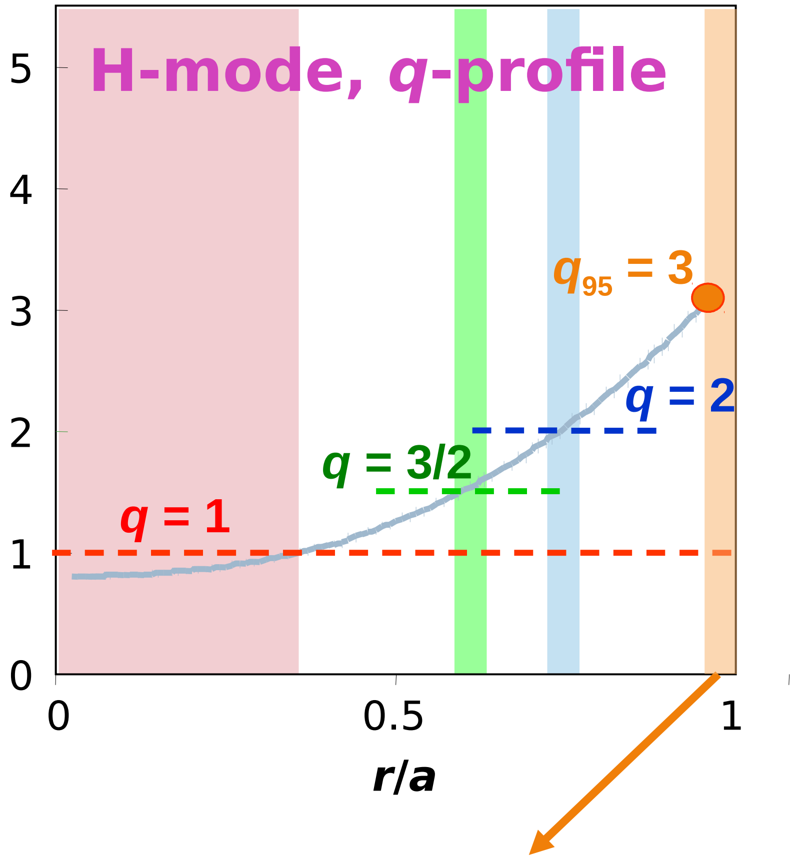
Fusion Reactor Technology 2
(459.761, 3 Credits)

Prof. Dr. Yong-Su Na

(32-206, Tel. 880-7204)

H-mode: Limitations

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



Periodic collapses of the ETB (ELMs)

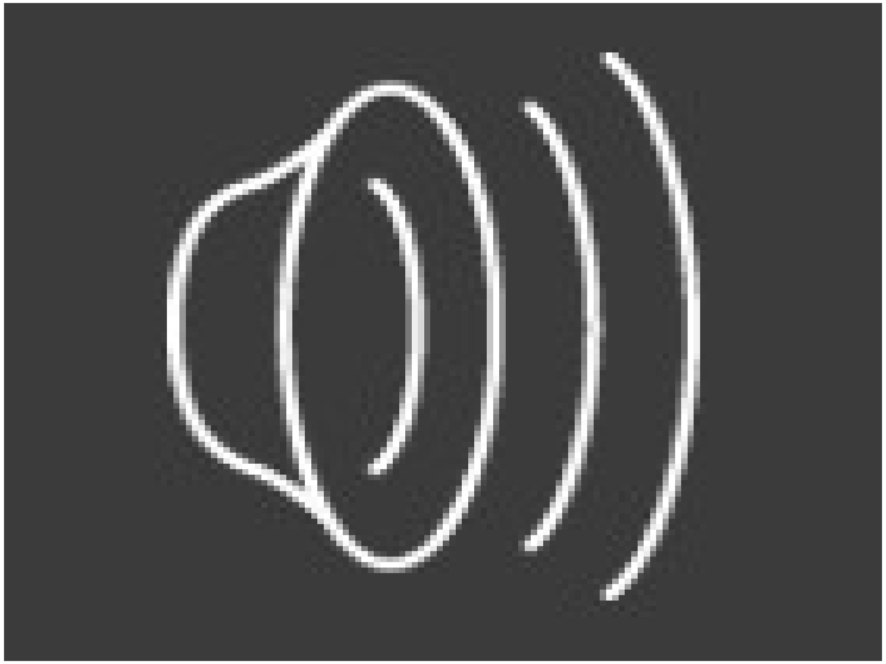
$q_0 < 1$: Sawtooth instability, periodic flattening of the pressure in the core

$q = 3/2$ 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: $\beta_N \leq 1.8$

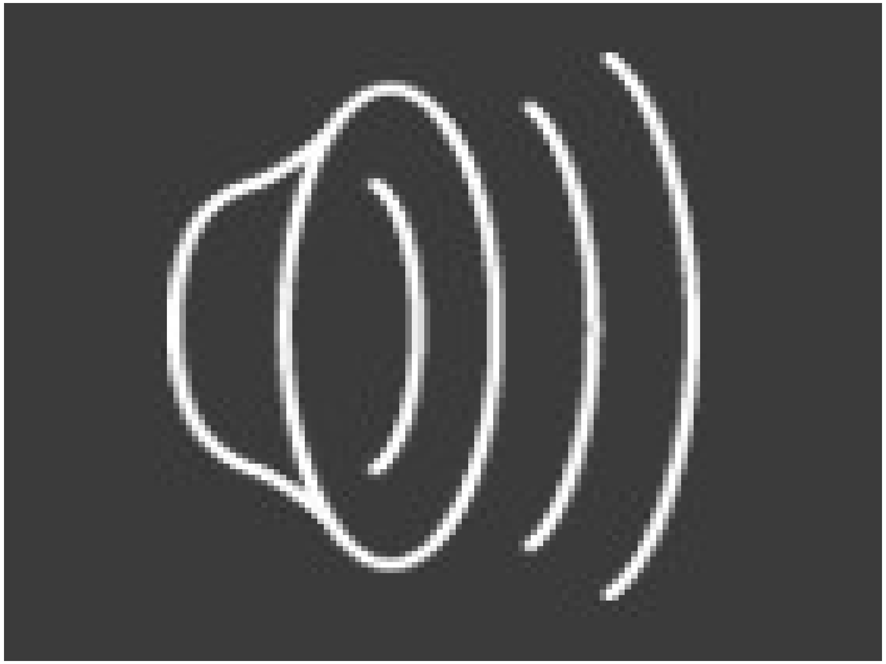
q_{95} ($\propto 1/I_p$) = 3: Safe operation at max. I_P

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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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).

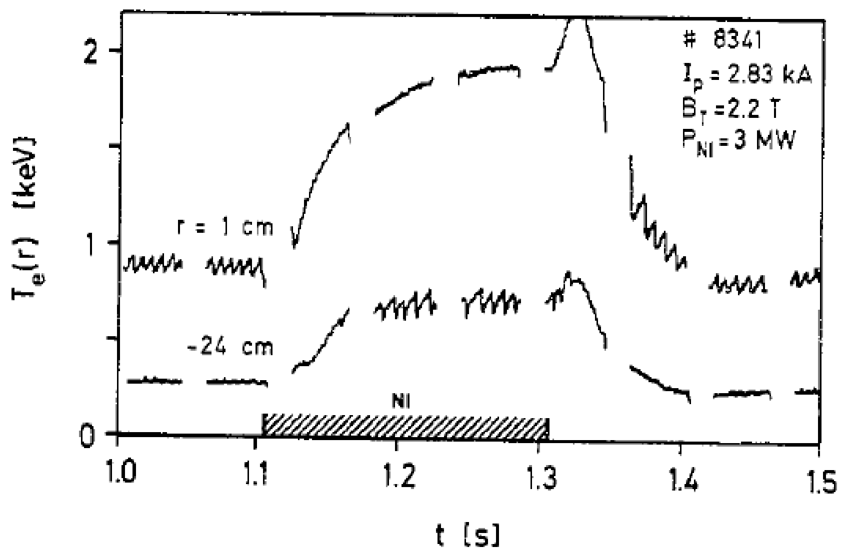

Fig. 11 ECE-measured electron temperature T_e at the plasma centre (r = 1 cm) and half-way to the edge (r = -24 cm) showing that the bursts observed during the H-phase are localized in the outer part of the plasma.

Edge Localised Mode (ELM)

Journal of Nuclear Materials 121 (1984) 115–125
North-Holland, Amsterdam

ATTAINMENT OF HIGH CONFINEMENT IN NEUTRAL BEAM HEATED DIVERTOR DISCHARGES IN THE PDX TOKAMAK

S.M. KAYE, M.G. BELL, K. BOL, D. BOYD [1], K. BRAU, D. BUCHENAUER, R. BUDNY, A. CAVALLO [1], P. COUTURE [2], T. CROWLEY, D.S. DARROW, H. EUBANK, R.J. FONCK, R. GOLDSTON, B. GREK, K.P. JAEHNIG, D. JOHNSON, R. KAITA, H. KUGEL, B. LEBLANC [3], J. MANICKAM, D. MANOS, D. MANSFIELD, E. MAZZUCATO, R. McCANN, D. McCUNE, K. McGUIRE, D. MUELLER, A. MURDOCK [1], M. OKABAYASHI, K. OKANO [4], D.K. OWENS, D.E. POST, M. REUSCH, G.L. SCHMIDT, S. SESNIC, R. SLUSHER [5], S. SUCKEWER, C. SURKO [5], H. TAKAHASHI, F. TENNEY, H. TOWNER, J. VALLEY [5]

Plasma Physics Laboratory, Princeton University, Princeton, NJ 08544, USA
[1] *University of Maryland, College Park, Maryland, USA*
[2] *Institut de Recherche d'Hydro-Quebec, Varennes, Que, Canada*
[3] *INRS-Energie, Que, Canada*
[4] *University of Tokyo, Tokyo, Japan*
[5] *Bell Laboratories, Murray Hill, NJ 07974, USA*

The PDX divertor configuration has recently been converted from an open to a closed geometry to inhibit the return of neutral gas from the divertor region to the main chamber. Since then, operation in a regime with high energy confinement in neutral beam heated discharges (ASDEX H-mode) has been routine over a wide range of operating conditions. These H-mode discharges are characterized by a sudden drop in divertor density and H_α emission and a spontaneous rise in main chamber plasma density during neutral beam injection. The confinement time is found to scale nearly linearly with plasma current, but can be degraded due either to the presence of edge instabilities or heavy gas puffing. Detailed Thomson scattering temperature profiles show high values of T_e near the plasma edge (~ 450 eV) with sharp radial gradients (~ 400 eV/cm) near the separatrix. Density profiles are broad and also exhibit steep gradients close to the separatrix.

Edge Localised Mode (ELM)

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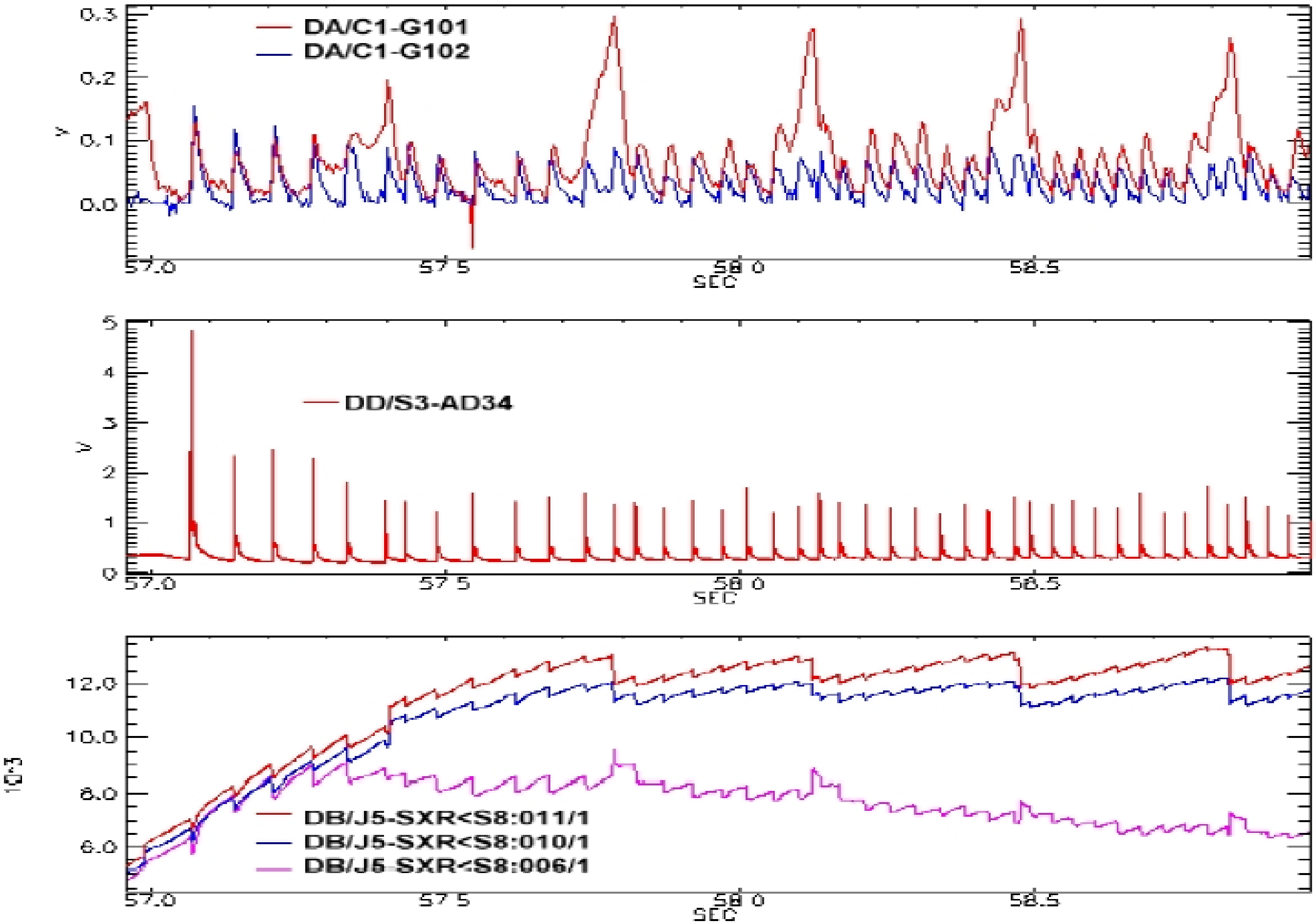
Edge Localised Mode (ELM)

The H_α spikes, which correlated with a reduction in confinement, are identified by the soft X-ray array as edge relaxation phenomena (ERP's) because of their sawtooth-like structure in the outer plasma. The top trace in fig. 4a is the divertor H_α emission on an expanded time scale, and three large H_α spikes are clearly observed. The second trace in fig. 4a is a Mirnov coil signal and represents the magnetic flucutation amplitude in the plasma. While the first H_α spike is not associated with oscillatory MHD activity, the later two are accompanied by bursting $m = 1$ activity. This MHD is identified as low amplitude fishbone activity [17] in

Edge Localised Mode (ELM)

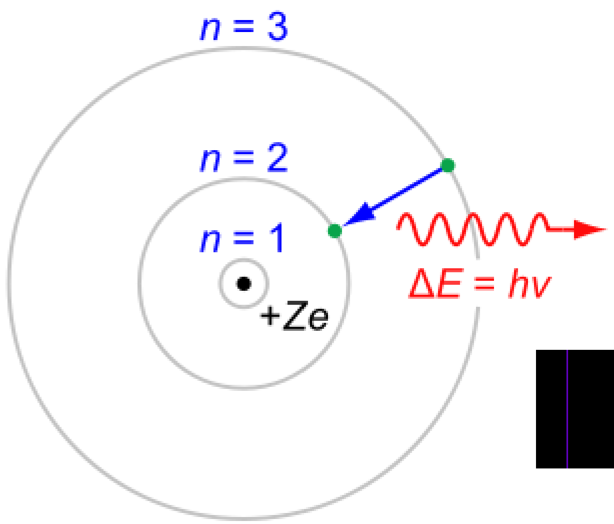
- **Example of sawteeth and ELMs**

JET, Pulse 52022



EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

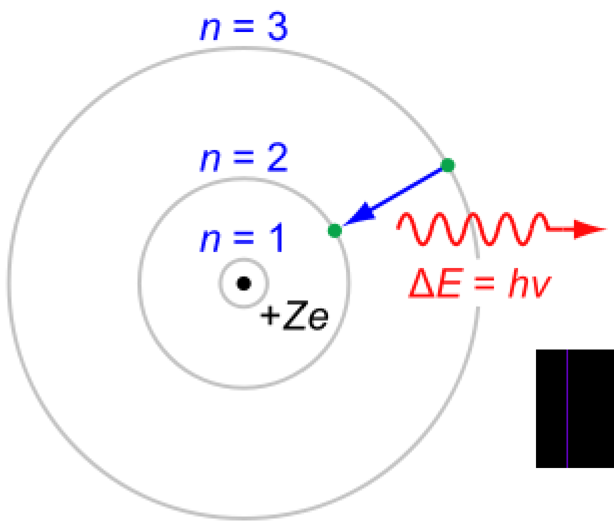
Edge Localised Mode (ELM)



- 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

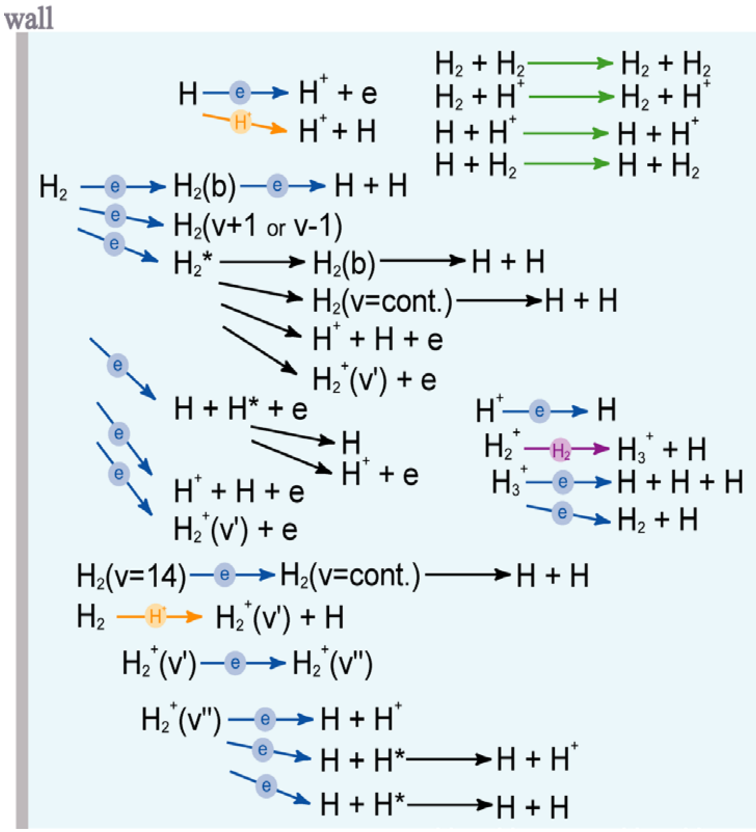
Edge Localised Mode (ELM)

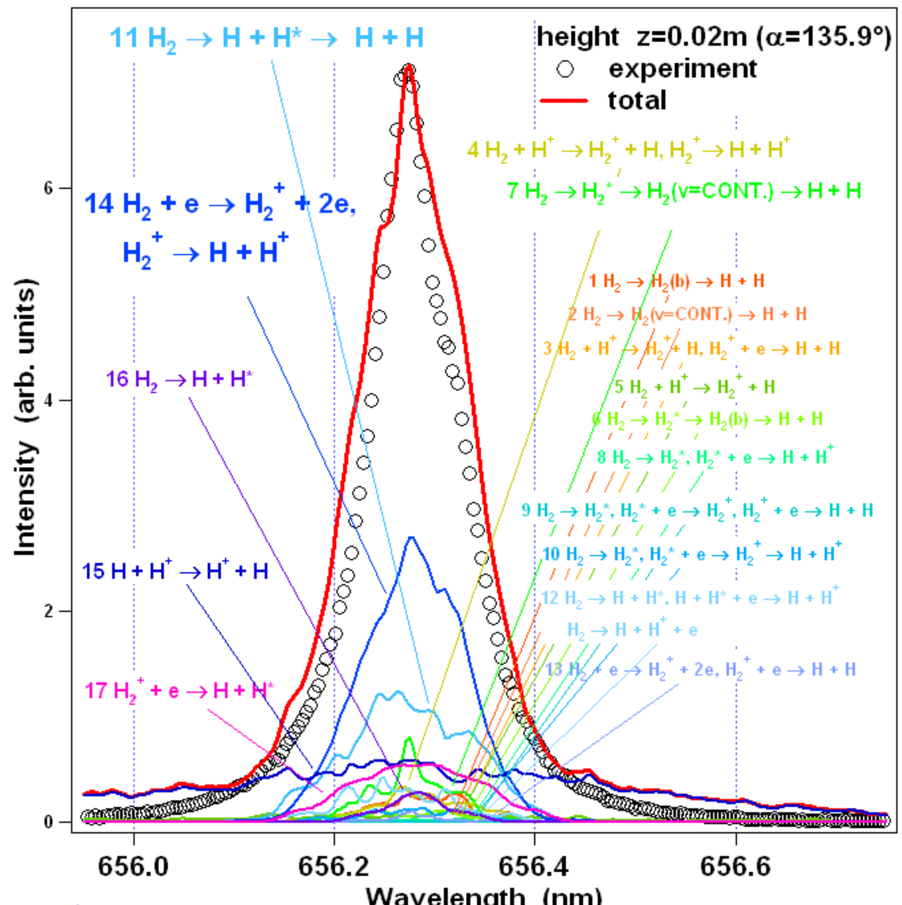


- Because of the different masses of H and D, the Balmer emission lines from D are at slightly shorter wavelengths than those from H; $\lambda_D/\lambda_H \sim 1\text{-}m_e/2m_p$

Edge Localised Mode (ELM)

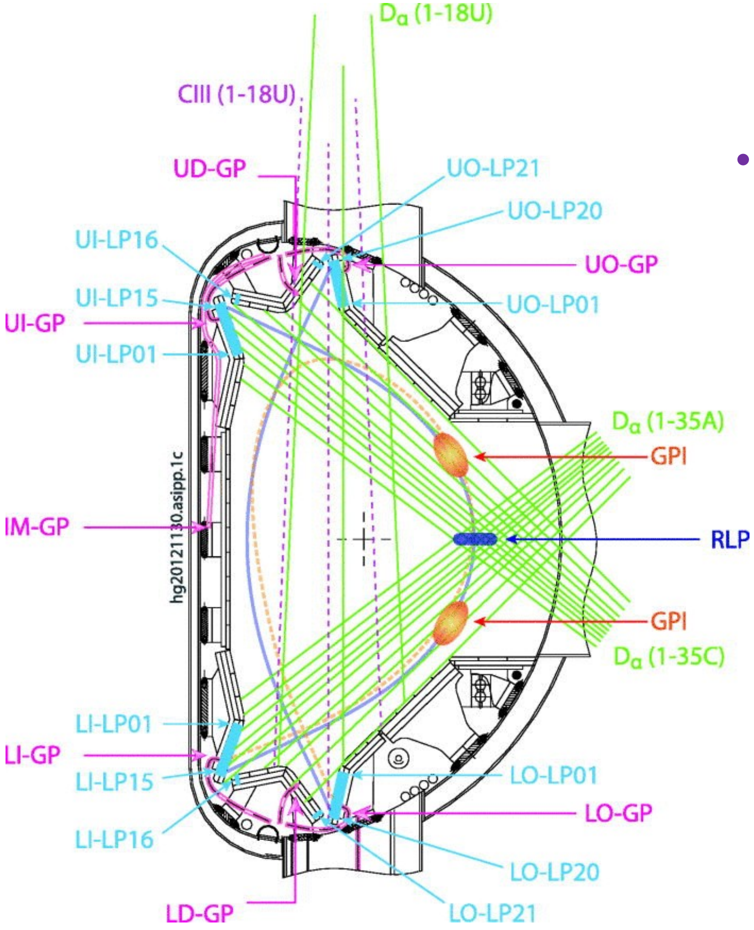
Molecular effects on H Balmer line intensity





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)



- Poloidal cross section of EAST showing key divertor/SOL diagnostics and divertor gas puff locations
  - CIII: Line emission of C++ ions
  - Dα: Balmer-alpha emission of deuterium
  - GP: Gas Puff Inlet
  - GPI: Gas Puff Imaging
  - IM: Inner Midplane
  - LO(I): Lower Outboard (Inboard) divertor
  - LP: Langmuir Probe
  - RLP: Reciprocating Langmuir Probe
  - U(L)D: Upper (Lower) divertor Dome
  - UO(I): Upper Outboard (Inboard) divertor

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
  → loss of edge confinement
  → temporary reduction of the ∇p
  → eventual recovery of the ∇p
  → 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.

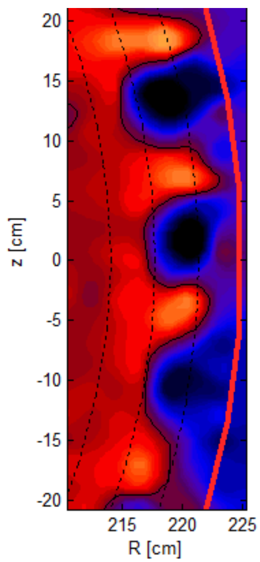
Edge Localised Mode (ELM)

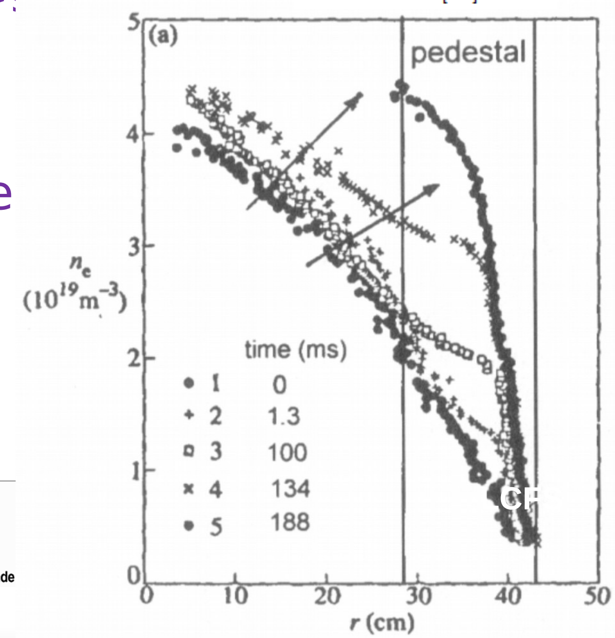
- **Edge Localised Modes (ELMs)**

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

→ Plasma particles and energy are expelled, and the enh
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)





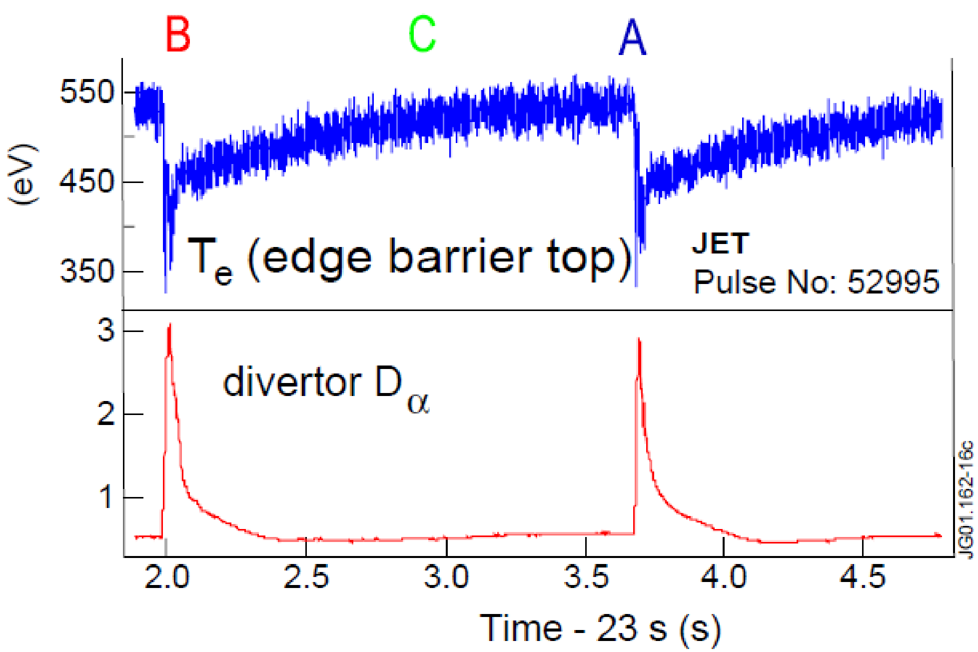
Edge Localised Mode (ELM)

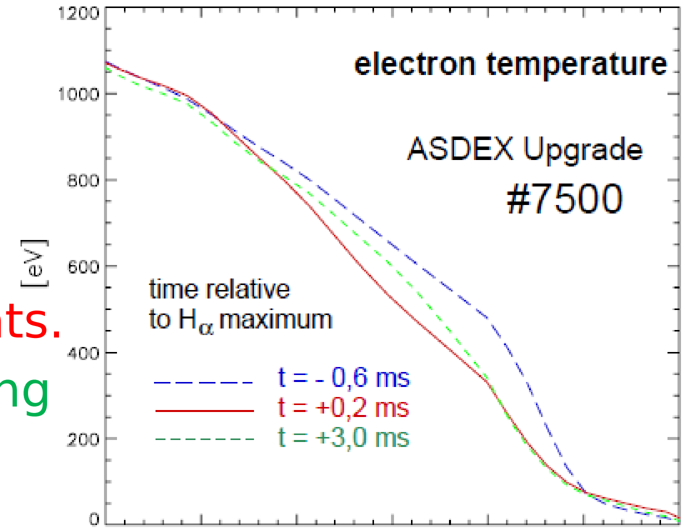
- **ELM Oscillations**

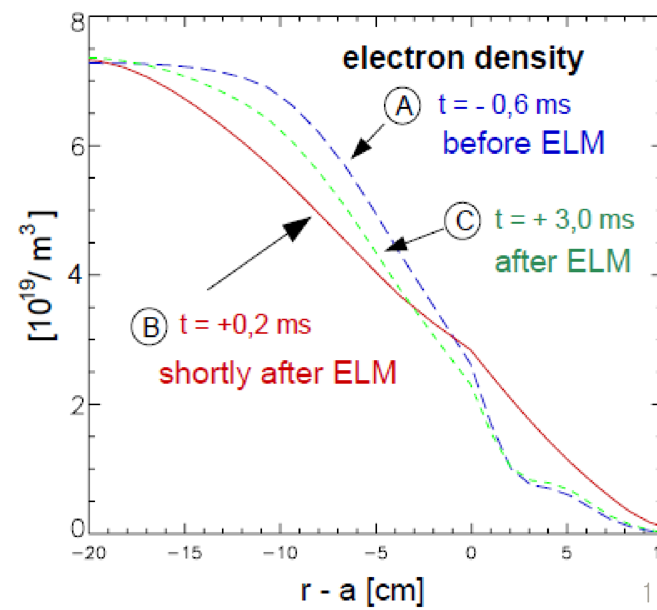
A. Critical ∇p in ETB region reached
   → short unstable phase (ELM event)

B. Energy and particle loss reduces gradients.

C. Gradients build up during reheat/refuelling phase.







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)*

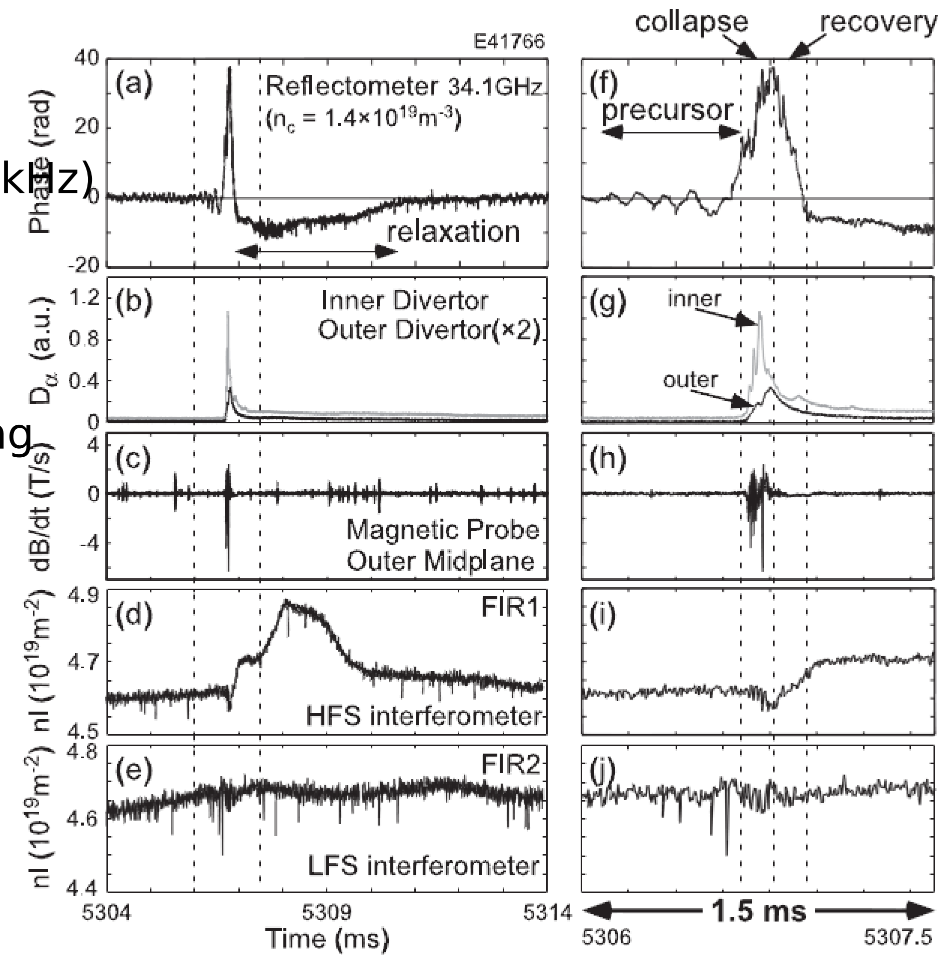


Figure 2. Waveforms of (*a*) phase change of the reflectometer signal, (*b*) D_α intensity at the inner (grey) and outer (black) divertors, (*c*) magnetic fluctuation at the outer midplane, (*d*) and (*e*) line-integrated density at the HFS and LFS, respectively. (*f*)–(*j*) show the magnified waveforms 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

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

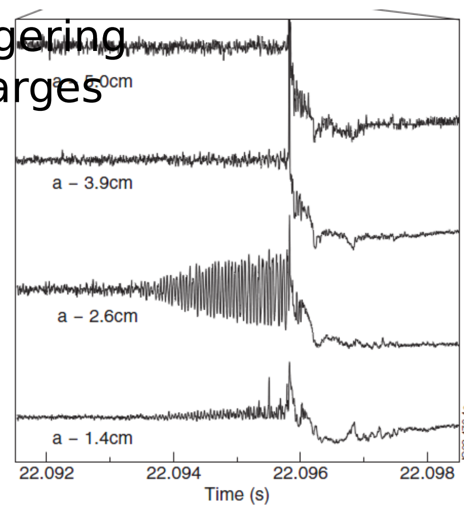


Figure 4. Edge ECE signals together with the distance of the measurement radii to the separatrix as calculated by EFIT. The second picture shows a zoom of the shorter precursor prior to the first ELM.

* N. Oyama, Nuclear Fusion, 2011

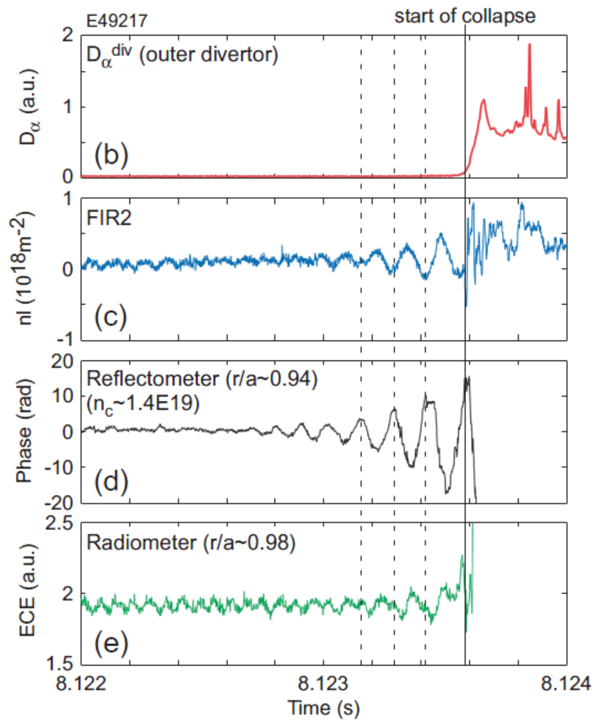
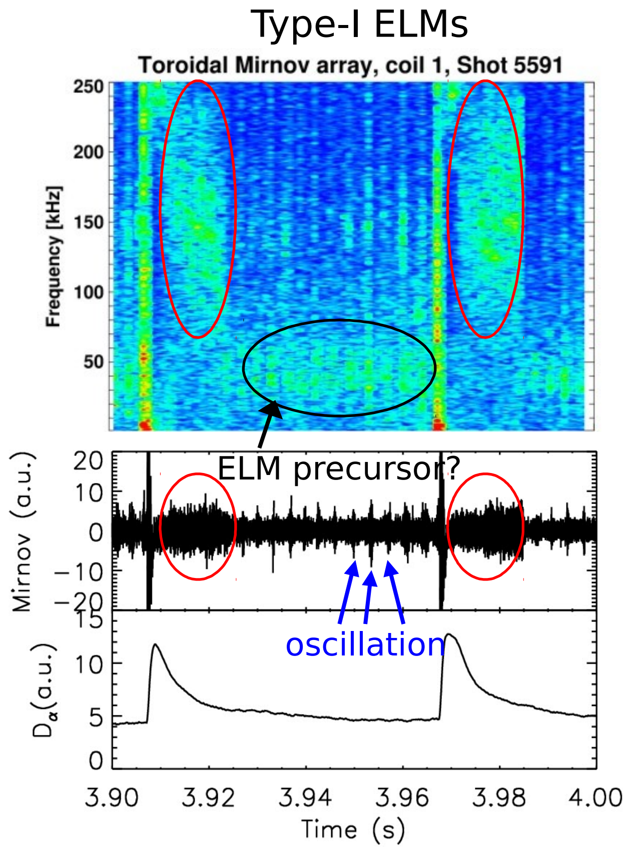


Figure 1. (*a*) Plasma configuration for ELM precursor measurement together with the line of sight of two FIR interferometers, D_α intensity, reflectometer and measured location of ECE radiometer. Waveforms of (*b*) D_α intensity at outer divertor, (*c*) line-integrated density, (*d*) phase change of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

Edge Localised Mode (ELM)

- **Example of ELM precursor**



KSTAR

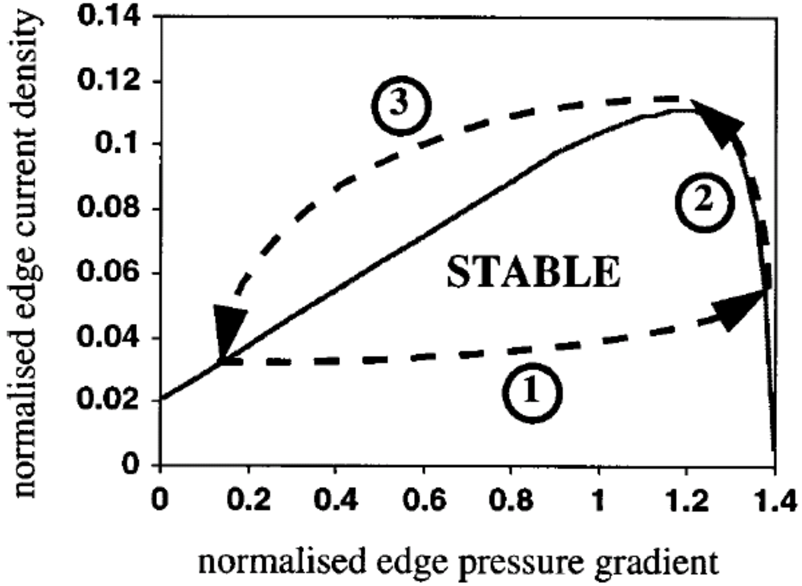
J-W. Ahn, et al, NF ***52*** *114001 (2012)*

Edge Localised Mode (ELM)

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

Edge Localised Mode (ELM)

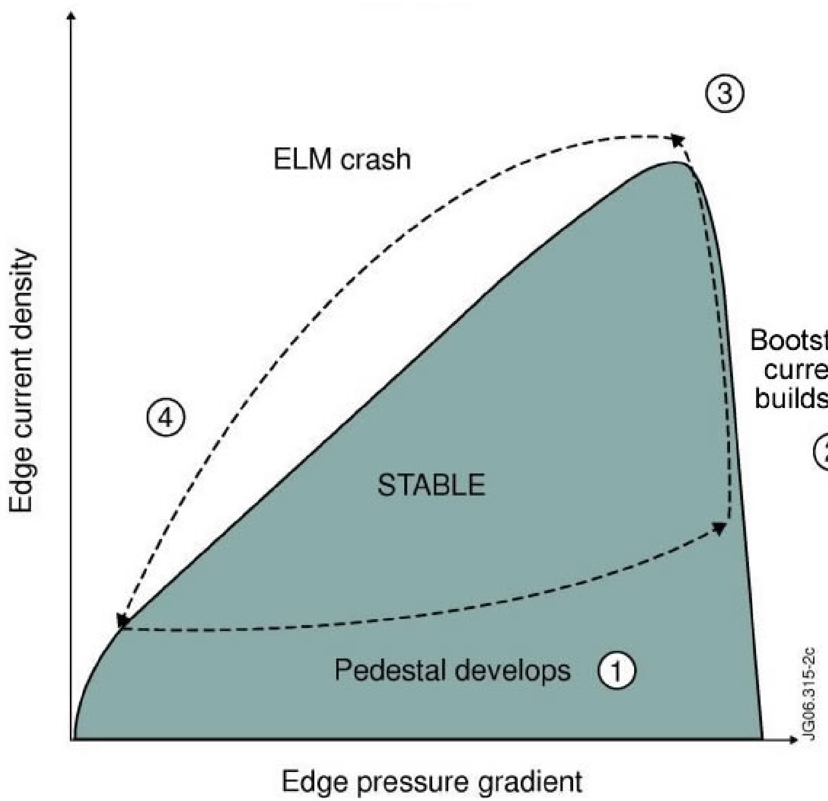
- **Peeling-Ballooning model for ELM cycle**



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

Edge Localised Mode (ELM)

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

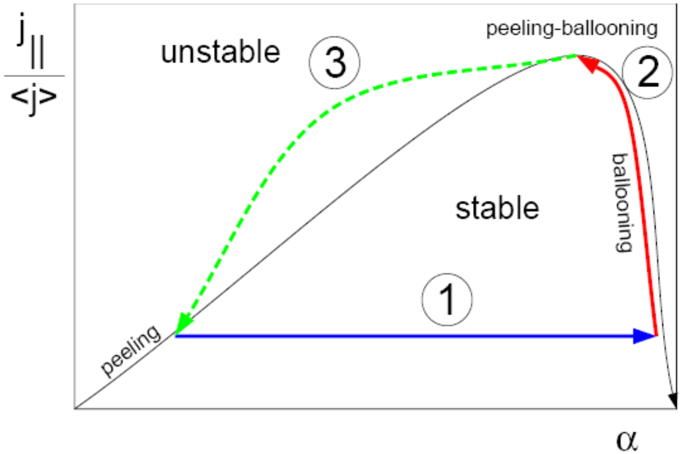


- The ELM cycle starts with a low pressure gradient as a result of the previous ELM crash that has removed the edge pressure "pedestal".
- Due to the edge transport barrier, the edge pressure pedestal devel-ops quickly (1).
- The growth of the pedestal stops at the so called "ballooning stability" limit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

HW. Bootstrap current time scale?

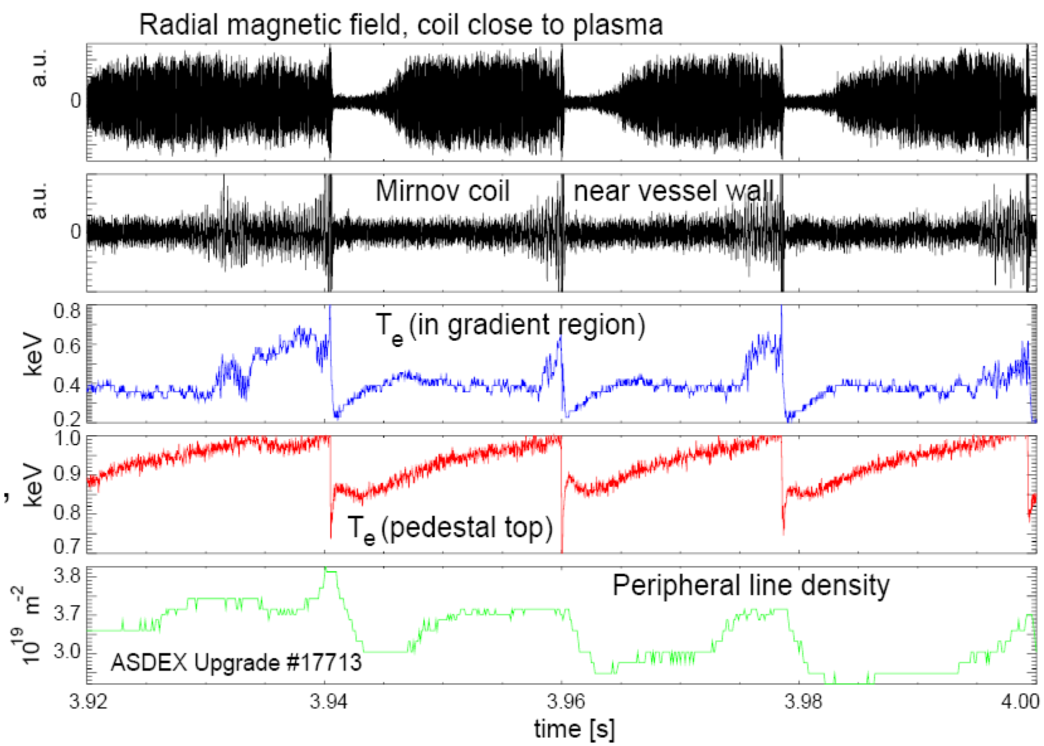
Edge Localised Mode (ELM)

- **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

ASDEX Upgrade H Zohm et. al., H-mode WS 2003



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

measure of the pressure gradient

Edge Localised Mode (ELM)

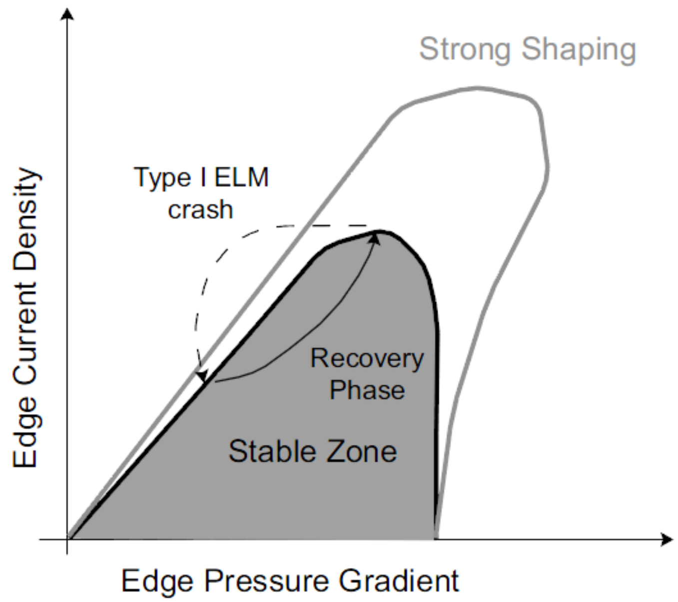
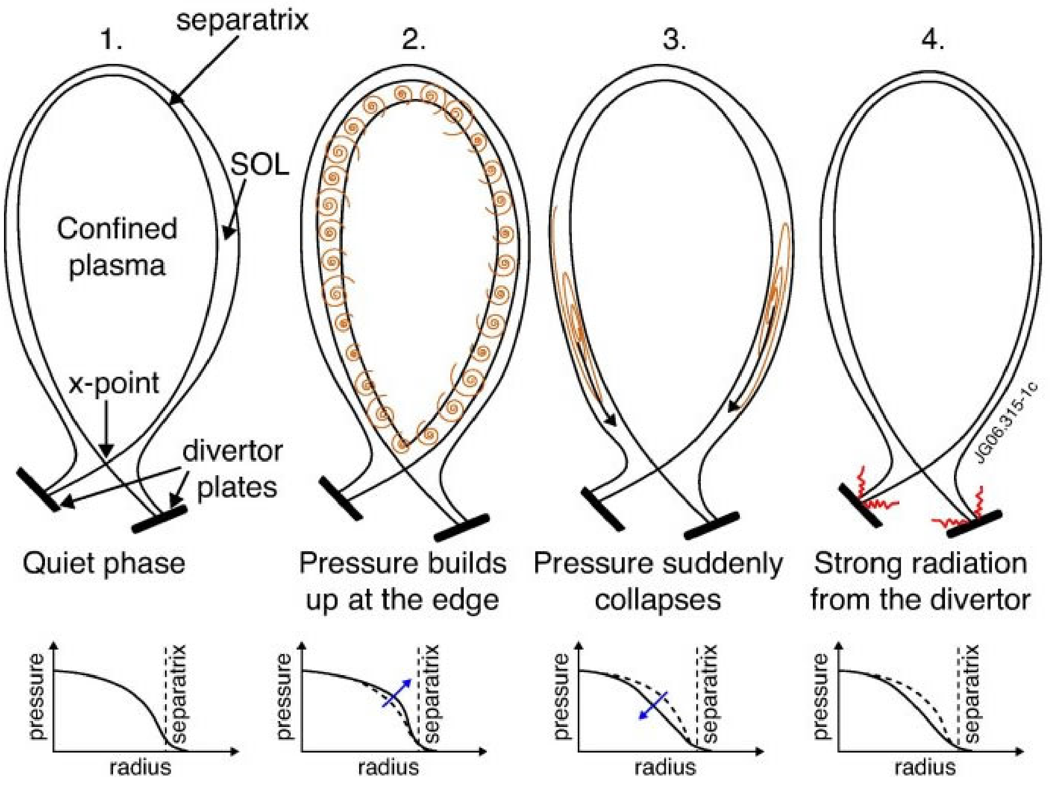
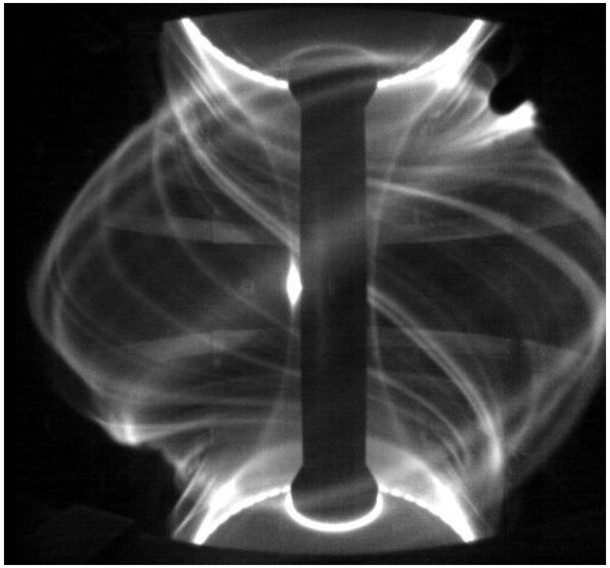


Figure 2. Schematic view of the edge stability boundaries showing the variation of pedestal boundaries with discharge shaping, limiting instabilities and model of the type-I ELM cycle.

* 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

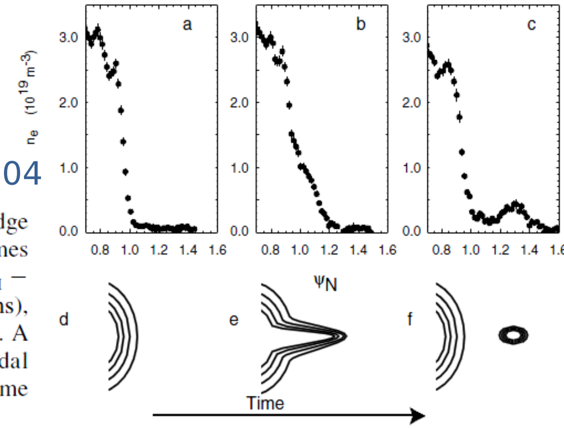
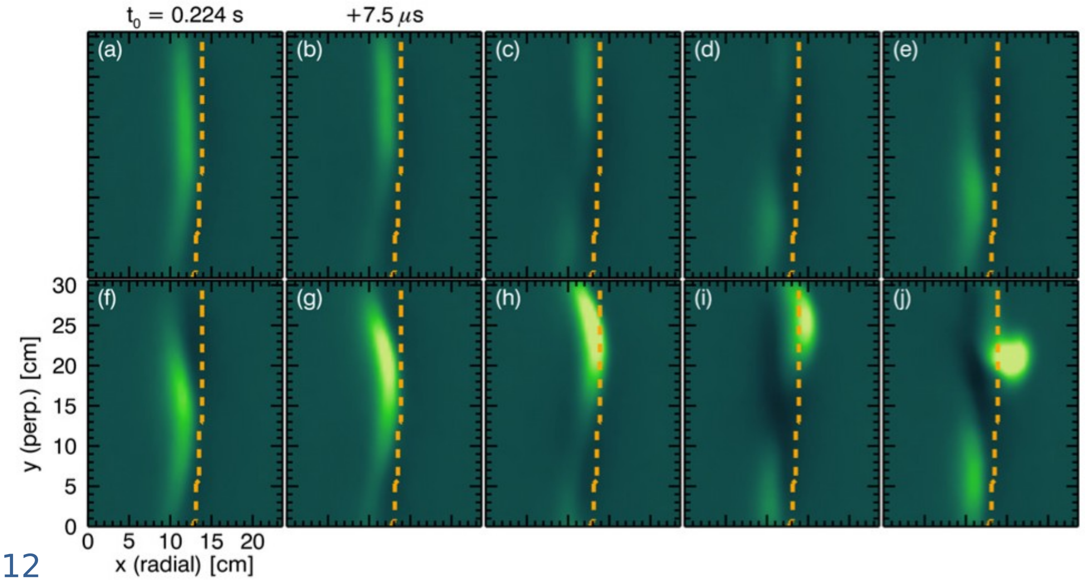


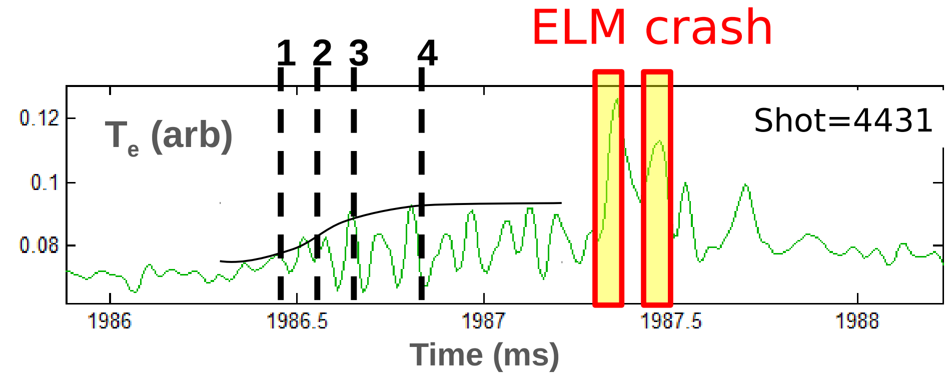
FIG. 2. Thomson scattering profiles of the outboard edge density in normalized flux coordinates at different times with respect to the start of a similar ELM. (a) Before (t_{ELM} − 770 ms), (b) in the middle of the ELM rise (t_{ELM} + 140 ms), and (c) near the end of the ELM rise time (t_{ELM} + 180 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.

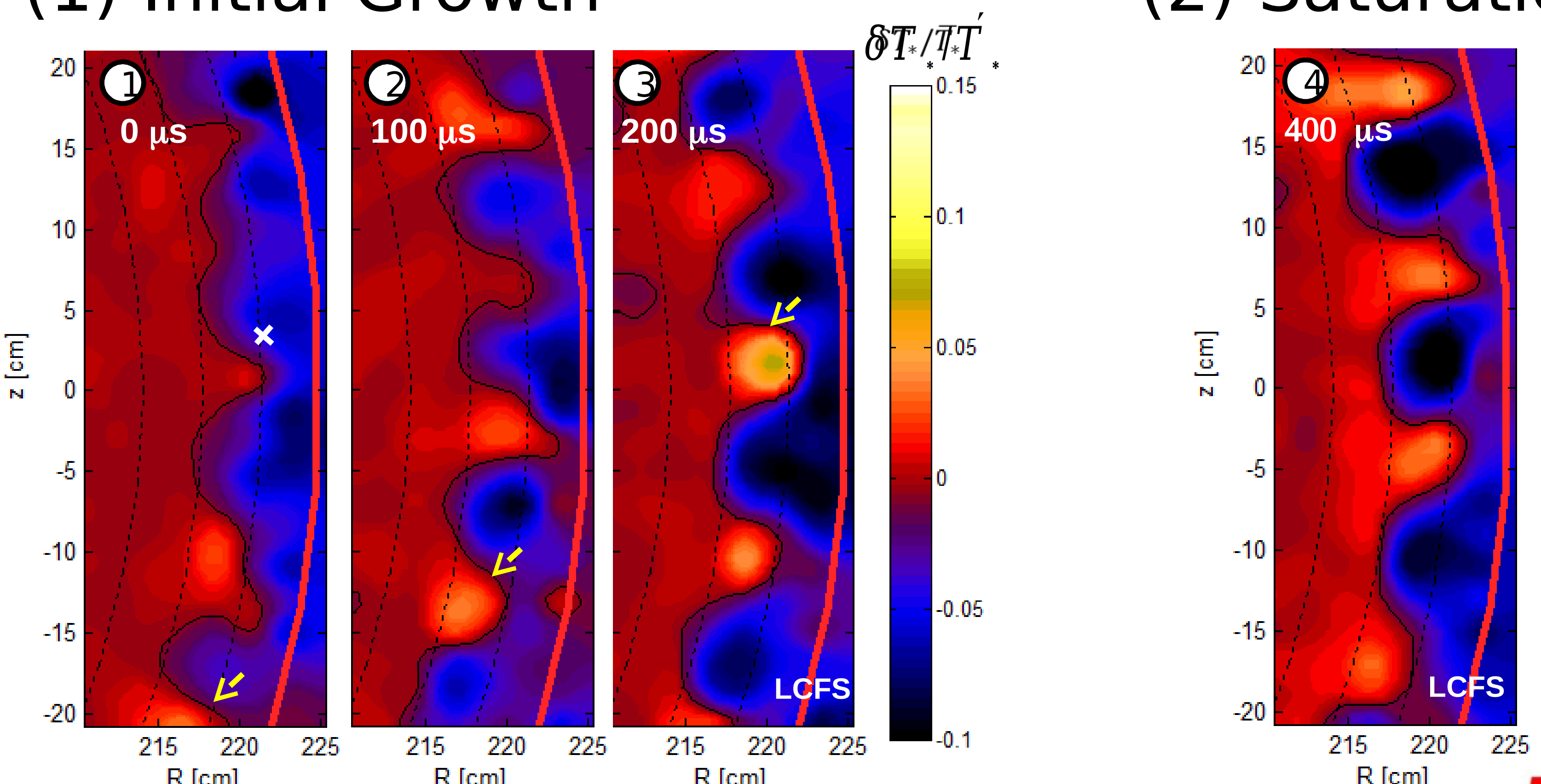
Standard ELM dynamics in the KSTAR visualized by an ECEI system*



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

(1) Initial Growth

(2) Saturation

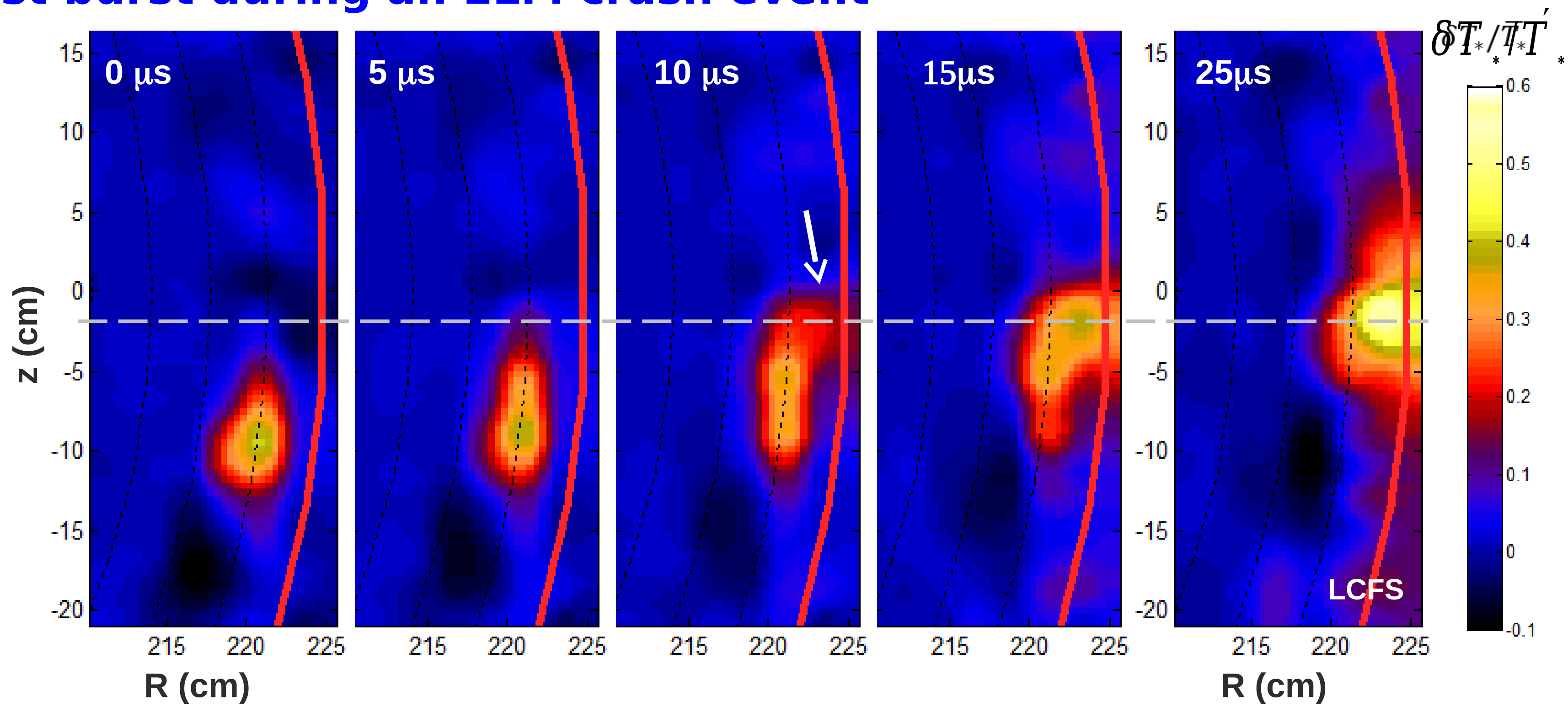


(3) Transient Period

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

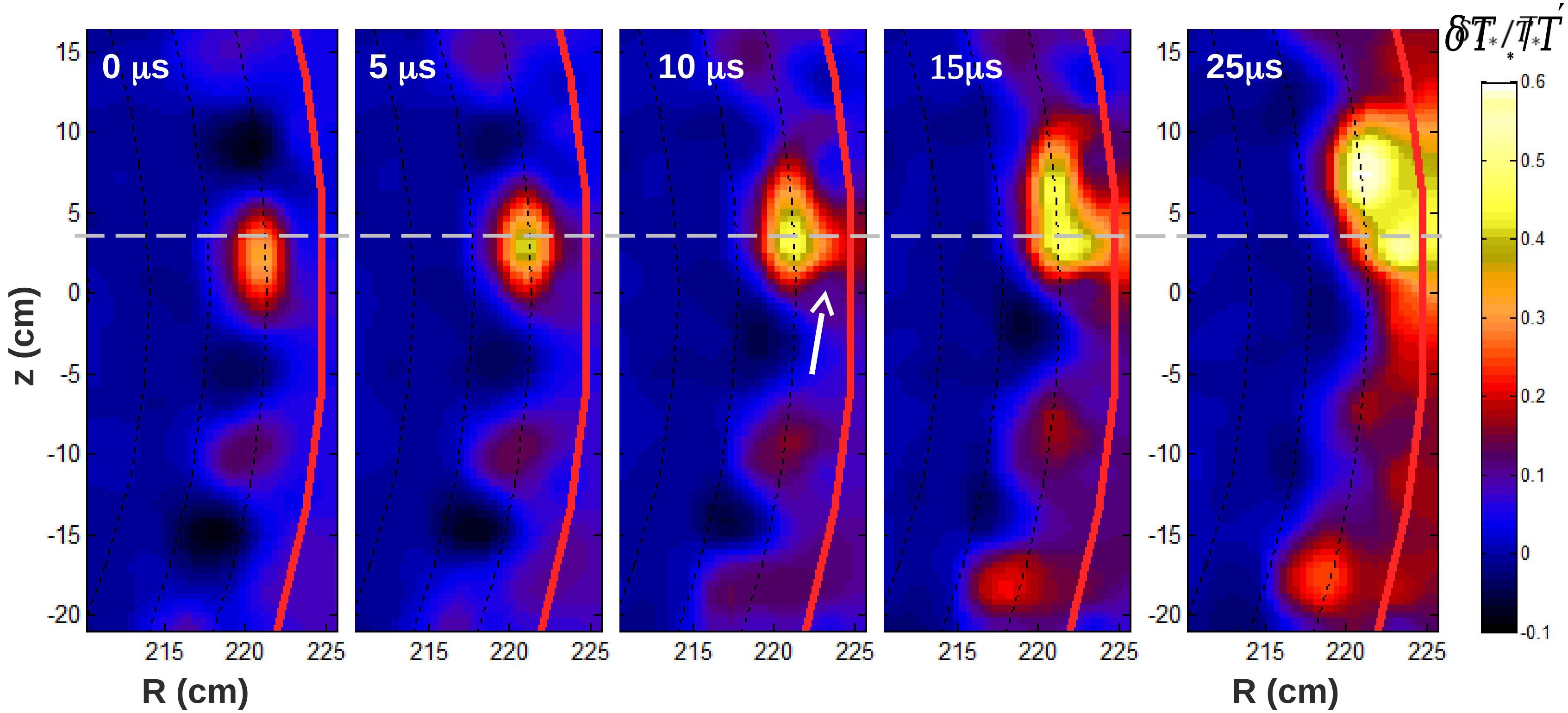
(4) ELM Crash = Multiple bursts of the filaments

he first burst during an ELM crash event



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

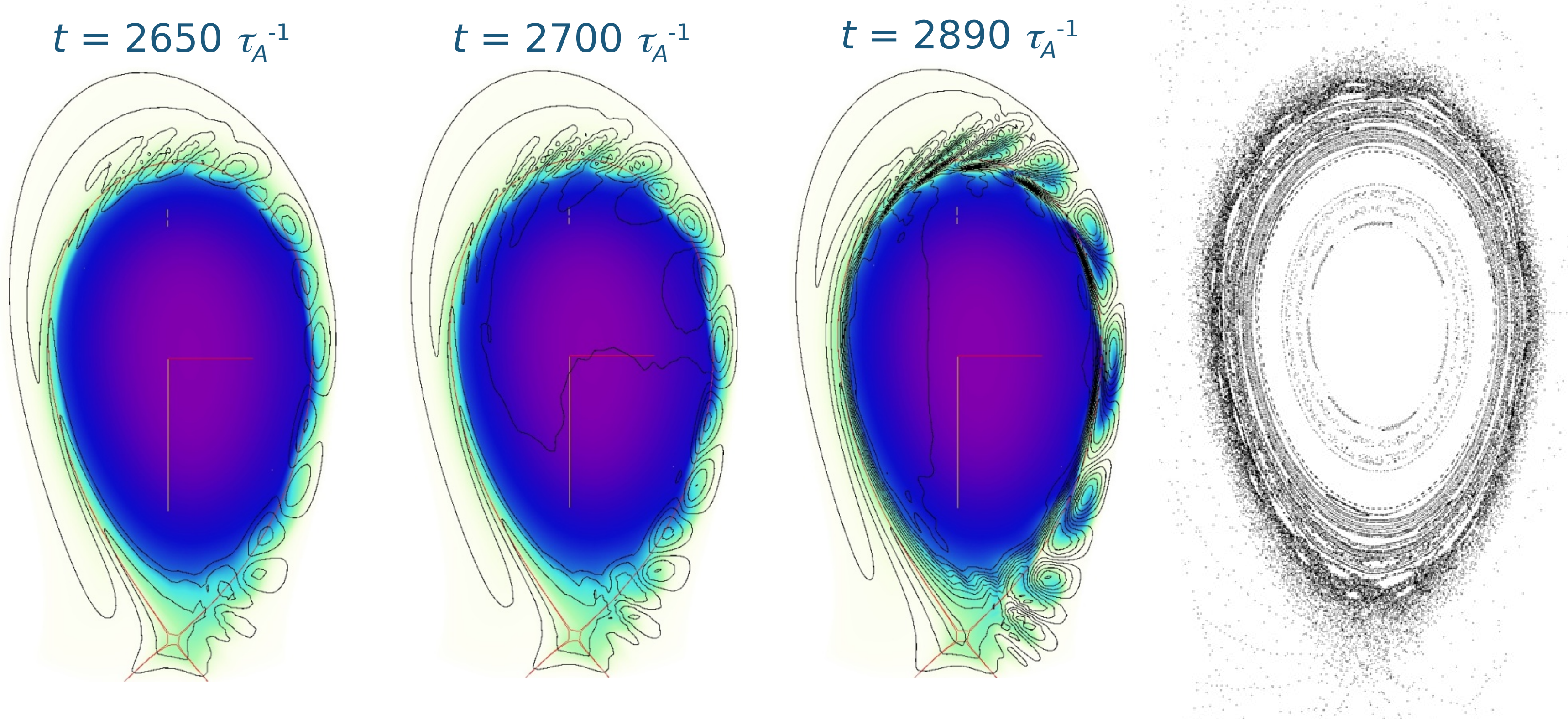
Another burst during the same ELM crash event



- **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.

Edge Localised Mode (ELM)

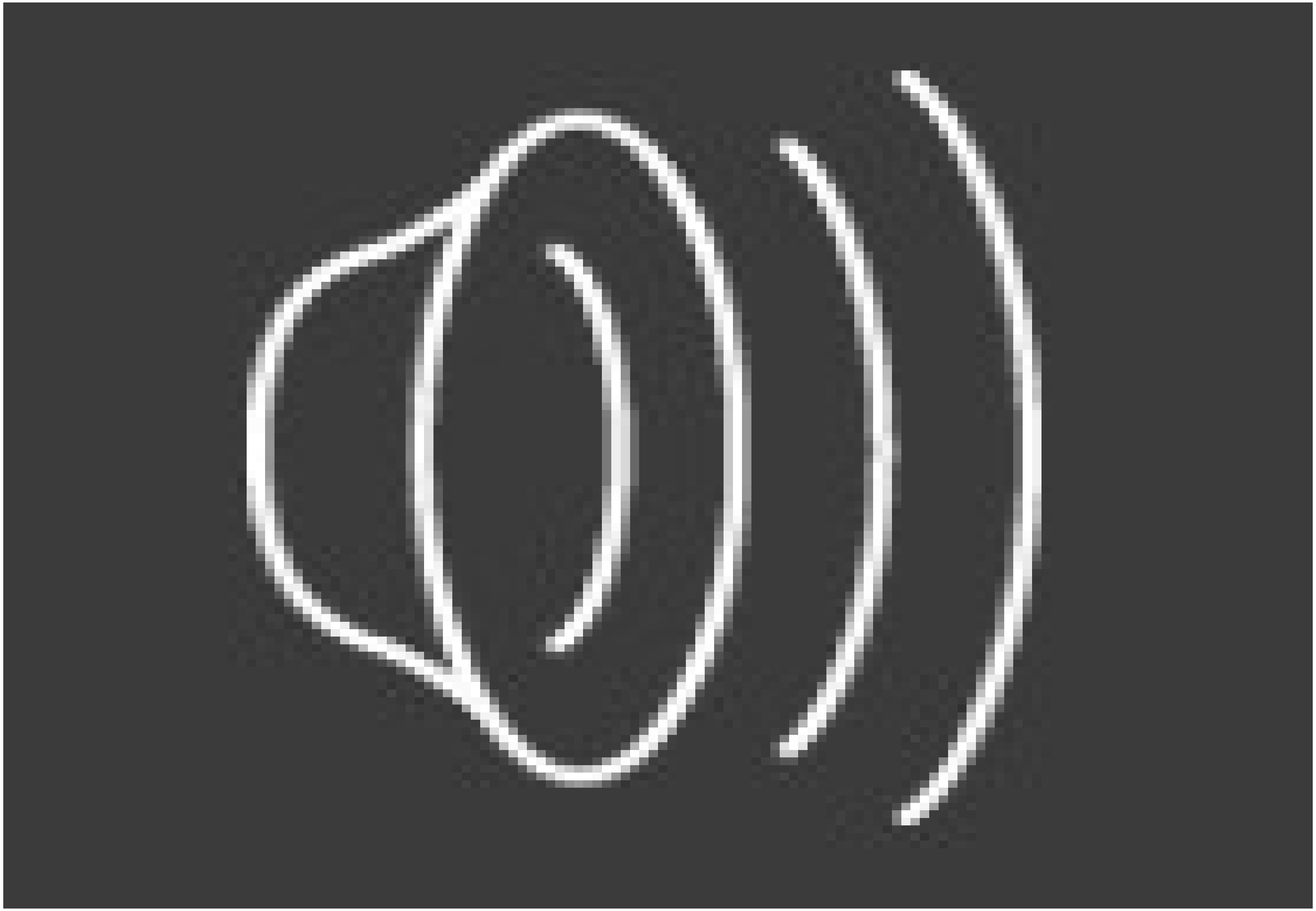
- Non-linear MHD simulations with JOREK reproduce the formation of multiple filaments expulsed from plasma



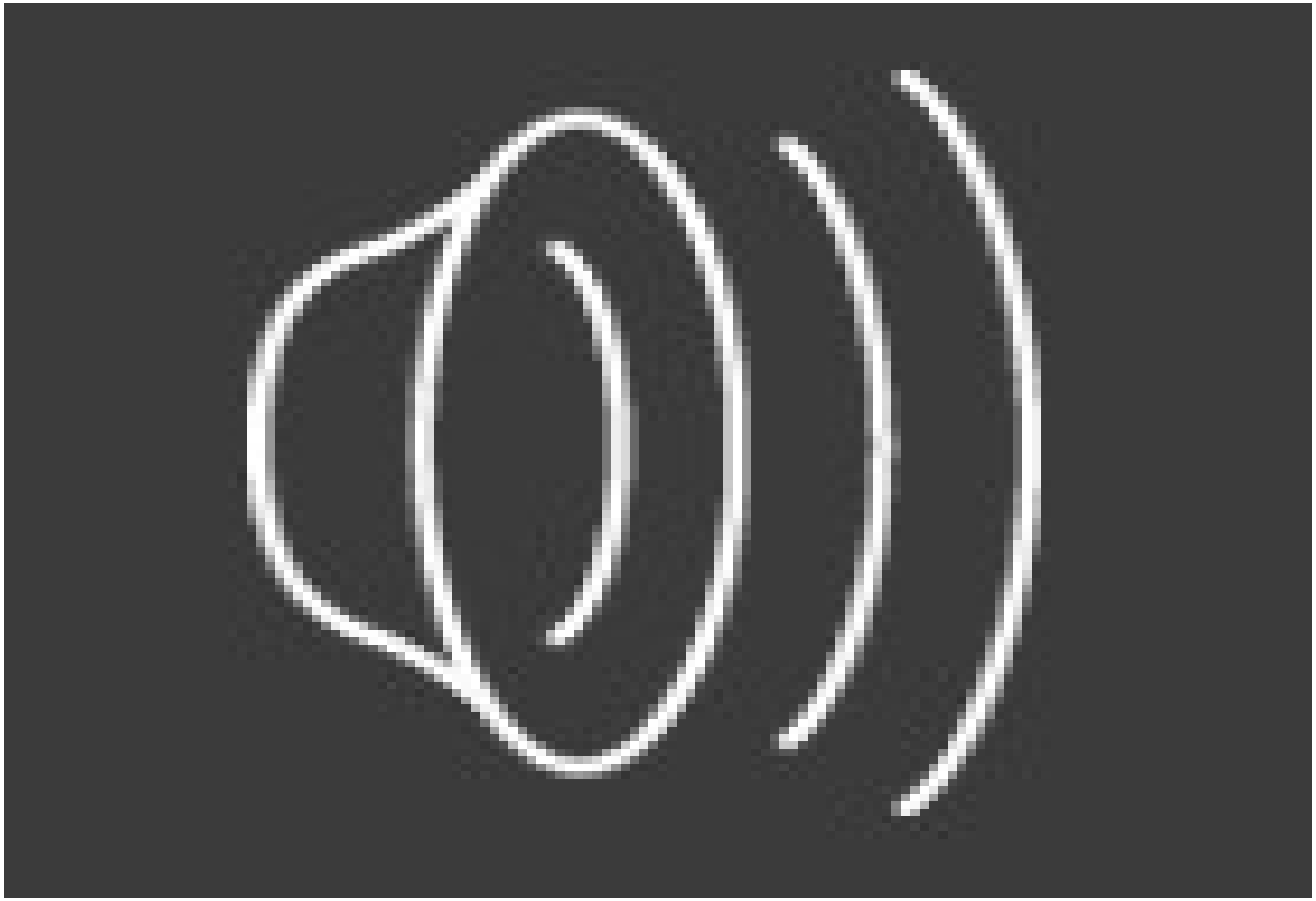
Evolution of n = 6 ballooning mode

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

Edge Localised Mode (ELM)



Edge Localised Mode (ELM)



By SangKyeun Kim (SNU)

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)

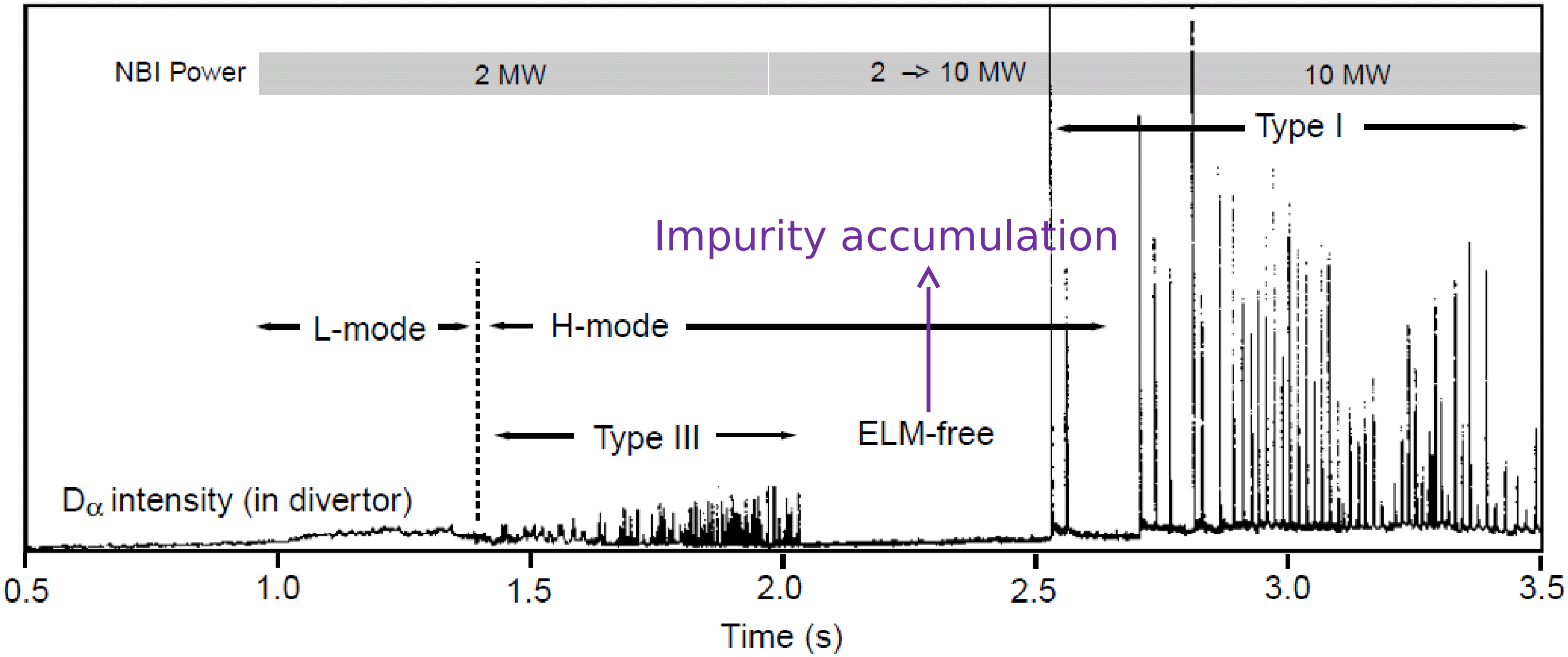
- **Type of ELMs**

- ‘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 → advantage of ELMs
- 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_{α} 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)

- **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, $|\phi_q|^2$

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

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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)	$\gamma > 0$	$\gamma > \Delta\omega\gamma_d\alpha^{-1}$	$\gamma > \Delta\omega\gamma_d\alpha^{-1}$

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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

Multiple predators are possible

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

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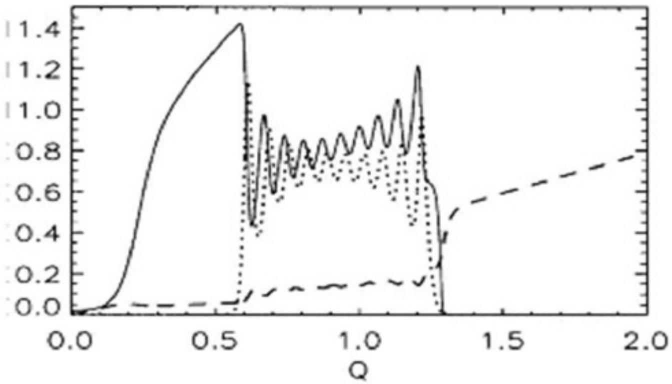
Edge Localised Mode (ELM)

- **Dithering or I-phase**

Feedback Loops III, cont'd

- 

Solid - $\mathcal{E}$

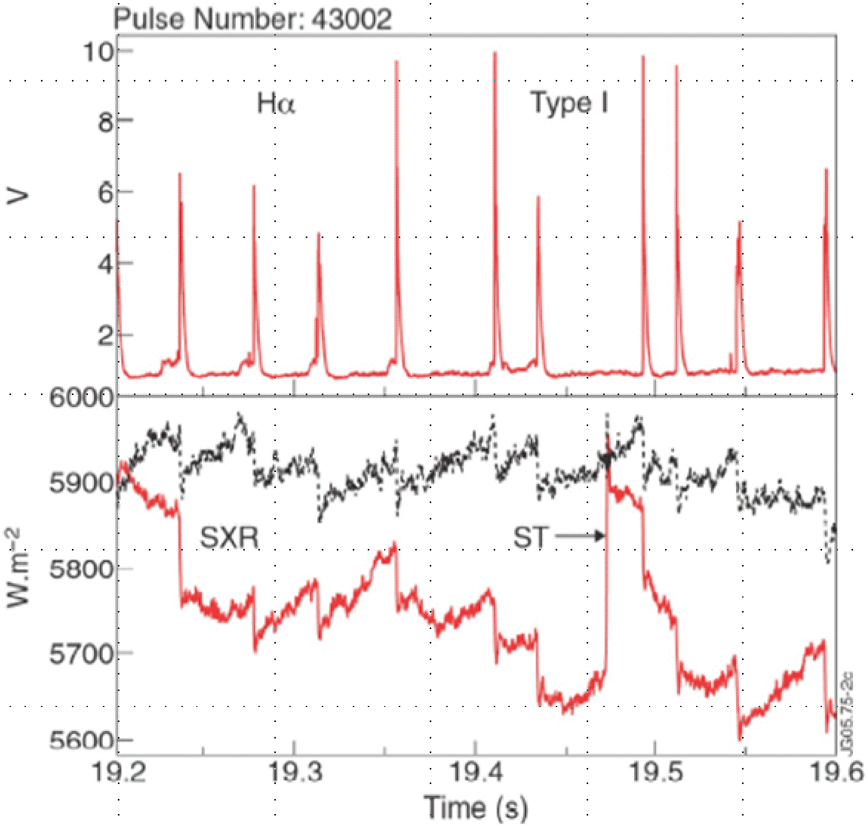
Dotted - V_{ZF}

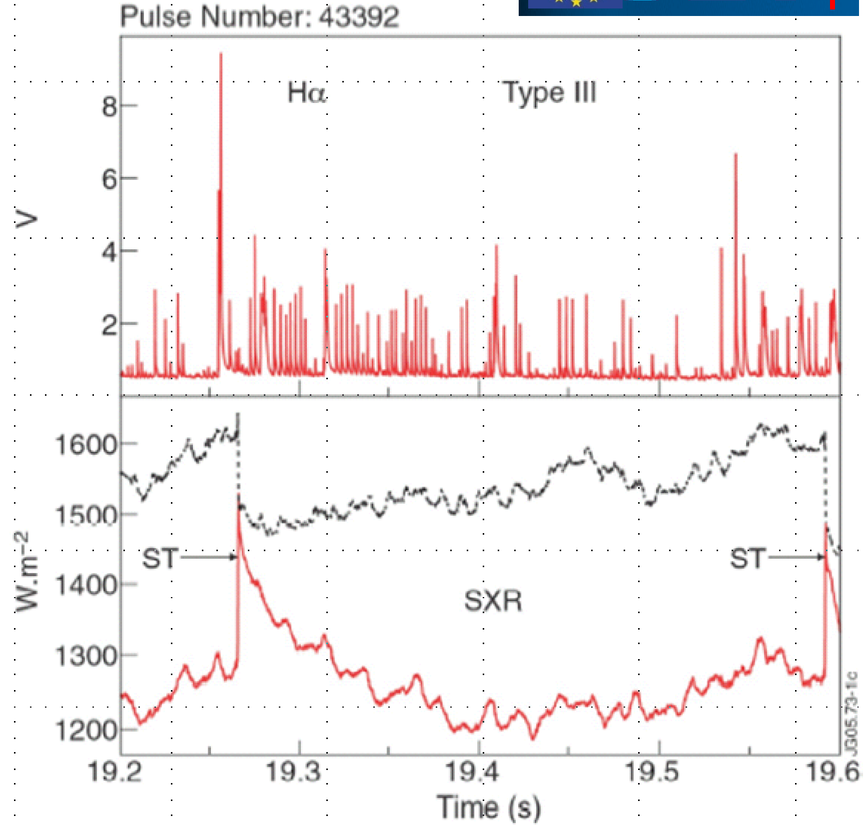
Dashed - $\nabla\langle P\rangle$

- 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 $\uparrow$
  - 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**



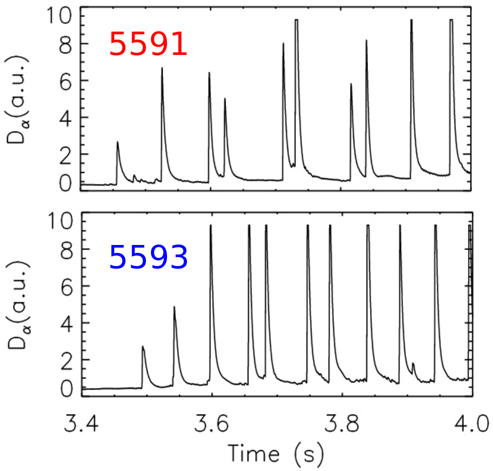


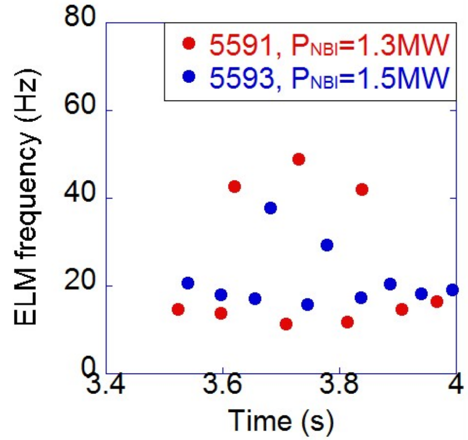
- **Type I:** „Large“ ELMs
  – low frequency which rises with input power with significant effect (lowering) of ETB pressure.

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

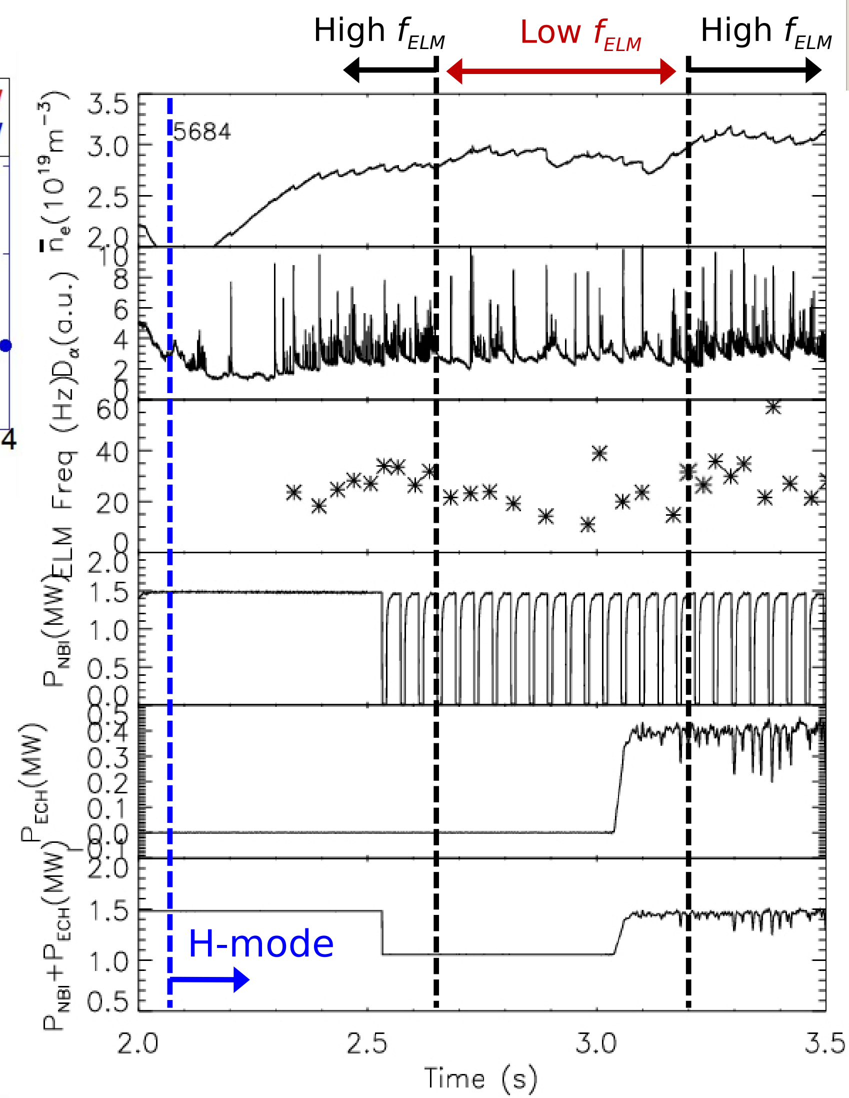
Edge Localised Mode (ELM)

Large ELMs





Mixed ELMs

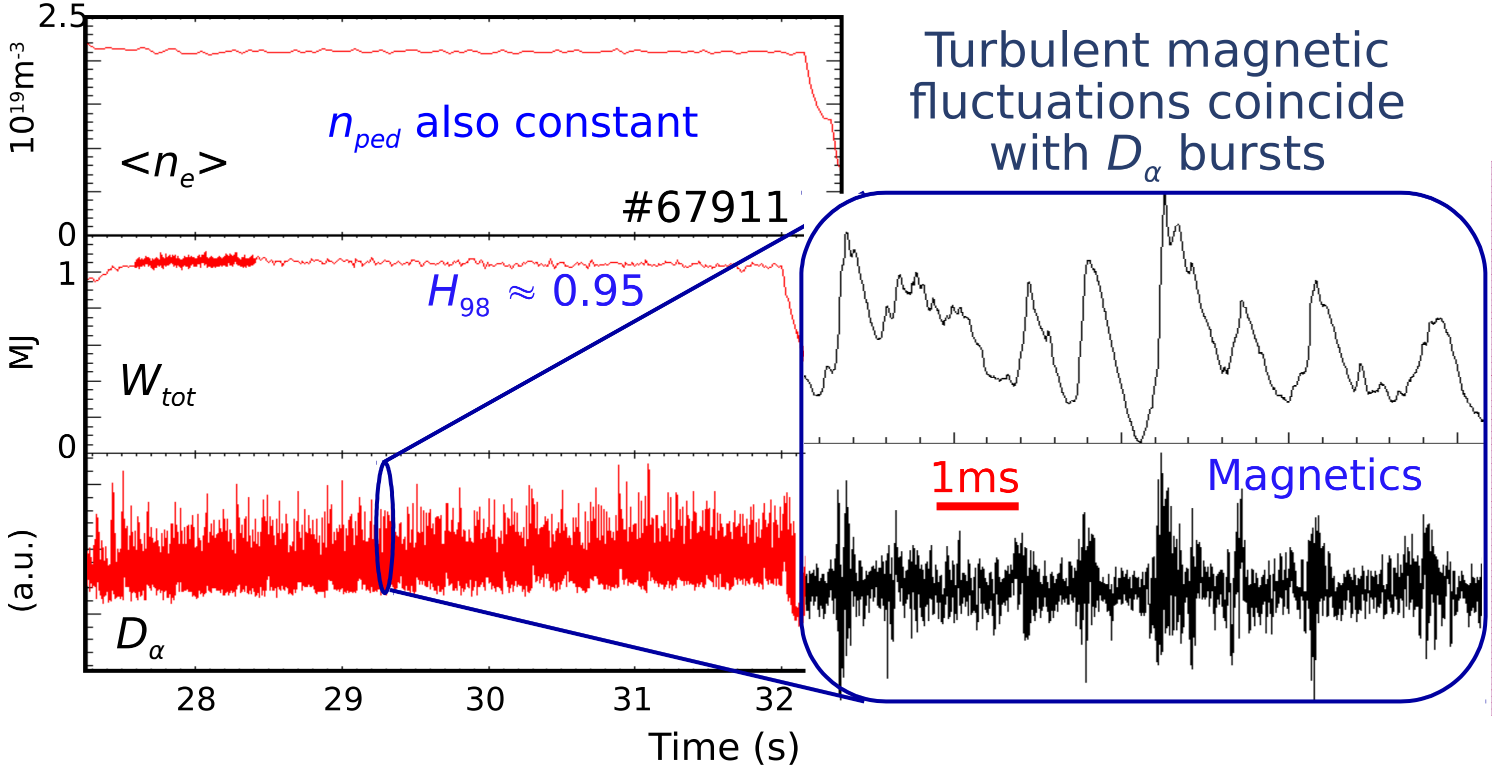


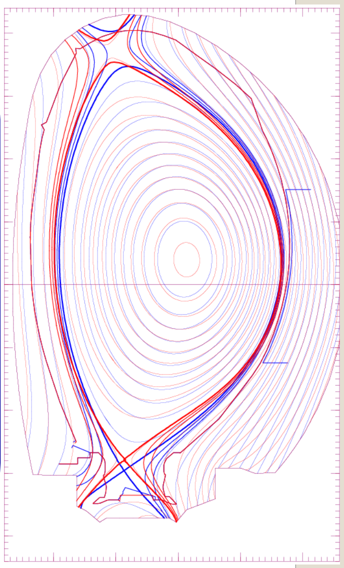
- Power scan shows f_{ELM} goes up with increasing NBI power □ type-I ELMs
- Large peaks of mixed ELM also follows the characteristics of type-I ELMs with the combined power of NBI+ECH

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

Edge Localised Mode (ELM)

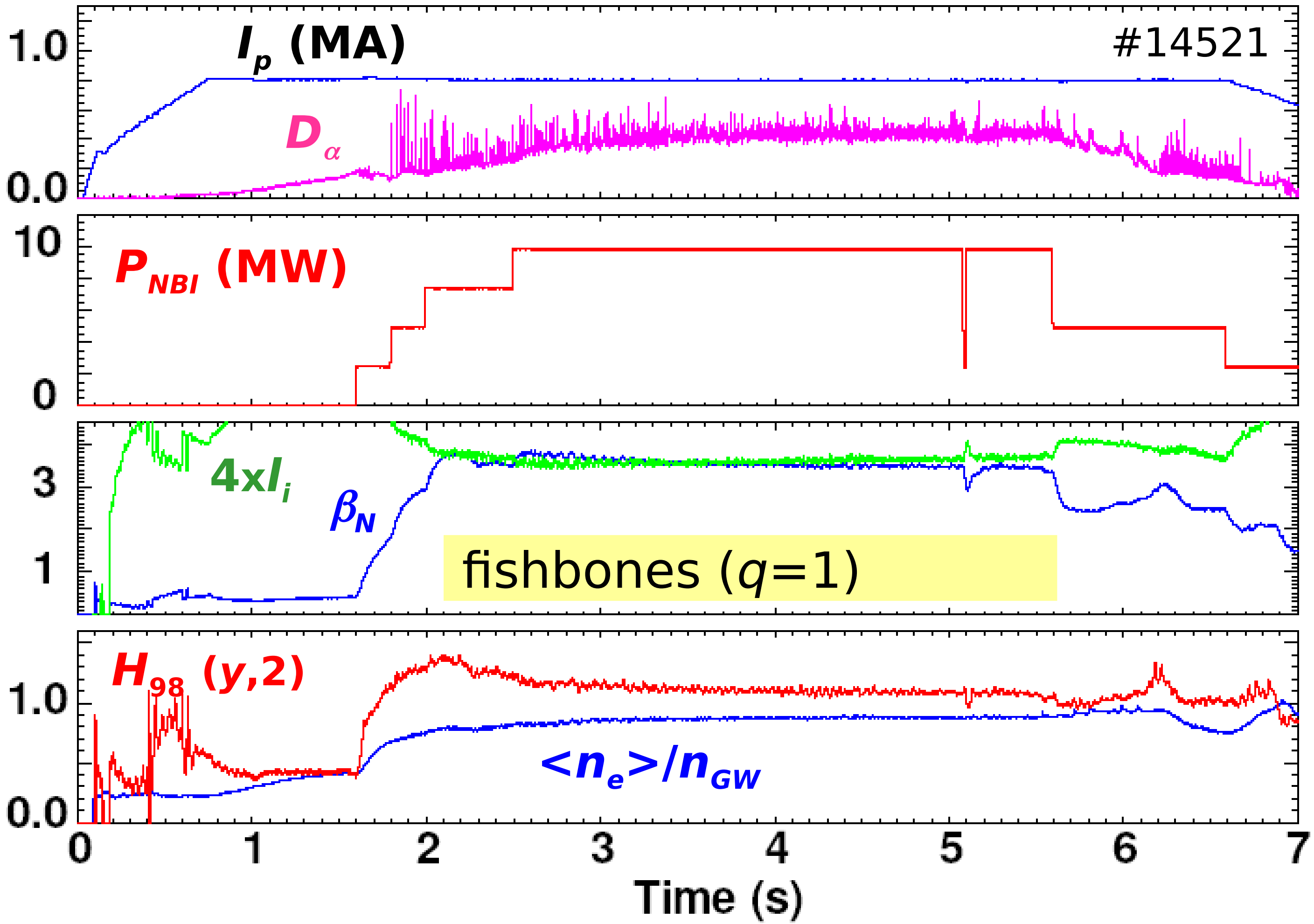
- **Type II (or 'grassy') ELMs**





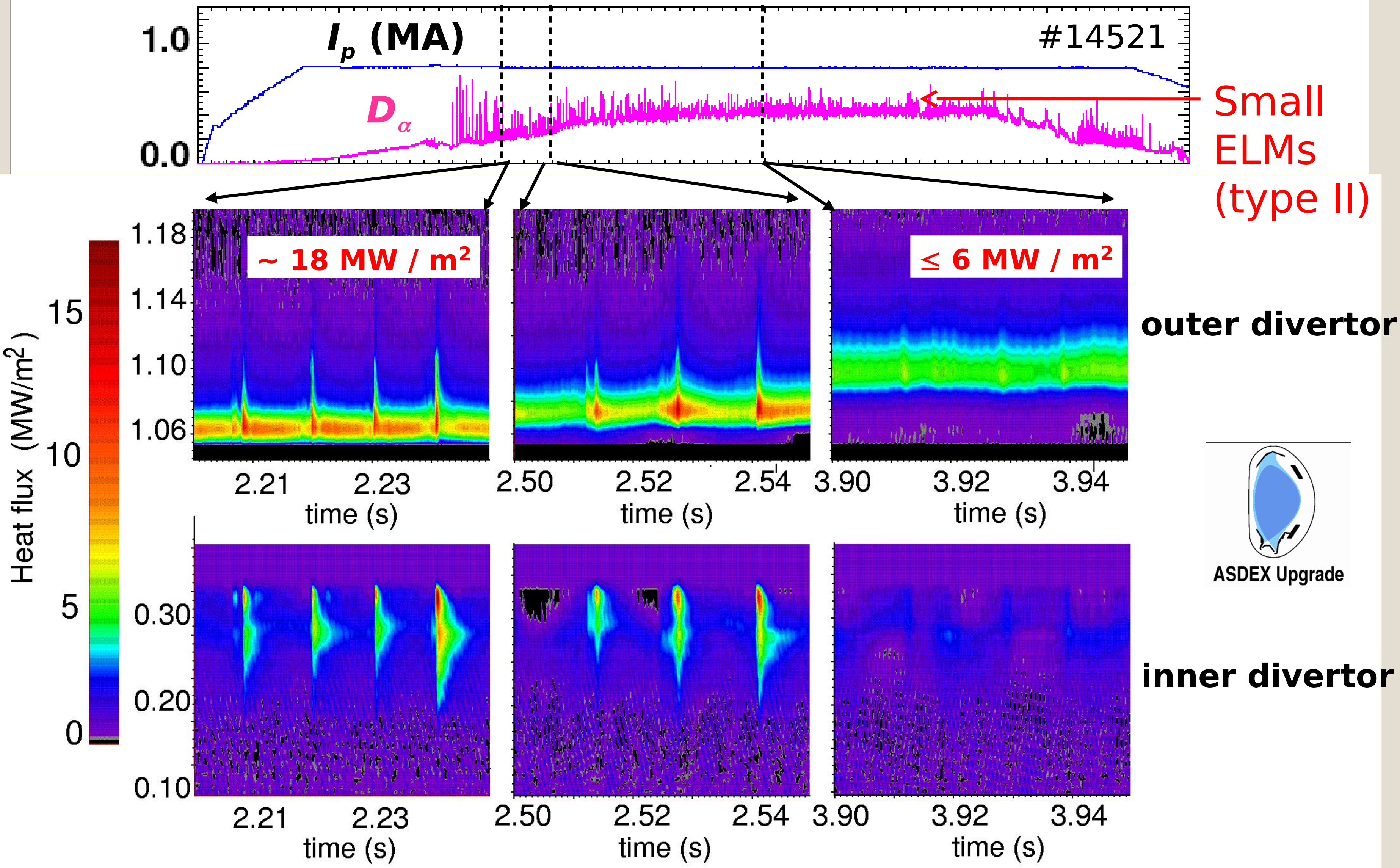
- ELM behaviour constant over pulse
- Very fine scale activity: distinct ELMs almost indistinguishable

Edge Localised Mode (ELM)



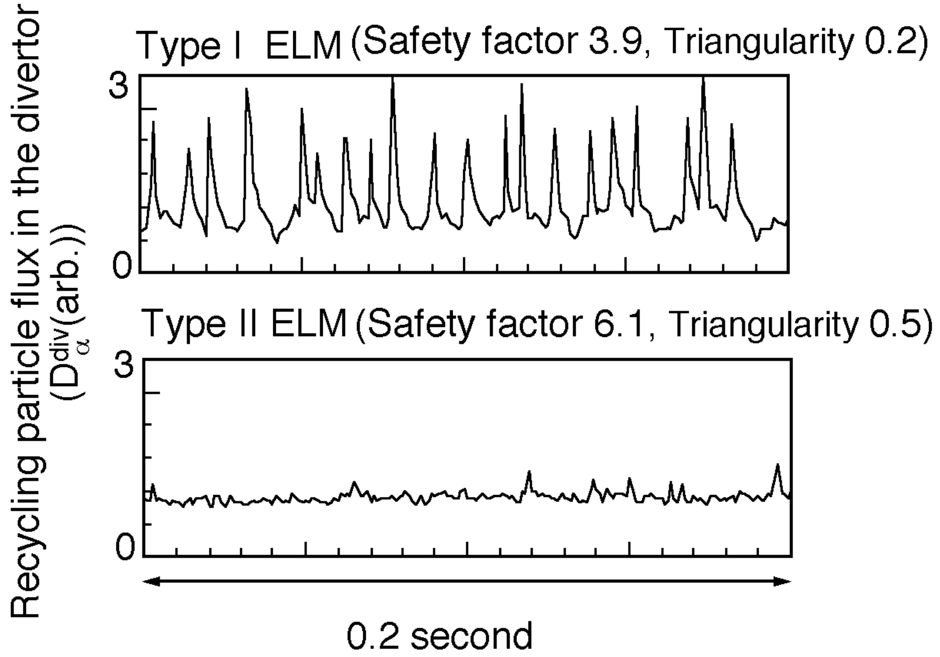
- No sawteeth, good confinement, and $\beta_N \sim 3.5$, $T_i \sim T_e$, $<n_e>/n_{GW} \sim 0.88$, averaged over 3.6 seconds ($\sim 50\ \tau_E$).

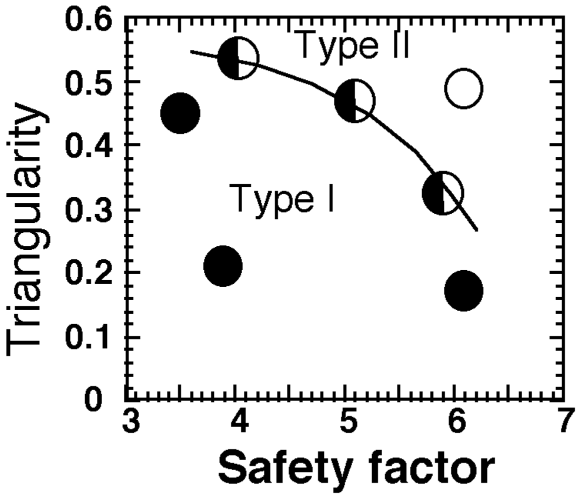
Edge Localised Mode (ELM)



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.

Edge Localised Mode (ELM)

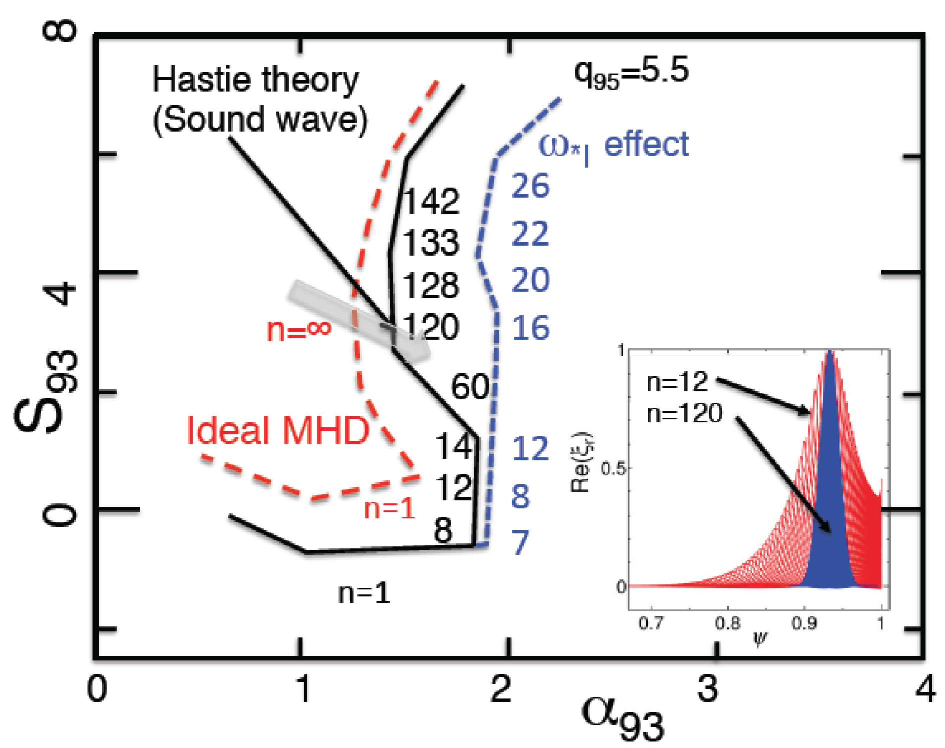
- **Type II (or ‘grassy’) ELMs**

- 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)

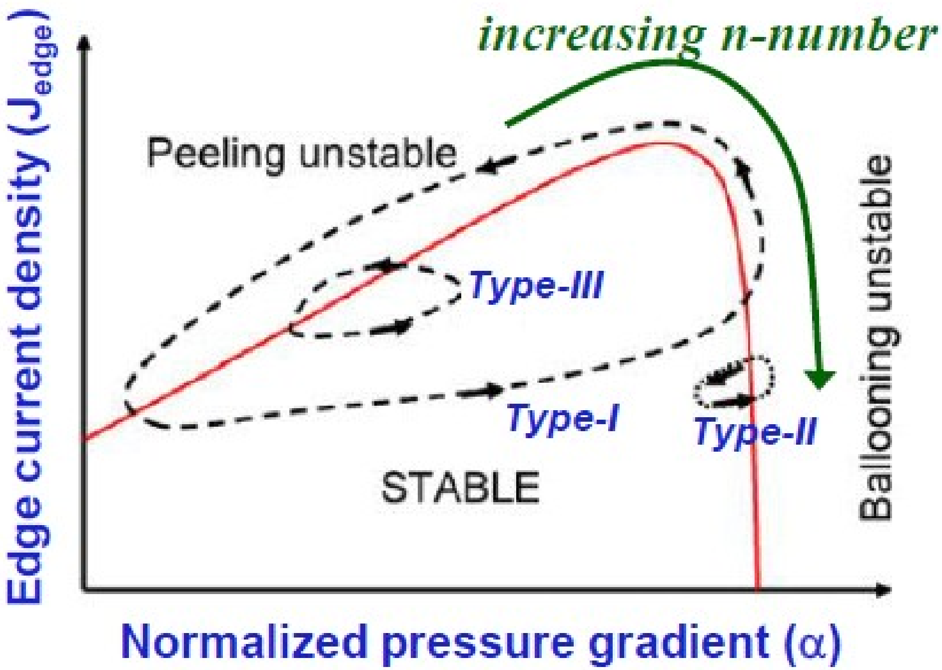
- **Type II (or 'grassy') ELMs**



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

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)

ASIPP

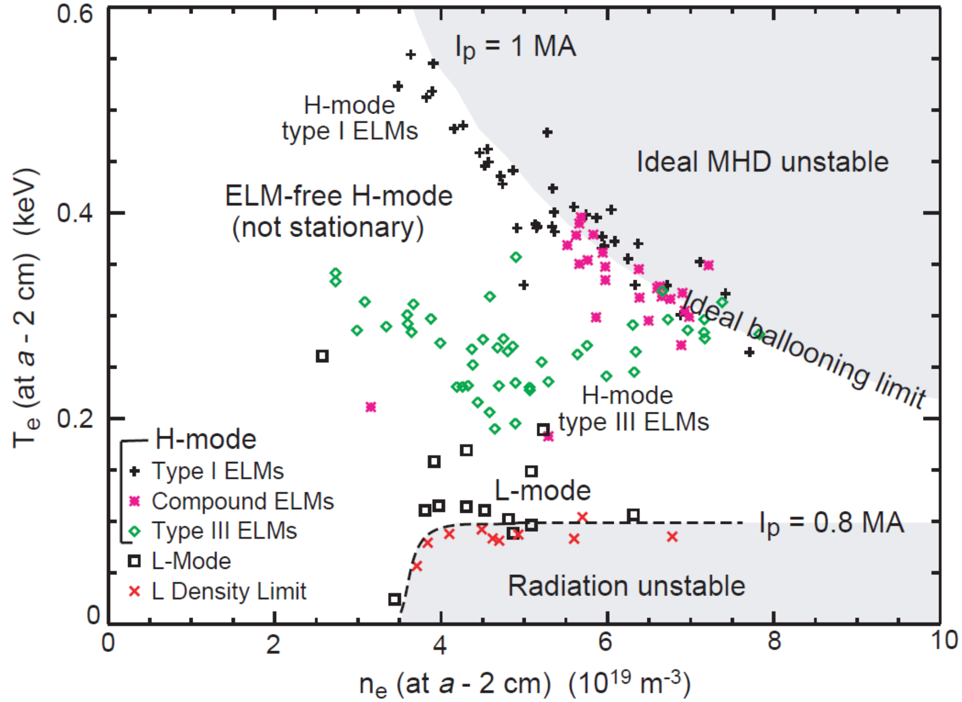
- **Type of ELMs**

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:** H-mode operational diagram



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

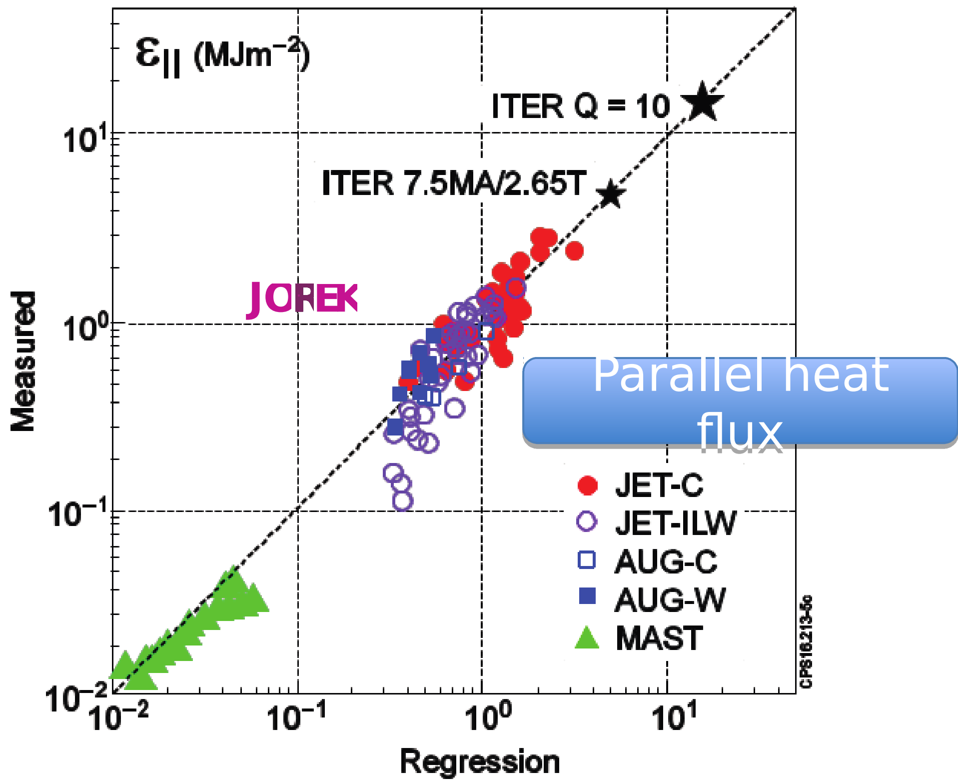
- Boundaries indicating different types of confinement regime marked
- The limiting bound of edge pressure (*nT*) corresponds closely to the predicted ∇*p* for onset of ideal MHD ballooning limit for type I ELMs.
- Discharges can sit at the ballooning limit for some time before an ELM occurs → suggesting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

Revised ELM Divertor heat flux Scaling Projects to smaller ELMs in ITER

- **Peak ELM heat load proportional to machine size and pedestal pressure**
- **Projection for ITER significantly lower than previous estimates (10x reduction)**
- **ELM simulation with JOREK reproduces empirical scaling**

Litaudon, FEC2016, OV1-4
Pamela, FEC2016, TH/8-2

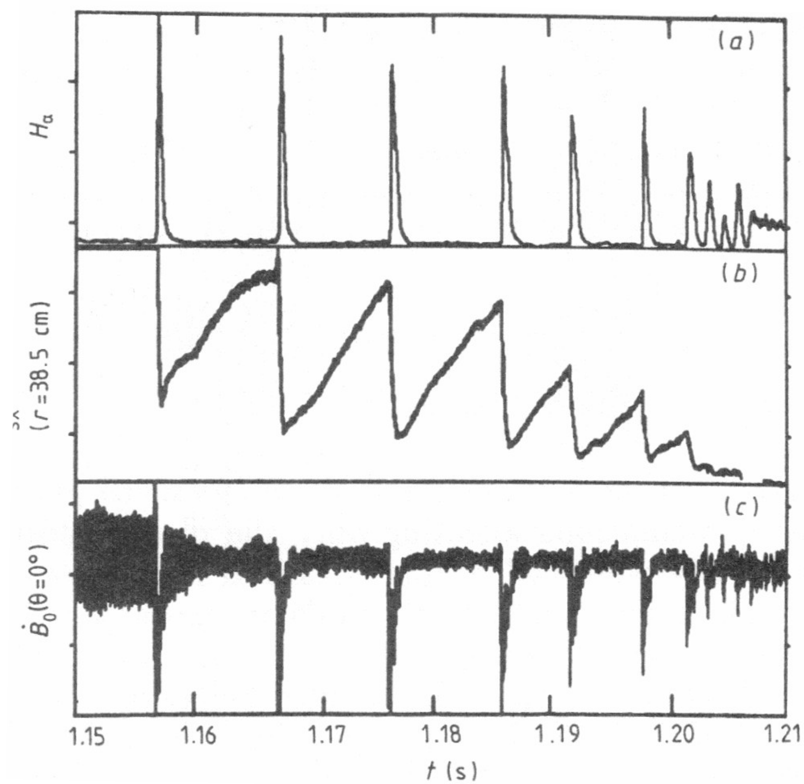
$$\varepsilon_{\|}\left(MJ/m^{2}\right) \propto R^{1.0} n_{e,ped}^{0.75} T_{e,ped}^{0.98} \left(\Delta W/W\right)^{0.5}$$



Edge Localised Mode (ELM)

ASDEX Upgrade

- **Type of ELMs**



- During the H-L transition phase

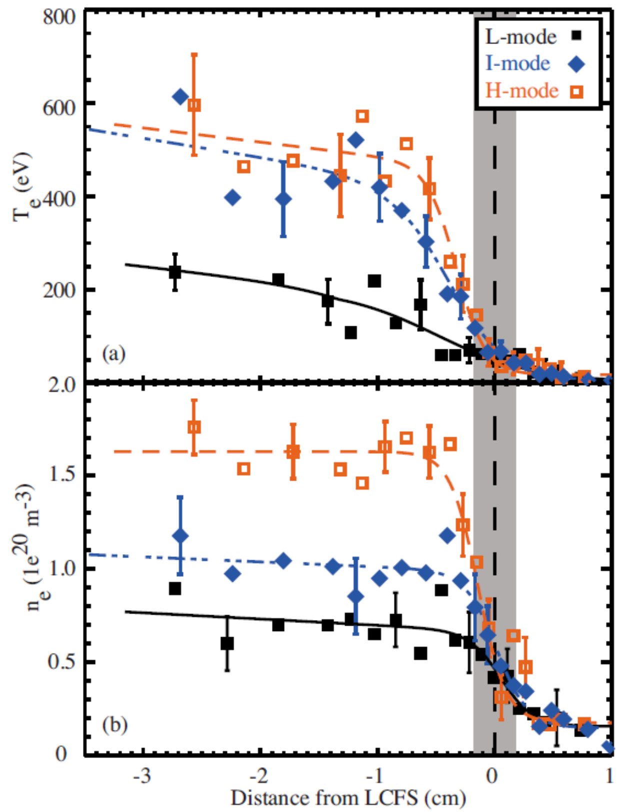
- Frequency of relaxation oscillations grows gradually, the amplitude decays, and towards the end of the ELM a transition from H- to L-mode confinement occurs.

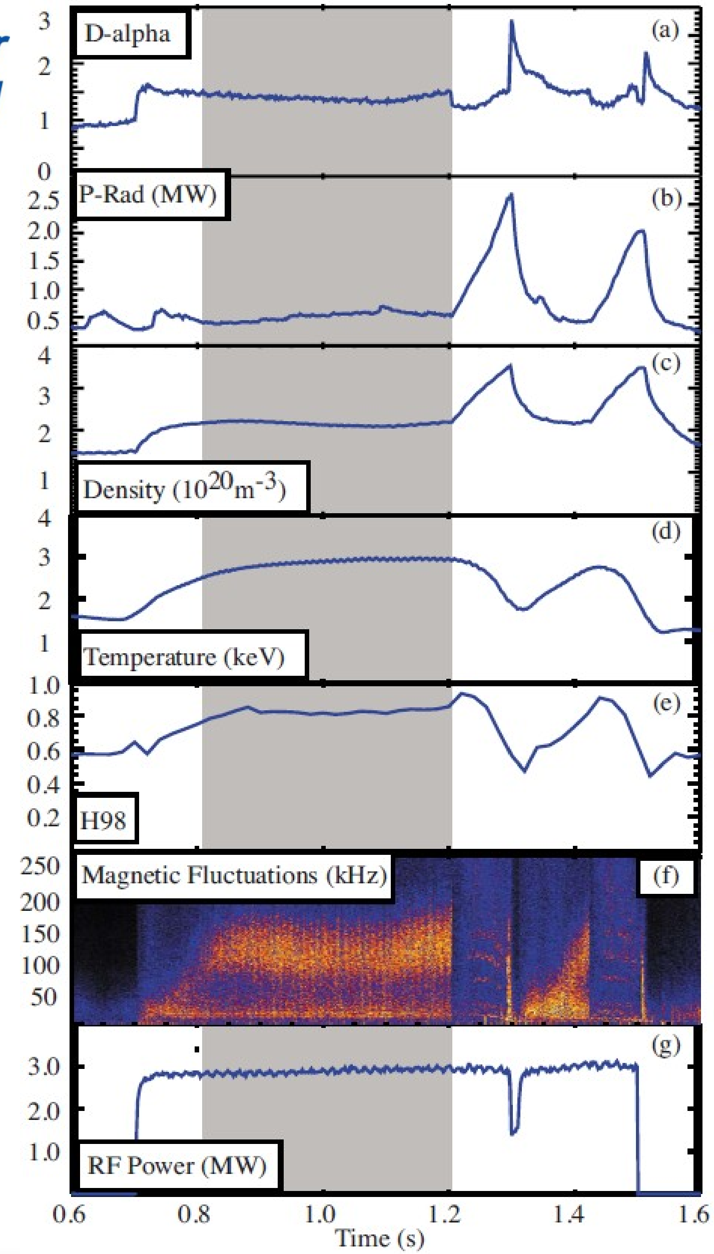
Fusion Reactor Technology 2
(459.761, 3 Credits)

Prof. Dr. Yong-Su Na

(32-206, Tel. 880-7204)

I-mode

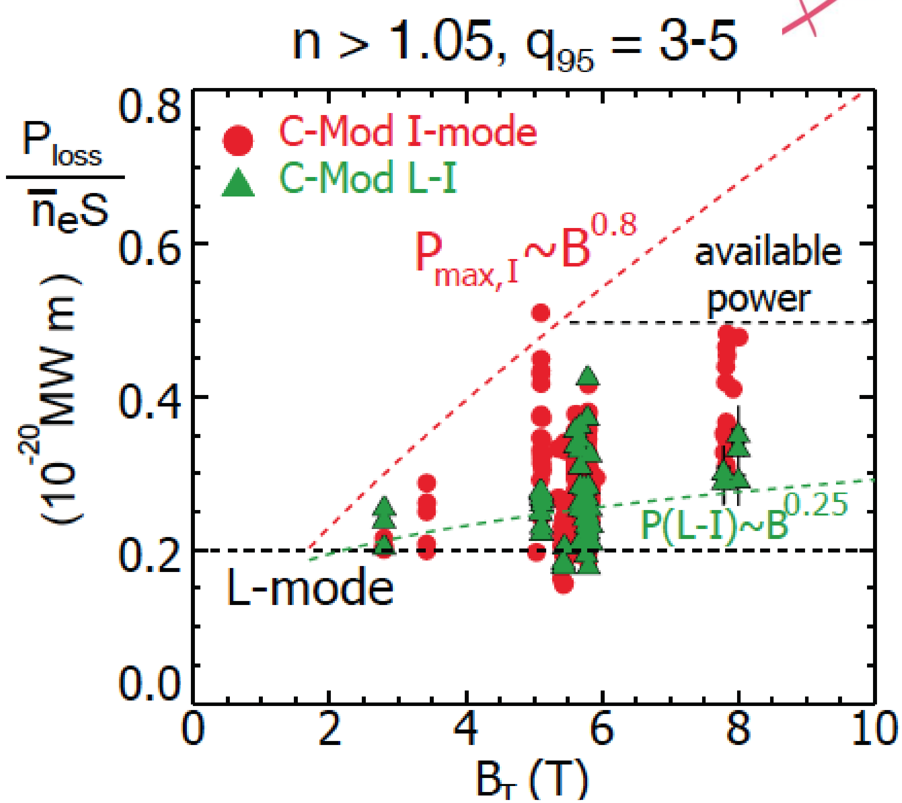


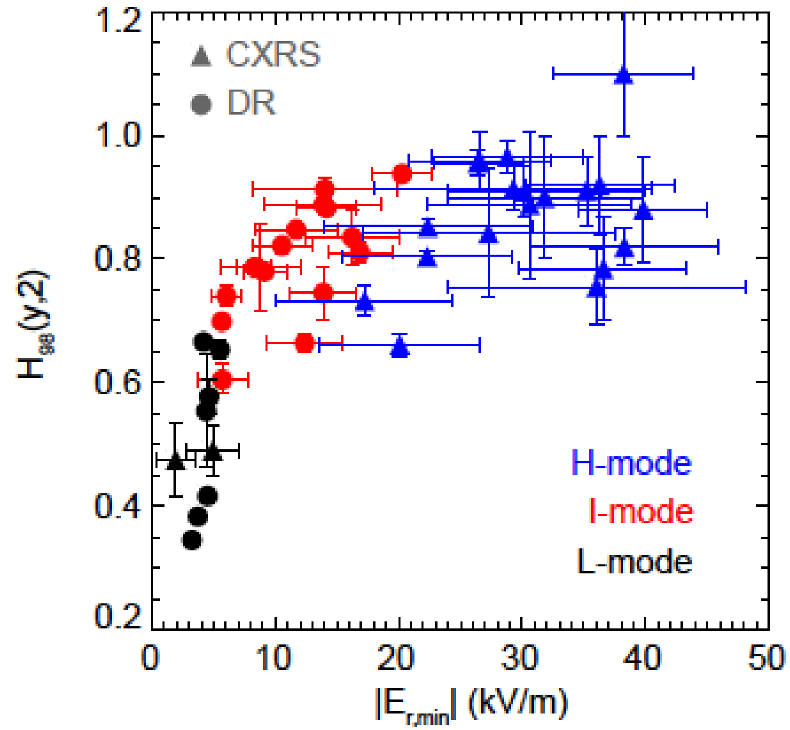


- Only observed in discharges with the *X*-point in the unfavorable drift direction
- suggesting that edge conditions altered such that the particle and energy transport can be decoupled.

McDermott et al, Phy. Plasmas 16 056103 (2009)

I-mode


n > 1.05, q95 = 3-5
C-Mod I-mode
C-Mod L-I
Pmax,I~B0.8
available power
P(L-I)~B0.25
L-mode
Ploss / neS (10-20MW m)
BT (T)
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10


CXRS
DR
H-mode
I-mode
L-mode
H98(y,2)
|Er,min| (kV/m)
1.2
1.0
0.8
0.6
0.4
0.2
0
10
20
30
40
50

EDA-mode

H.W. What is EDA-mode?

In which devices is it being observed?

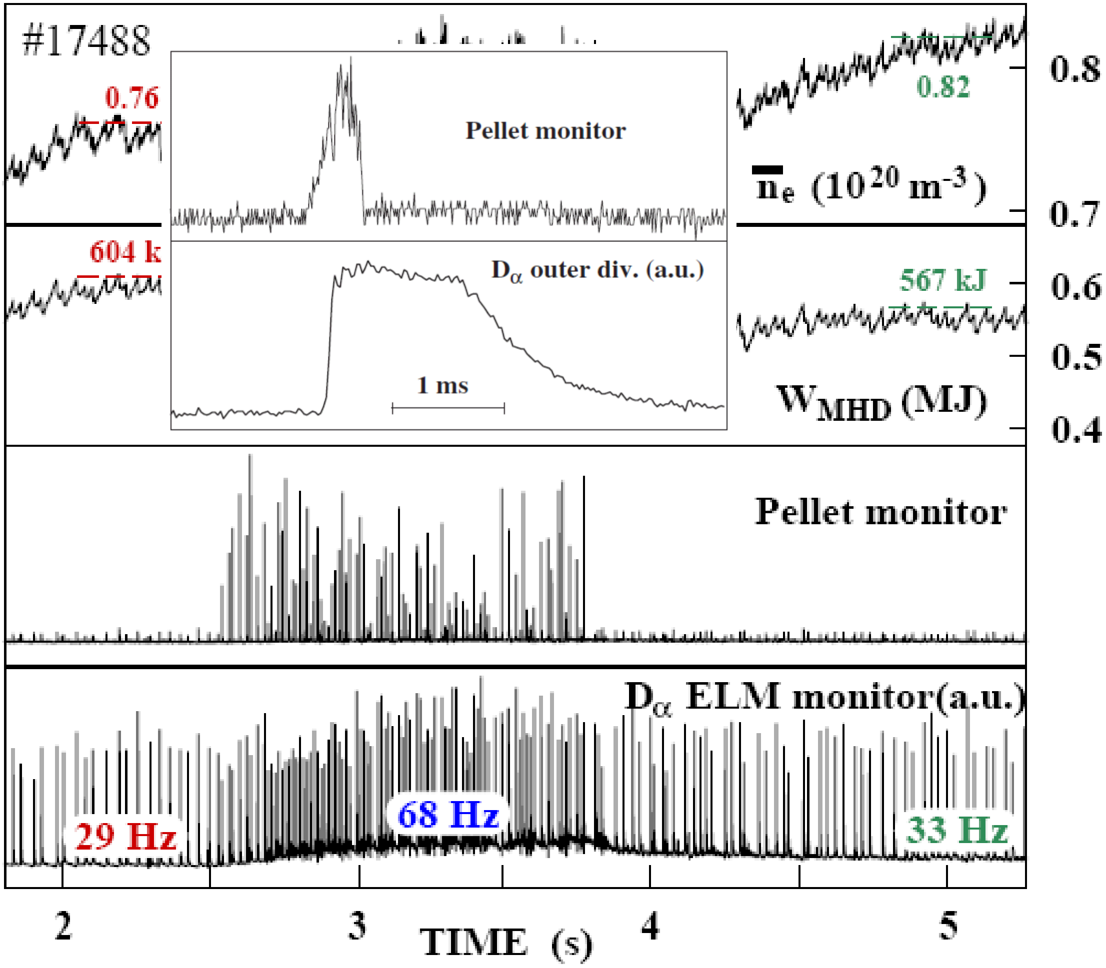
QH-mode

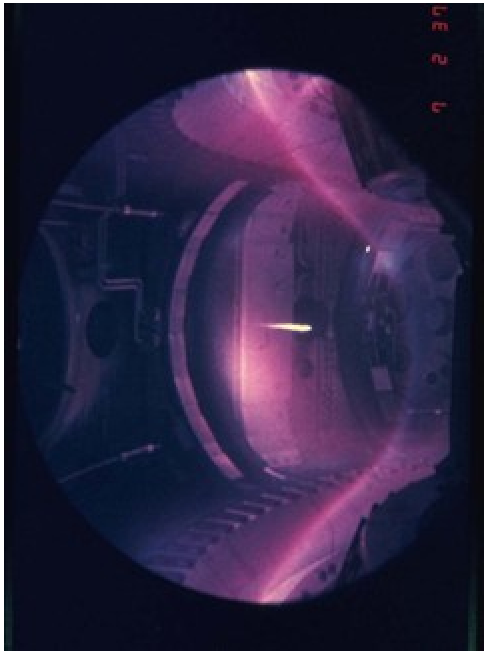
H.W. What is QH-mode?

In which devices is it being observed?

Edge Localised Mode (ELM)

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

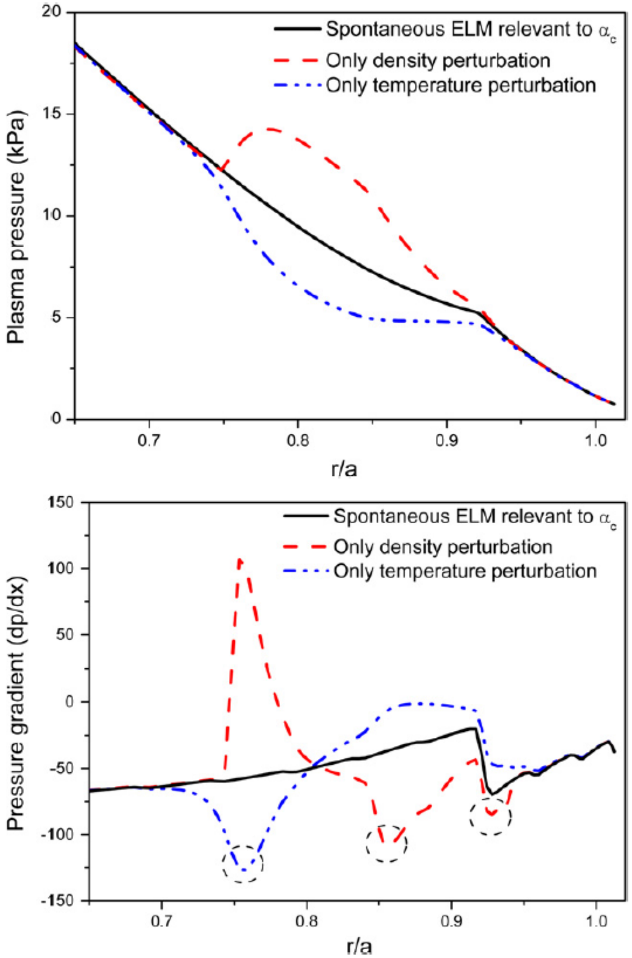


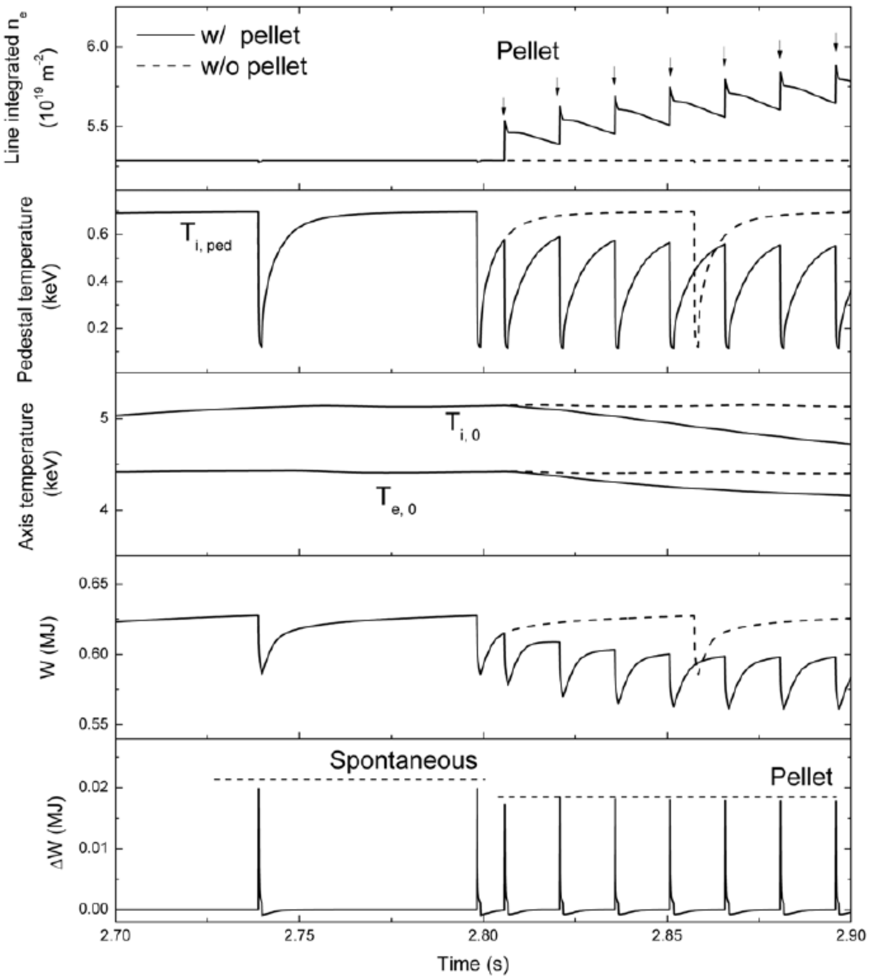


*1st Paper: P. T. Lang et al, Nuclear Fusion **43** 1110 (2003)*

Edge Localised Mode (ELM)

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





Kimin Kim et al, Nuclear Fusion ***50*** *055002 (2010)*

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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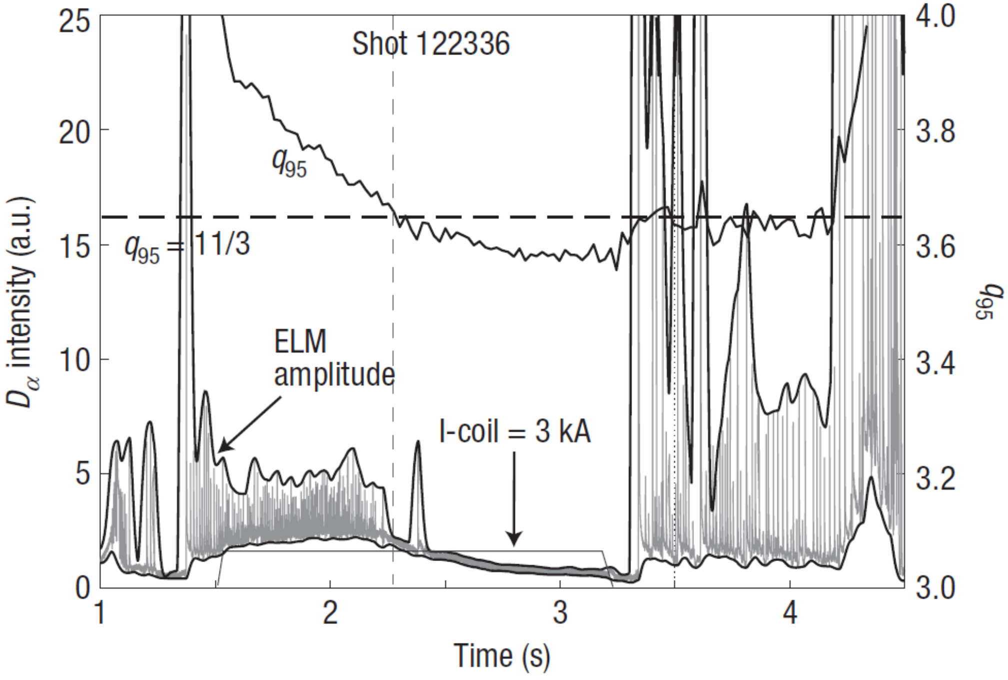
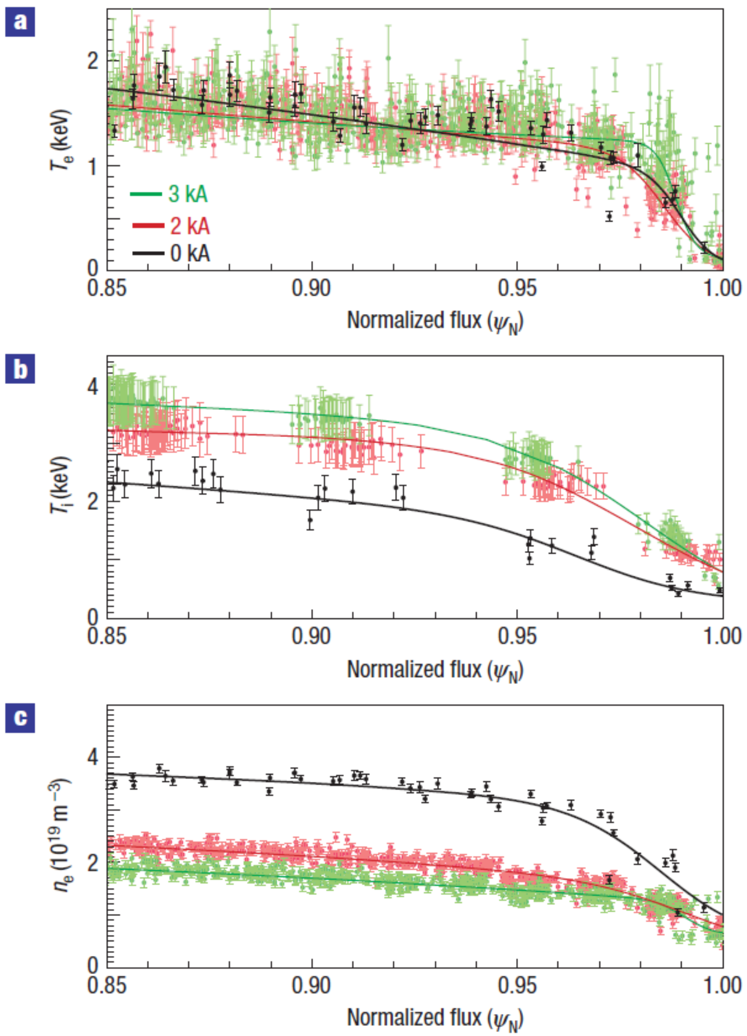
[4]Association EURATOM-CEA, CEA Cadarache, F-13108, St. Paul Lez Durance, France
[5]Sandia National Laboratories, Albuquerque, New Mexico 87185, USA
*e-mail: evans@fusion.gat.com

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

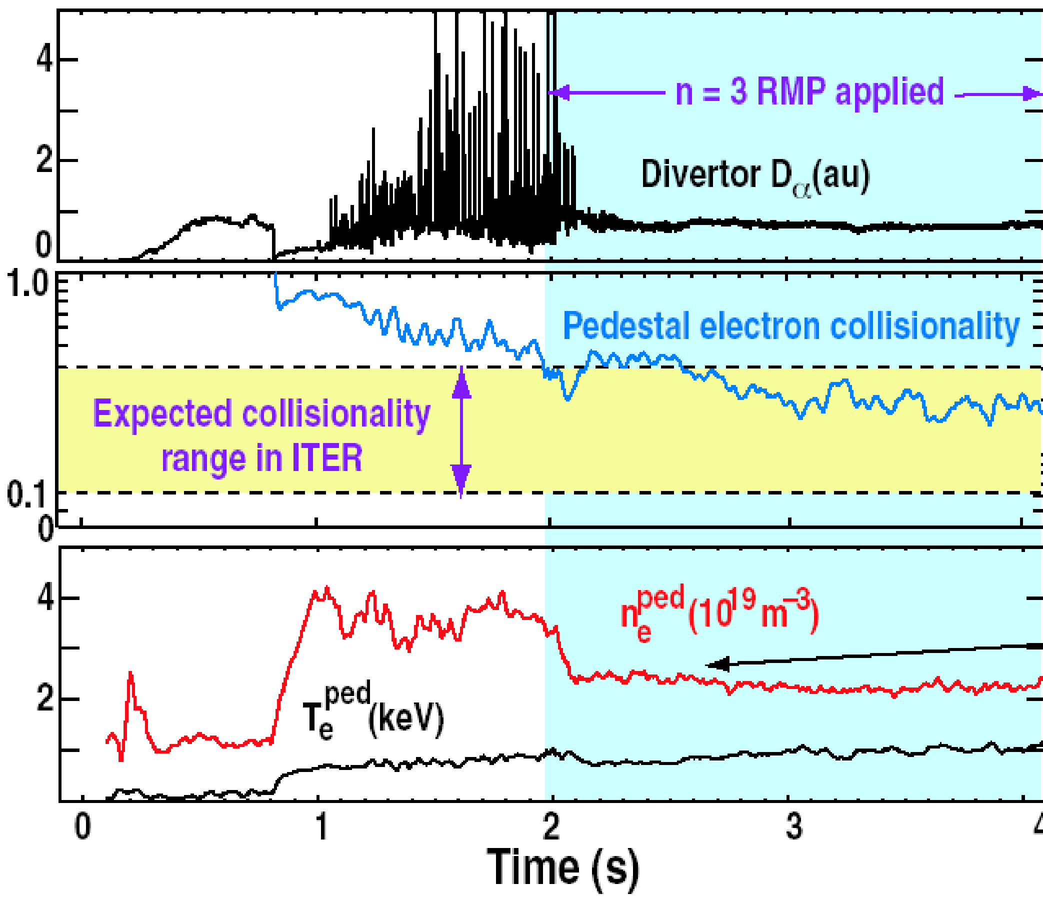
Edge Localised Mode (ELM)

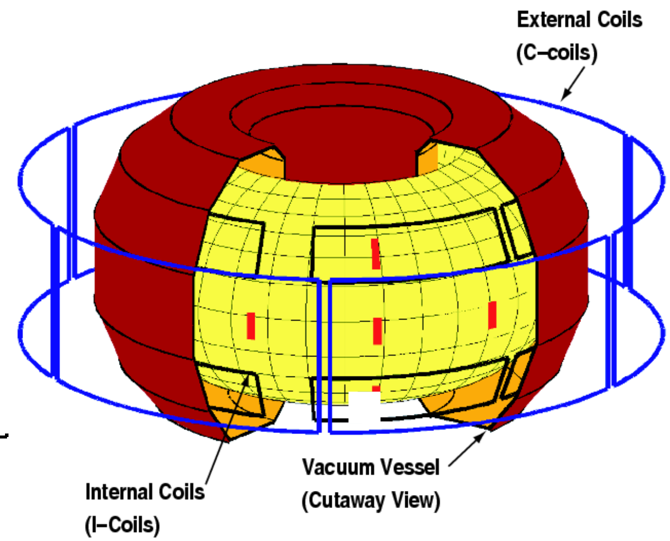




Edge Localised Mode (ELM)

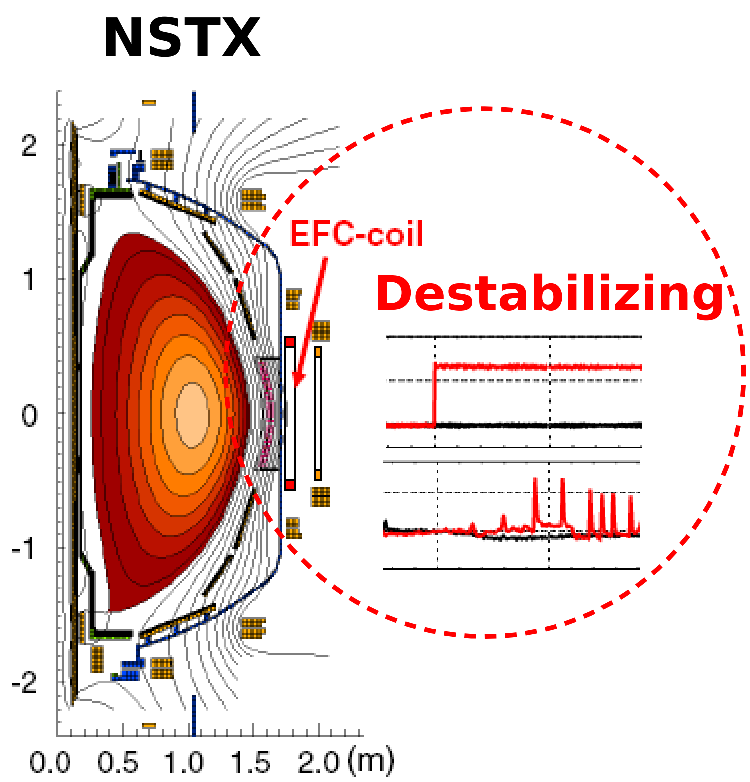
- **Control of ELMs: RMP (Resonant Magnetic Perturbation)**

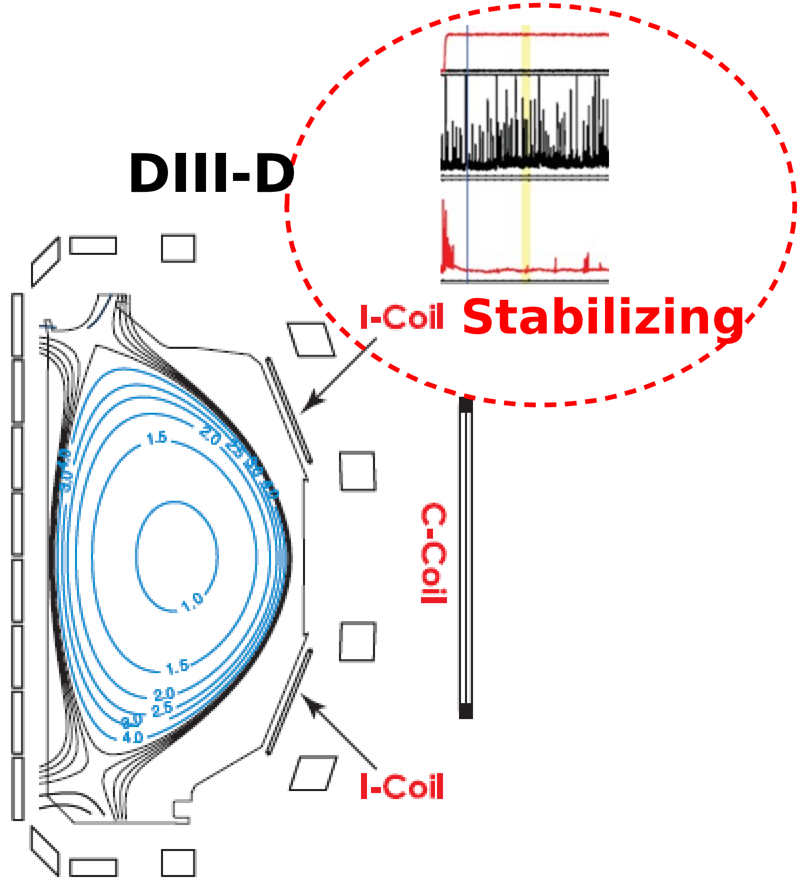




Edge Localised Mode (ELM)

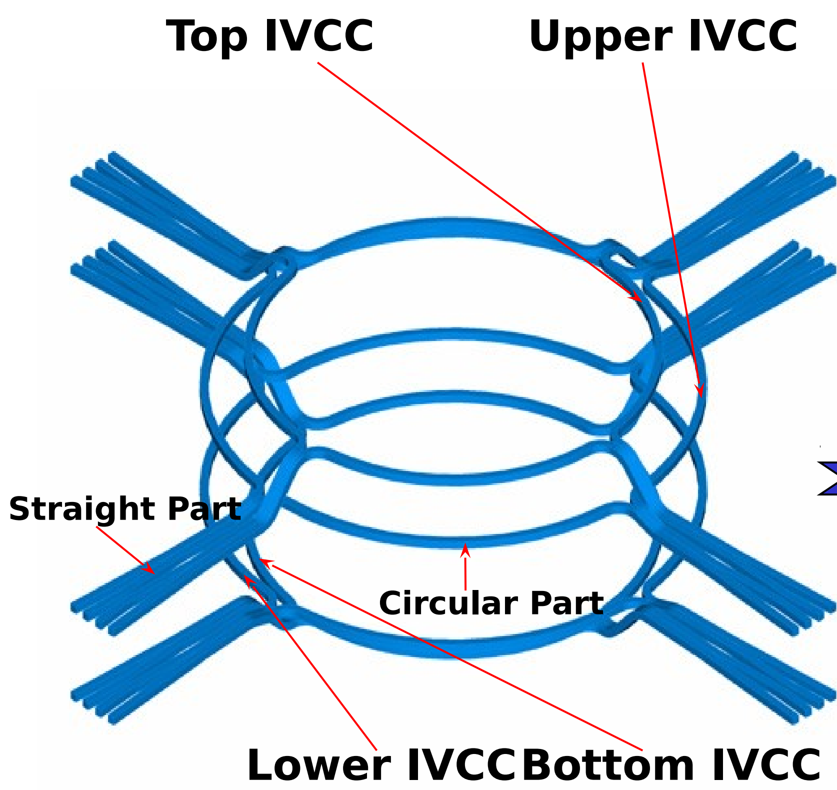
- **Control of ELMs: RMP (Resonant Magnetic Perturbation)**
  - RMPs can be destabilizing and/or stabilizing

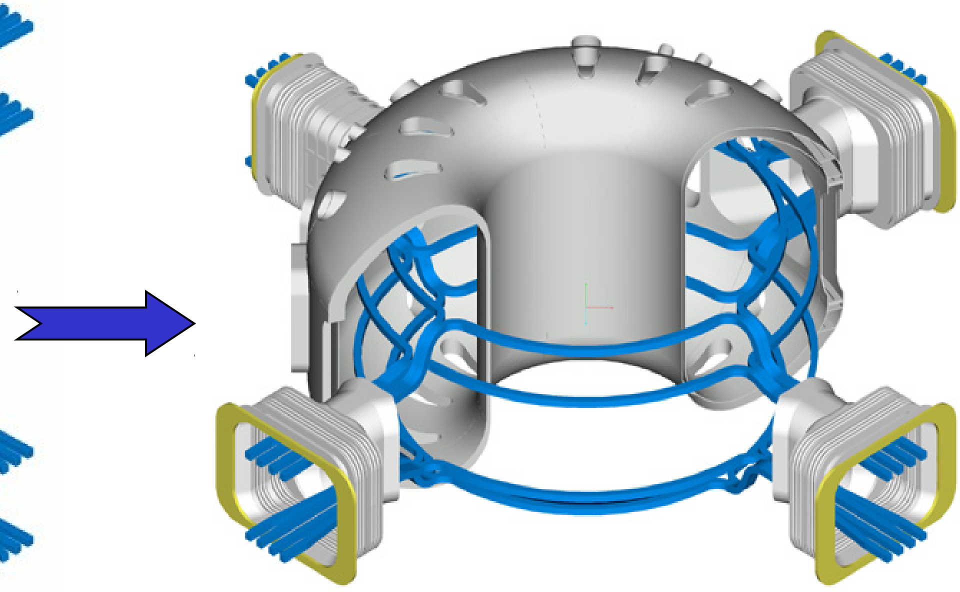




Courtesy from Jong-kyu Park (PPPL)

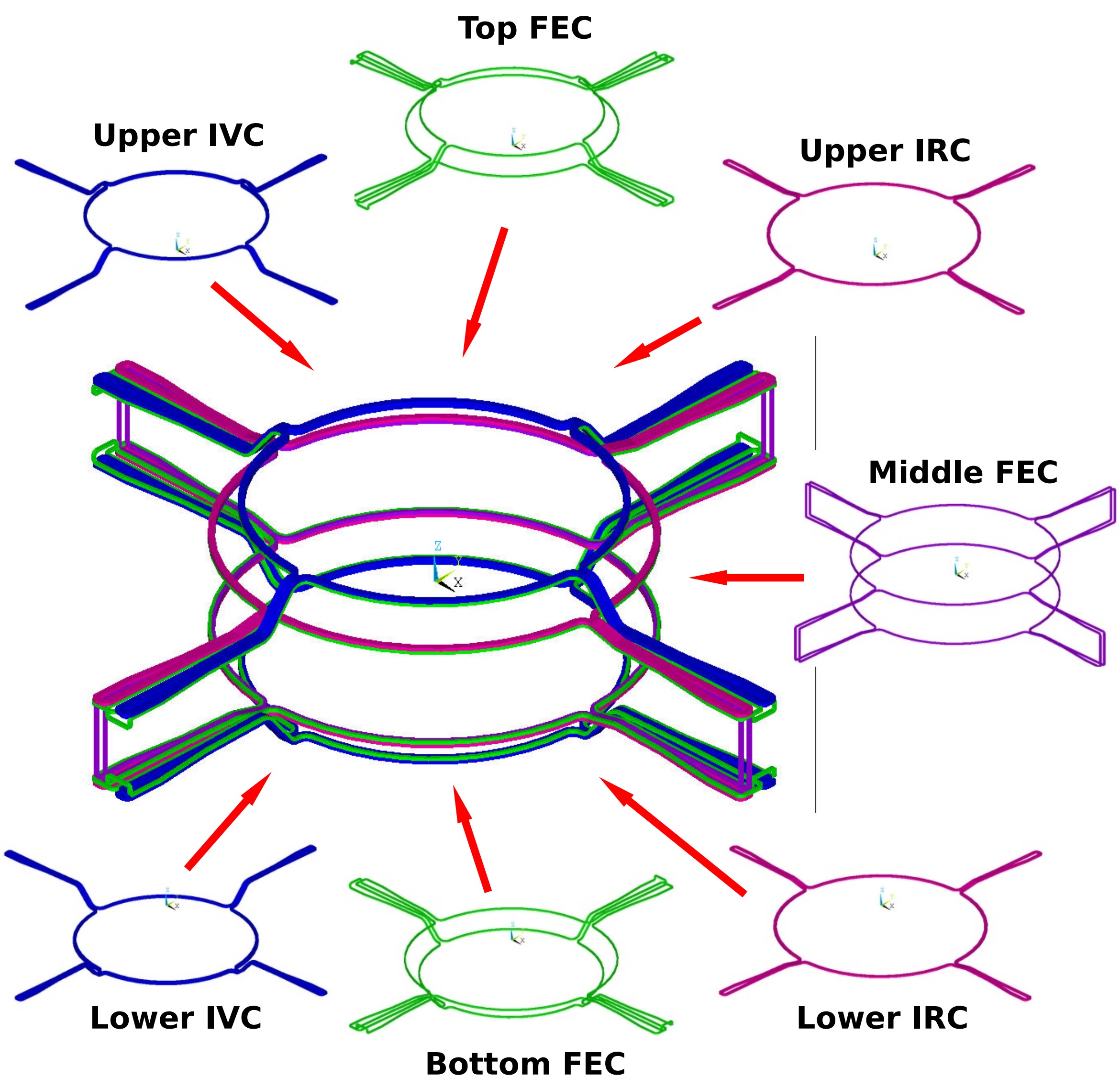
KSTAR Has A Versatile In-Vessel Control Coil (IVCC) System

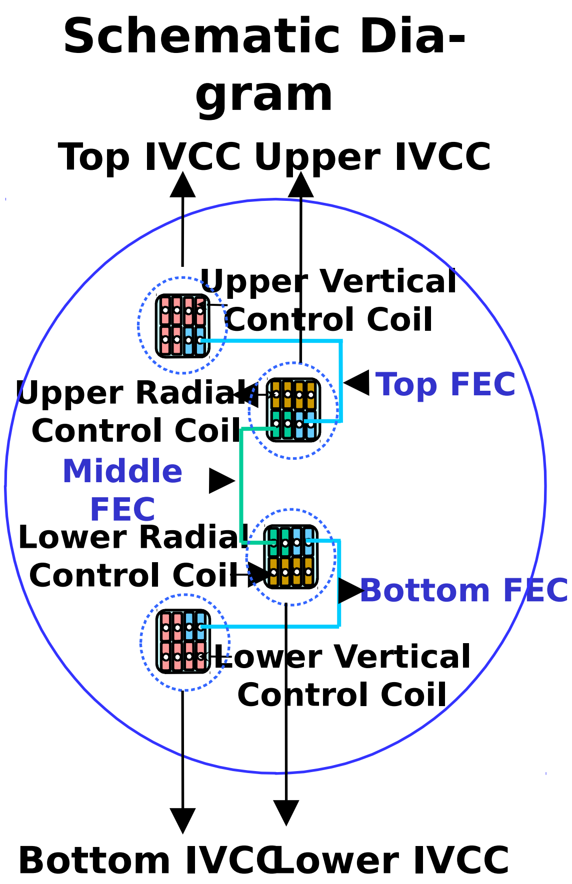




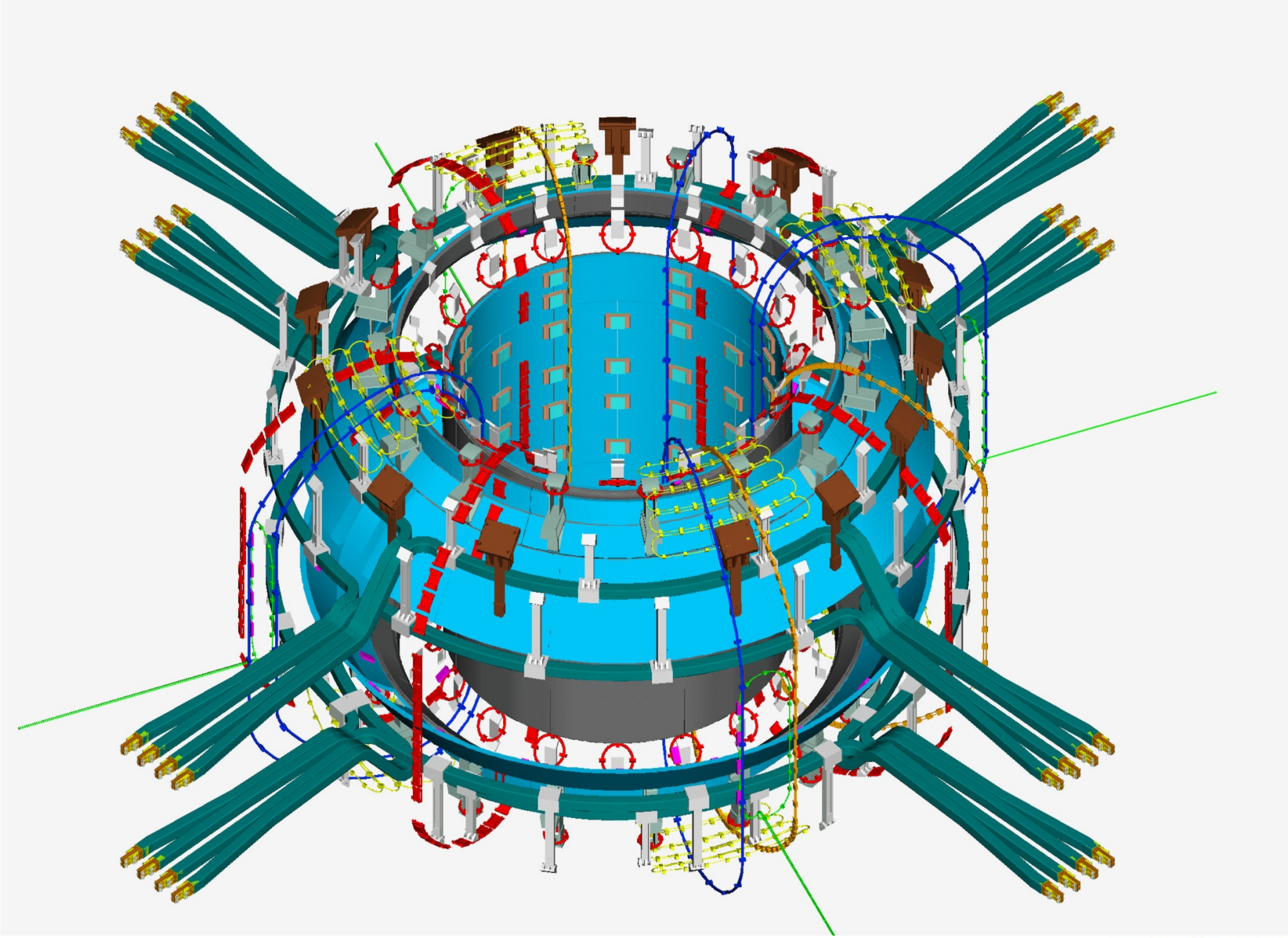
- Four coils for position control and FEC (or RWM)
- Each coil is split into four quadrants (or segments) and inserted into the vessel through the vacuum port

KSTAR Has A Versatile In-Vessel Control Coil (IVCC) System



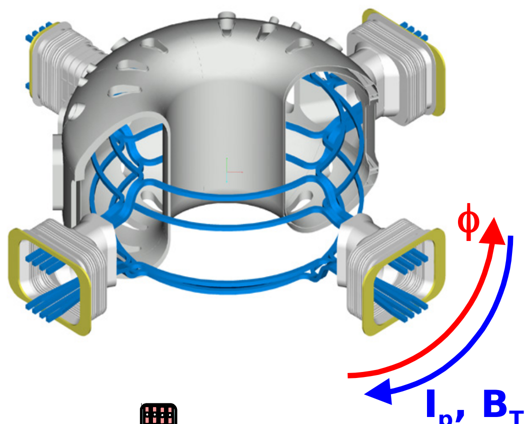


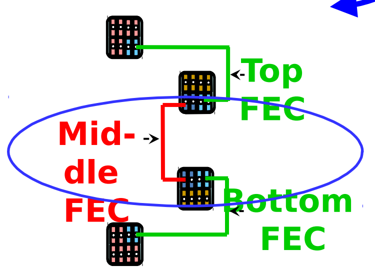
KSTAR Has A Versatile In-Vessel Control Coil (IVCC) System



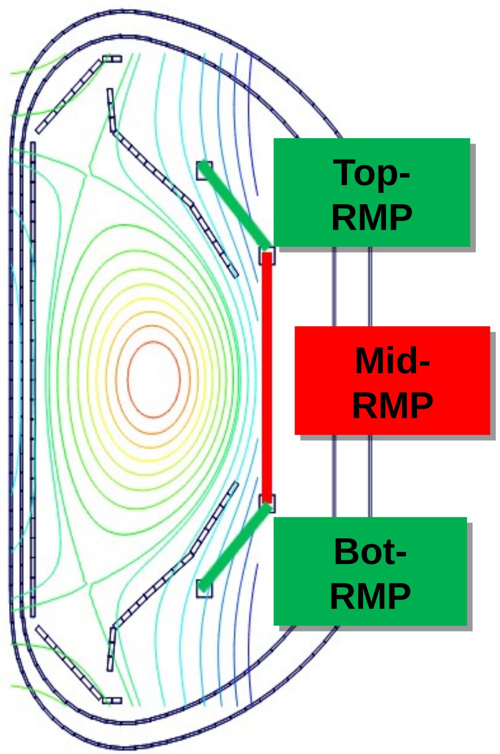
KSTAR Can Provide Wide Spectra of Magnetic Perturbations

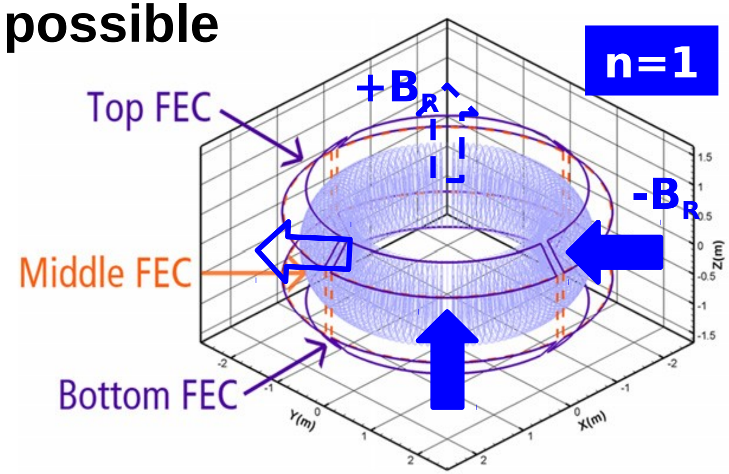
- **3-by-4 3D field coils available having 2 turns for each**
  - all internal and segmented with saddle loop configurations
  - n=1 and 2 applicable
- **Wide spectra of magnetic perturbations are possible**
  - Poloidal helicity change for n=1
  - Even/odd parity change for n=2

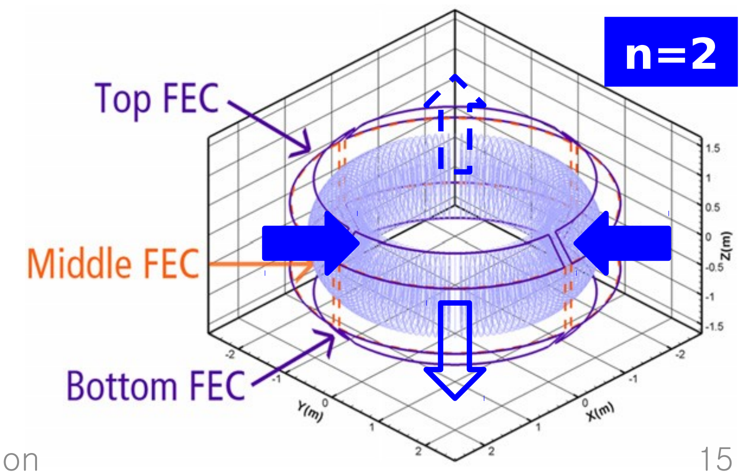




KSTAR Picture-Framed IVCC



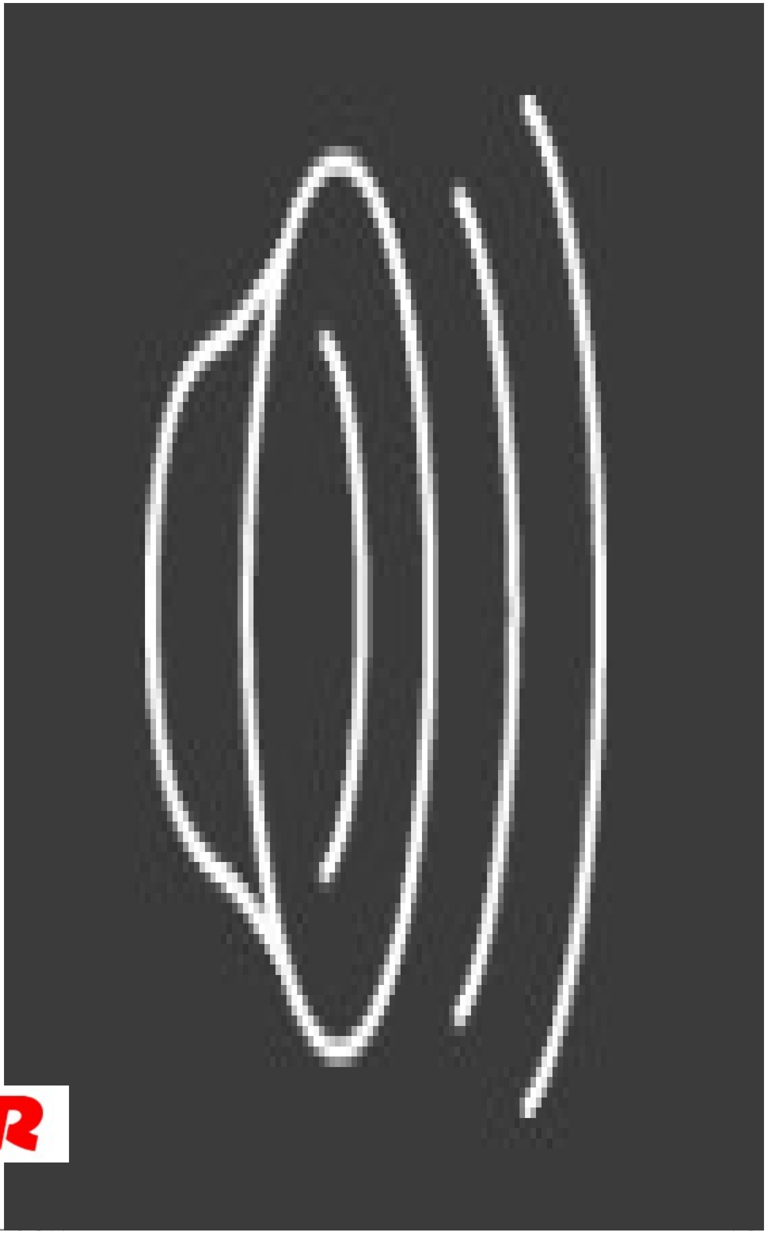




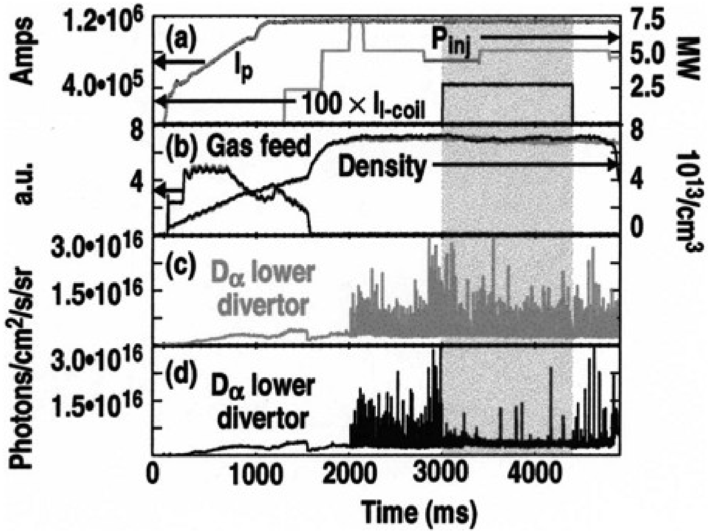
ELM Mitigation/Suppression by 3D-MP

- COMPASS-D (n=1): triggered (2001)
- DIII-D (n=3): suppressed (2004)
- JET (n=1 or 2): mitigated (2007)
- NSTX (n=3): triggered (2010)
- MAST (n=3): mitigated (2011)
- ASDEX-U (n=2): mitigated/suppressed (2011)

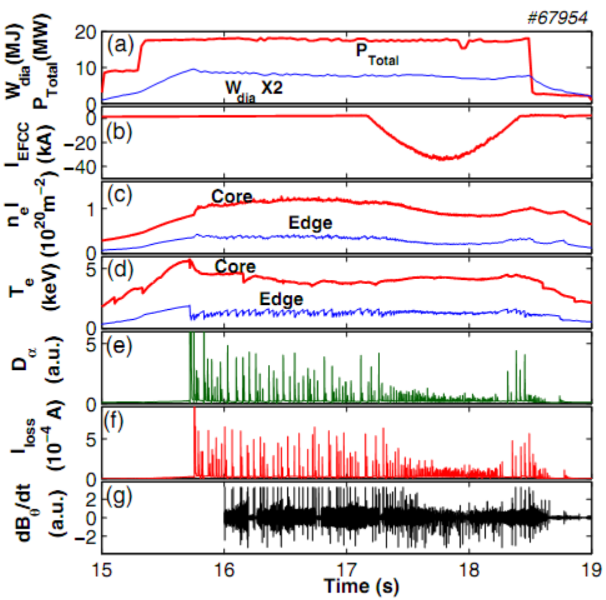
- KSTAR (n=1): ELMs suppressed (2011)

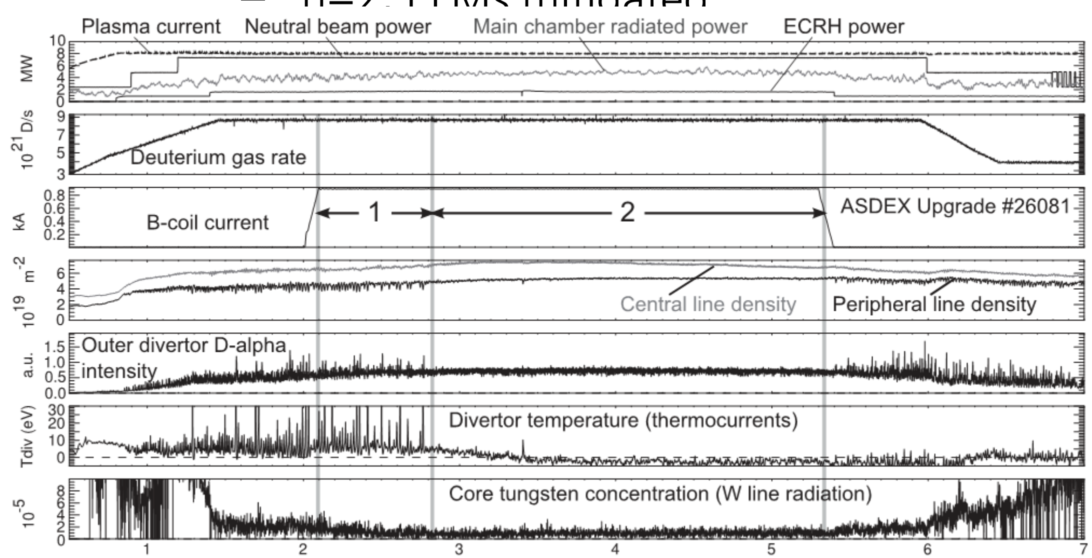


MP ELM controls in other tokamaks



- DIII-D (TE Evans et al, PRL 2004)
  - n=3; ELMs suppressed.
  - Stochastic boundary claimed.
- JET (Y Liang et al, PRL 2007)
  - n=1; ELMs mitigated (i.e. reduced crash a mplitude)
- ASDEX-U (W Suttrop et al, PRL 2011)
  - n=2; ELMs mitigated





POSTECH PDS^{2}O

Applicable Spectra of n=1 and n=2 MP

n=1, -90 phase

-	-	+	+	top
-	+	+	-	mid
+	+	-	-	bot

n=1, 0 phase

+	+	-	-	top
+	+	-	-	mid
+	+	-	-	bot

n=1, +90 phase

+	+	-	-	top
-	+	+	-	mid
-	-	+	+	bot

θ B_P ϕ

n=1, 180 phase

+	+	-	-	top
-	-	+	+	mid
+	+	-	-	bot

n=1, mid-RMP alone

				top
+	+	-	-	mid
				bot

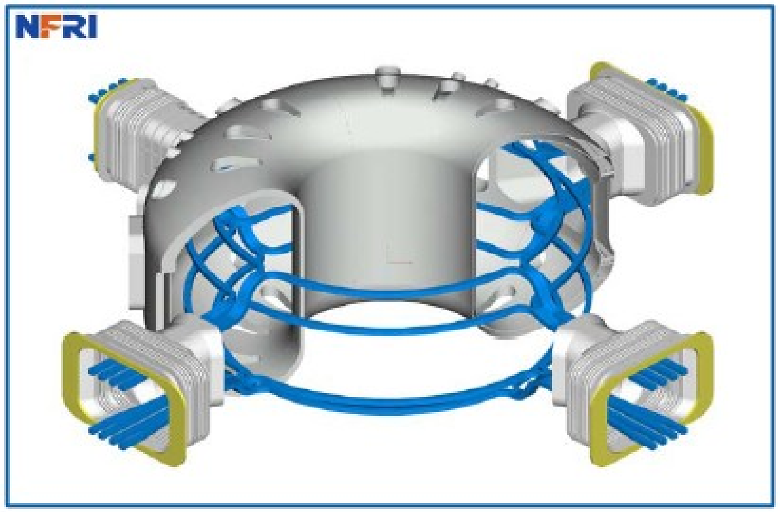
n=2, even parity

+	-	+	-	top
-	+	-	+	mid
+	-	+	-	bot

n=2, odd parity

+	-	+	-	top
				mid
-	+	-	+	bot

n=1 MP applied



- Injection time = 3~6 s
- Current in each coil = 1.5 kA
- Relative phase = 90° btw adjacent coil sets

Top coils	+	+	-	-
Mid coils	-	+	+	-
Bot coils	-	-	+	+

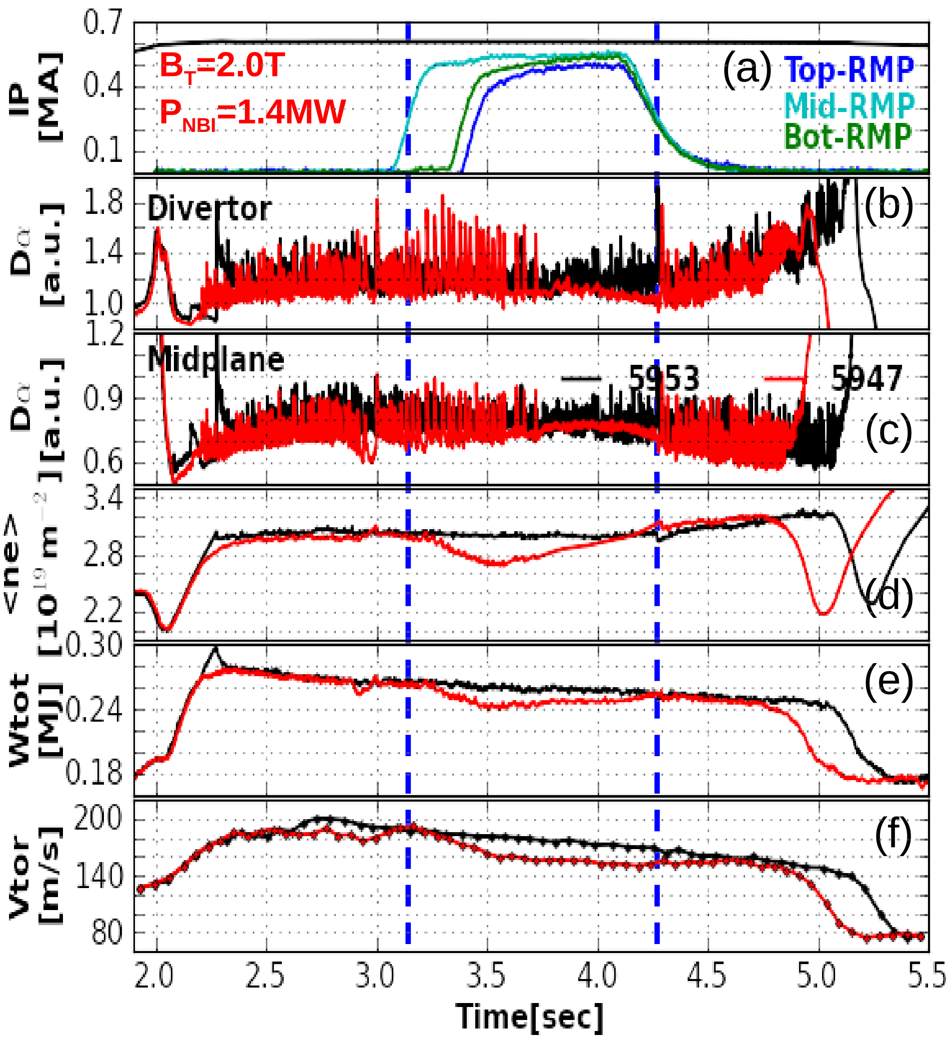
Poloidal direction

Toroidal direction (co-current)

KSTAR

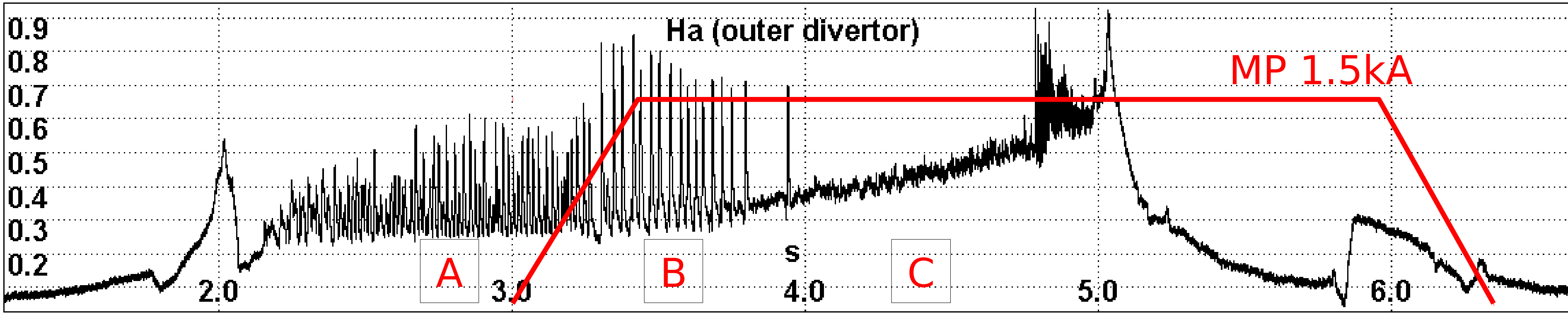
POSTECH PDS²O

ELMs Suppressed For the First Time by n=1, +90 RMP

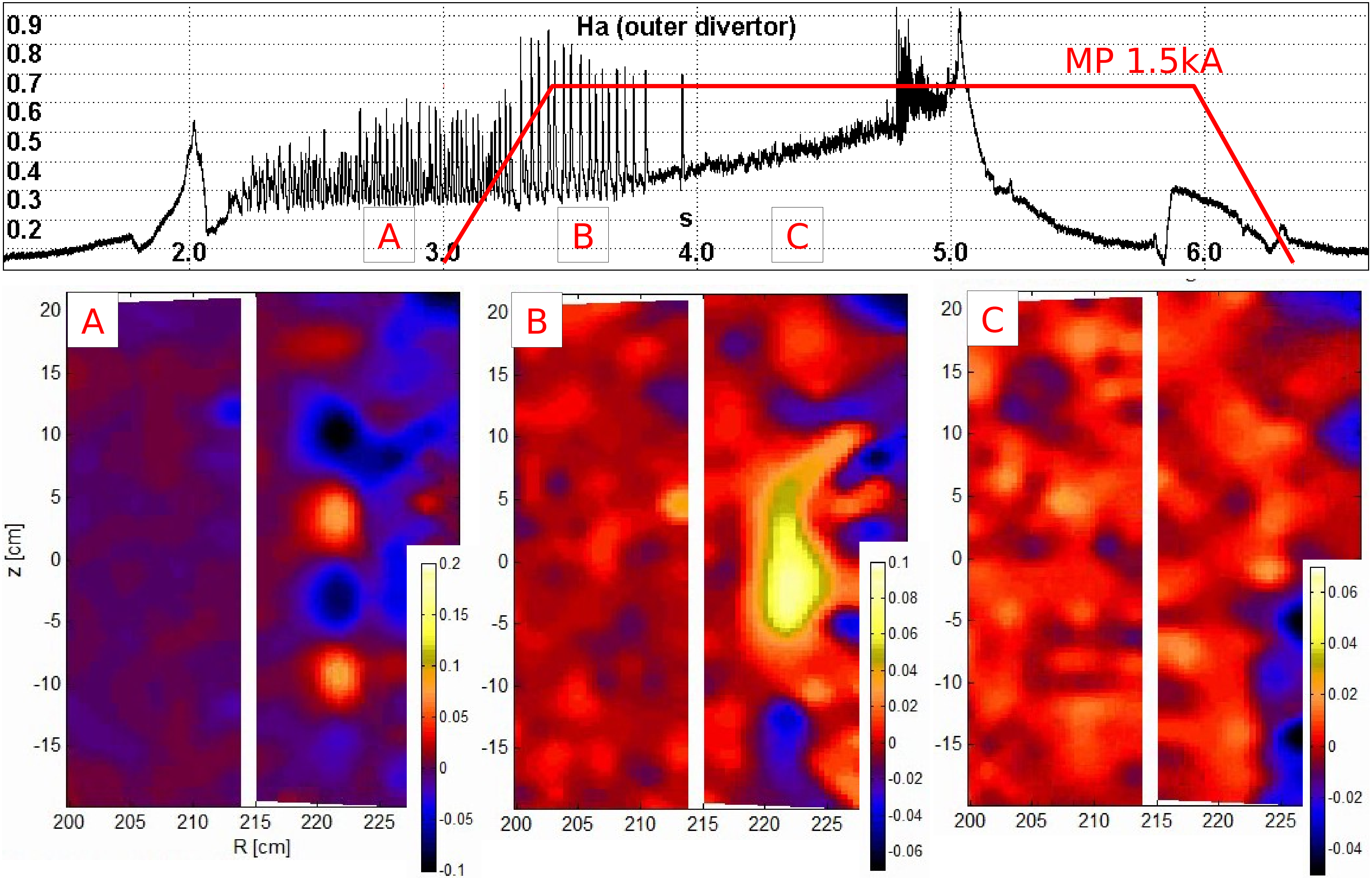


- **90 phasing RMP strongly mitigated or suppressed ELMs**
  - In JET, ELM mitigated by n=1 (Y.Liang, PRL, 2007)
- **Two distinctive phases** observed
  - **(1)ELM excitation phase**
  - **(2)ELM suppression phase**
- **Density** (~10%) pumping out initially. Then, increased when ELM suppressed
- **Stored energy** drop by ~8% initially. Then slightly increased or sustained when ELM suppressed
- **Rotation** decreased (~10%) initially. Then sustained when ELM suppressed
- **Te/Ti** changes were relatively small

Three phases

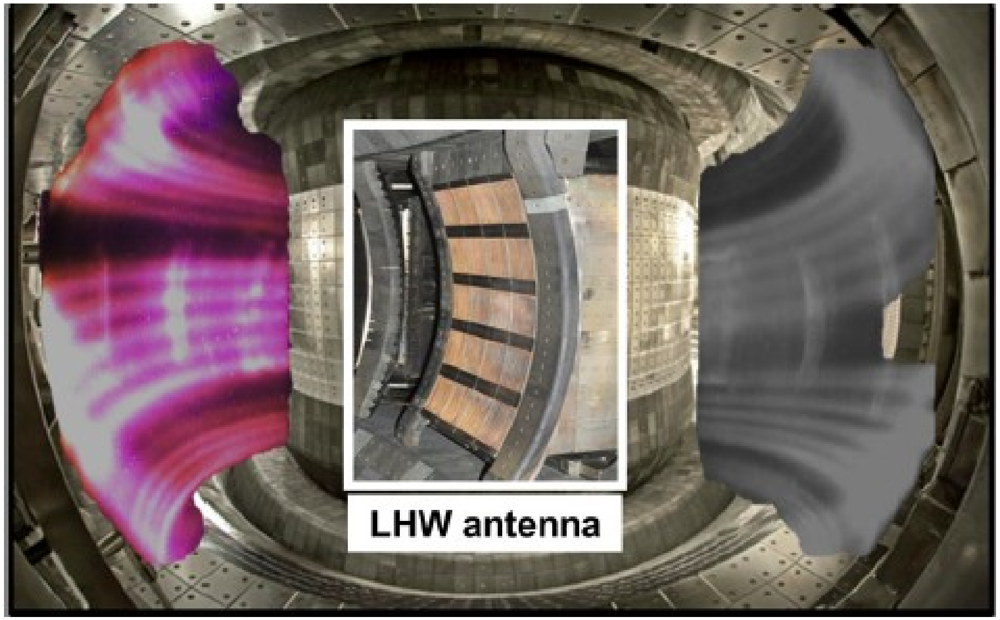


Changes of the ELM structure

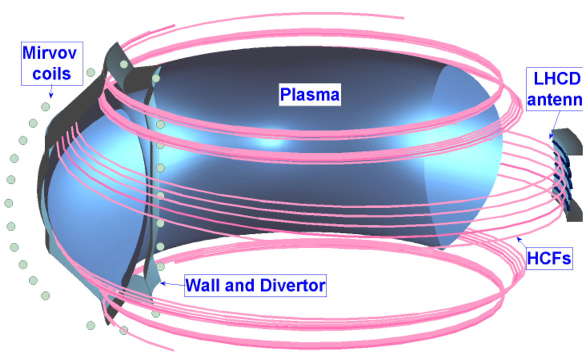


Demonstrated for the 1st time Edge magnetic topology change by LHCD

ASIPP

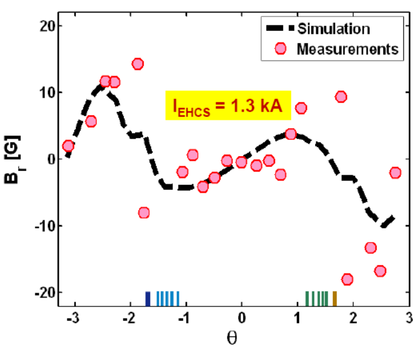


Helical Radiation Belts (helical current sheets)

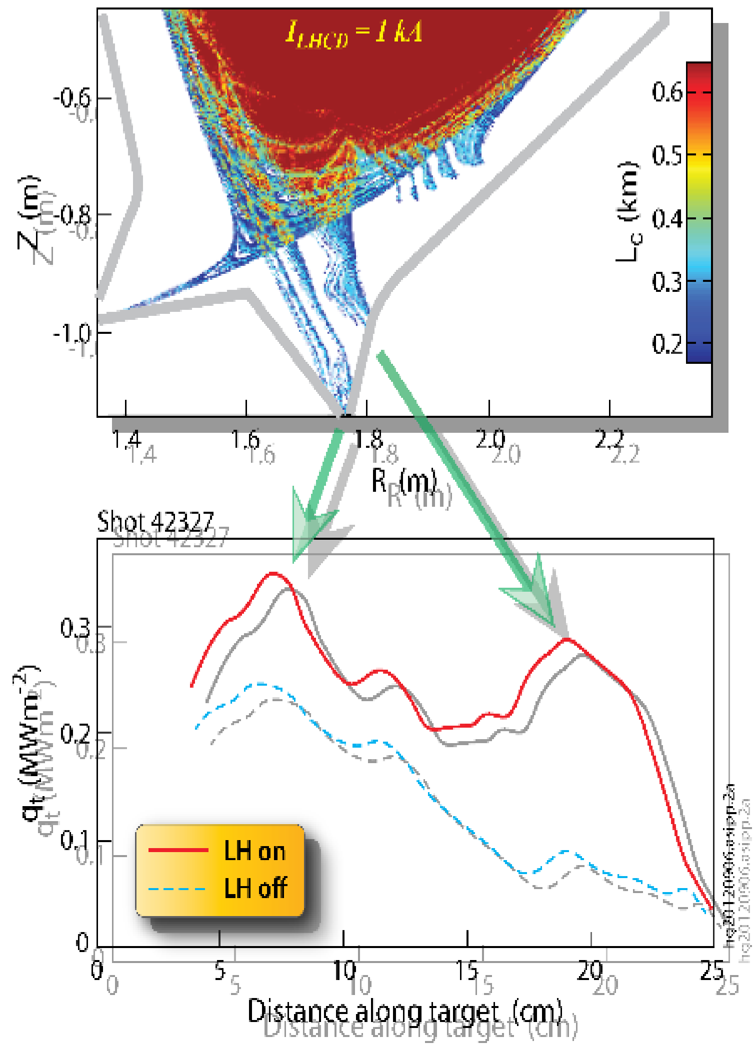


Poloidal Projection of SOL Field Lines

Measurement of Magnetic perturbation due to EHCS



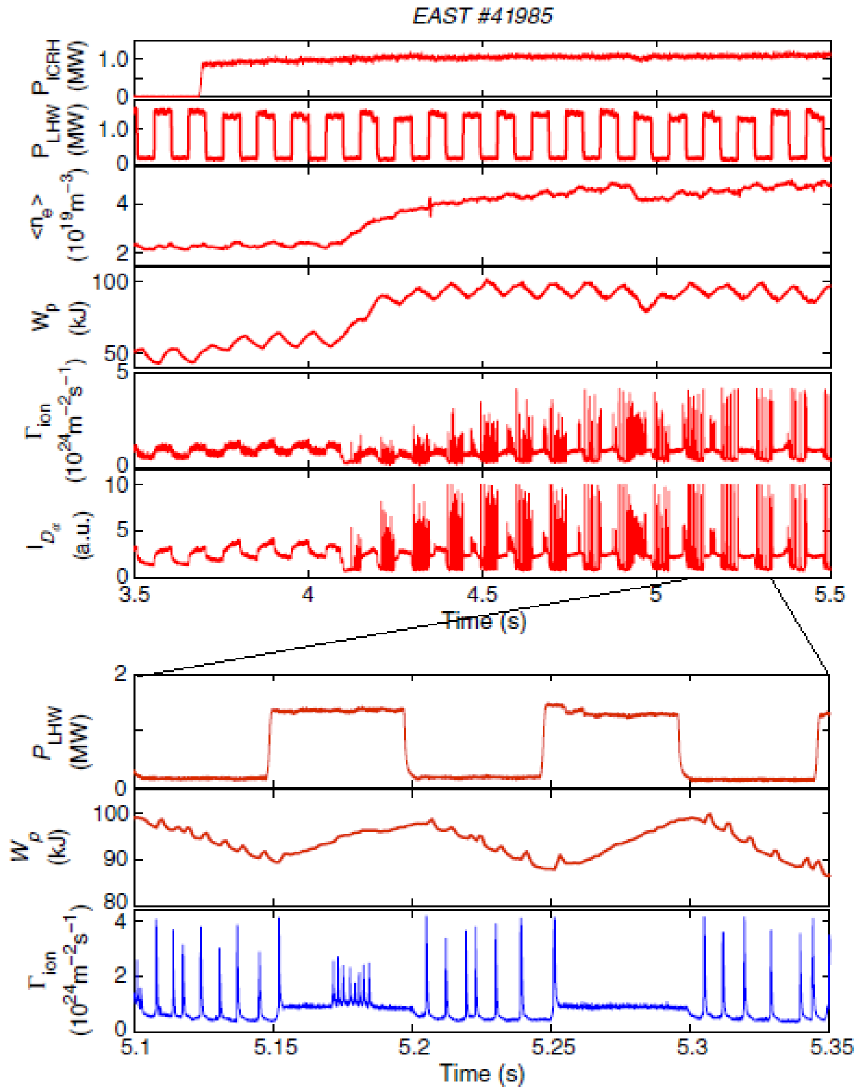
Change of Edge Magnetic Topology



Y. Liang, et al., PRL 110 235002 (2013)

Strong mitigation of ELMs with LHCD

ASIPP

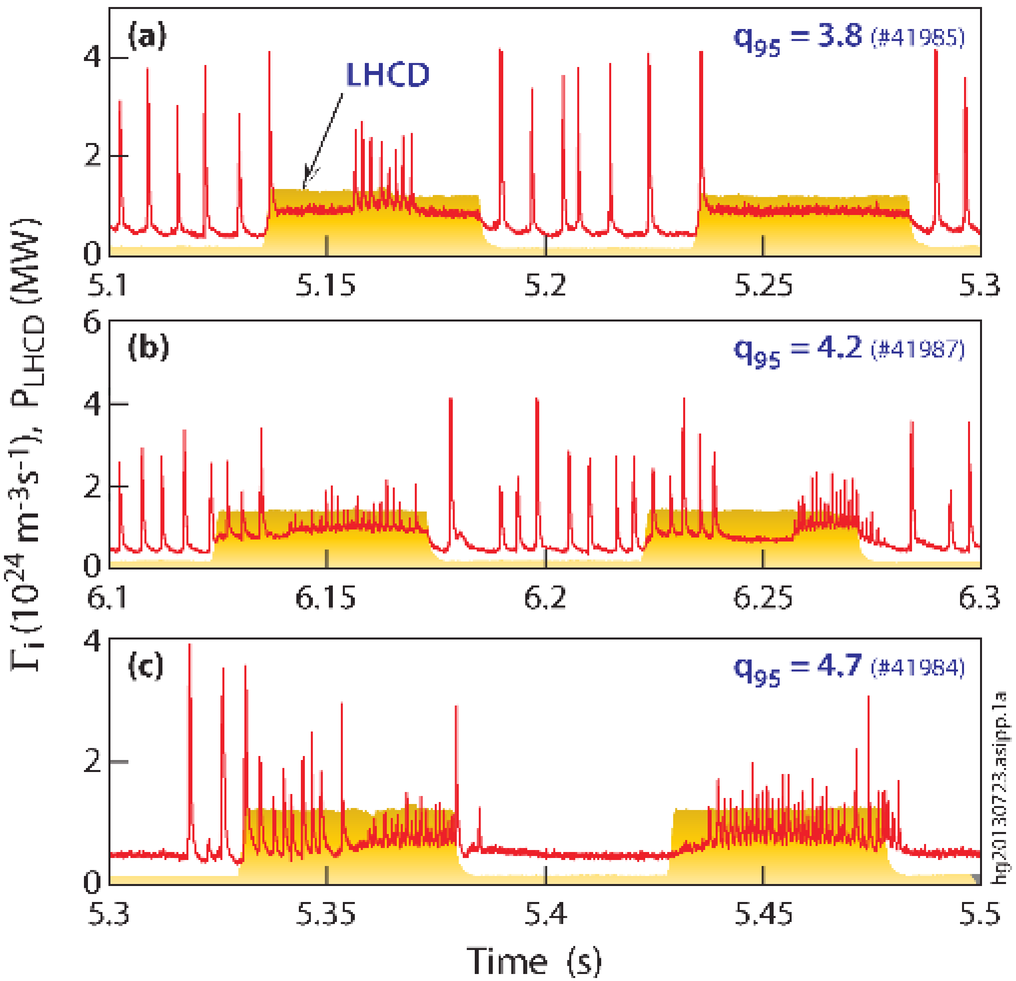


- ICRF-dominated + 10Hz LHW modulation (LHW-off: 50ms ~ ½τ_E)
- H_{98}=0.8; $W_{dia}|_{L\square H}$: 50 □100kJ
- LHW off: f_{ELM} ~150Hz
- LHW on: ELMs disappear or sporadically appear w/ f_{ELM}~600Hz
- Peak particle flux: ↓ by 2-4
- W_{dia} varied slightly: within ±5%
- A quick reduction of $\Gamma_{i,div}$ during inter-ELM can be seen wh

Y. Liang, et al., PRL 110 235002 (2013)

Flexible boundary control with LHCD

ASIPP

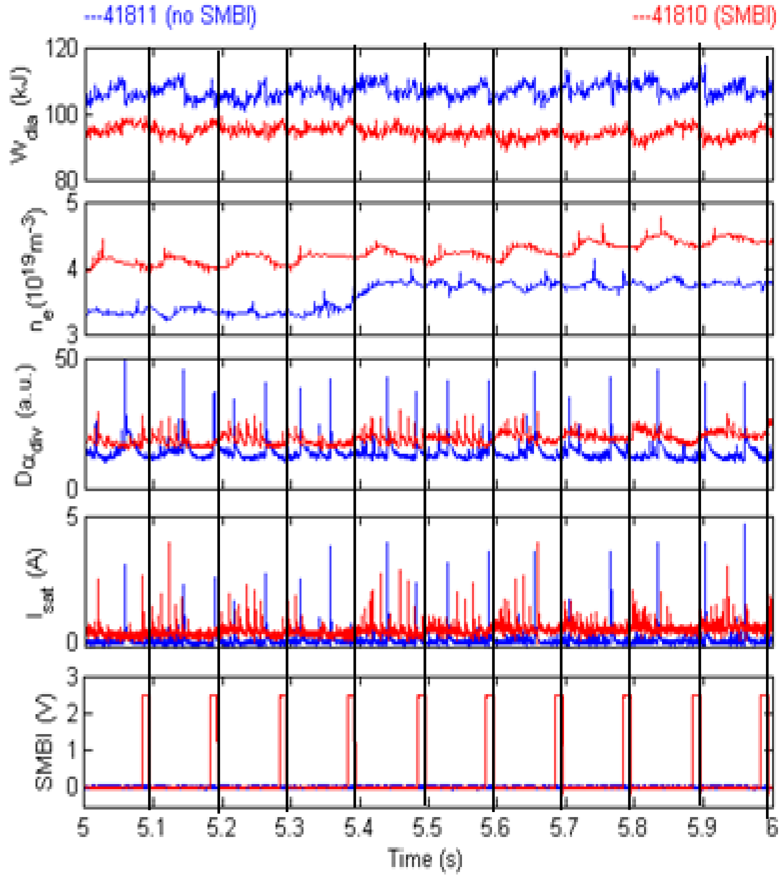


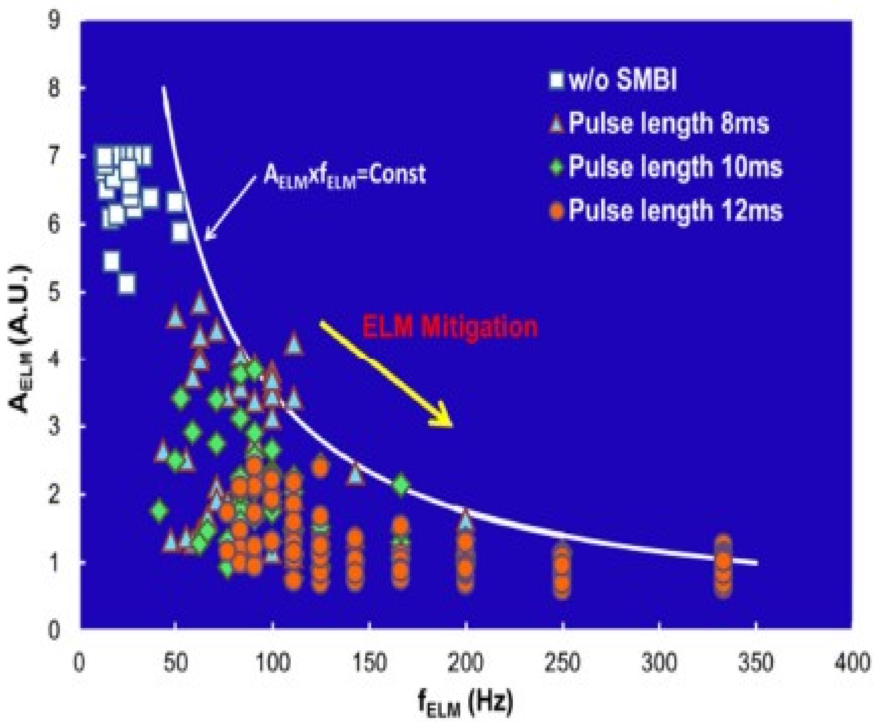
- The long pulse H-mode was achieved with dominant LHCD, with additional ICRH.
- LHCD induces n=1 helical currents at edge, leading to 3D distortion of magnetic topology, similar to RMP.
- **LHCD appears to be effective at controlling ELMs over a broad range q_{95}, in contrast to fixed RMP coils.**

ELM control by SMBI

ASIPP

SMBI: Supersonic Molecular Beam Injection, Initially developed by SWIP (CN), successfully applied on HL-2A, KSTAR & EAST

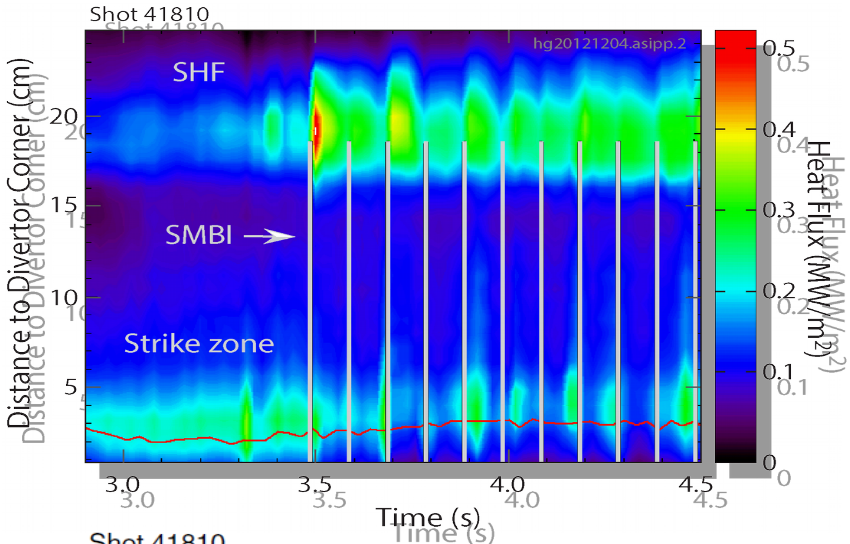


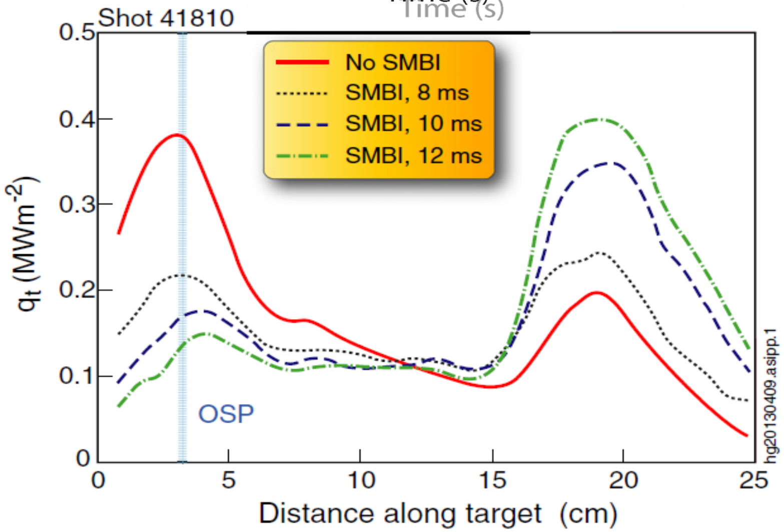


X. L. Zou et al., 24th IAEA FEC, San Diego

SHF can be actively controlled with SMBI

ASIPP



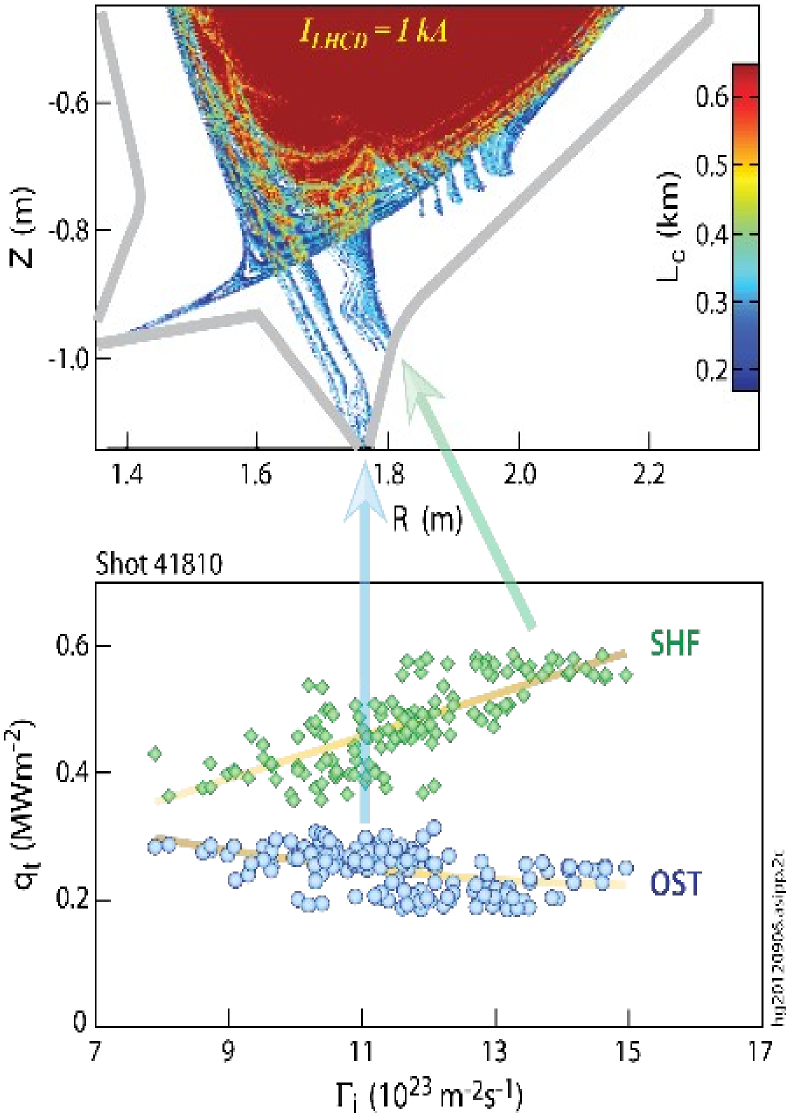


- **Striated Heat Flux (SHF) region in the far-SOL can be actively controlled with SMBI.**
- **Characteristic of LHCD heating scheme**
- **SMBI significantly enhancing SHF, while reducing peak heat fluxes near strike point.**
- **Achieving similar results with conventional gas puff or Ar seeding.**

OSZ(P): Original Strike Zone(Point)

SHF can be actively controlled by regulating edge particle fluxes

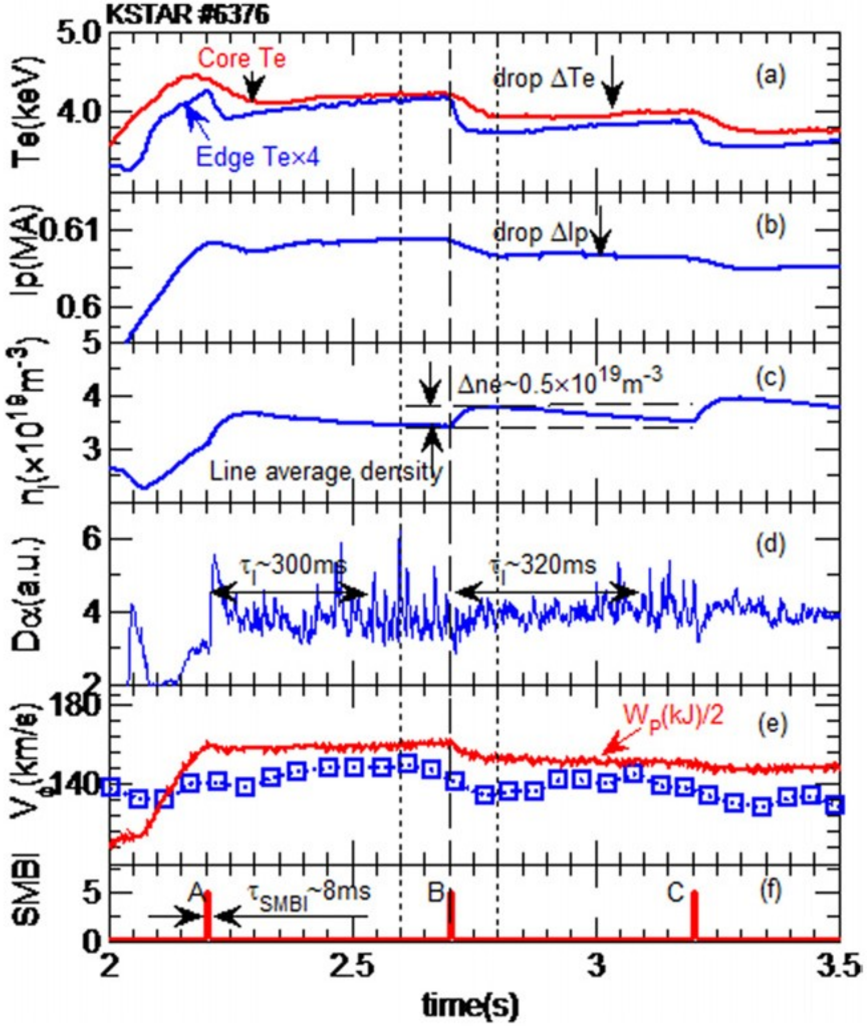
ASIPP

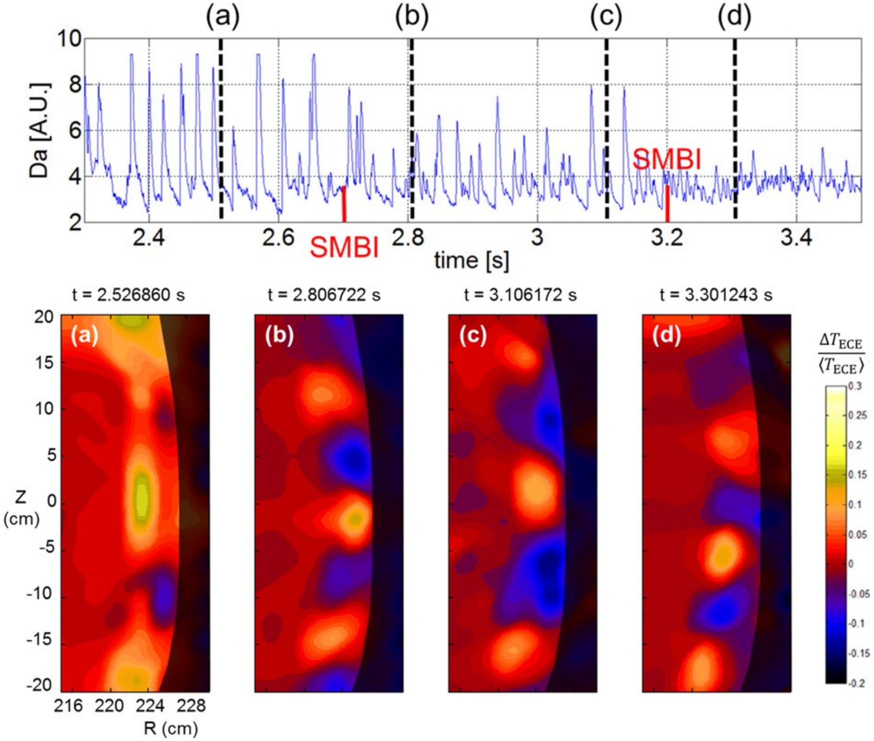


- **For SHF: $q_{SHF} \sim \Gamma_i T_{ped}$, $T_{ped} \sim$ 350 eV**
  □ q_{SHF} increases with Γ_i.
- **At OST: $q_{OST} \sim \Gamma_i T_{div}$, $T_{div} \sim \Gamma_i^{-1}$,**
  □ q_{OST} remains similar.
- **A unique physics feature of ergodized plasma edge by LHCD.**
- **Allowing control of the ratio of q_{SHF}/q_{OST}, thus divertor power deposition area via control of divertor plasma conditions.**

J. Li et al., **Nature Phys. 9** 817 (2013)

ELM Control by SMBI





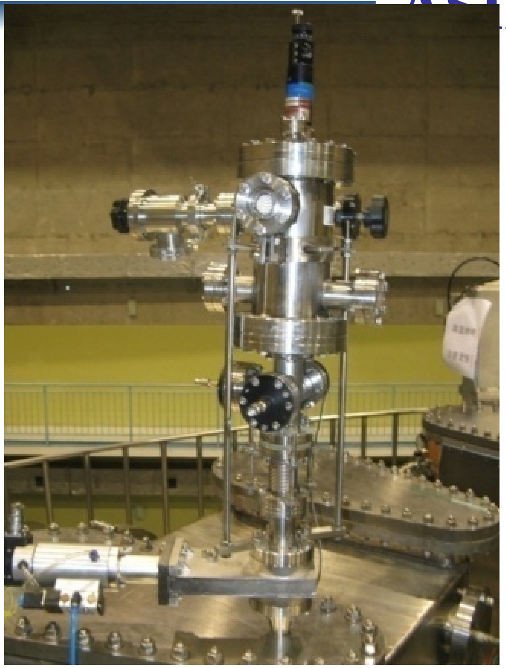
Jayhyun Kim et al., Nucl. Fusion ***52*** *114011 (2012)*

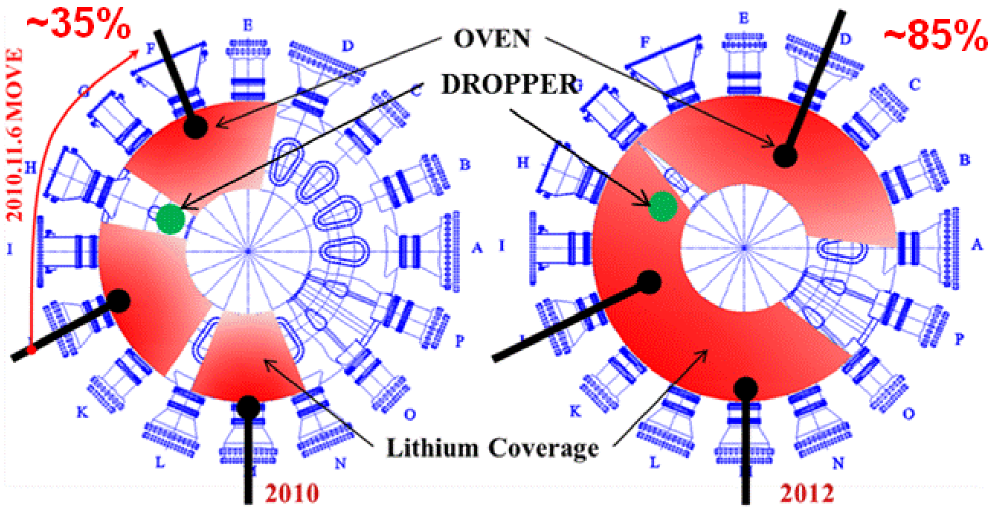
Lithium wall conditionings

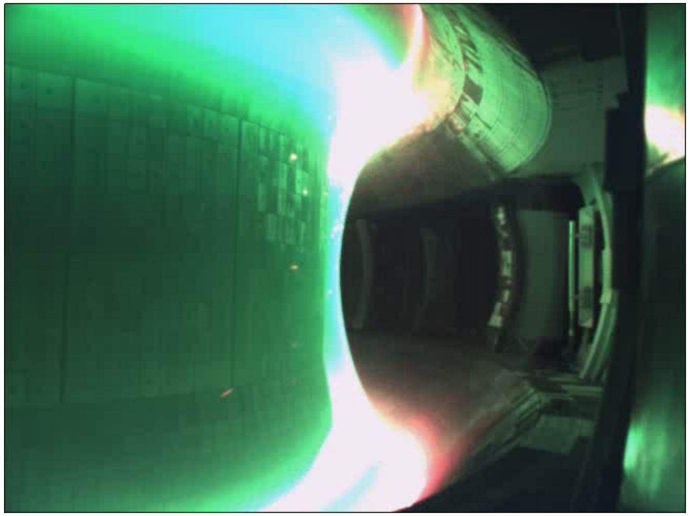
ASIPP

- Reduce recycling
- Suppress impurities
- Benefit ICRF &LHCD coupling
- Mitigate ELMs

- Increasing Li Coverage (85% @2012 vs 30% @2010)
- Active Li injection to help operate long pulse H-mode
- Need one more oven for full surface coating.





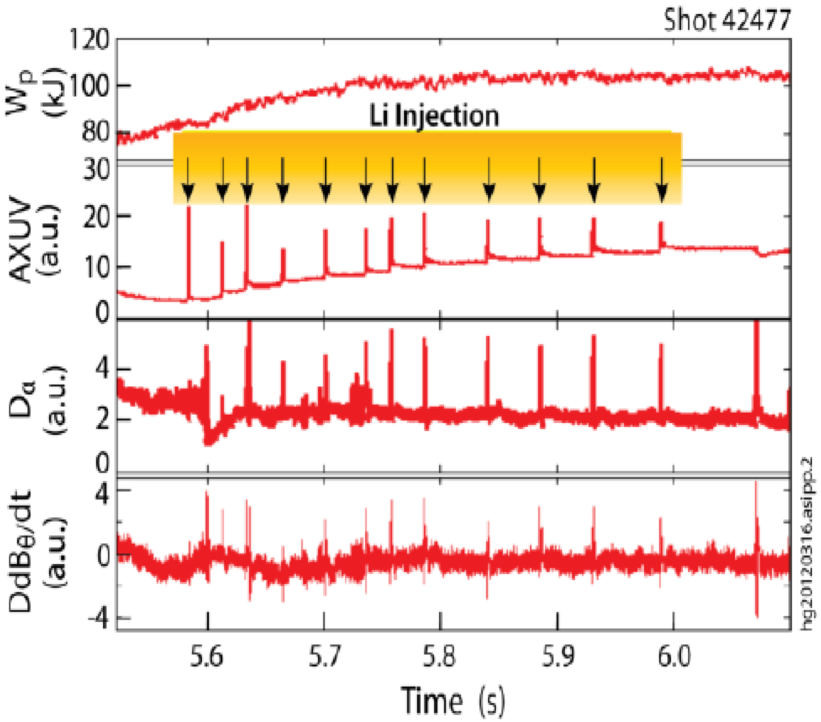


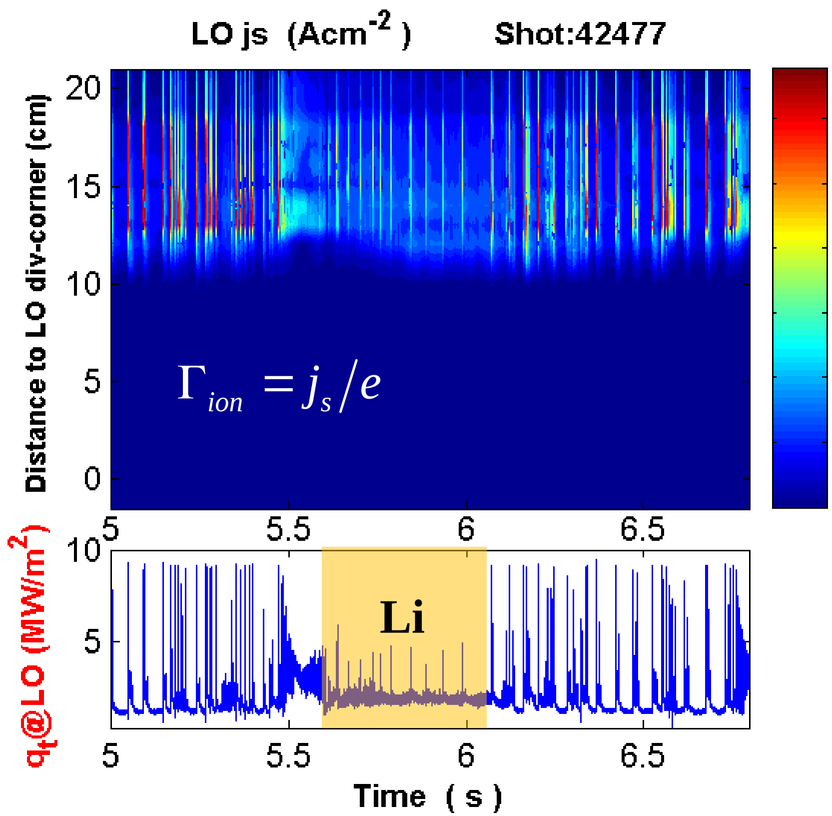
green light emissions from lithium

Demonstrated for the 1st time ELM Pacing by Innovative Li-granule Injection

ASIPP

Collaborated with PPPL





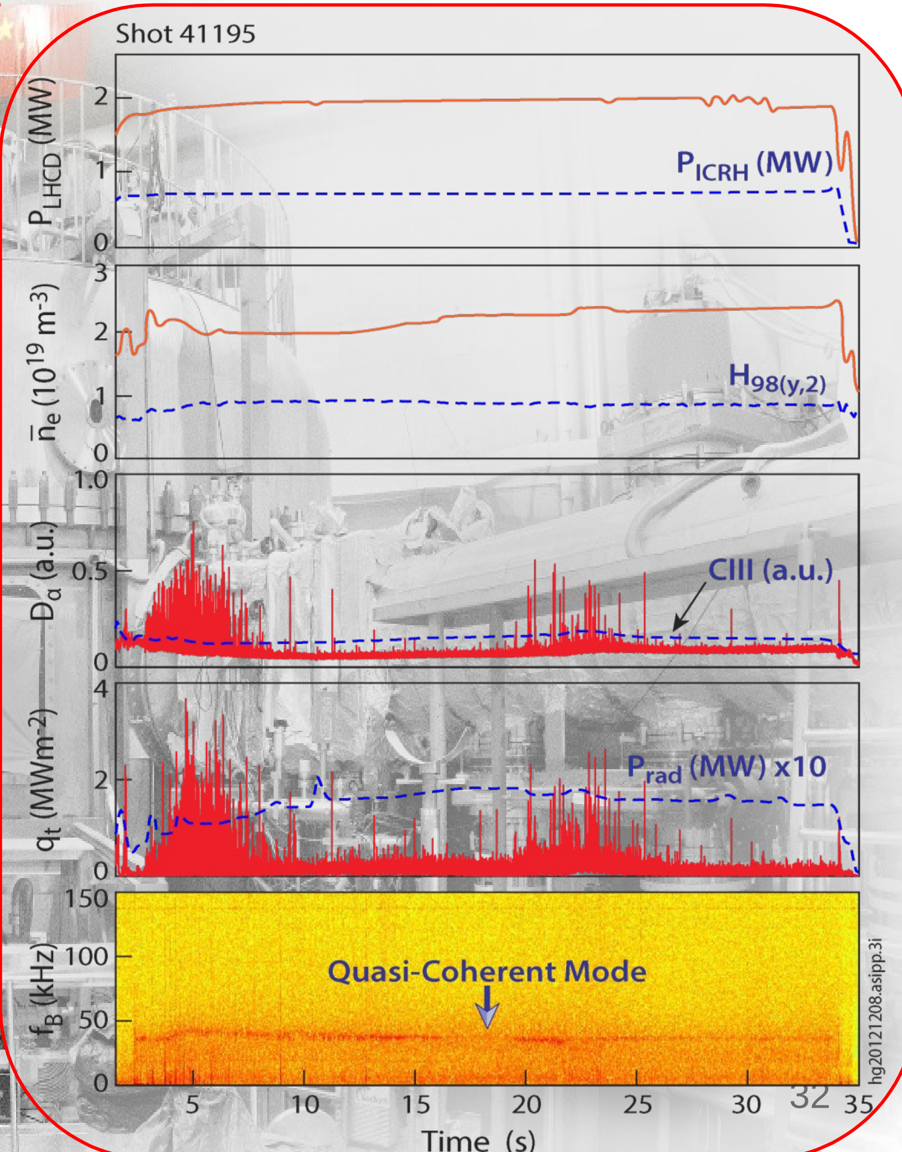
- Triggering ELMs (~25 Hz) with 0.7 mm Li granules @ ~45 m/s.
- ELM trigger efficiency after L-H transition: ~100%.
- Much lower divertor particle/heat loads than intrinsic type-I ELMs.

*D. Mansfield et al., Nucl. Fusion **53** 113023 (2013)*

Achieved long pulse H-mode over 30s w/ small ELMs to minimize transient heat load

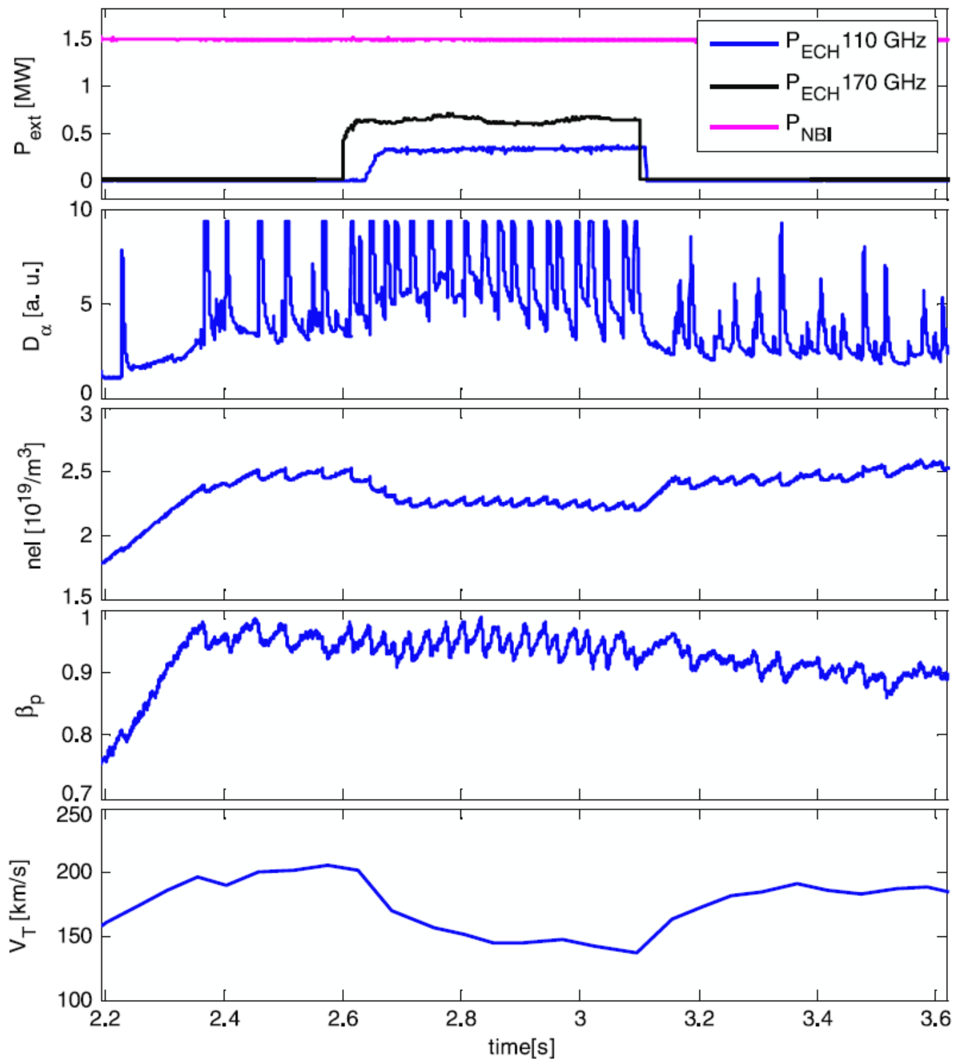
ASIPP

- Predominantly small ELMs with $H_{98} \sim 0.9$, between type-I and type-III ELMy H-modes.
- Target heat flux is largely below 2 MW/m².
- Accompanied by QCM, continuously removing heat and particles.



J. Li et al., Nature Physics **9** 817 (2013)

ELM Control by ECH/CD

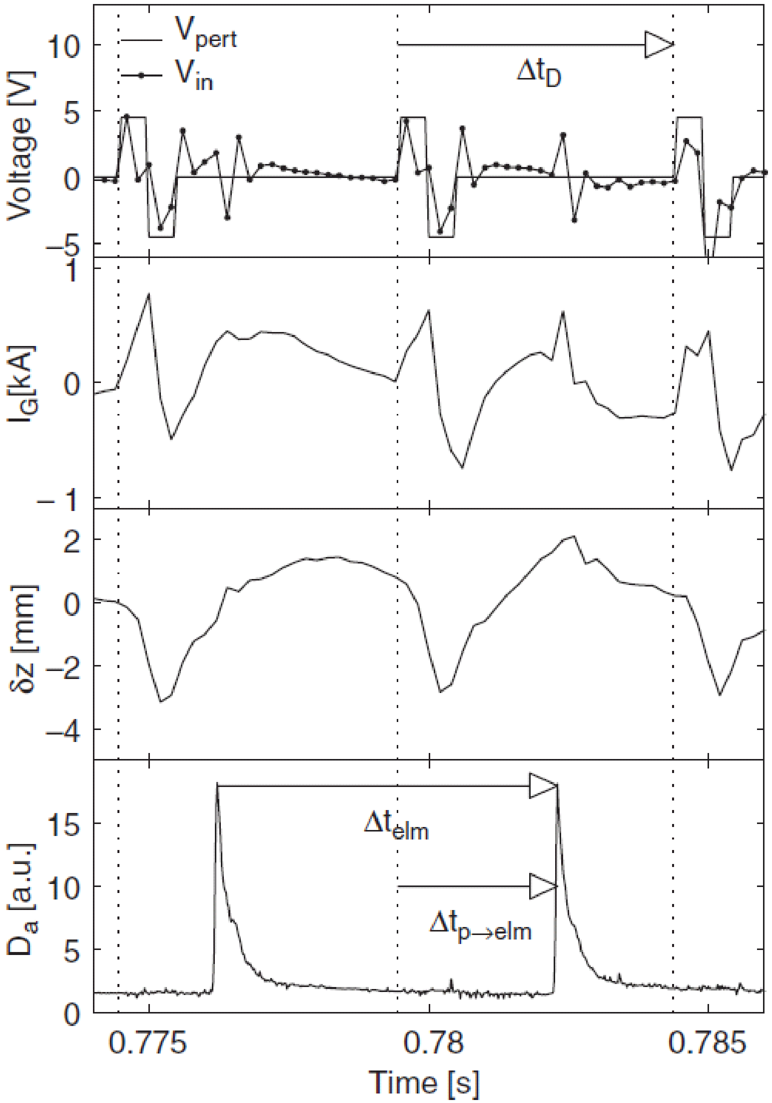


KSTAR

ECH/CD to change the peeling-ballooning boundary

Jayhyun Kim et al., Nucl. Fusion ***52*** *114011 (2012)*

ELM Control by Vertical Jogs

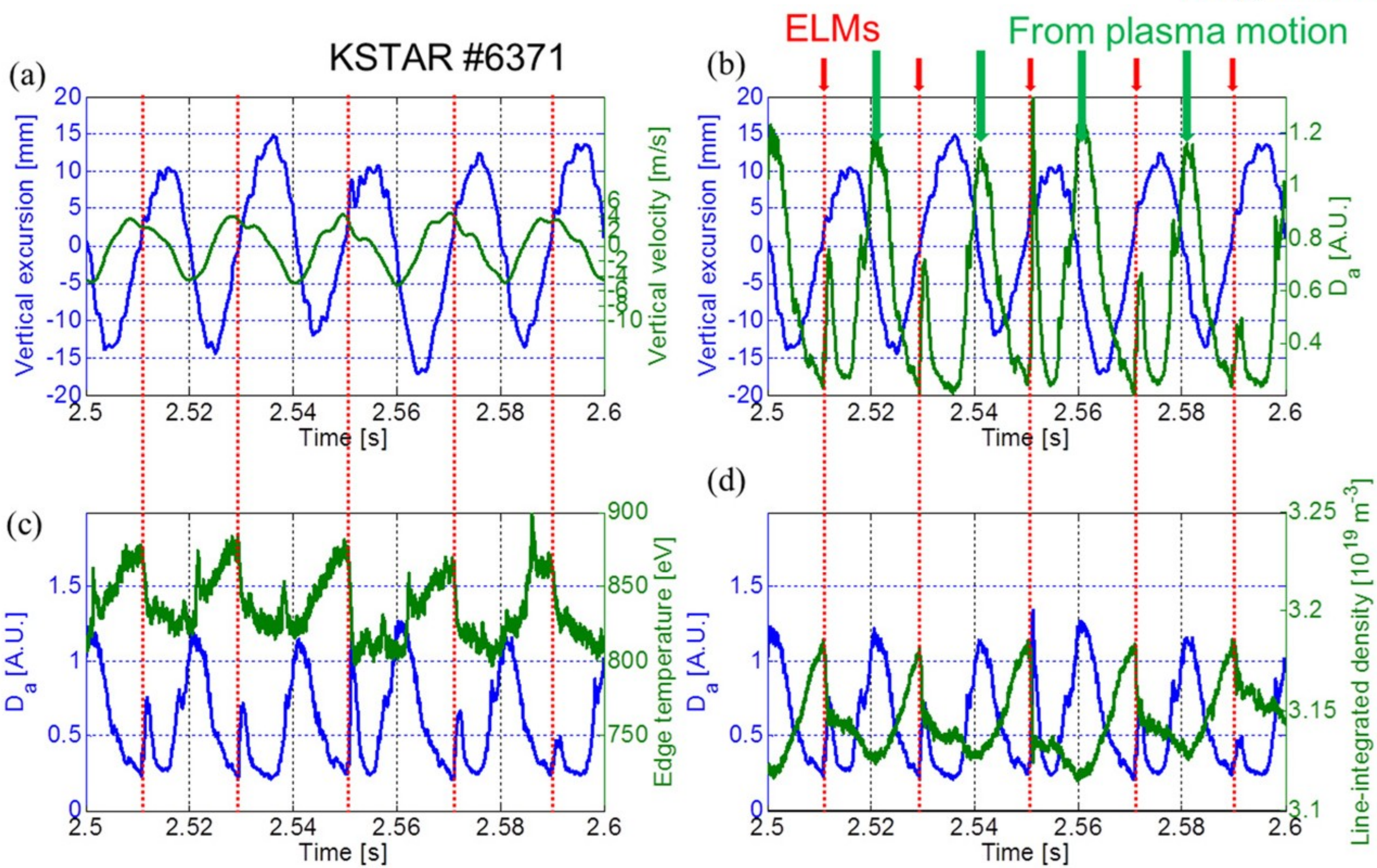


- Experiments on the TCV tokamak have shown that rapid vertical movement of diverted ELMy H-mode plasmas can affect the time sequence of ELMs.

- The effect is attributed to the induction of an edge current during the movement of the plasma column in the spatially inhomogeneous vacuum field of a single-null configuration.

*A.W. Degeling et al., PPCF **45** 1637 (2003)*

ELM Control by Vertical Jogs



Jayhyun Kim et al., Nucl. Fusion ***52*** *114011 (2012)*