Fusion Reactor Technology I
(459.760, 3 Credits)

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(32-206, Tel. 880-7204)

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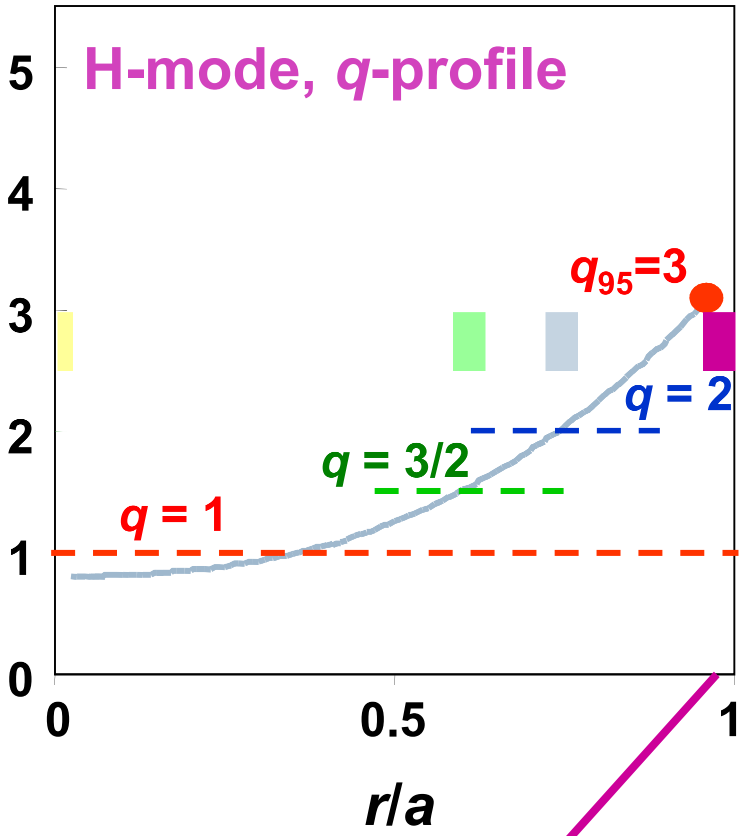
H–modes: Limitations

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 $q = 2$:

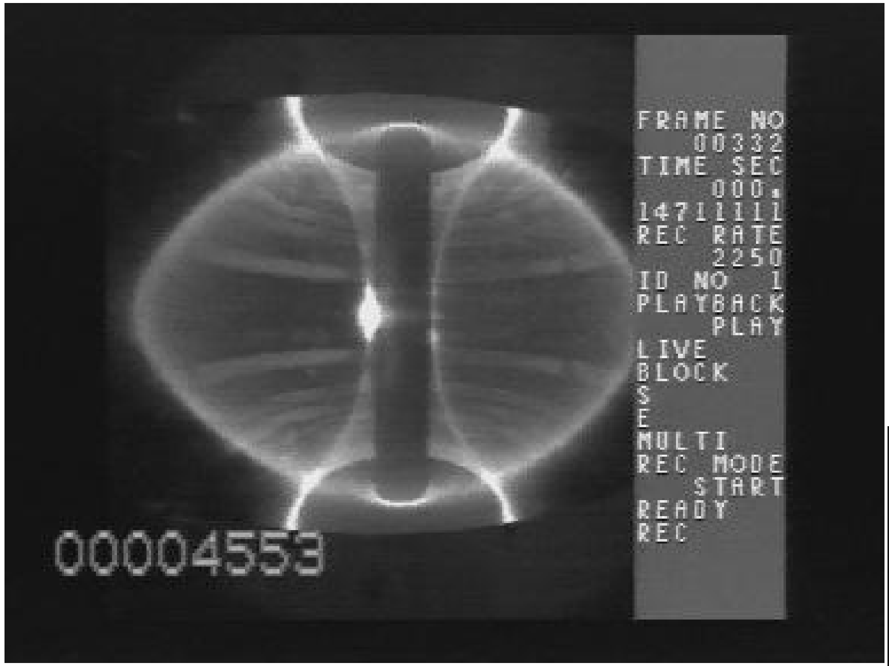
Neoclassical Tearing Modes (NTMs):

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

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

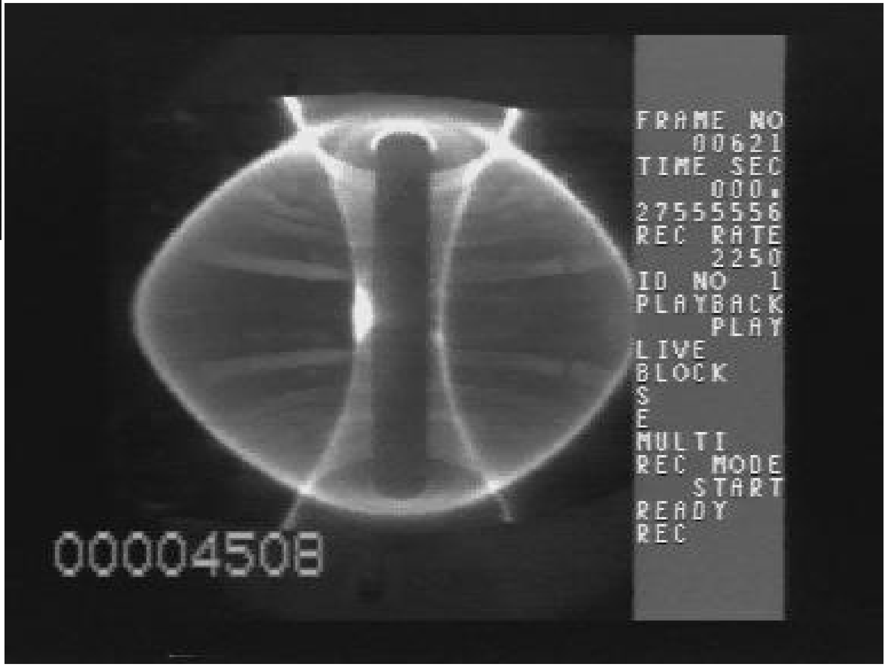
q_{95} ($\propto 1/I_p$) = 3: Safe operation at max. I_P

Edge Localised Mode (ELM)



Edge Localised Mode

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

CONFINEMENT STUDIES IN L AND H-TYPE ASDEX DISCHARGES

M. Keilhacker and G. Becker, K. Bernhardi, A. Eberhagen, M. ElShaer[1], G. Fußmann, O. Gehre, J. Gernhardt, G. v. Gierke, E. Glock, G. Haas, F.Karger, S. Kissel[2], O. Klüber, M. Kornherr, K. Lackner, G. Lisitano, G.G. Lister, J. Massig, H.-M. Mayer, K. McCormick, D. Meisel, E. Meservey[3], E.R. Müller, H. Murmann, H. Niedermeyer, W. Poschenrieder, H. Rapp, B. Richter, H. Röhr, F. Ryter[1], F. Schneider, G. Siller, P. Smeulders, F. Söldner, E. Speth, A. Stäbler, K. Steinmetz, K.-H. Steuer, Z. Szymanski[4], G. Venus, O. Vollmer, F. Wagner

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EURATOM Association, D-8046 Garching

ABSTRACT

The characteristics of neutral-beam-heated ASDEX discharges exhibiting either low (L)- or high (H)-confinement are described. H-mode discharges, which are by now observed over a wide range of operating conditions, show a spontaneous improvement in particle and energy confinement after a short L-phase at the beginning of neutral injection. H-discharges yield high β_p values comparable to the aspect ratio A ($\beta_p \leq 2.65 \sim 0.65$ A). The most important parameter for transition to the H-mode seems to be a high edge electron temperature: T_e values of ~600 eV only a few centimeters inside the separatrix with radial gradients of ~300 eV/cm are measured. This requirement of high edge temperatures explains the lack of success in obtaining the H-regime in limiter discharges. Numerical simulation of the broad n_e and T_e profiles typical of H-mode plasmas indicates a reduction in electron thermal 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)

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).

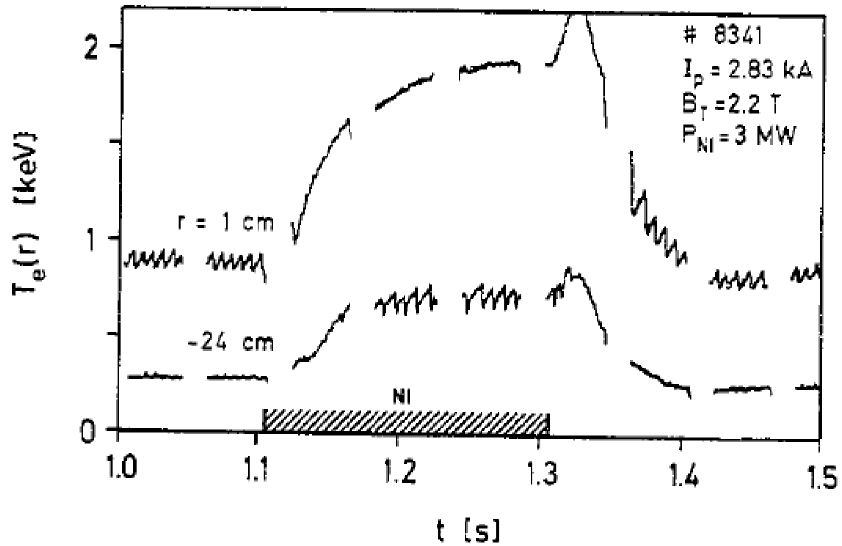
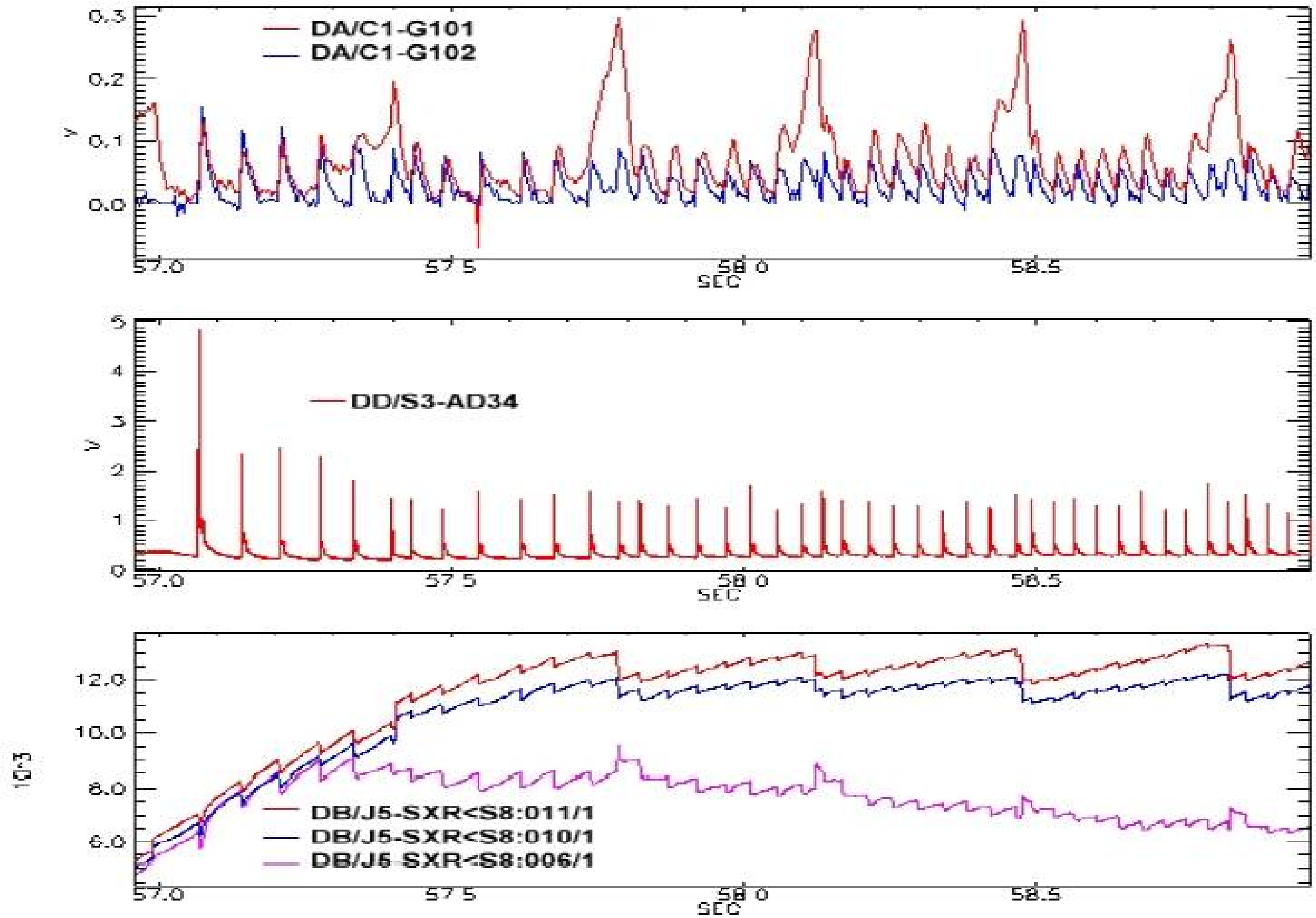


Fig. 11 ECE-measured electron temperature T_e at the plasma centre (r = 1 cm) and half-way to the edge (r = -24 cm) showing that the bursts observed during the H-phase are localized in the outer part of the plasma.

Edge Localised Mode (ELM)

- **Example of sawteeth and ELMs**

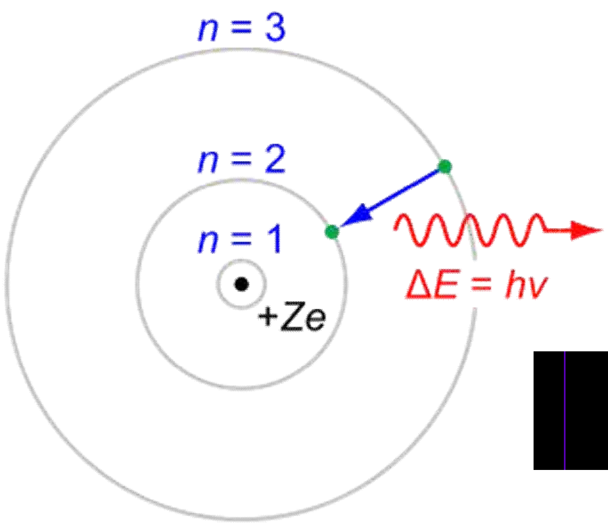
JET, Pulse 52022



EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT

JET

Edge Localised Mode (ELM)

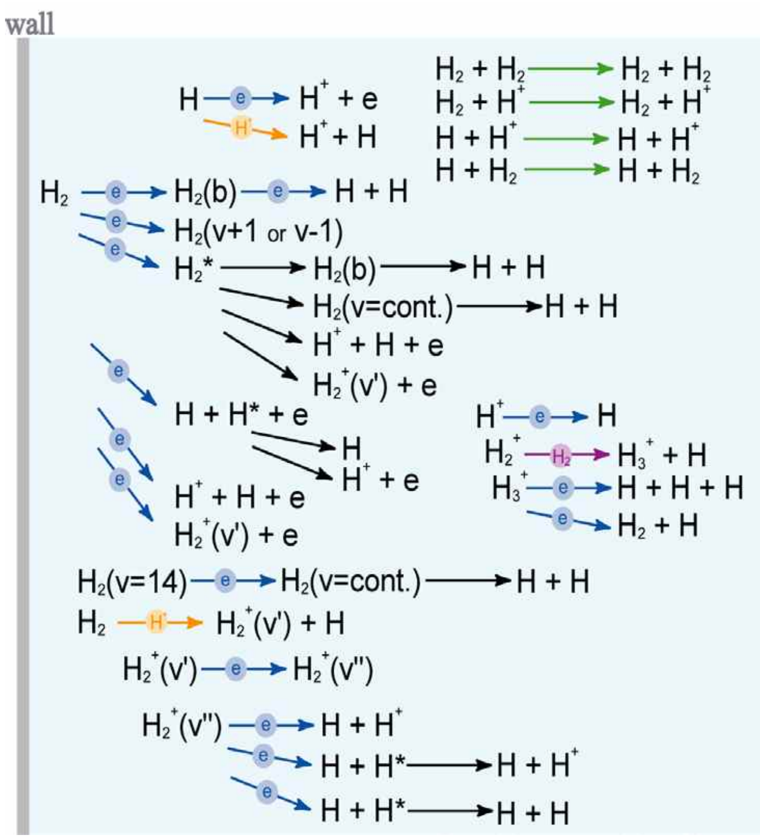


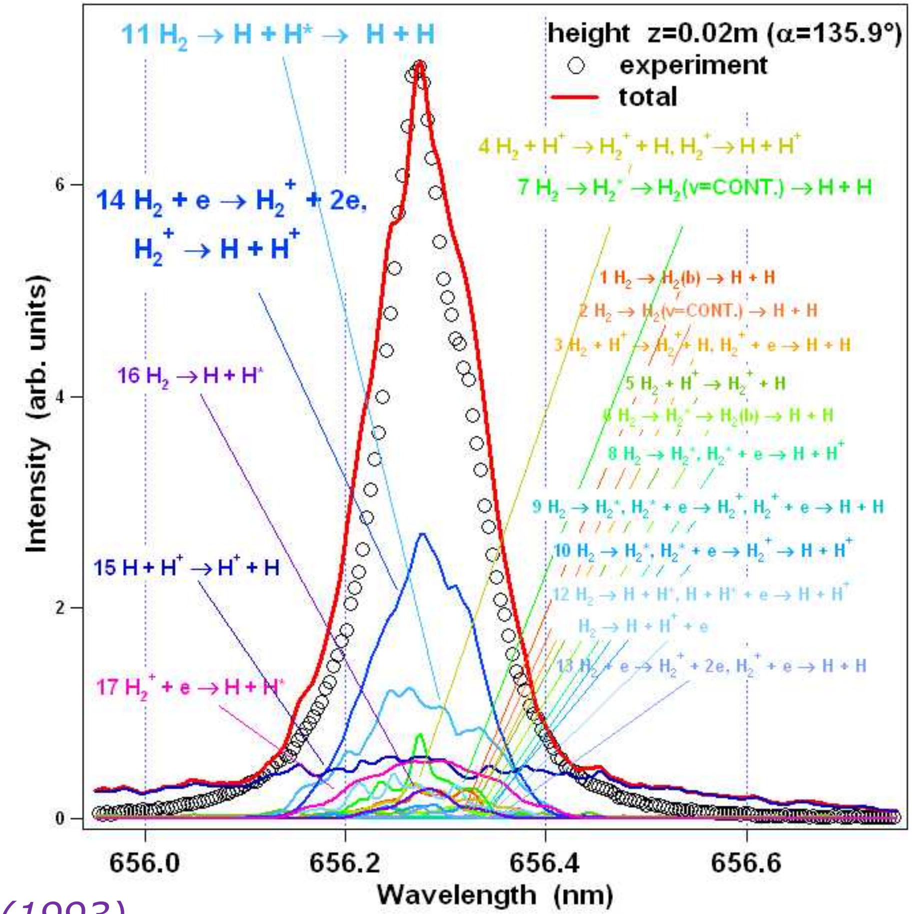
- H(or Balmer)-alpha (H_α) is a specific red visible spectral line created by hydrogen with a wavelength of 656.28 nm, which occurs when a hydrogen electron falls from its third to second lowest energy level.
- It is difficult for humans to see H-alpha at night, but due to the abundance of hydrogen in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

Molecular effects on H Balmer line intensity





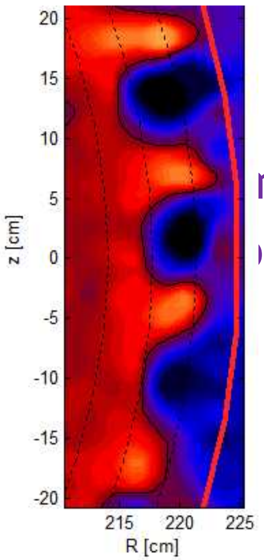
K. Sawada et al. J. Appl. Phys. ***73*** *8122 (1993)*
K. Sawada, T. Fujimoto, J. Appl. Phys. ***78*** *2913 (1995)*
H.-K. Chung, SNU seminar (2013)

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)

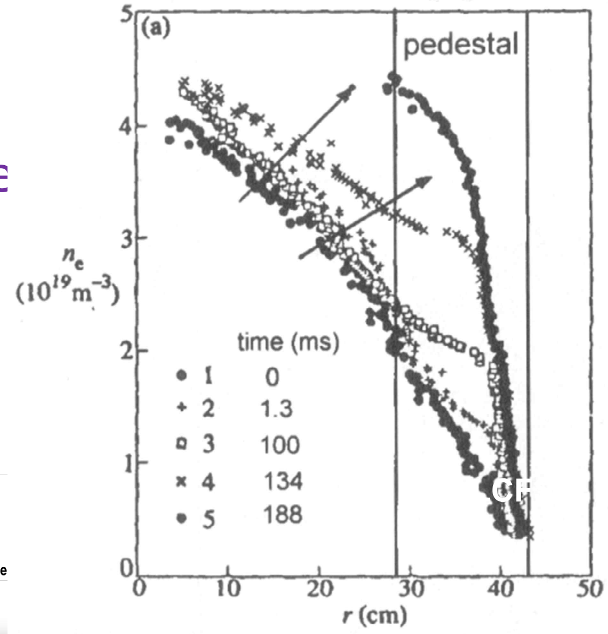


- **Edge Localised Modes (ELMs)**

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

→ Plasma particles and energy are expelled, and the en
  recycling increases D_a 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 FPDS²O ASDEX Upgrade

Structure and Phase of ELMs

Phase of the ELMs

Precursor *(200-500us)*
coherent density precursor (5-25 kHz)
Collapse *(100-350us)*
collapse of density pedestal
Recovery *(200-500us)*
recovery of density pedestal
overshoot due to divertor recycling
Relaxation *(6-10ms)*

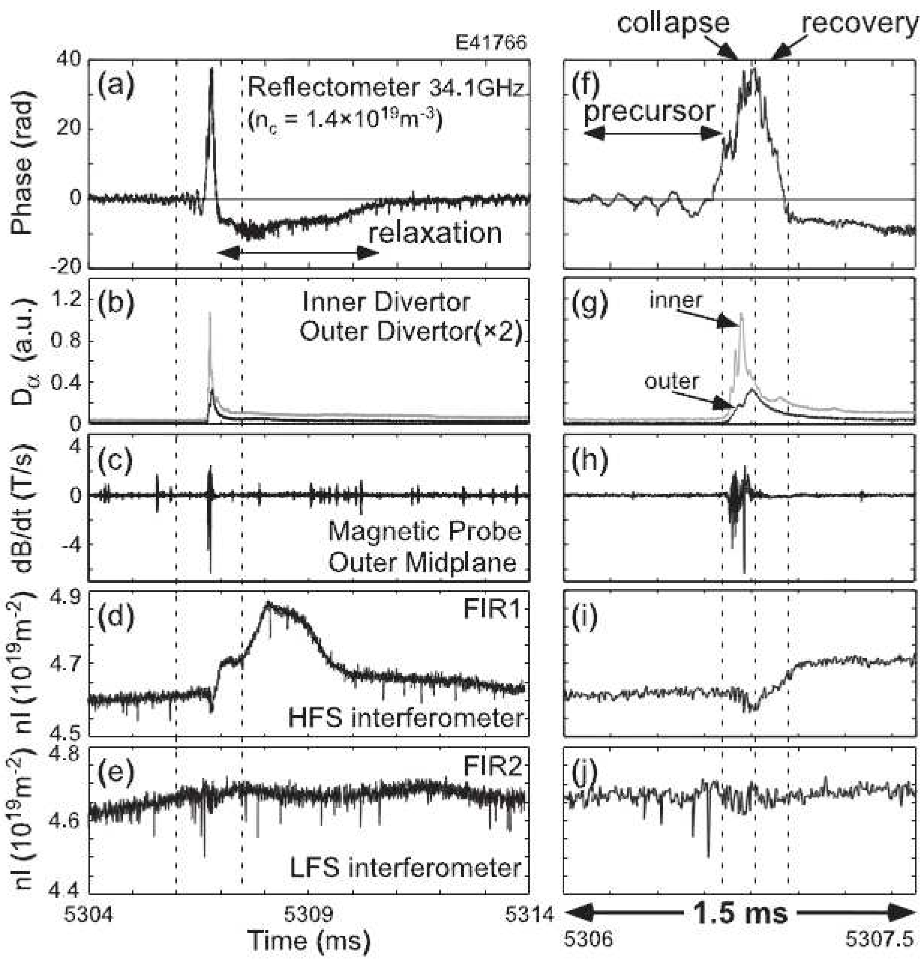


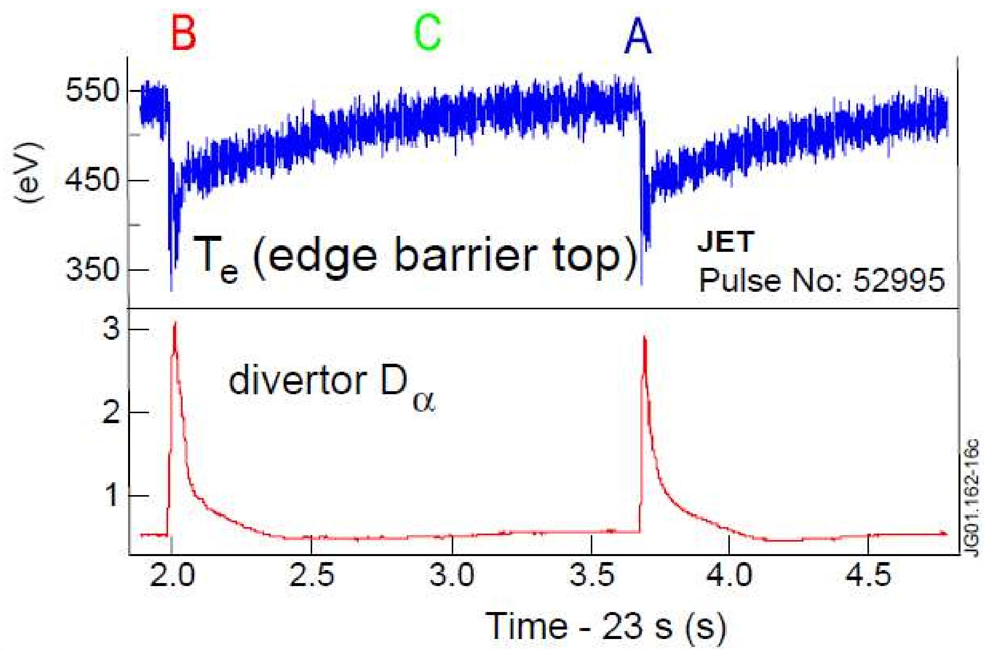
Figure 2. Waveforms of (*a*) phase change of the reflectometer signal, (*b*) D_α intensity at the inner (grey) and outer (black) divertors, (*c*) magnetic fluctuation at the outer midplane, (*d*) and (*e*) line-integrated density at the HFS and LFS, respectively. (*f*)–(*j*) show the magnified waveforms corresponding to the region between the two dotted lines on the left-hand side figures for a 1.5 ms time window. The sampling time of the reflectometer, D_α intensity and magnetic probe is 1 μs, and that of the interferometer is 5 μs. All diagnostics are synchronized within 5 μs.

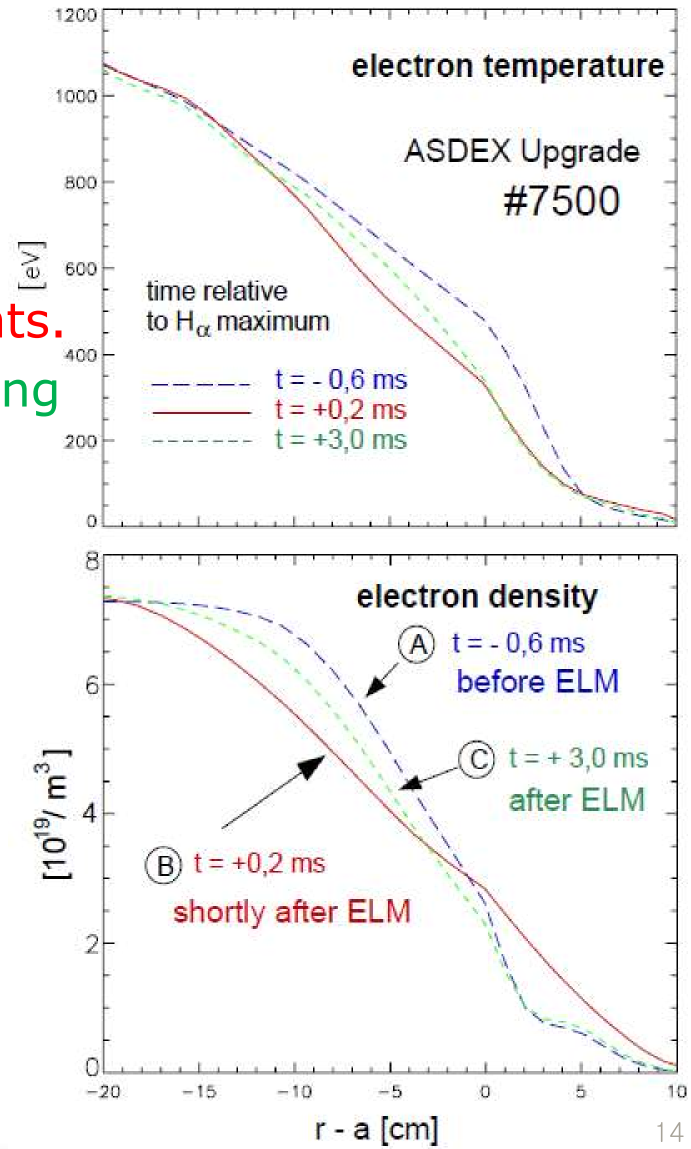
* N. Oyama, Nuclear Fusion, 2004

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.





Precursors of ELMs

Precursors of ELMs

Characteristics

frequency: < 25 kHz
duration: ~ 1 ms (until ~ 0.2 ms before crash)
propagation: ion diamagnetic drift
localization: in the pedestal (1 – 1.5 cm)
toroidal mode number: 1 ~ 13

ELM Triggering

not strongly related with ELM triggering
absent in high collisionality discharges

* C. P. Perez, Nuclear Fusion, 2004

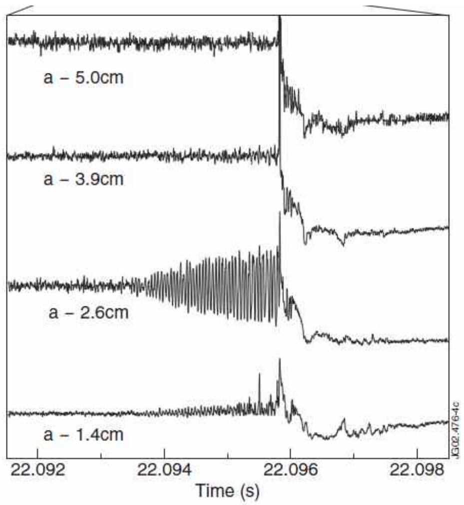


Figure 4. Edge ECE signals together with the distance of the measurement radii to the separatrix as calculated by EFIT. The second picture shows a zoom of the shorter precursor prior to the first ELM.

* N. Oyama, Nuclear Fusion, 2011

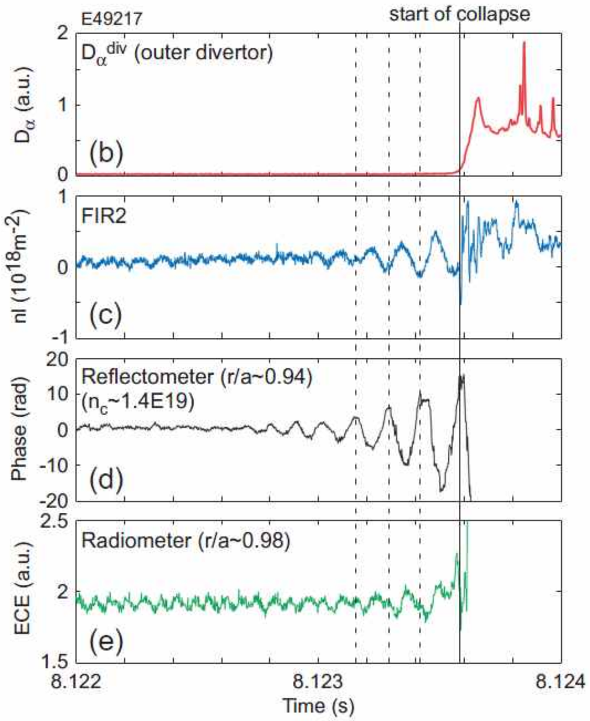
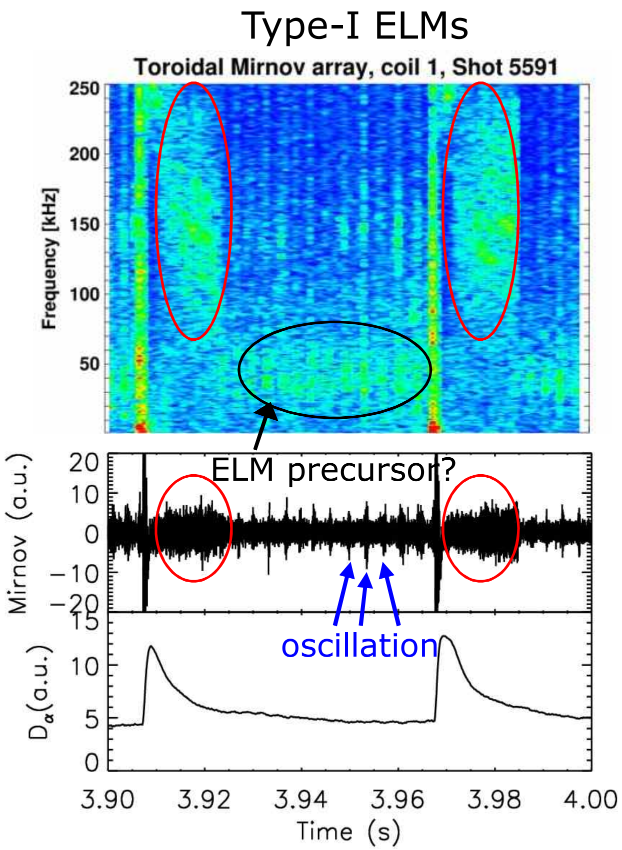


Figure 1. (*a*) Plasma configuration for ELM precursor measurement together with the line of sight of two FIR interferometers, D_α intensity, reflectometer and measured location of ECE radiometer. Waveforms of (*b*) D_α intensity at outer divertor, (*c*) line-integrated density, (*d*) phase change of reflectometer signal and (*e*) ECE intensity of radiometer.

Edge Localised Mode (ELM)

- **Example of ELM precursor**



KSTAR

J-W. Ahn, et al, NF ***52*** *114001 (2012)*

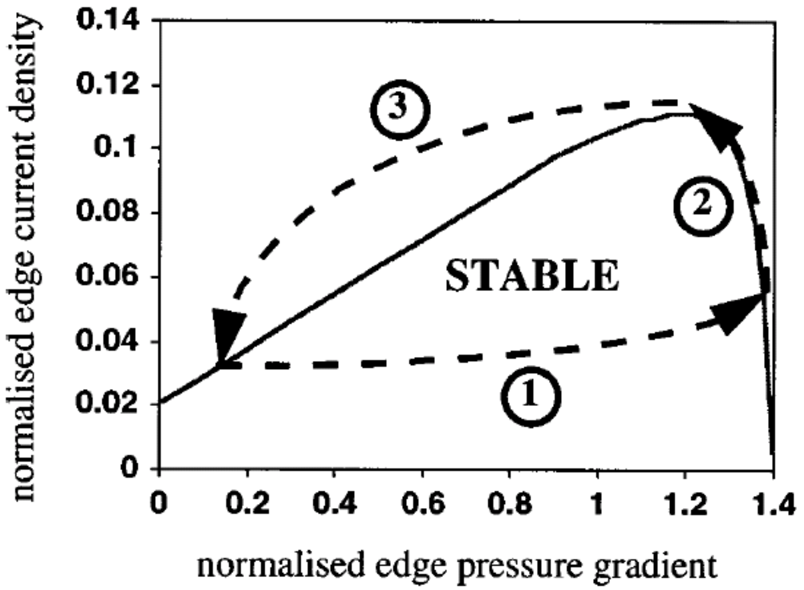
Edge Localised Mode (ELM)

- **ELM Oscillations**

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

Edge Localised Mode (ELM)

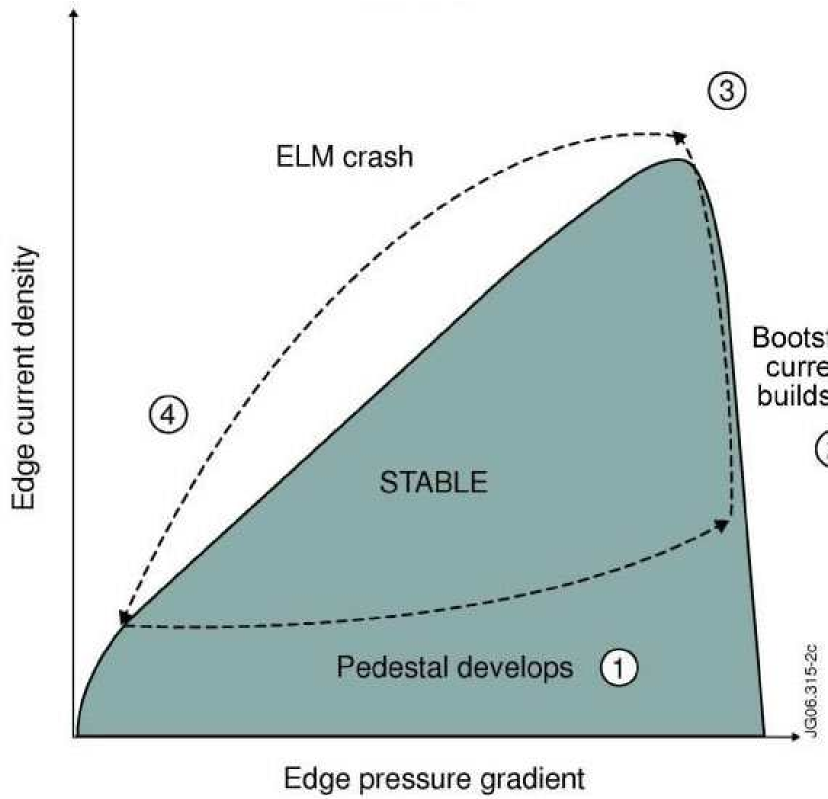
- **Peeling-Ballooning model for ELM cycle**



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

Edge Localised Mode (ELM)

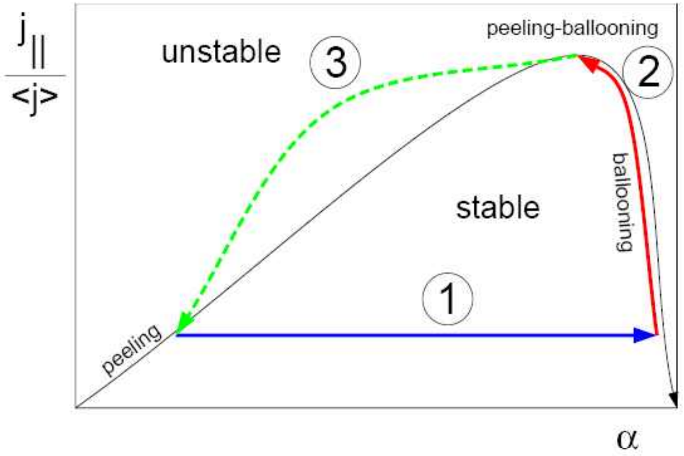
- **Peeling-Ballooning model for ELM cycle**



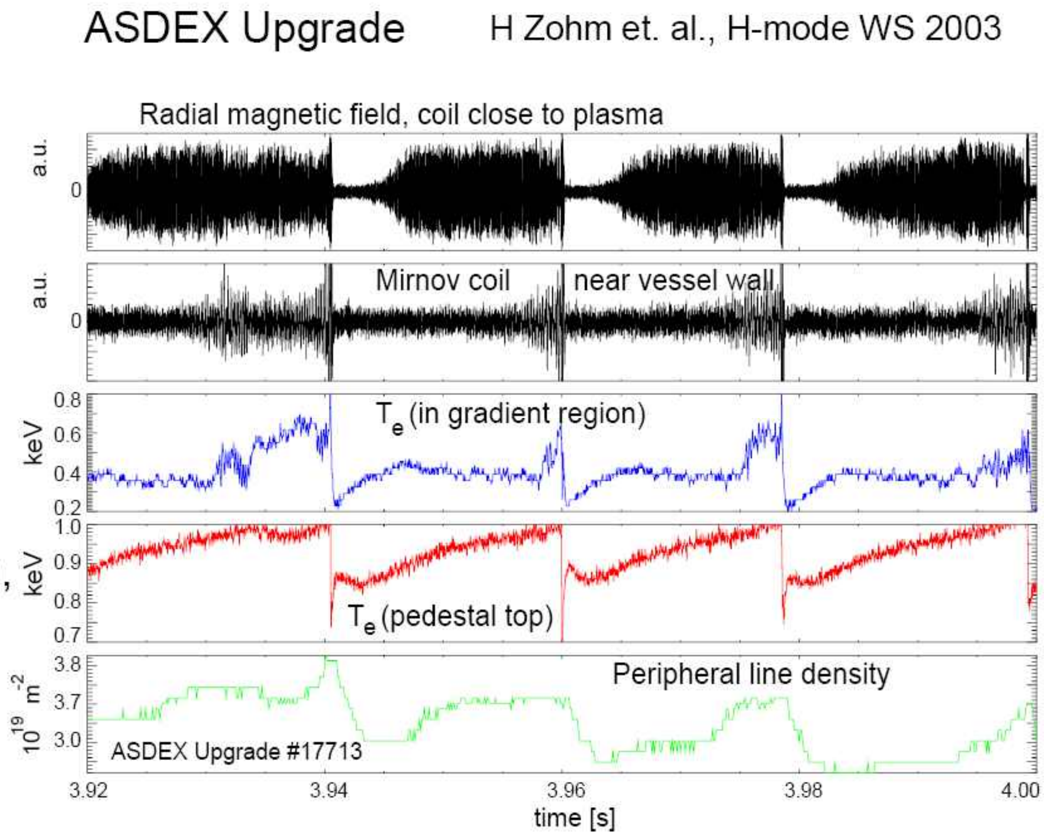
- The ELM cycle starts with a low pressure gradient as a result of the previous ELM crash that has removed the edge pressure "pedestal".
- Due to the edge transport barrier, the edge pressure pedestal develops quickly (1).
- The growth of the pedestal stops at the so called "ballooning stability" limit (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**



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



$$\alpha = -\frac{2\mu_0 r^2 p'}{R_0 B_\theta^2} = -\frac{r^2 B_0^2}{R_0^2 B_\theta^2} \cdot R_0 \cdot \frac{p'}{B_0^2 / 2\mu_0} = -q^2 R_0 \beta'$$

measure of the pressure gradient

Edge Localised Mode (ELM)

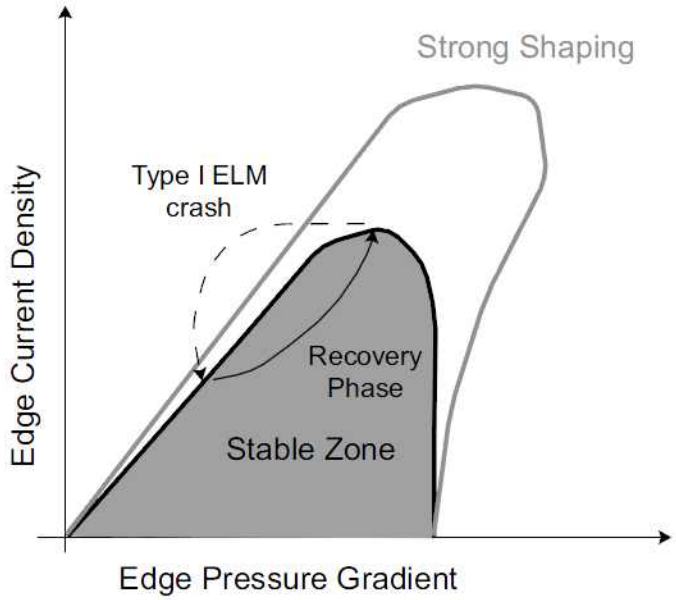
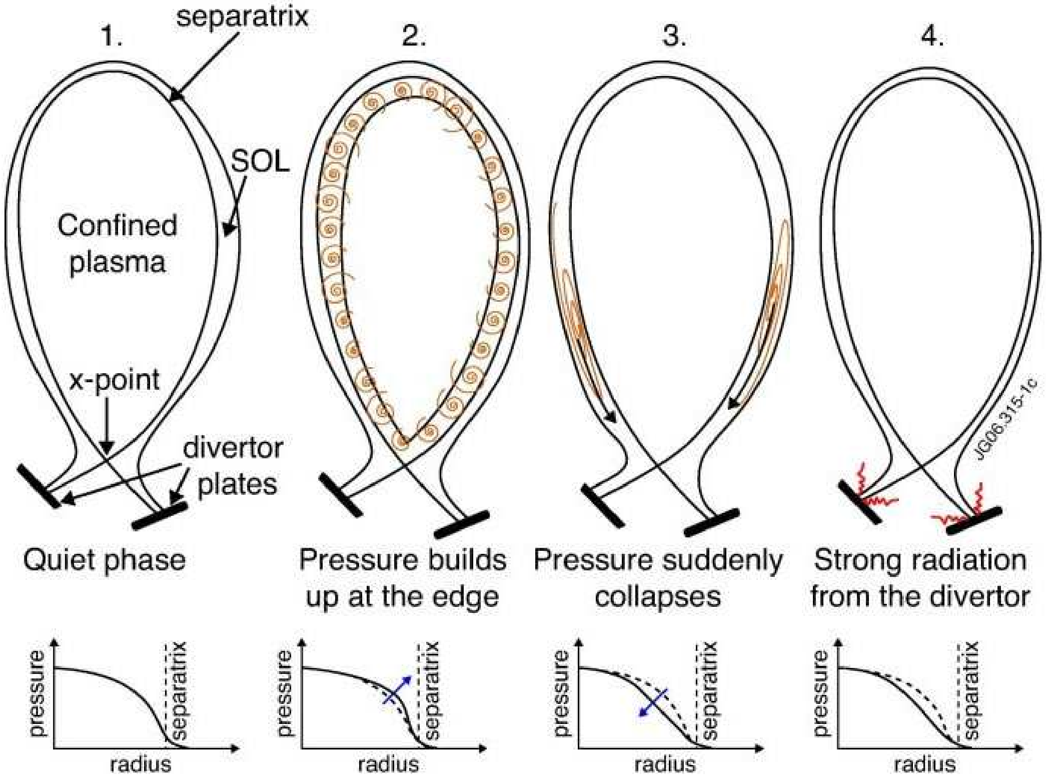
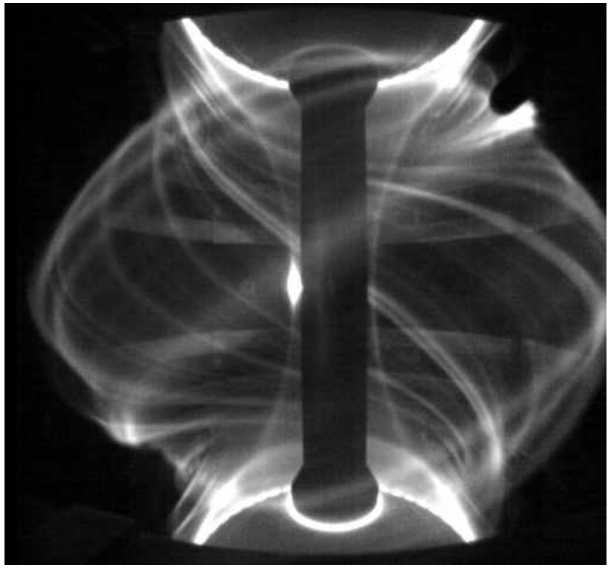


Figure 2. Schematic view of the edge stability boundaries showing the variation of pedestal boundaries with discharge shaping, limiting instabilities and model of the type-I ELM cycle.

* P.T.Lang, Nuclear Fusion, 2013

Edge Localised Mode (ELM)





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

Structure and Phase of ELMs

Structure of the ELMs

Filamentary structure

spatially (3D) localized
highly elongated along field line
toroidal mode number ~ 10
perpendicular wavenumber
~ 0.1 cm^{-1}

* A. Kirk, Physical Review Letters, 2004

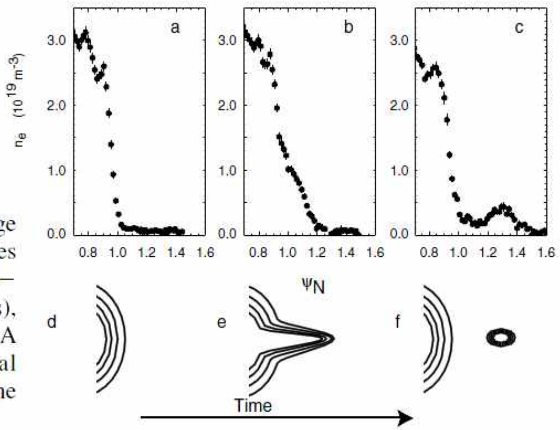
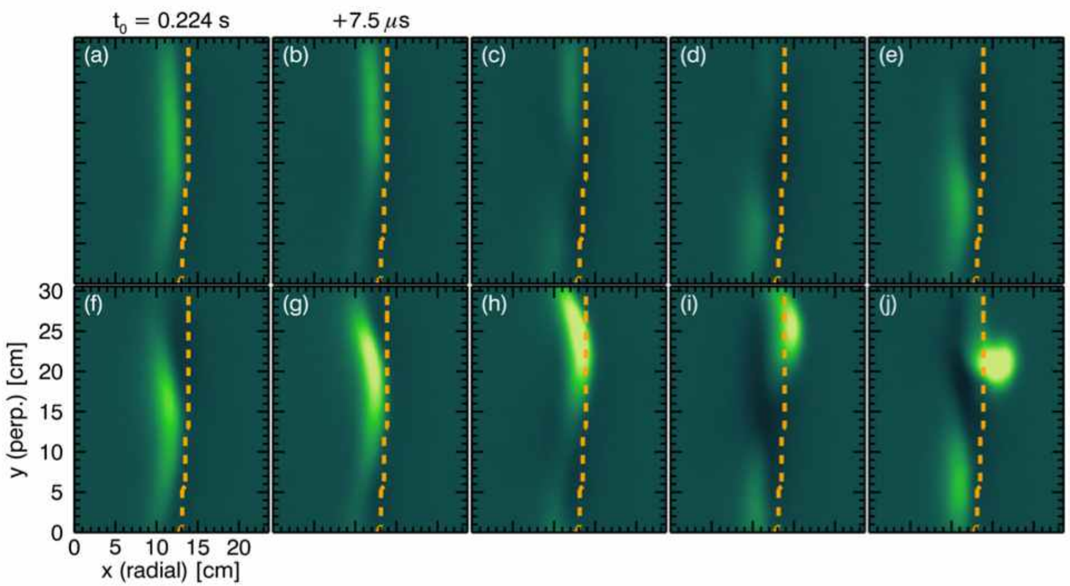


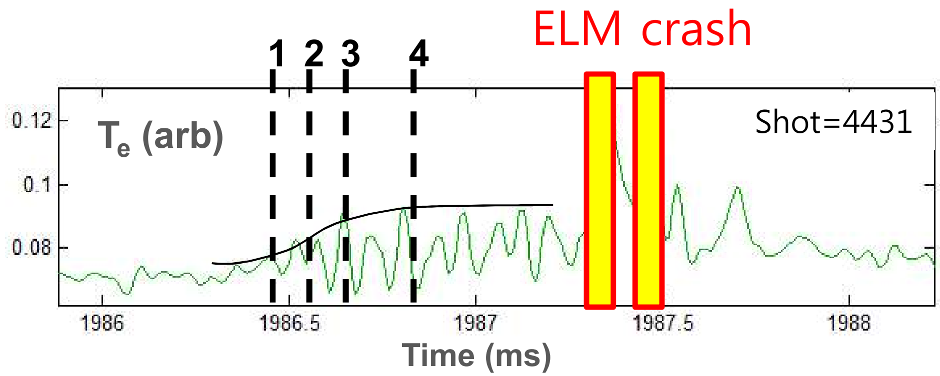
FIG. 2. Thomson scattering profiles of the outboard edge density in normalized flux coordinates at different times with respect to the start of a similar ELM. (a) Before (t_{ELM} − 770 ms), (b) in the middle of the ELM rise (t_{ELM} + 140 ms), and (c) near the end of the ELM rise time (t_{ELM} + 180 ms). A schematic of the proposed magnetic geometry in the poloidal cross section at the outboard plasma edge for the same time periods is shown in (d), (e), and (f), respectively.



* Y. Sechrest, Nuclear Fusion, 2012

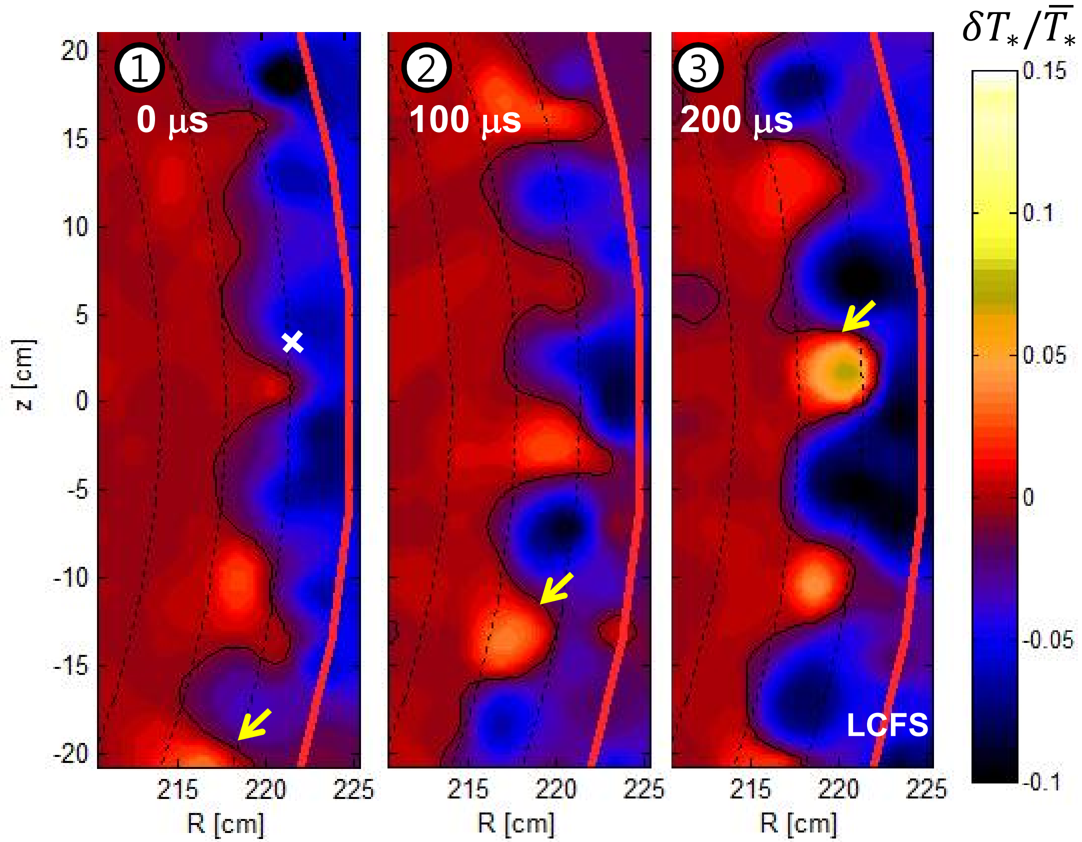
Figure 2. Multiframe image stills of an ELM event with precursor intensity fluctuations from shot 141918. The time between frames is ~7.5 μs. Distinct mode structure can be seen in precursor oscillations leading to the ejection of the filament in the last two frames. The approximate location of the separatrix is indicated by the dashed line.

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

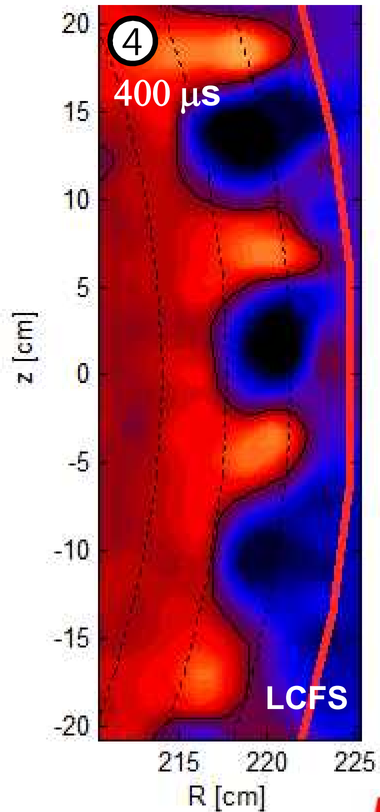


** G.S. Yun et al., PRL (2011)*

(1) Initial Growth



(2) Saturation



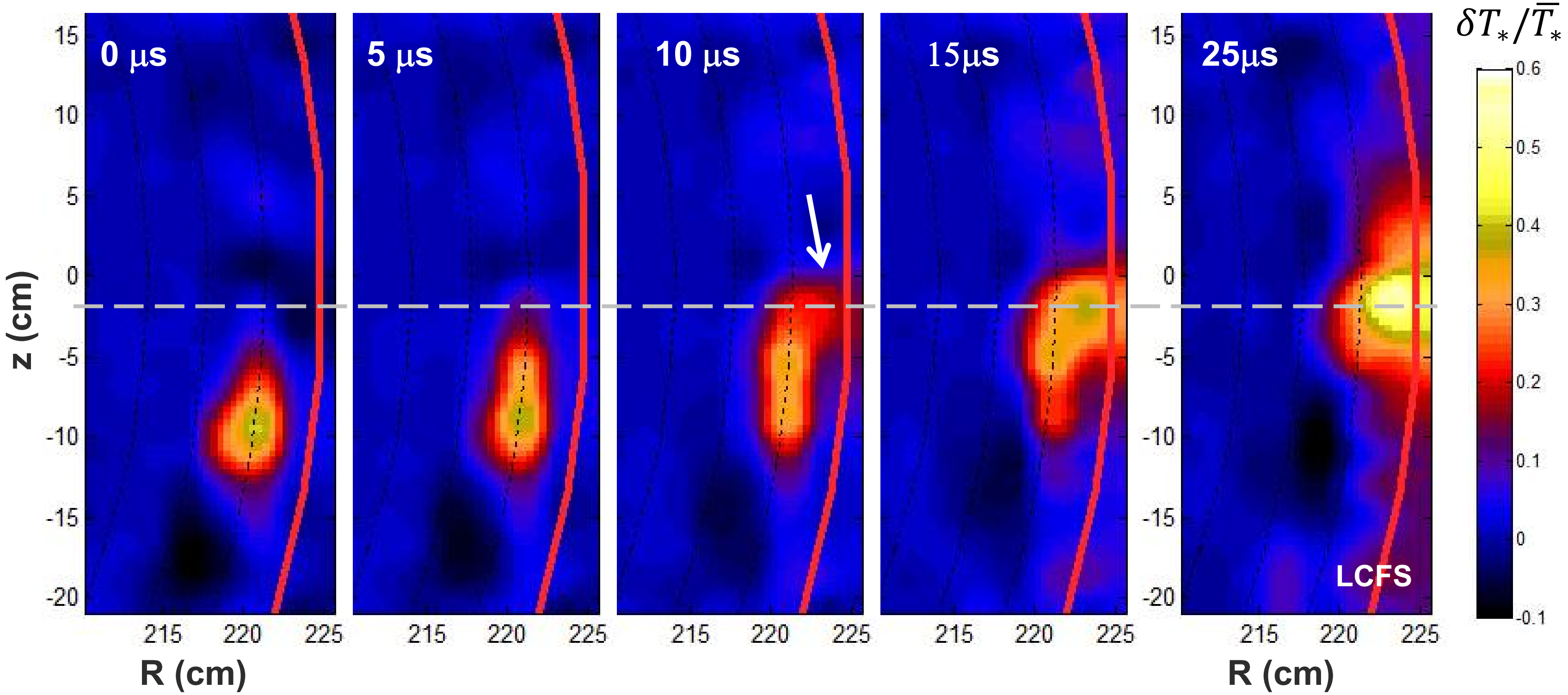
KSTAR

(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

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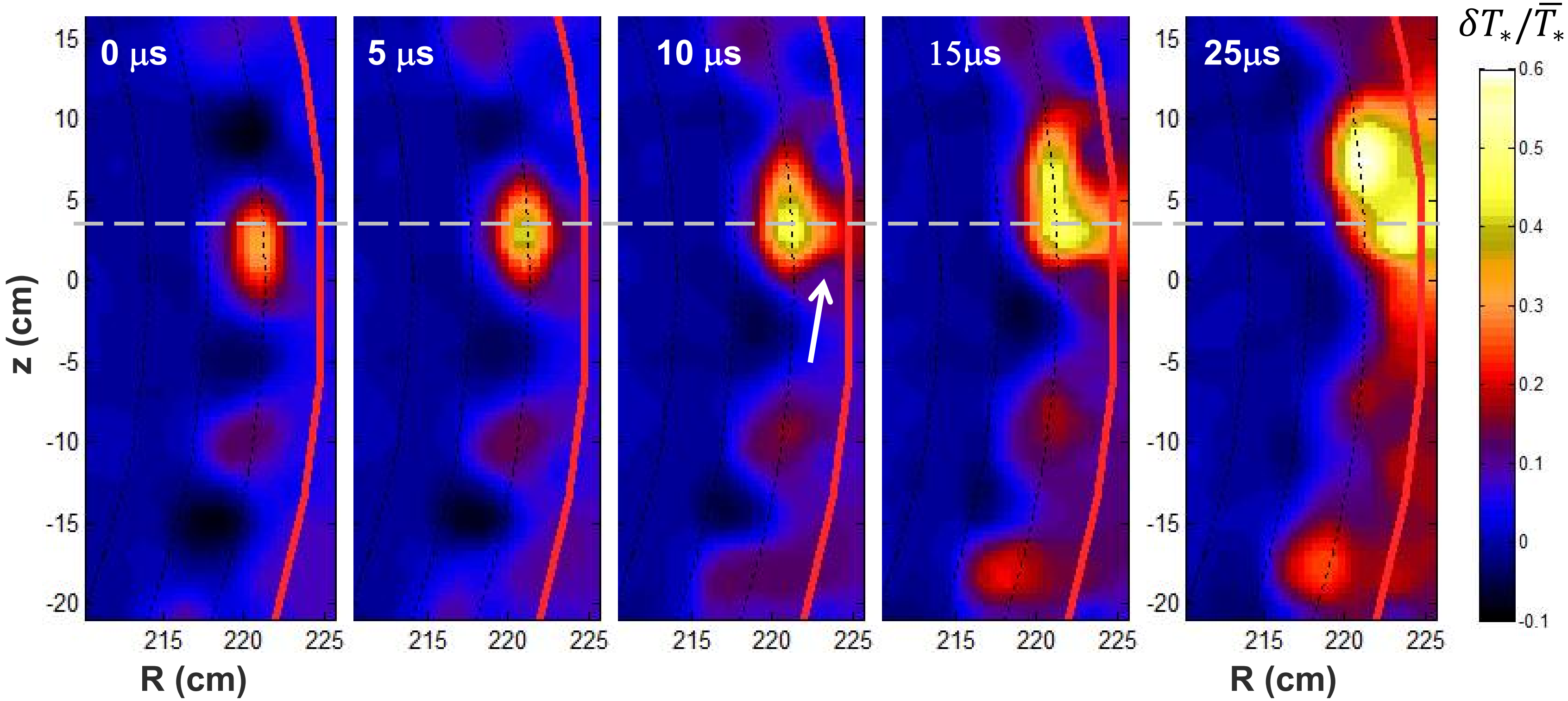
Another burst during the same ELM crash event



- **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.

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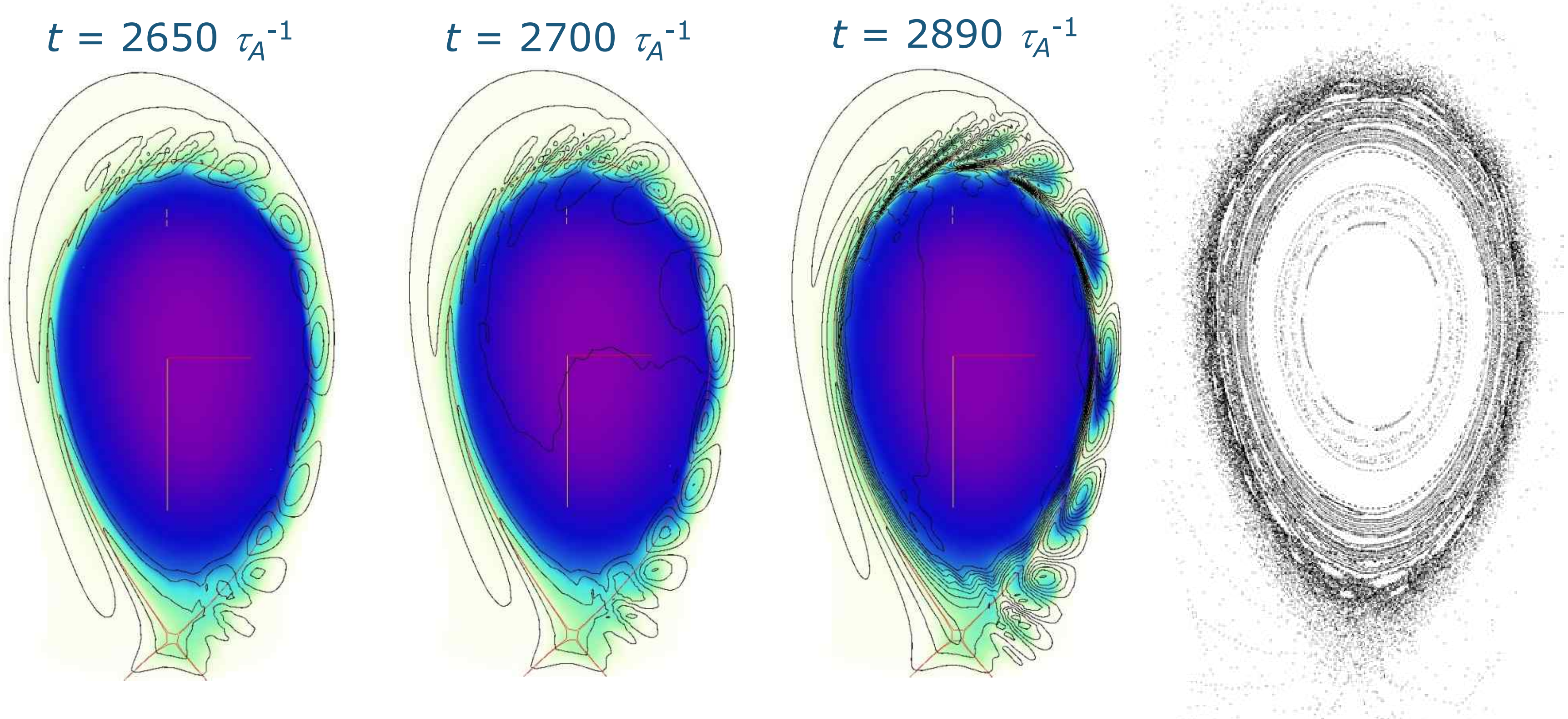
Edge Localised Mode (ELM)

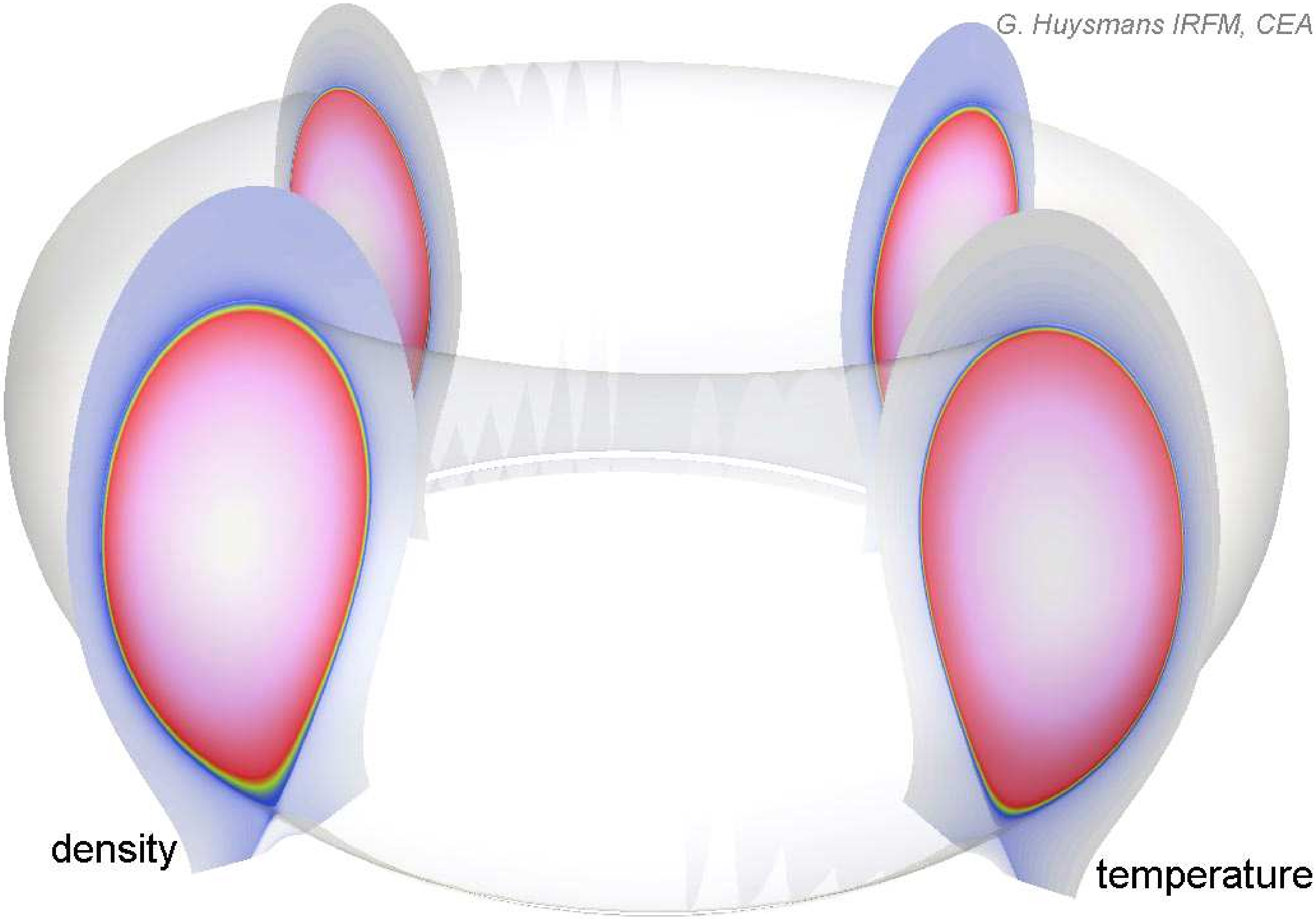
- Non-linear MHD simulations with JOREK reproduce the formation of multiple filaments expulsed from plasma



Evolution of n = 6 ballooning mode

*Huysmans, Czarny, NF **47** 659 (2007)*

Edge Localised Mode (ELM)



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.

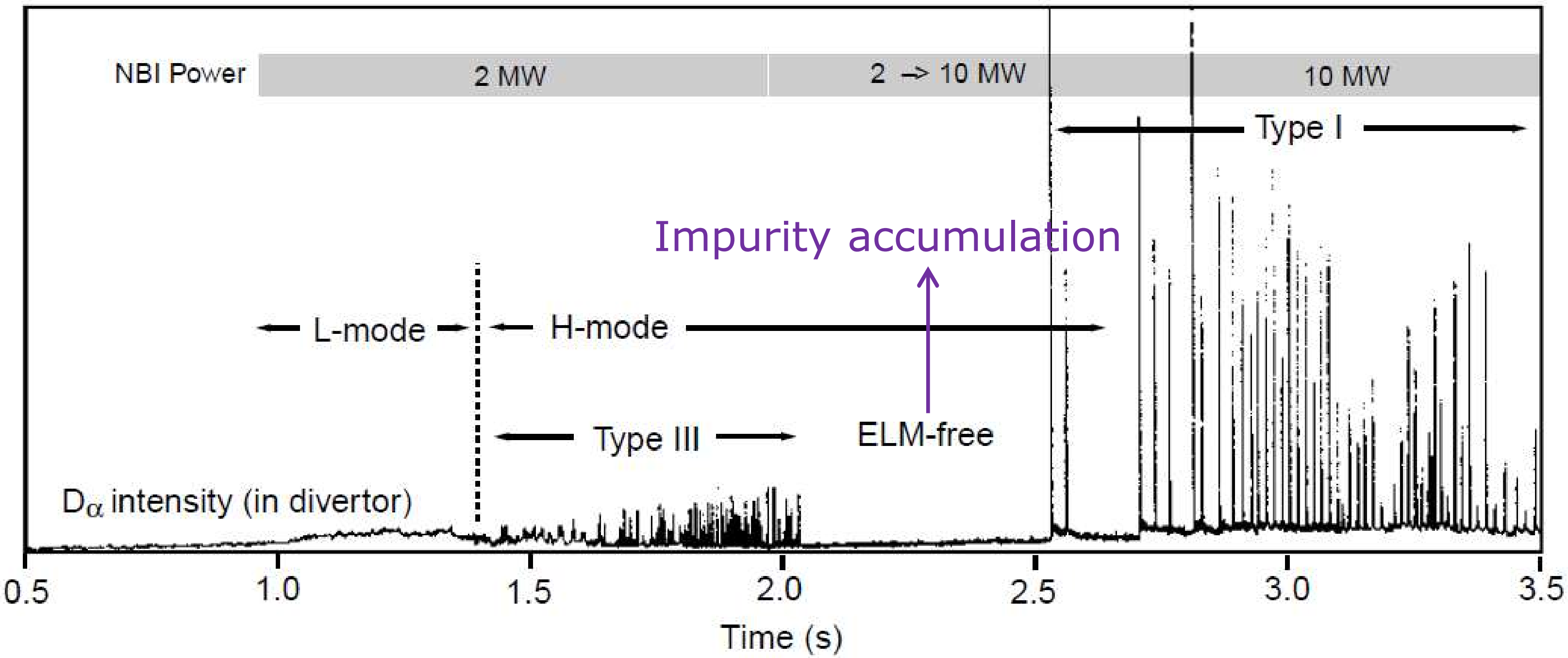
Edge Localised Mode (ELM)

- **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**



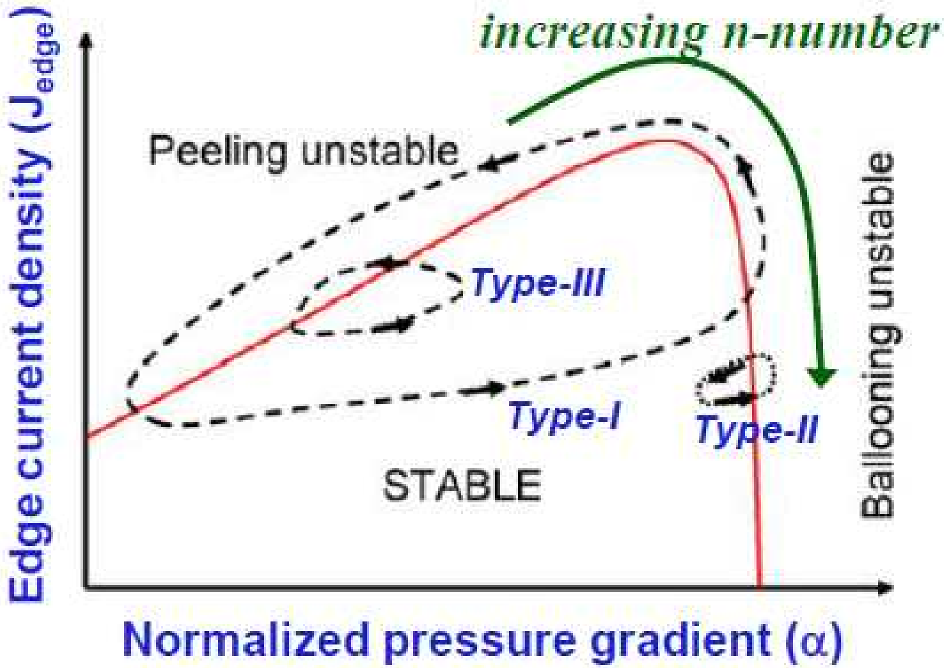
- Divertor region D_a intensity in a typical DIII-D plasma with slowly increasing NBI power

- 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**



- Several types of ELMs are envisioned in the framework of ideal MHD theory
  – Edge (pedestal) current density (j_{edge}) → Peeling instability
  – Pressure gradient (p'_{edge}) → Ballooning instability
  – Bootstrap current (j_{BS}) links j_{edge} and p'_{edge}
- Toroidal mode number (n) increases from peeling to the ballooning side

Edge Localised Mode (ELM)

- **Dithering or I-phase**

Feedback Loops I

- Closing the loop of shearing and Reynolds work

- Spectral 'Predator-Prey' equations

Prey → Drift waves, <N>

$$\frac{\partial}{\partial t}\langle N\rangle - \frac{\partial}{\partial k_r} D_k \frac{\partial}{\partial k_r}\langle N\rangle = \gamma_k \langle N\rangle - \frac{\Delta\omega_k}{N_0}\langle N\rangle^2$$

Predator → Zonal flow, $|\phi_q|^2$

$$\frac{\partial}{\partial t}|\phi_q|^2 = \Gamma_q\left[\frac{\partial\langle N\rangle}{\partial k_r}\right]|\phi_q|^2 - \gamma_d|\phi_q|^2 - \gamma_{NL}[|\phi_q|^2]|\phi_q|^2$$

Edge Localised Mode (ELM)

- **Dithering or I-phase**

Feedback Loops II

- Recovering the 'dual cascade':
  - Prey → <N> ~ <Ω> ⇒ induced diffusion to high k_r { ⇒ Analogous → forward potential enstrophy cascade; PV transport
  - Predator → $|\phi_q|^2 \sim \langle V_{E,\theta}^2 \rangle$ { ⇒ growth of *n=0*, *m=0* Z.F. by turbulent Reynolds work; ⇒ Analogous → inverse energy cascade

- Mean Field Predator-Prey Model

  (P.D. et. al. '94, DI²H '05)

$$\frac{\partial}{\partial t} N = \gamma N - \alpha V^2 N - \Delta\omega N^2$$

$$\frac{\partial}{\partial t} V^2 = \alpha N V^2 - \gamma_d V^2 - \gamma_{NL}(V^2) V^2$$

System Status

State	No flow	Flow ($\alpha_2 = 0$)	Flow ($\alpha_2 \neq 0$)
N (drift wave turbulence level)	$\frac{\gamma}{\Delta\omega}$	$\frac{\gamma_d}{\alpha}$	$\frac{\gamma_d + \alpha_2 \gamma \alpha^{-1}}{\alpha + \Delta\omega\alpha_2\alpha^{-1}}$
V^2 (mean square flow)	0	$\frac{\gamma}{\alpha} - \frac{\Delta\omega\gamma_d}{\alpha^2}$	$\frac{\gamma - \Delta\omega\gamma_d\alpha^{-1}}{\alpha + \Delta\omega\alpha_2\alpha^{-1}}$
Drive/excitation mechanism	Linear growth	Linear growth	Linear growth Nonlinear damping of flow
Regulation/inhibition mechanism	Self-interaction of turbulence	Random shearing, self-interaction	Random shearing, self-interaction
Branching ratio $\frac{V^2}{N}$	0	$\frac{\gamma - \Delta\omega\gamma_d\alpha^{-1}}{\gamma_d}$	$\frac{\gamma - \Delta\omega\gamma_d\alpha^{-1}}{\gamma_d + \alpha_2\gamma\alpha^{-1}}$
Threshold (without noise)	$\gamma > 0$	$\gamma > \Delta\omega\gamma_d\alpha^{-1}$	$\gamma > \Delta\omega\gamma_d\alpha^{-1}$

Edge Localised Mode (ELM)

- **Dithering or I-phase**

Feedback Loops III

- ∇P coupling
  - γ_L drive
  - $\langle V_E \rangle'$

$$\partial_t \varepsilon = \varepsilon N - a_1 \varepsilon^2 - a_2 V^2 \varepsilon - a_3 V_{ZF}^2 \varepsilon$$

$$\partial_t V_{ZF} = b_1 \frac{\varepsilon V_{ZF}}{1 + b_2 V^2} - b_3 V_{ZF}$$

$$\partial_t N = -c_1 \varepsilon N - c_2 N + Q$$

$\mathcal{E} \equiv$ DW energy

$V_{ZF} \equiv$ ZF shear

$N \equiv \nabla\langle P \rangle \equiv$ pressure gradient

$V = dN^2$ (radial force balance)

- Simplest example of 2 predator + 1 prey problem (E. Kim, P.D., 2003)

  i.e. prey sustains predators, predators limit prey } usual feedback

  now:
  - 2 predators (*ZF*, *$\nabla\langle P \rangle$*) compete
  - *$\nabla\langle P \rangle$* as both drive and predator

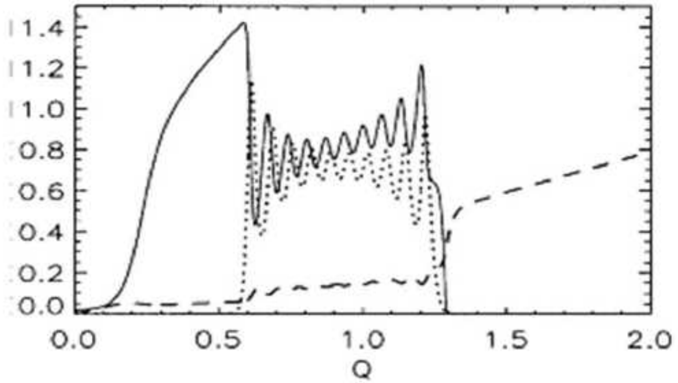
- Relevance: LH transition, ITB
  - Builds on insights from Itoh's, Hinton
  - ZF ⇒ triggers
  - *$\nabla\langle P \rangle$* ⇒ 'locking in'

Multiple predators are possible

Edge Localised Mode (ELM)

- **Dithering or I-phase**

Feedback Loops III, cont'd

- 

Solid - $\mathcal{E}$

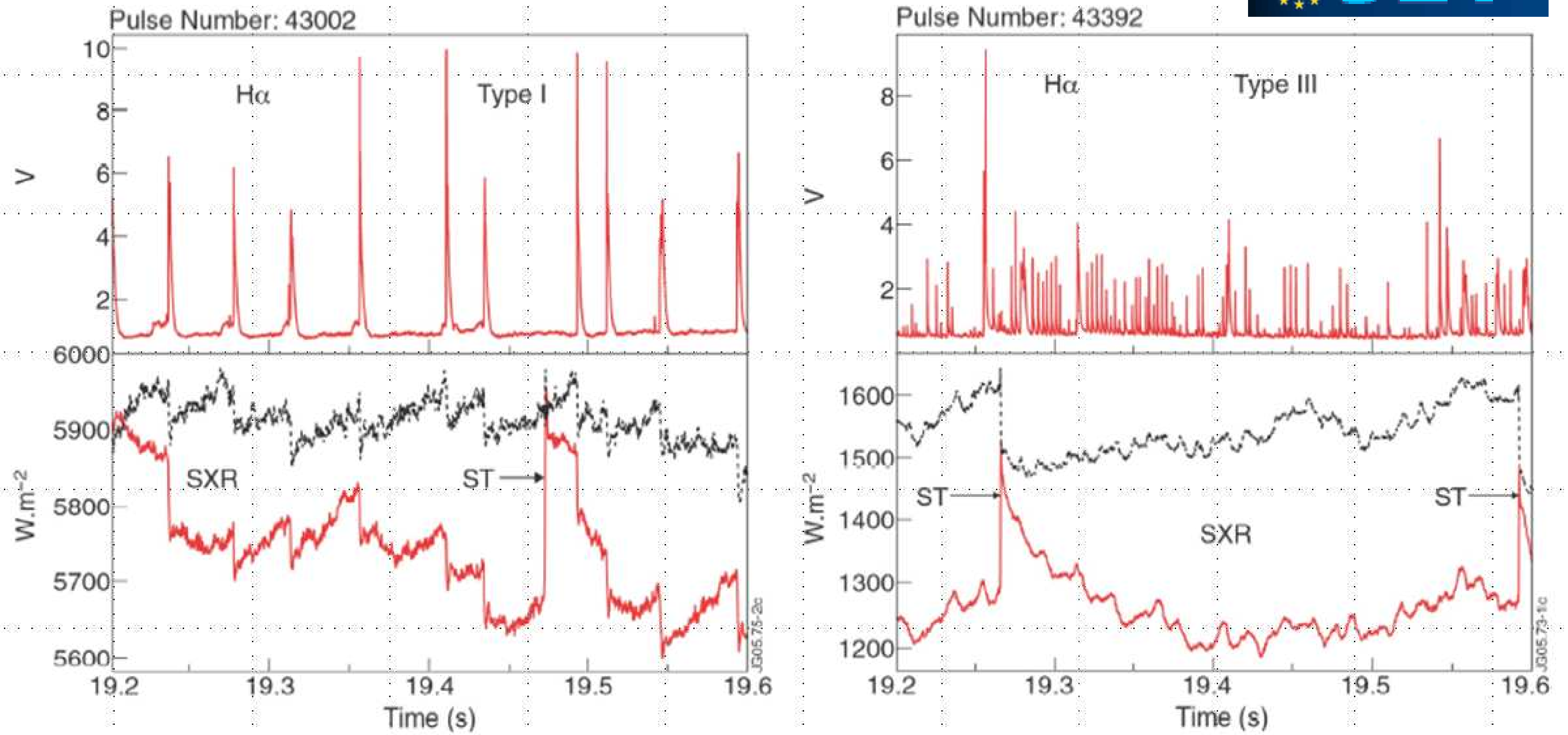
Dotted - V_{ZF}

Dashed - $\nabla\langle P\rangle$

- Observations:
  - ZF's trigger transition, $\nabla\langle P\rangle$ and $\langle V\rangle$ lock it in
  - Period of dithering, pulsations .... during ZF, $\nabla\langle P\rangle$ oscillation as Q ↑
  - Phase between $\mathcal{E}$, V_{ZF}, $\nabla\langle P\rangle$ varies as Q increases
  - $\nabla\langle P\rangle \Leftrightarrow$ ZF interaction $\Rightarrow$ effect on wave form

Edge Localised Mode (ELM)

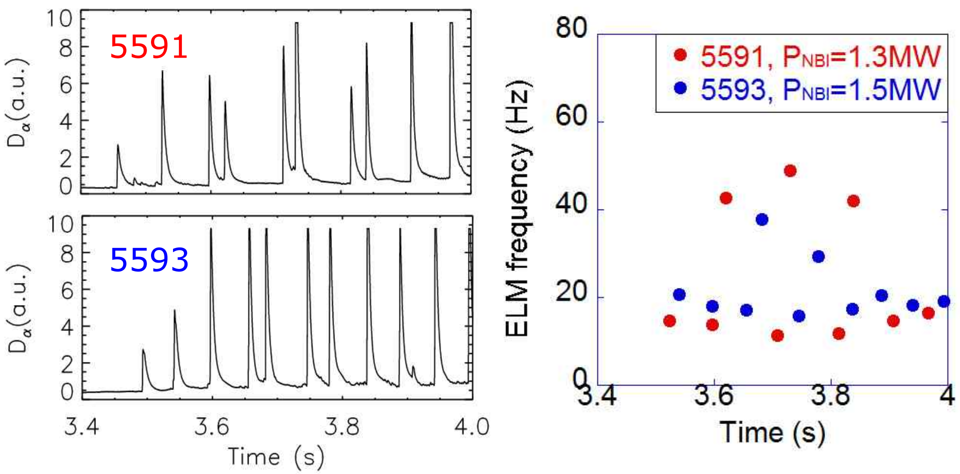
- **Type of ELMs**



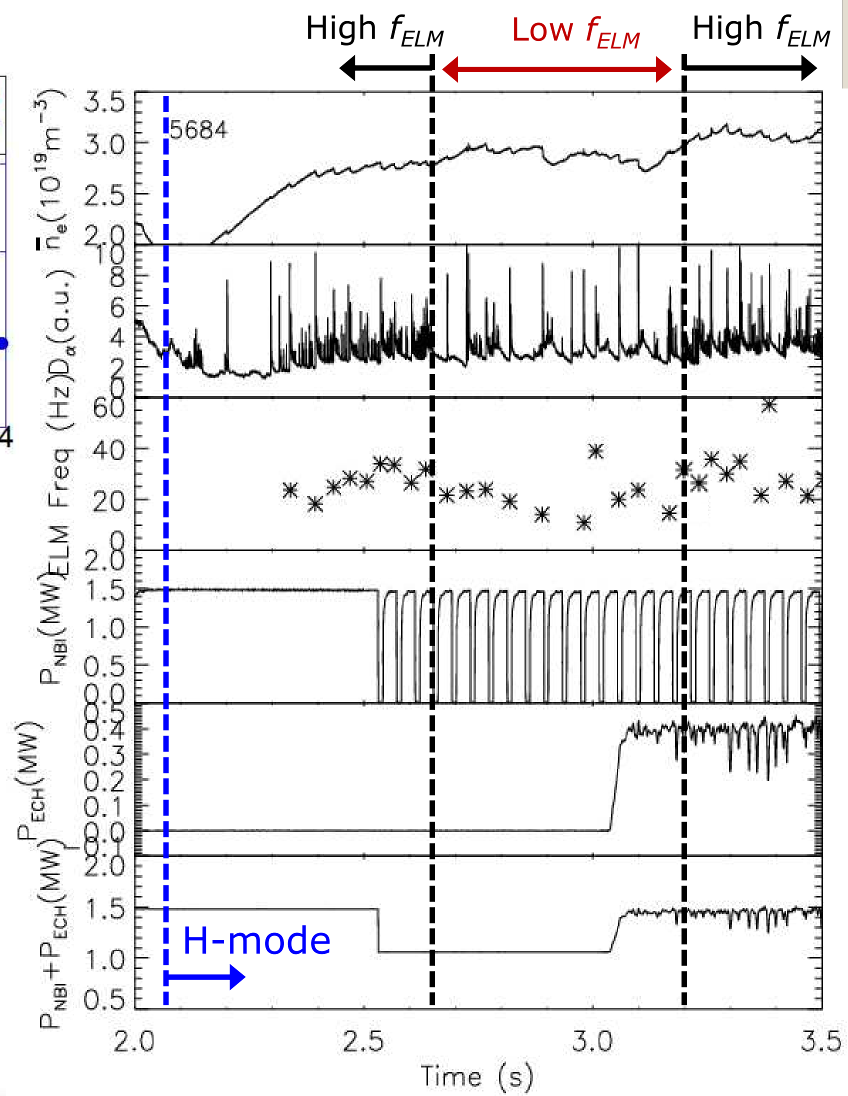
- **Type I:** „Large" ELMs – low frequency which rises with input power with significant effect (lowering) of ETB pressure.
- **Type III:** „Small" ELMs – high frequency with little or no effect on height of (ETB)

Edge Localised Mode (ELM)

Large ELMs



Mixed ELMs



- Power scan shows f_{ELM} goes up with increasing NBI power → type-I ELMs
- Large peaks of mixed ELM also follows the characteristics of type-I ELMs with the combined power of NBI+ECH

*J-W. Ahn, et al, NF **52** 114001 (2012)*

Edge Localised Mode (ELM)

ASIPP

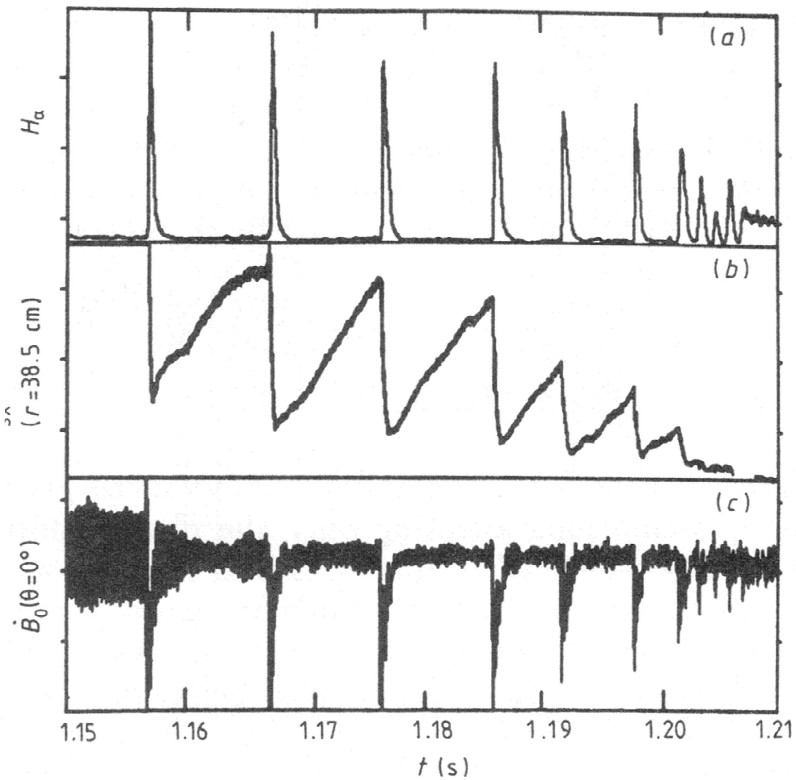
- **Type of ELMs**

ELM type		$\Delta W_{dia}/W_{dia}$	$\Delta W_{div}/W_{dia}$	q_{peak} (MW m^{-2})	$H_{98}(y,2)$	f_{ELM} (Hz)
Type I		8%	5%	~10	~1	<50
Compound		4.5%	5% (in a few ms)	3–5	~1	~50
Small	Type III	Undetected	1–2%	2	0.5–0.8	0.2–0.8k
	Type-II like	Too small to be measured		<1	0.8–0.85	0.8–1.5k

*L. Wang et al., Nucl. Fusion **53** 073028 (2013)*

Edge Localised Mode (ELM)

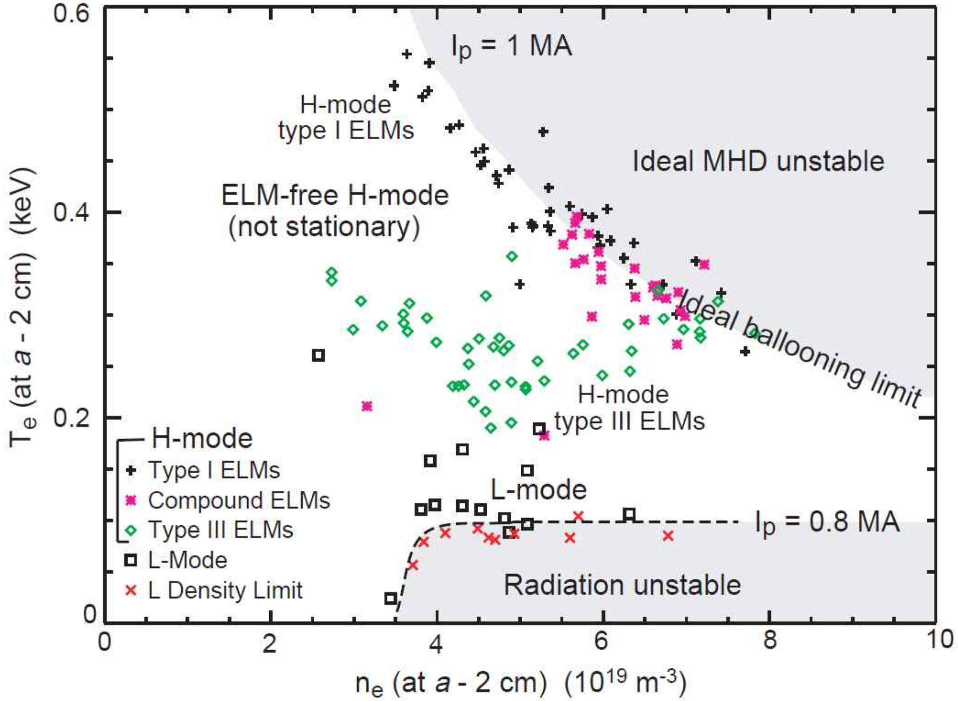
- **Type of ELMs**



- 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:** H-mode operational diagram

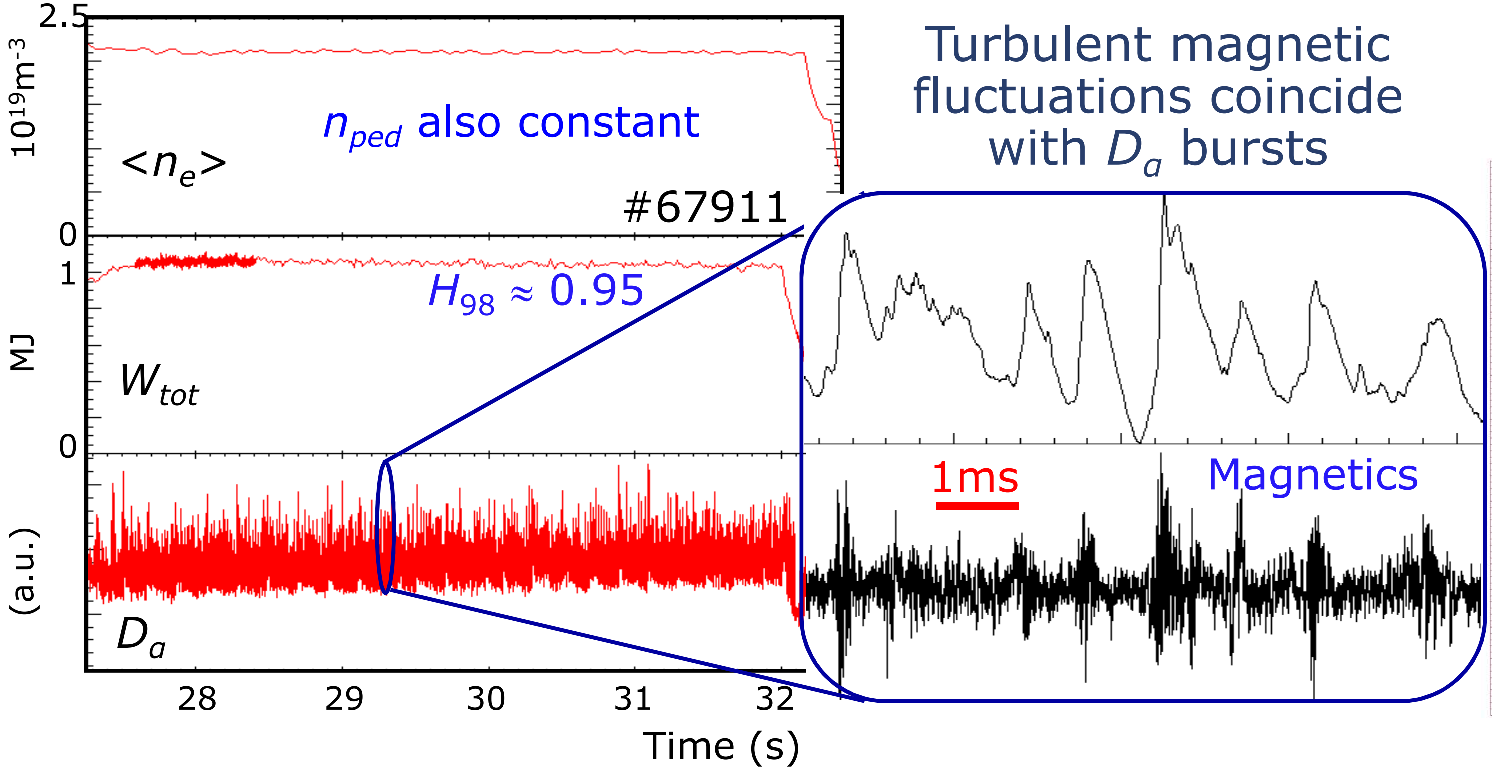


Measured data at 2 cm inside the separatrix (corresponding to the top of the H-mode pedestal)

- 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.

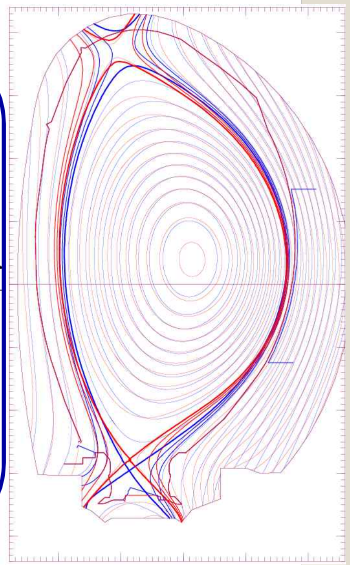
Edge Localised Mode (ELM)

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



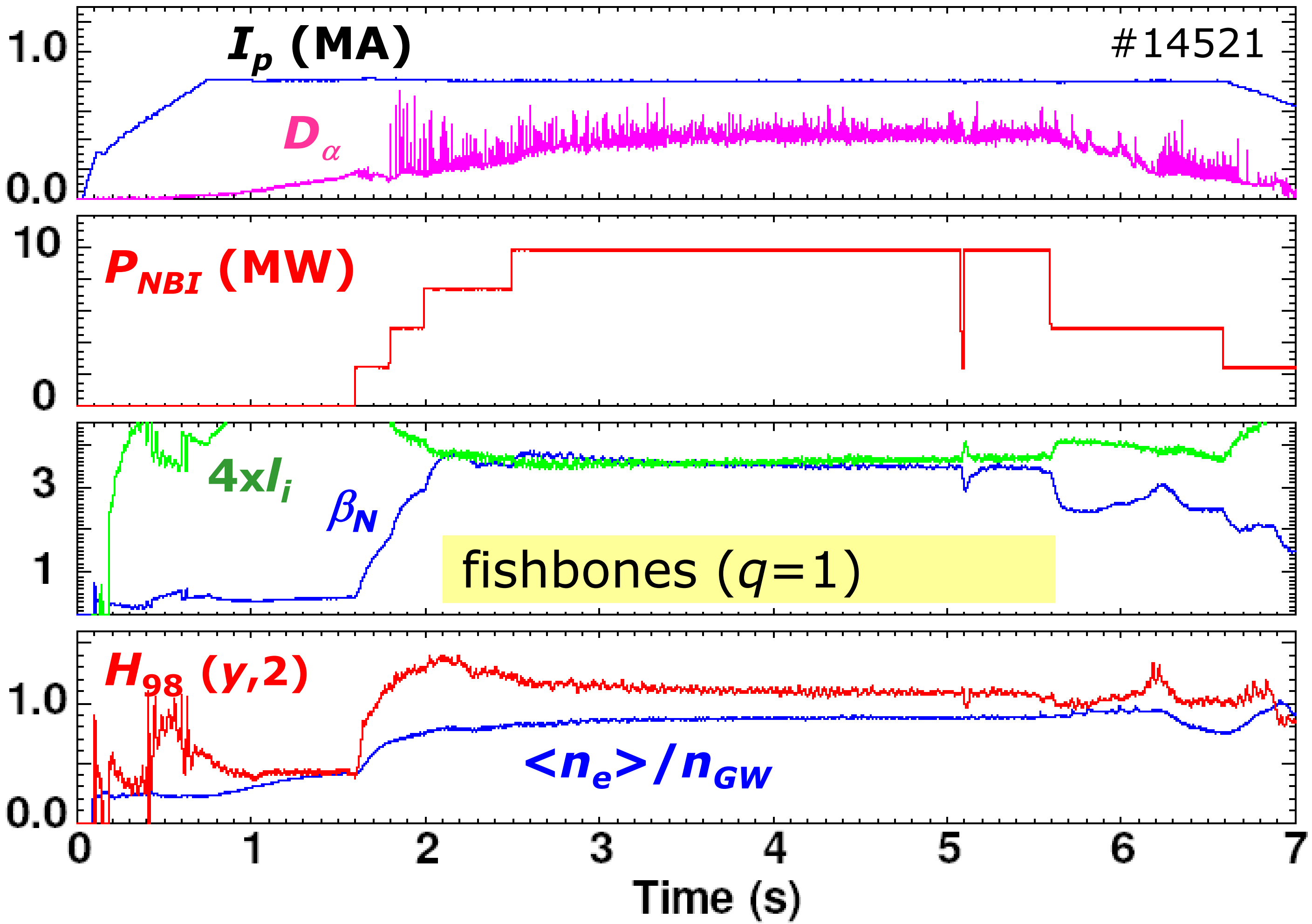
Blue: New #66476

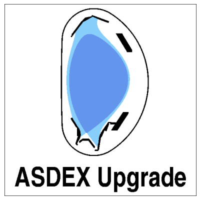
Red:Previous experiment #62430



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

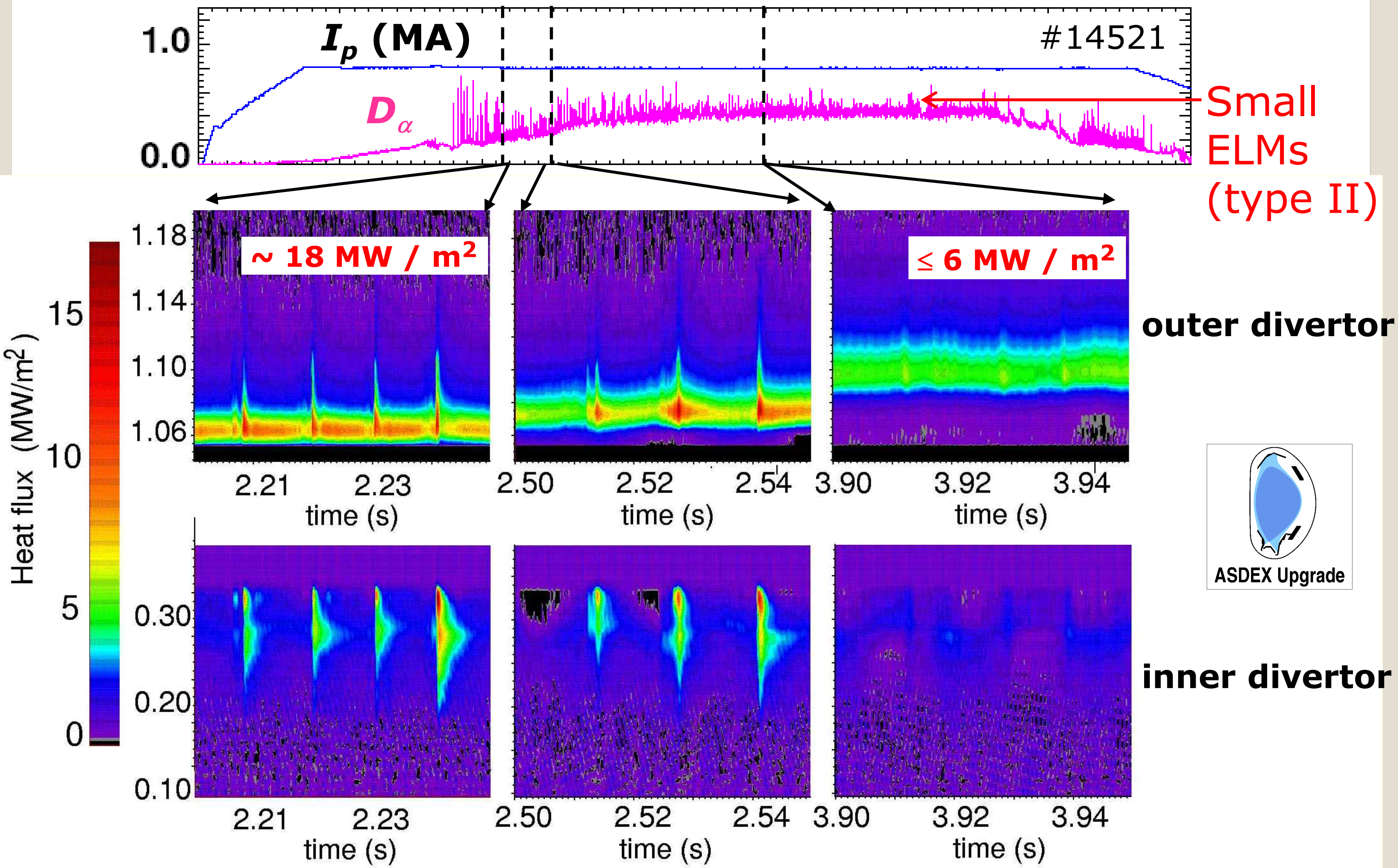
Edge Localised Mode (ELM)





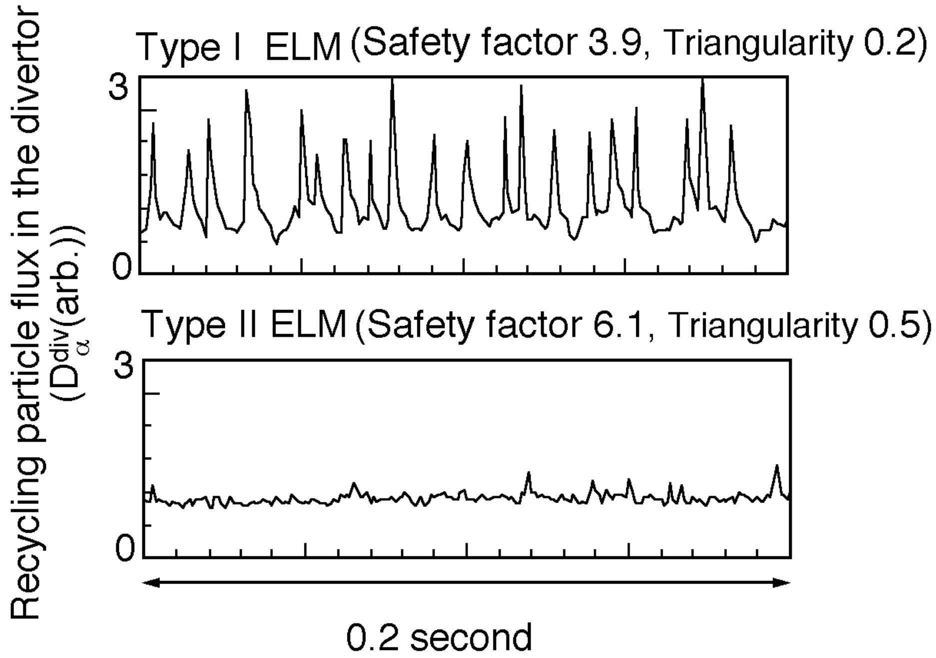
- No sawteeth, good confinement, and $\beta_N \sim 3.5$, $T_i \sim T_e$, $<n_e>/n_{GW} \sim 0.88$, averaged over 3.6 seconds ($\sim 50\ \tau_E$).

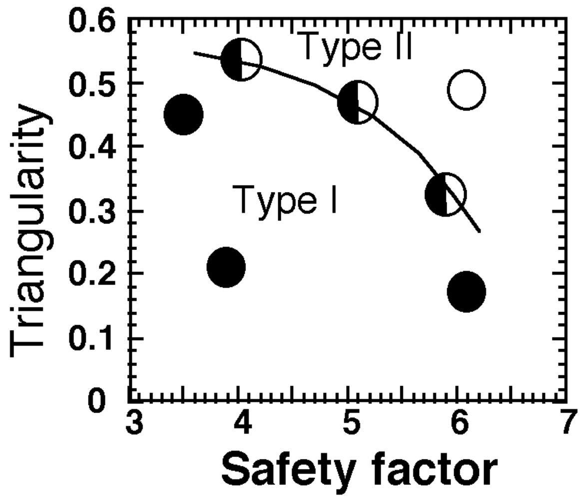
Edge Localised Mode (ELM)



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)

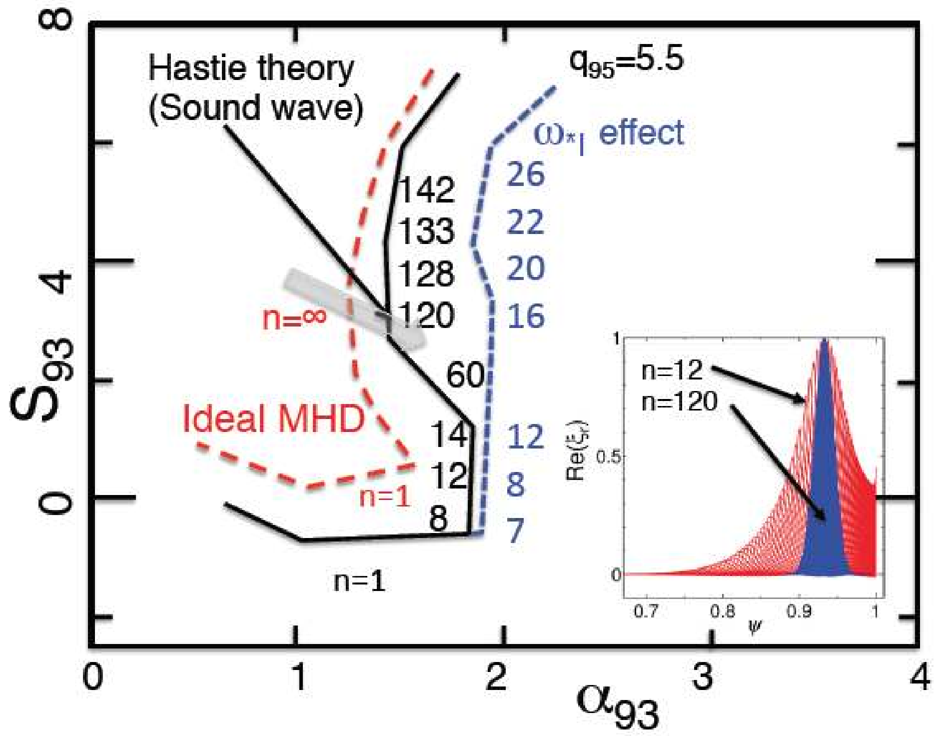
- **Type II (or ‘grassy’) ELMs**

- Numerical stability analysis is performed to identify the origin of ‘grassy ELMs’ on the basis of current understanding of kinetic effects on ballooning mode stability.
- Short wavelength ballooning mode can play an important role in a grassy ELM stability even when kinetic effects are taken into account.
- lower κ is preferable to realize a grassy ELM plasma due to destabilizing ballooning mode by preventing access to the 2nd stability region of the ballooning mode.
- ω^* and sound wave correction is made to P-B modes

N. Aiba, N. Oyama, NF ***52*** *114002 (2012)*

Edge Localised Mode (ELM)

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



*N. Aiba, N. Oyama, NF **52** 114002 (2012)*