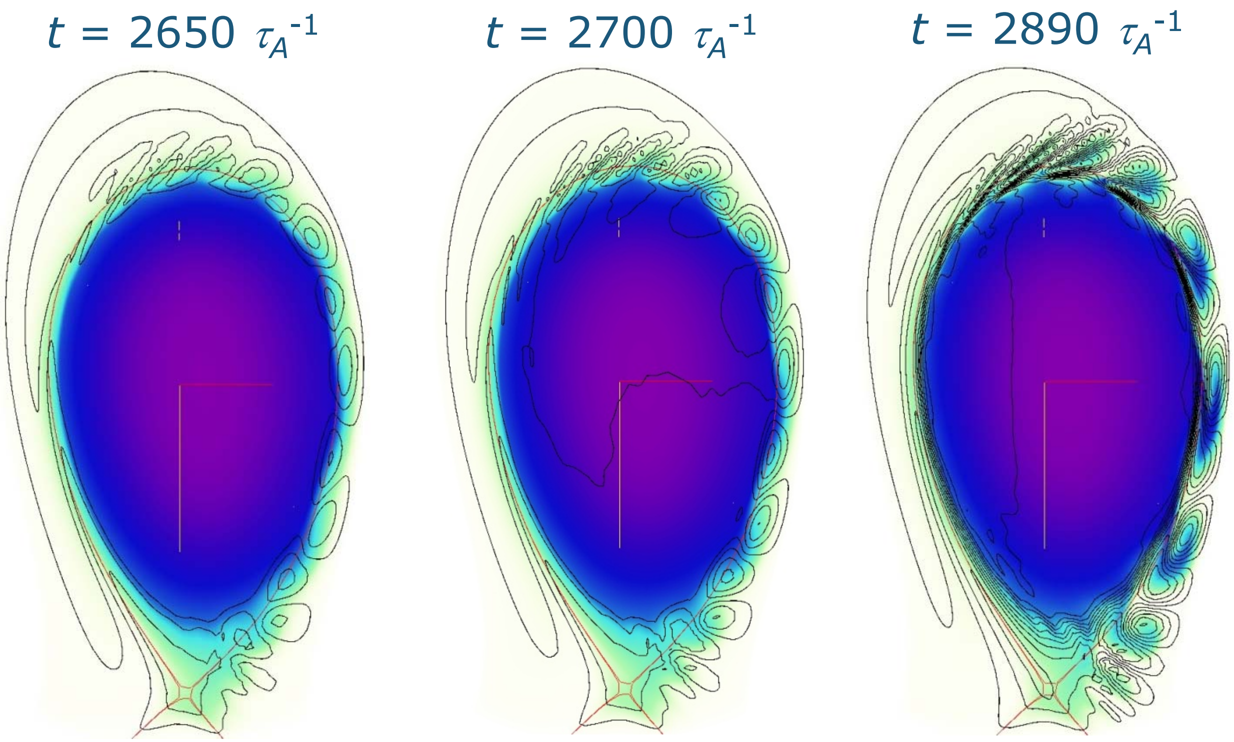
1. ∇p rises on transport time scale

2. ∇p clamped by high n ballooning, edge current density rises on resistive time scale

3. Medium n instability ("peeling") p and j lost until stable again

Edge Localised Mode (ELM)

- Non-linear MHD simulations with JOREK reproduce the formation of multiple filaments expulsed from plasma

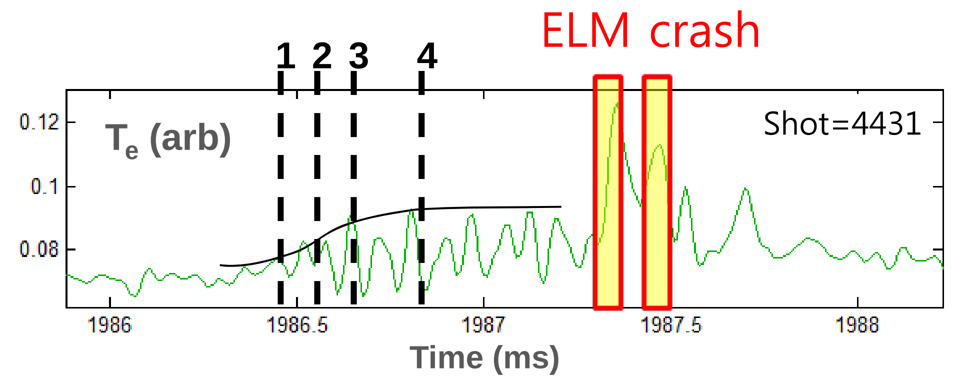


Evolution of n = 6 ballooning mode

Huysmans, Czarny, NF 47 659 (2007)

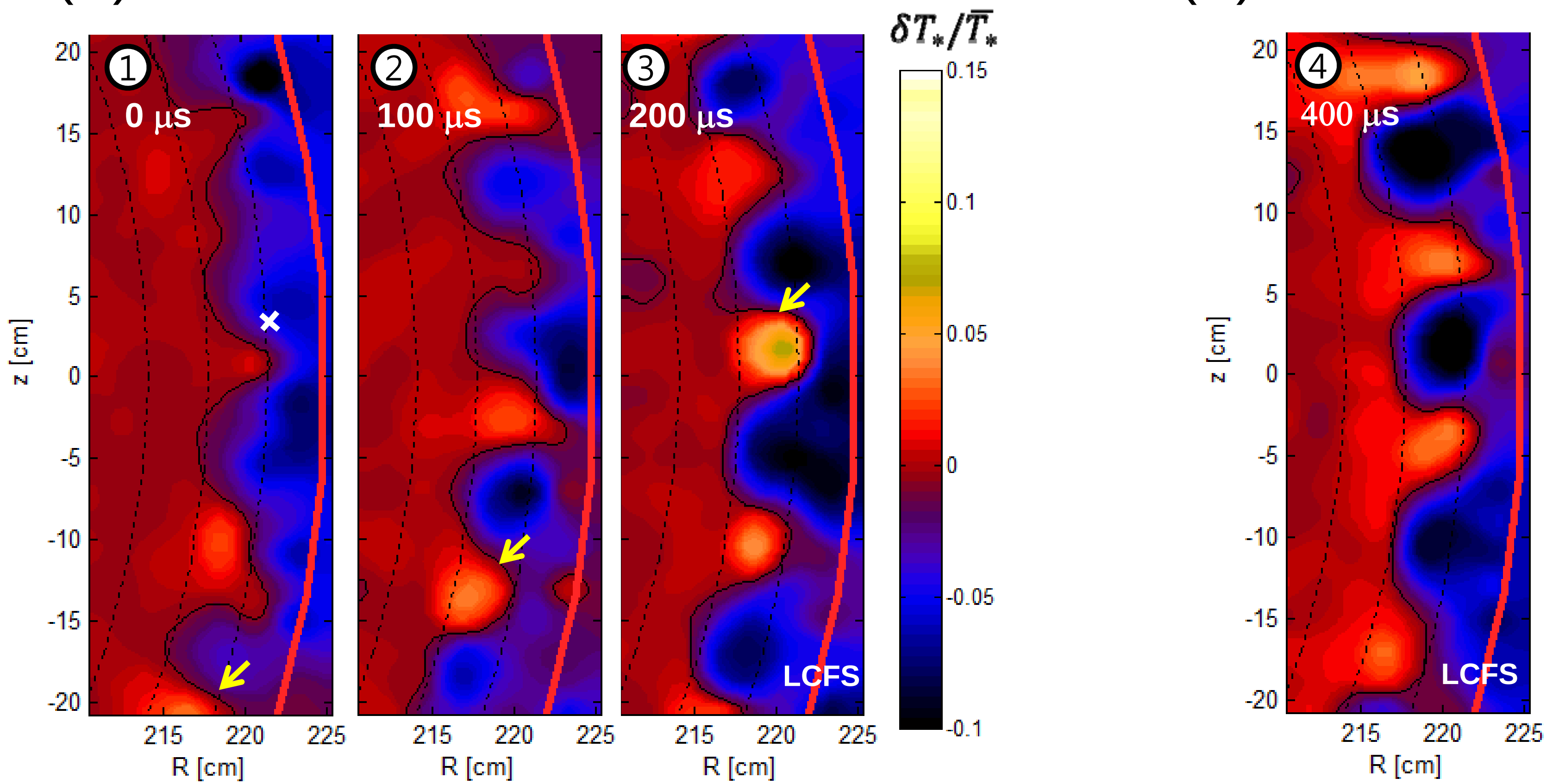
Standard ELM dynamics in the KSTAR visualized by an ECEI system*

* GS Yun et al., PRL 2011



(1) Initial Growth

(2) Saturation

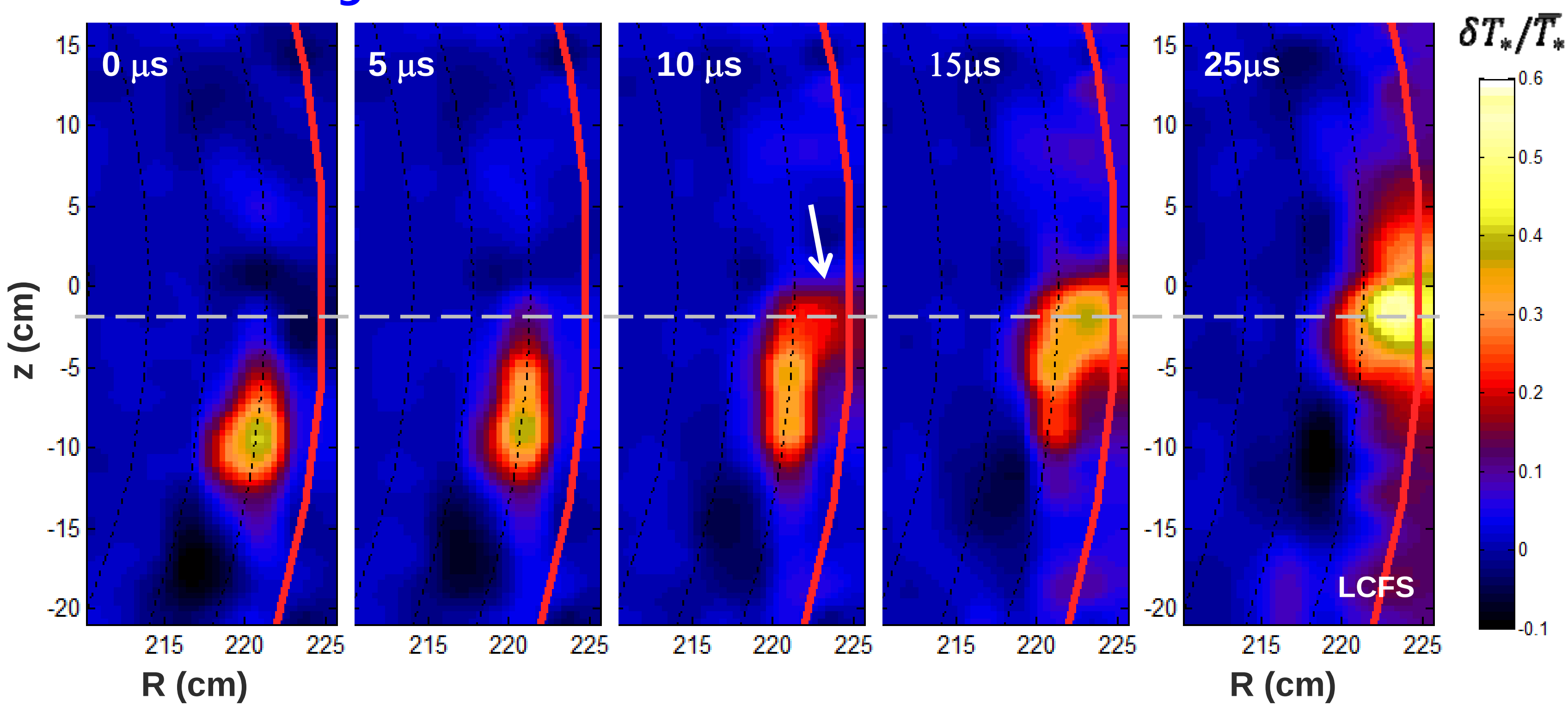


(3) Transient Period

Very short (< 50 μs) period preceding the crash. The filaments almost disappear and then re-emerge with a reduced *m*

(4) ELM Crash = Multiple bursts of the filaments

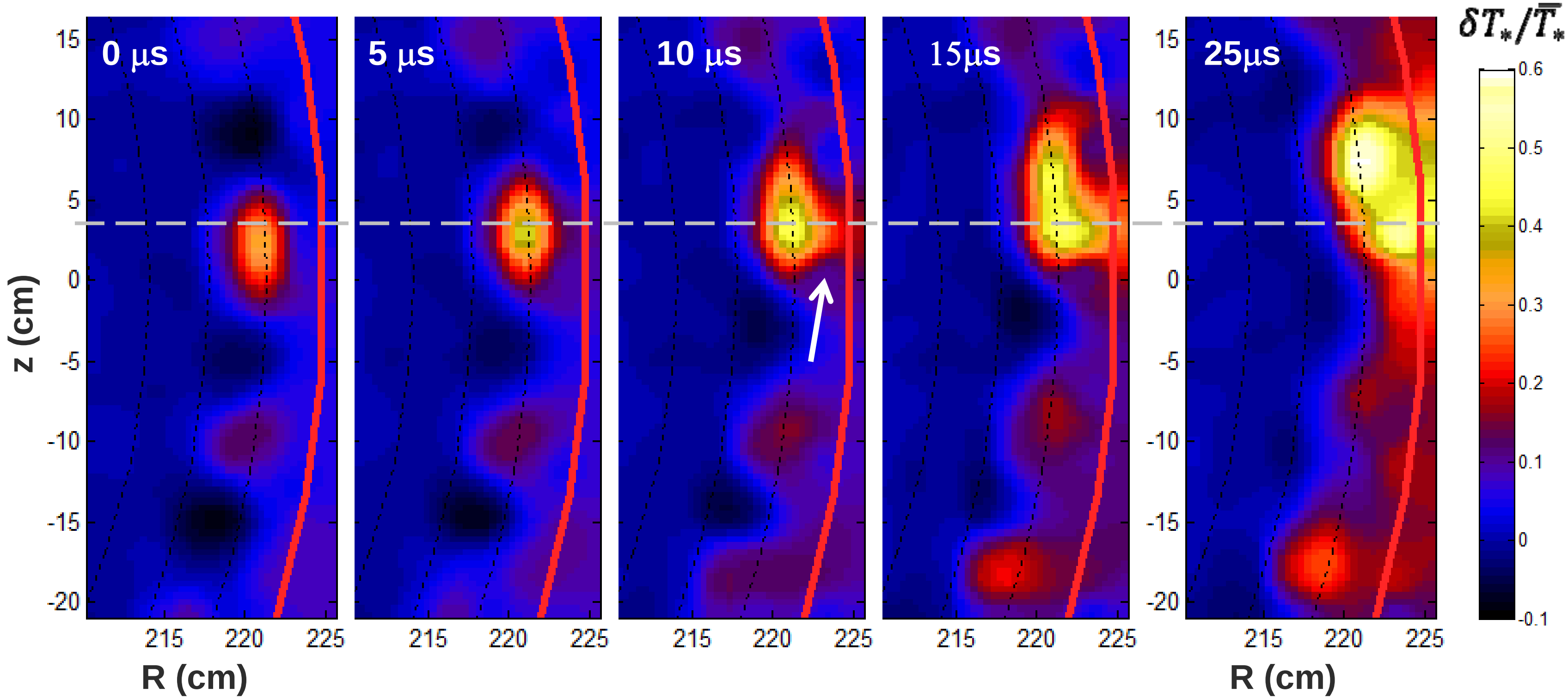
The first burst during an ELM crash event



Filaments elongate poloidally ⇨ A narrow **finger**-like structure develops ⇨ Particles/heat transport through the finger

* GS Yun et al., PRL 2011

Another burst during the same ELM crash event



- **Fast burst < 50 μs**
- **Localized burst zone** (both poloidally and toroidally)
- **Convective and localized transport**
- **Poloidal rotation of the burst point slows down** compared to the rest of the filament region.

* GS Yun et al., PRL 2011

Edge Localised Mode (ELM)

- **Type of ELMs**

- Several types with different amplitudes, frequencies and power dependencies
- At least three major types of ELMs have been defined.
- In a given experiment, the level of the plasma heating power, P, or, more directly, the net power reaching the plasma edge $P_{edge} = P - P_{rad}$ is a key factor in determining the ELM type.

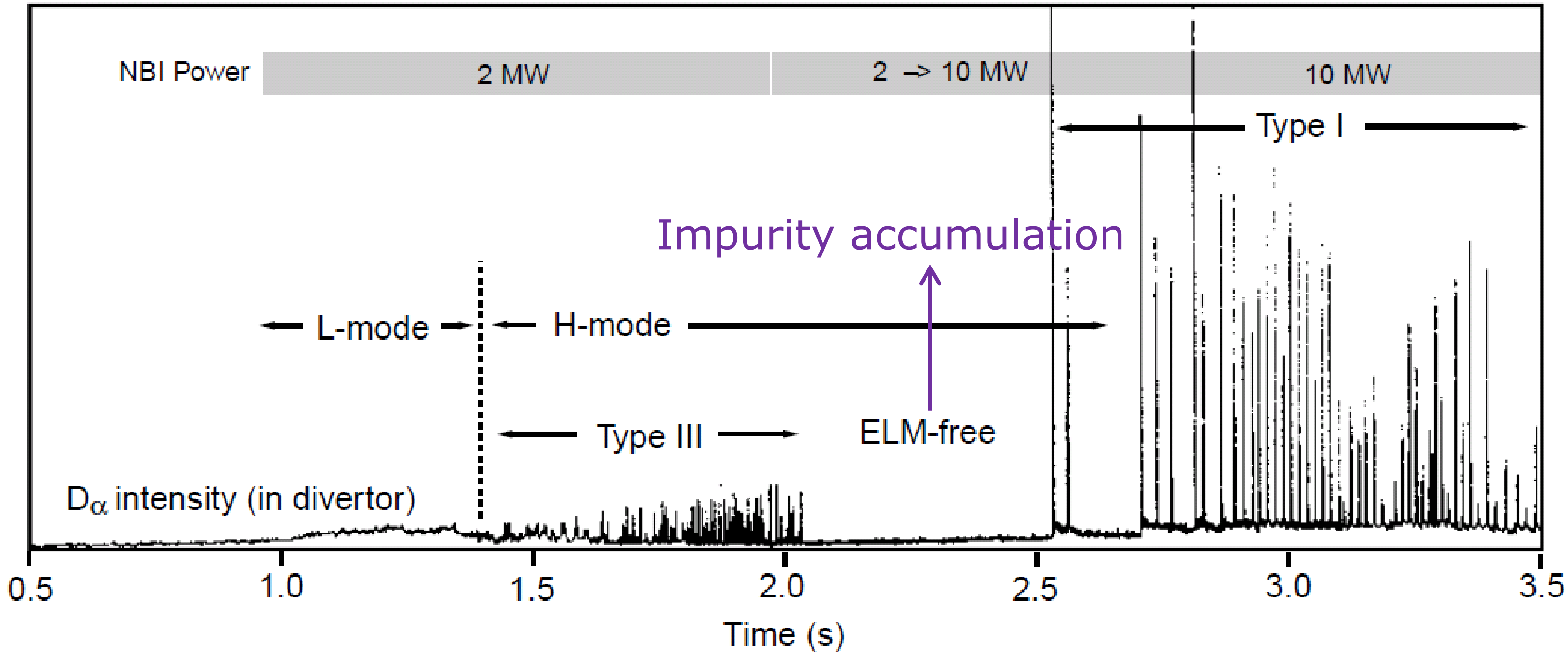
Edge Localised Mode (ELM)

- **Type of ELMs**

- ‘dithering' ELMs: For heating input or edge power levels at the corresponding L-H transition threshold. These are believed to be transitions back and forth between L-mode and H-mode.
- Type III (or ‘small’): small amplitude, high frequency, occurring when the flow of power to the plasma edge is only a little above the L-H transition threshold. Their frequency decreases with power.
- ELM free: instabilities absent. As the power increases further, the type III ELMs tend to disappear and an ELM free H-mode may be encountered. Sometimes leading to the accumulation of heavy impurities in the central region of plasma
- Type I (sometimes called ‘giant’): high amplitude, low frequency when the power flow substantially exceeds the threshold. Their frequency increases with increasing power.

Edge Localised Mode (ELM)

- **Type of ELMs**

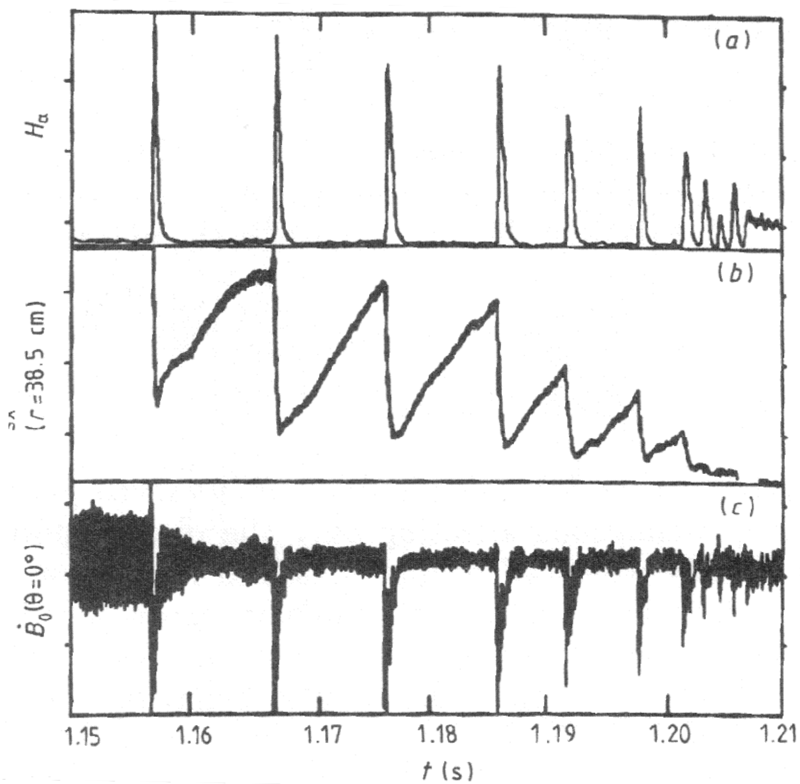


- Divertor region D_a intensity in a typical DIII-D plasma with slowly increasing NBI power
- Low amplitude type III ELMs appear after the L-H transition, when low NBI power is applied, and disappear as power is slowly increased.
- Larger type I ELMs with increasing frequency appear at high power.

*ITER Physics Basis, Nuclear Fusion **39** 2295 (1999)*

Edge Localised Mode (ELM)

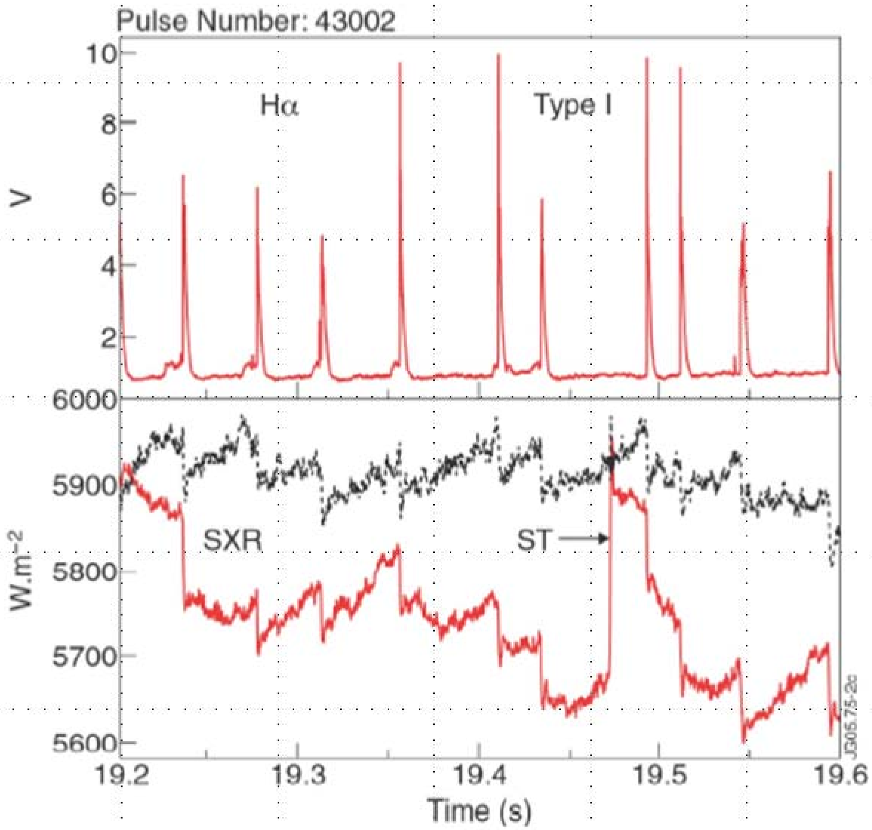
- **Type of ELMs**

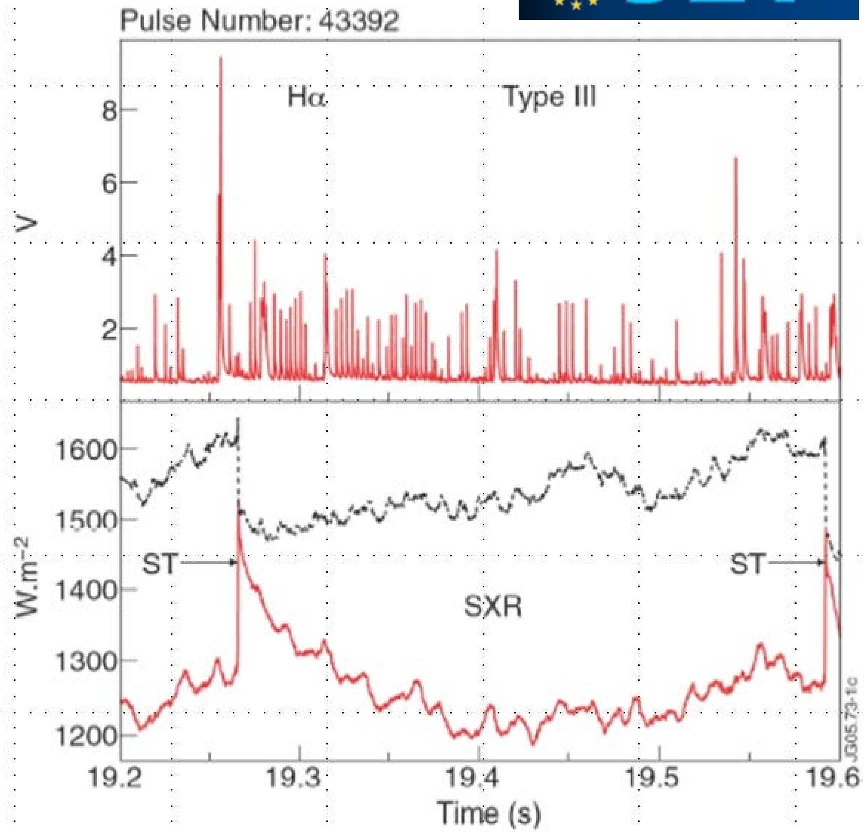


- During the H-L transition phase
- Frequency of relaxation oscillations grows gradually, the amplitude decays, and towards the end of the ELM a transition from H- to L-mode confinement occurs.

Edge Localised Mode (ELM)

- **Type of ELMs**



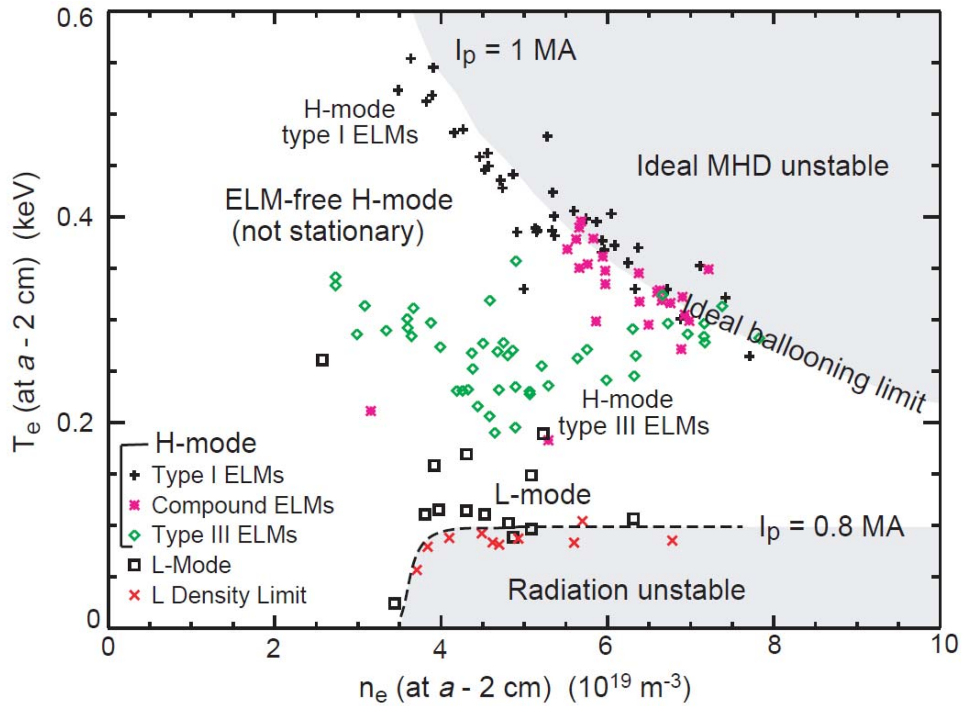


- **Type I:** „Large" ELMs
– low frequency which rises with input power with significant effect (lowering) of ETB pressure.

- **Type III:** „Small" ELMs
– high frequency with little or no effect on height of (ETB)

Edge Localised Mode (ELM)

- **Type of ELMs:** H-mode operational diagram

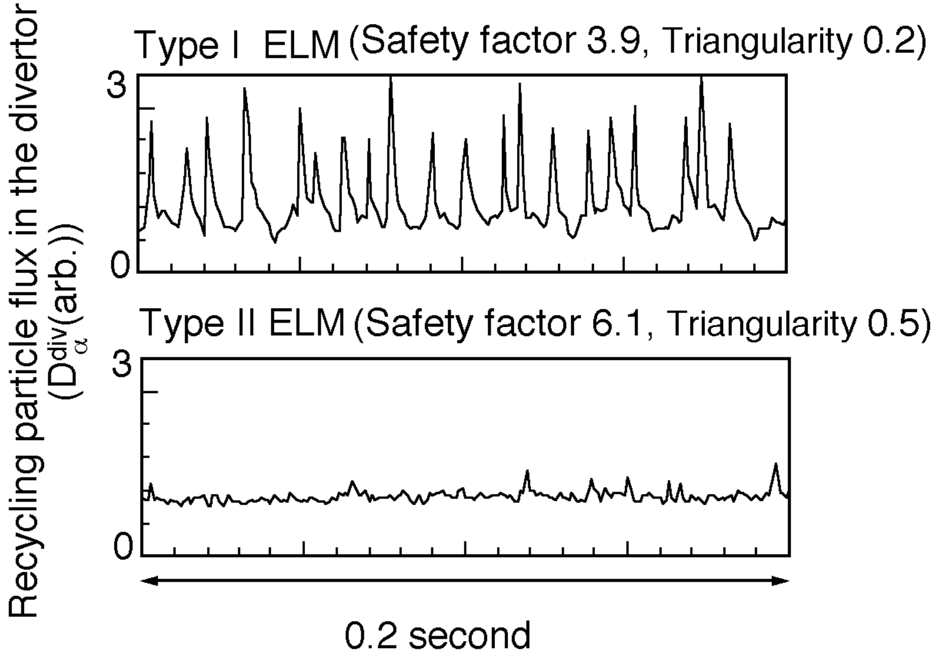


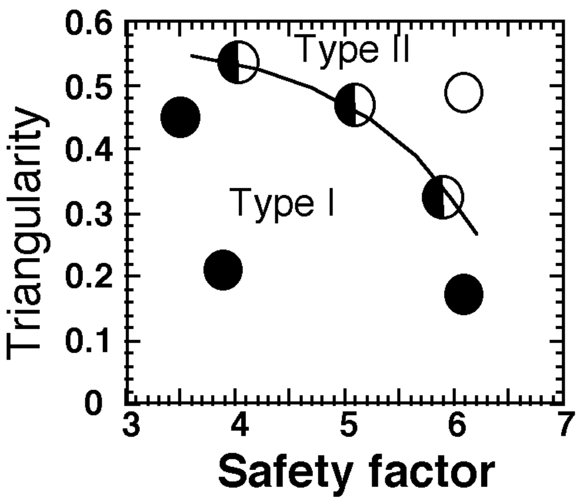
Measured data at 2 cm inside the separatrix (corresponding to the top of the H-mode pedestal)

- Boundaries indicating different types of confinement regime marked
- The limiting bound of edge pressure (*nT*) corresponds closely to the predicted ∇p for onset of ideal MHD ballooning limit for type I ELMs.
- Discharges can sit at the ballooning limit for some time before an ELM occurs → suggesting the need for an additional trigger, such as a low-*n* edge localized 'peeling' mode.

Edge Localised Mode (ELM)

- **Type II (or ‘grassy’) ELMs**



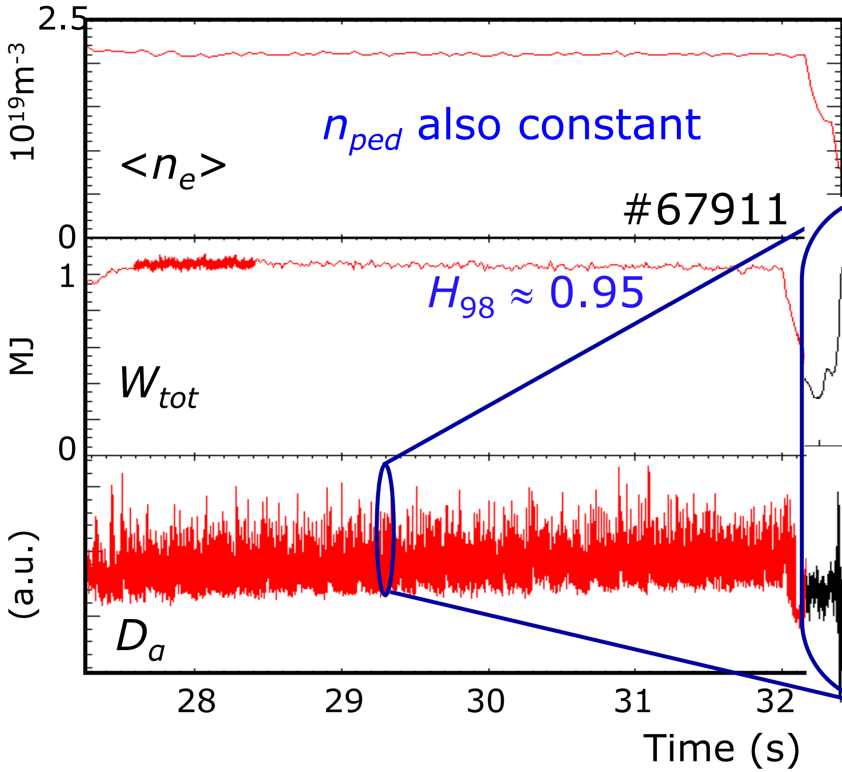


- confinement not degraded, relatively small impurity accumulation, lower heat load on divertor
- associated with strongly shaped tokamaks at high edge pressure when there is access to 2nd stability at the plasma edge.
- High values of the parameter s/q^2 in the plasma edge appear to be the principal factor in determining the onset of type II ELMs.

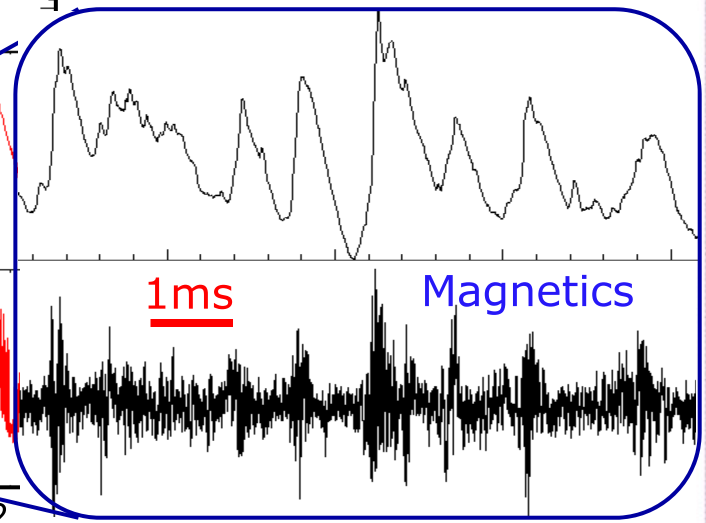
JT-60U

Edge Localised Mode (ELM)

- **Type II (or 'grassy') ELMs**

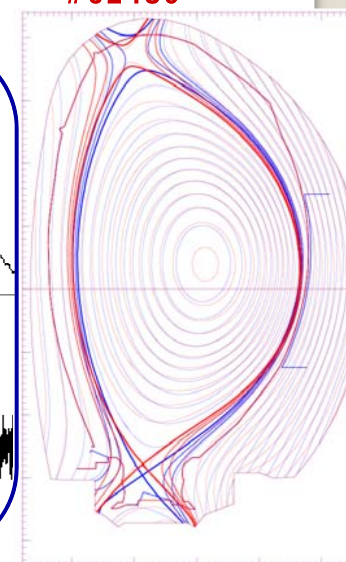


Turbulent magnetic fluctuations coincide with D_a bursts



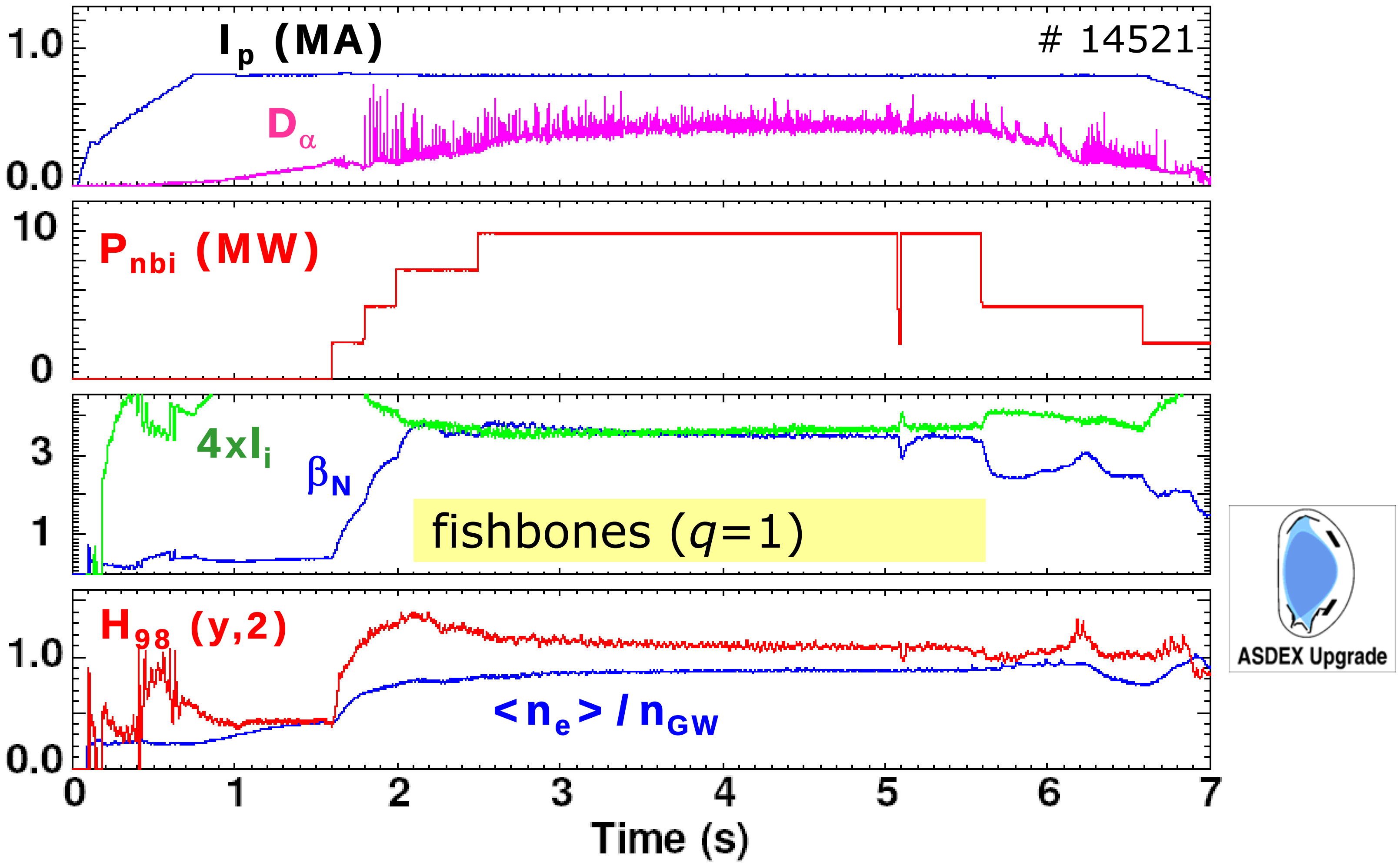
Blue: New #66476

Red:Previous experiment #62430



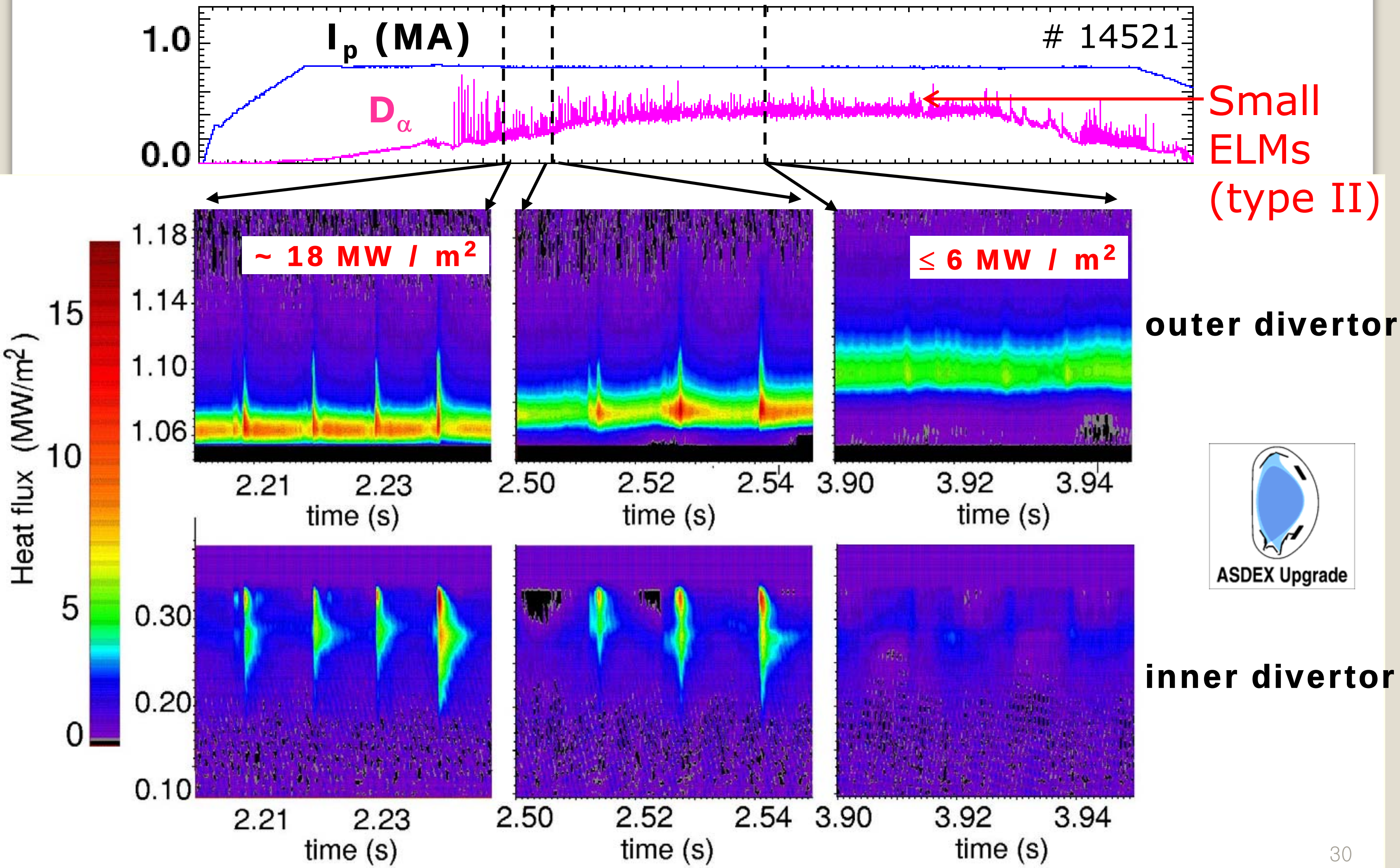
- ELM behaviour constant over pulse
- Very fine scale activity: distinct ELMs almost indistinguishable

Edge Localised Mode (ELM)



- No sawteeth, good confinement, and $\beta_N \sim 3.5$, $T_i \sim T_e$, $\langle n_e \rangle / n_{GW} \sim 0.88$, averaged over 3.6 seconds ($\sim 50\ \tau_E$).

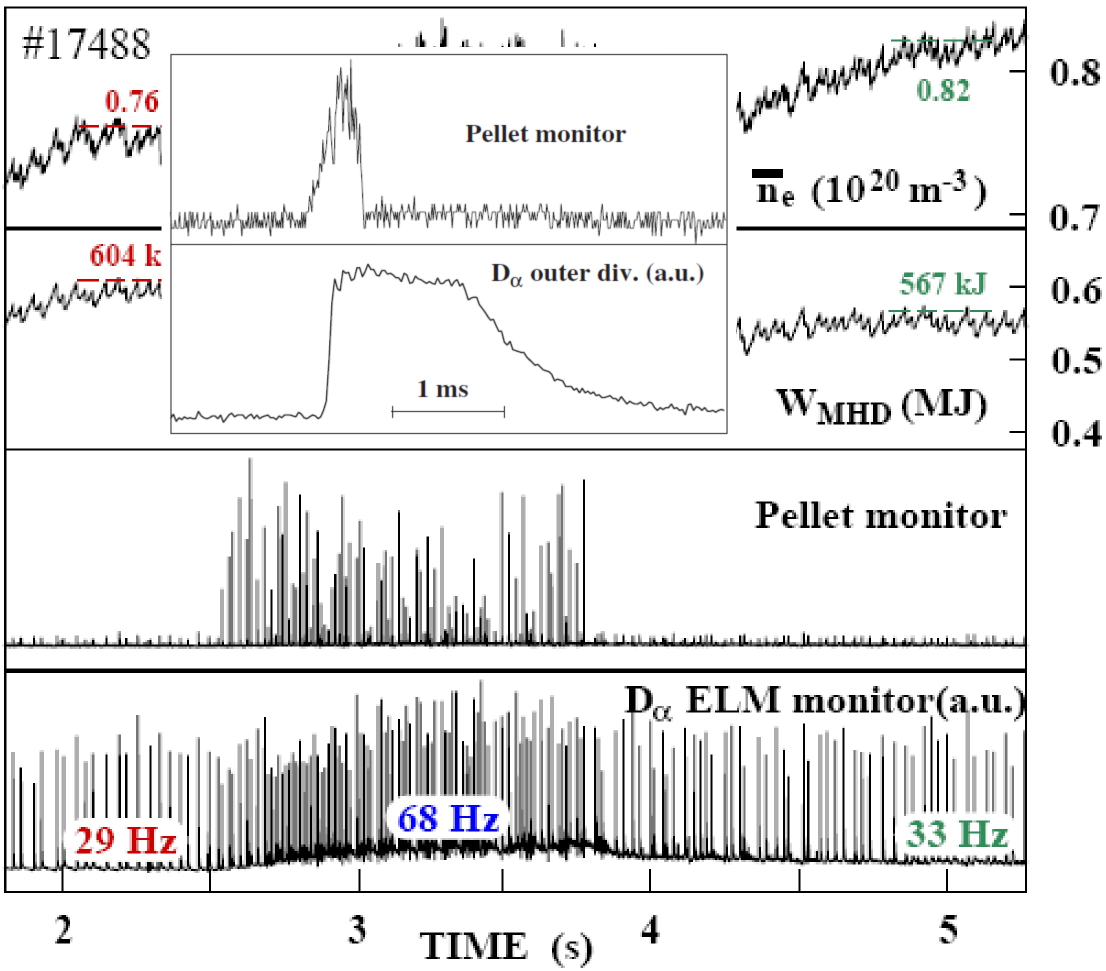
Edge Localised Mode (ELM)

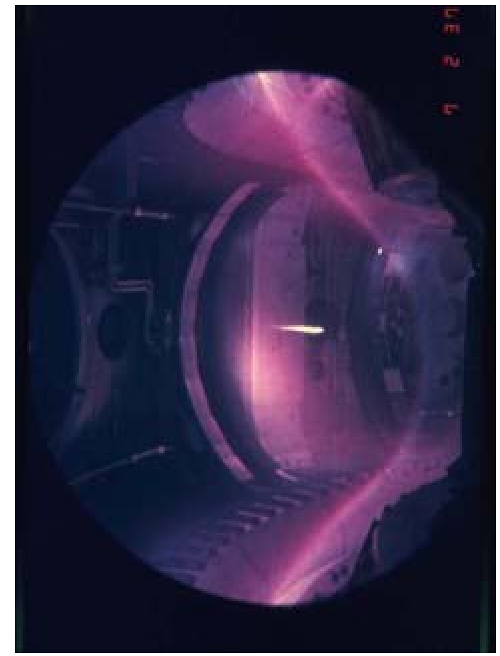


Edge Localised Mode (ELM)

ASDEX Upgrade

- **Control of ELMs: Pellet pace making**





*1st Paper: P. T. Lang et al, Nuclear Fusion **43** 1110 (2003)*

Edge Localised Mode (ELM)

- **Control of ELMs: RMP (Resonant Magnetic Perturbation)**

Published online: 21 May 2006; doi:10.1038/nphys312

Edge stability and transpc resonant magnetic pertur collisionless tokamak plas

TODD E. EVANS[1]*, RICHARD A. MOYER[2], KEITH H. BURRELL[1], ILON JOSEPH[2], ANTHONY W. LEONARD[1], THOMAS H. OSBORN MICHAEL J. SCHAFFER[1], PHILIP B. SNYDER[1], PAUL R. THOMA AND WILLIAM P. WEST[1]

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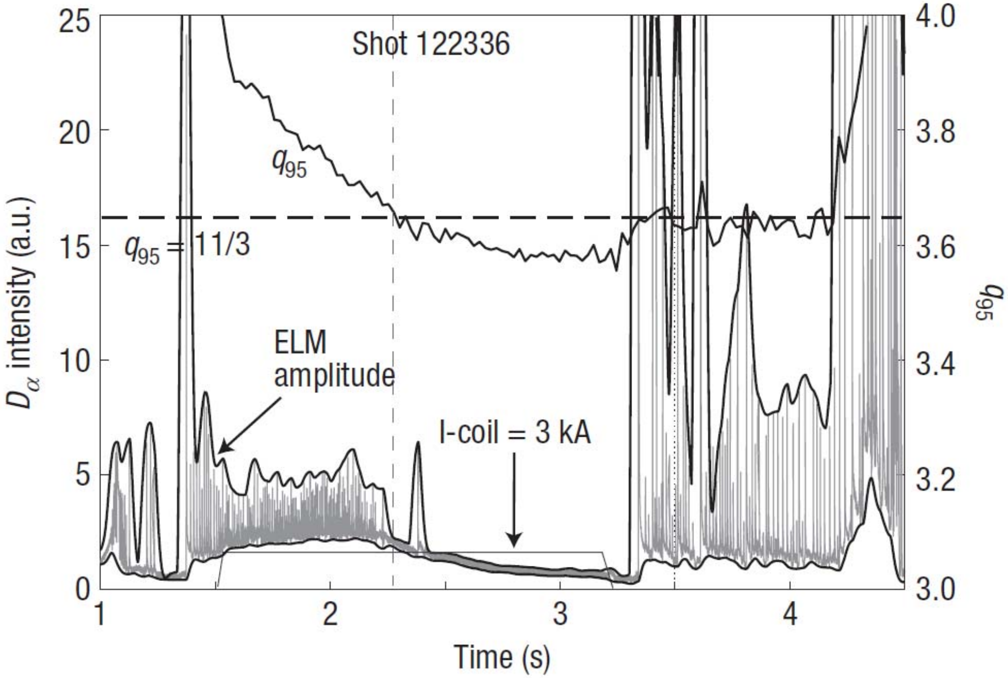
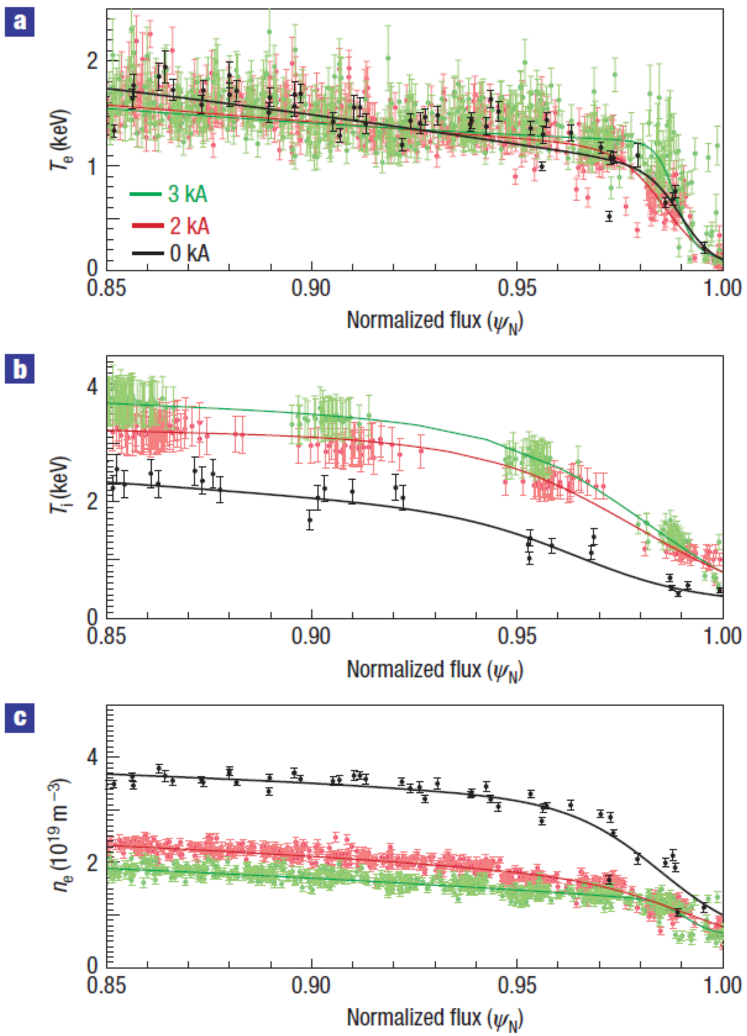
*e-mail: evans@fusion.gat.com

A critical issue for fusion-plasma research is the erosion of the first wall of the experimental device due to impulsive heating from repetitive edge magneto-hydrodynamic instabilities known as 'edge-localized modes' (ELMs). Here, we show that the addition of small resonant magnetic field perturbations completely eliminates ELMs while maintaining a steady-state high-confinement (H-mode) plasma. These perturbations induce a chaotic behaviour in the magnetic field lines, which reduces the edge pressure gradient below the ELM instability threshold. The pressure gradient reduction results from a reduction in the particle content of the plasma, rather than an increase in the electron thermal transport. This is inconsistent with the predictions of stochastic electron heat transport theory. These results provide a first experimental test of stochastic transport theory in a highly rotating, hot, collisionless plasma and demonstrate a promising solution to the critical issue of controlling edge instabilities in fusion-plasma devices.

nature physics | ADVANCE ONLINE PUBLICATION | www.nature.com/naturephysics

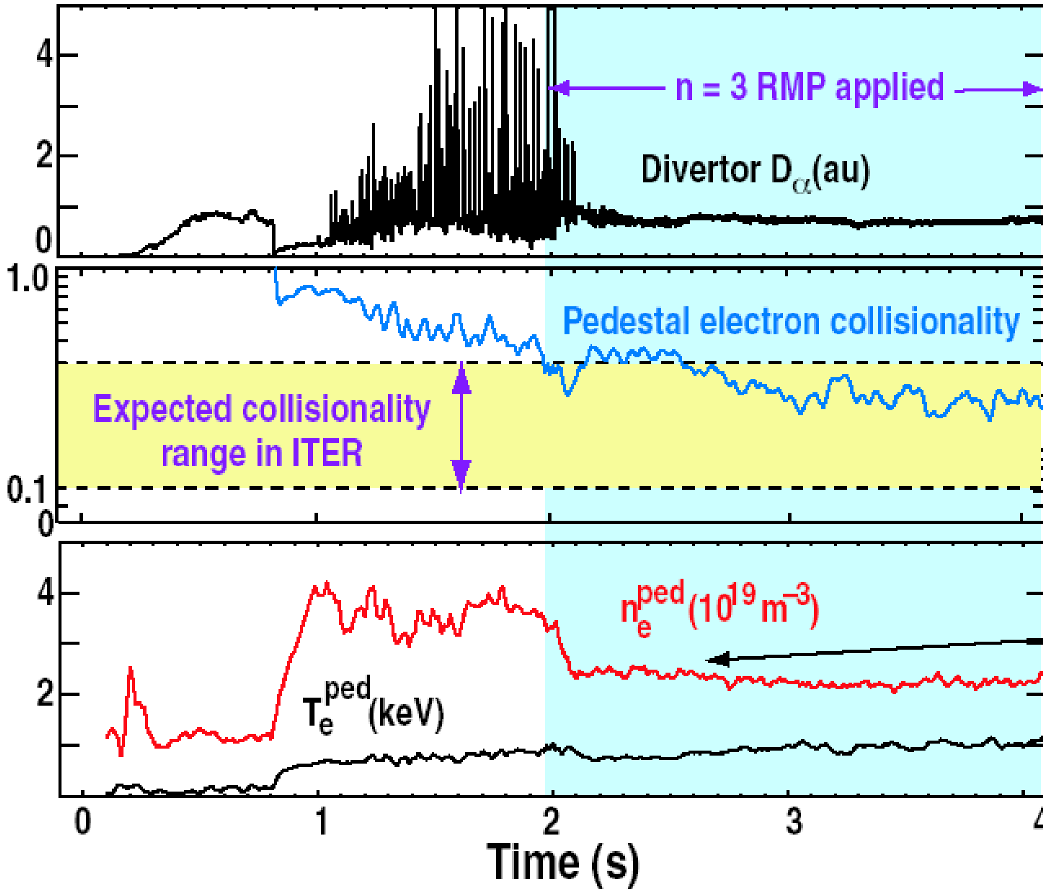
Edge Localised Mode (ELM)

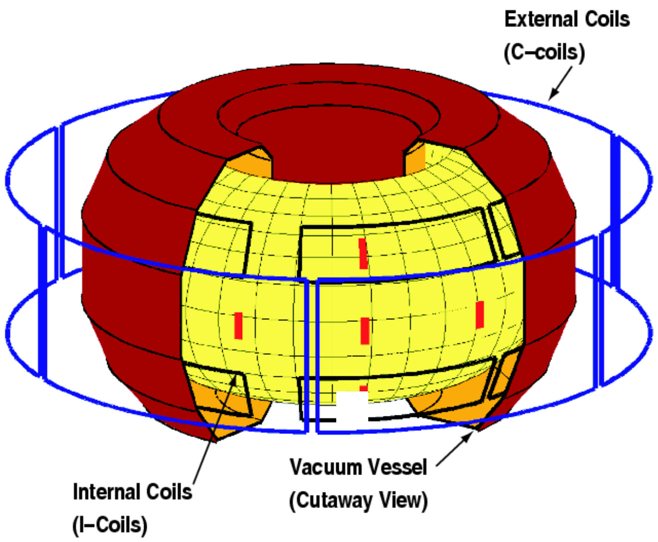




Edge Localised Mode (ELM)

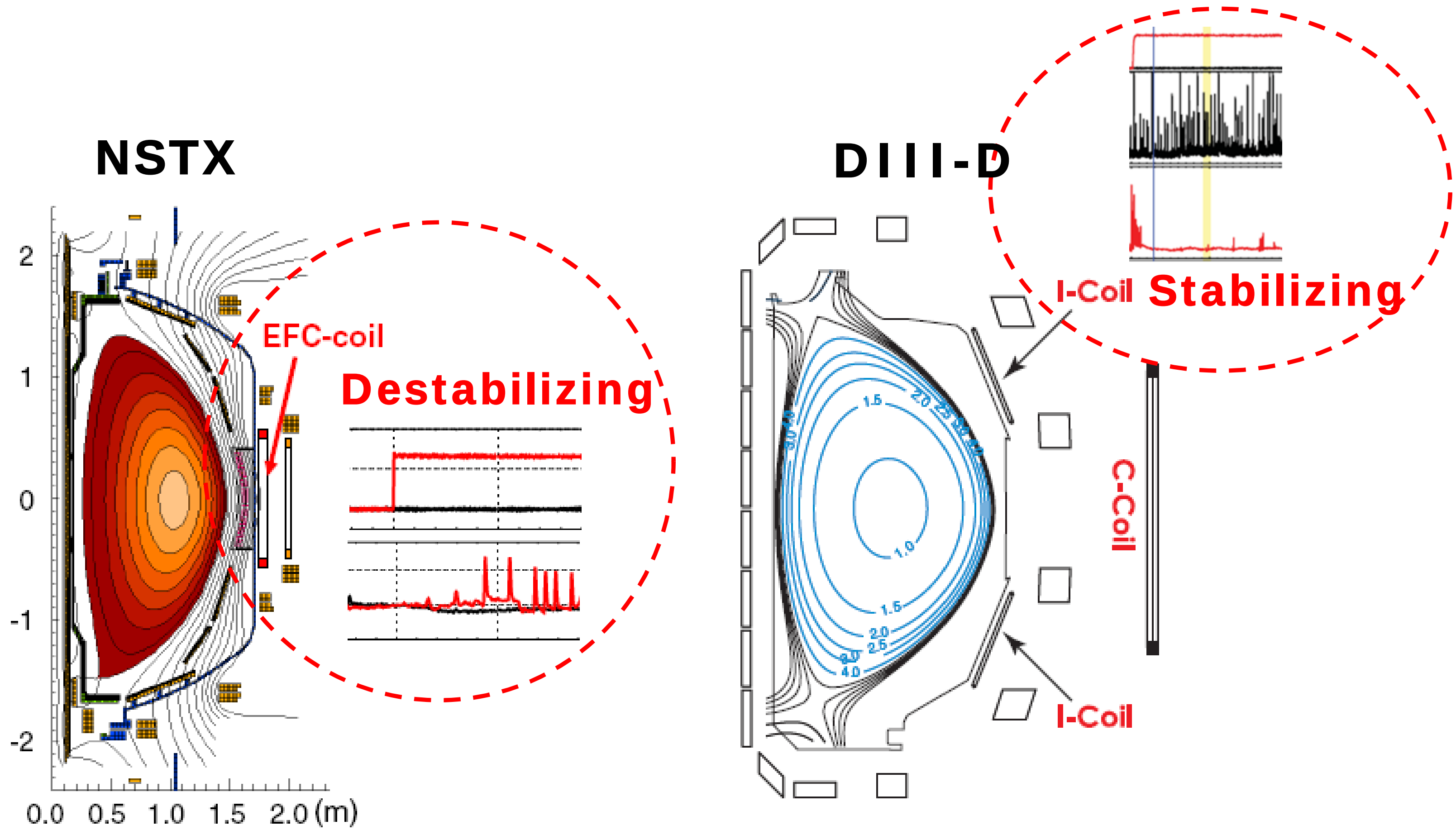
- Control of ELMs: RMP (Resonant Magnetic Perturbation)





Edge Localised Mode (ELM)

- **Control of ELMs: RMP (Resonant Magnetic Perturbation)**
- RMPs can be destabilizing and/or stabilizing



Courtesy from Jong-kyu Park (PPPL)