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The Role of Zonal Flow in the L-H Transition Near the Threshold and the Dynamics of a New Small-ELM Regime in EAST

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Outline

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1. The Role of Zonal Flows in the L-H Transition near Threshold Conditions on EAST

   G.S. Xu et al., PRL 107, 125001 (2011)

2. The Role of Zonal Flows in the Dynamics of a Small-ELM Regime on EAST

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How far are we from a final understanding of the L-H transition?

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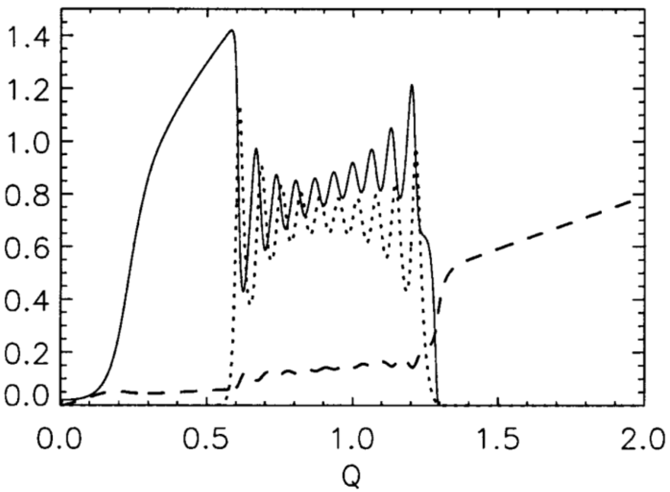
- ITER will be operated close to the H-mode power threshold in the initial Hydrogen phase. But the prediction of the ITER threshold power is still largely uncertain. So, understanding the L-H transition is crucial to successful ITER operation.

- Recent experiments in several devices, TJ-II, DIII-D, NSTX, ASDEX-U, and EAST have shown that as approaching the transition threshold an intermediate phase between L and H mode, so called "I-phase", appears, characterized by a period of dithering or limit-cycle oscillations.



[Kim-Diamond 2003 PRL]

- In this model the dithering or oscillation is thought to be induced by a modulation interaction between zonal flows and turbulence. Since zonal flow is turbulence driven, it can only trigger the transition but cannot sustain it. The mean diamagnetic flow slowly evolves with increasing pressure gradient, finally takes over and locks in the H mode.

A oscillation < 4 kHz << f_{GAM} at marginal input power prior to the L-H transition

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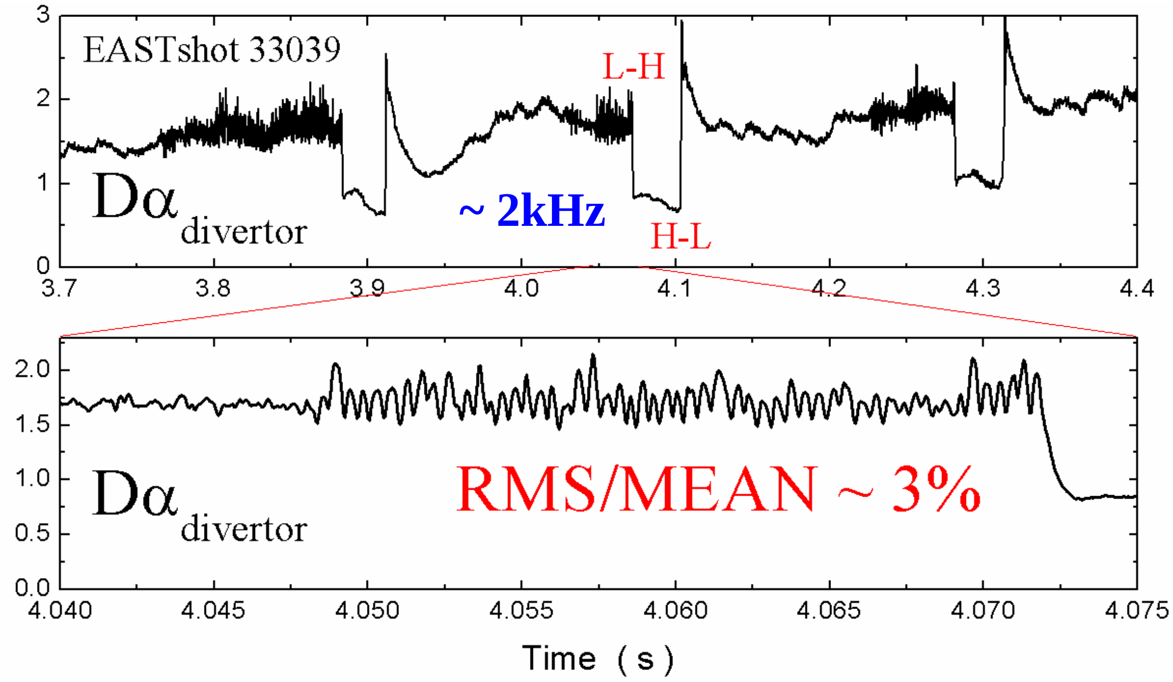

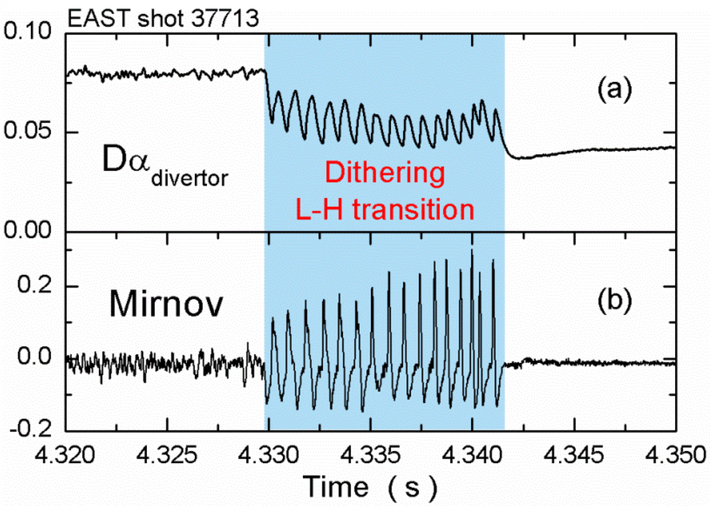

Different from the usual dithering transitions which have big amplitude and strong magnetic perturbations.

- **Small-amplitude dithering frequently appears prior to the typical sharp L-H transition at marginal input power with ~1MW LHCD**
- **Mainly electrostatic in nature (uncorrelated or sometimes only weakly correlated with a few channels of high-field-side Mirnov signals)**

A number of diagnostics located near the divertor detected this oscillation: SOL transport modulation

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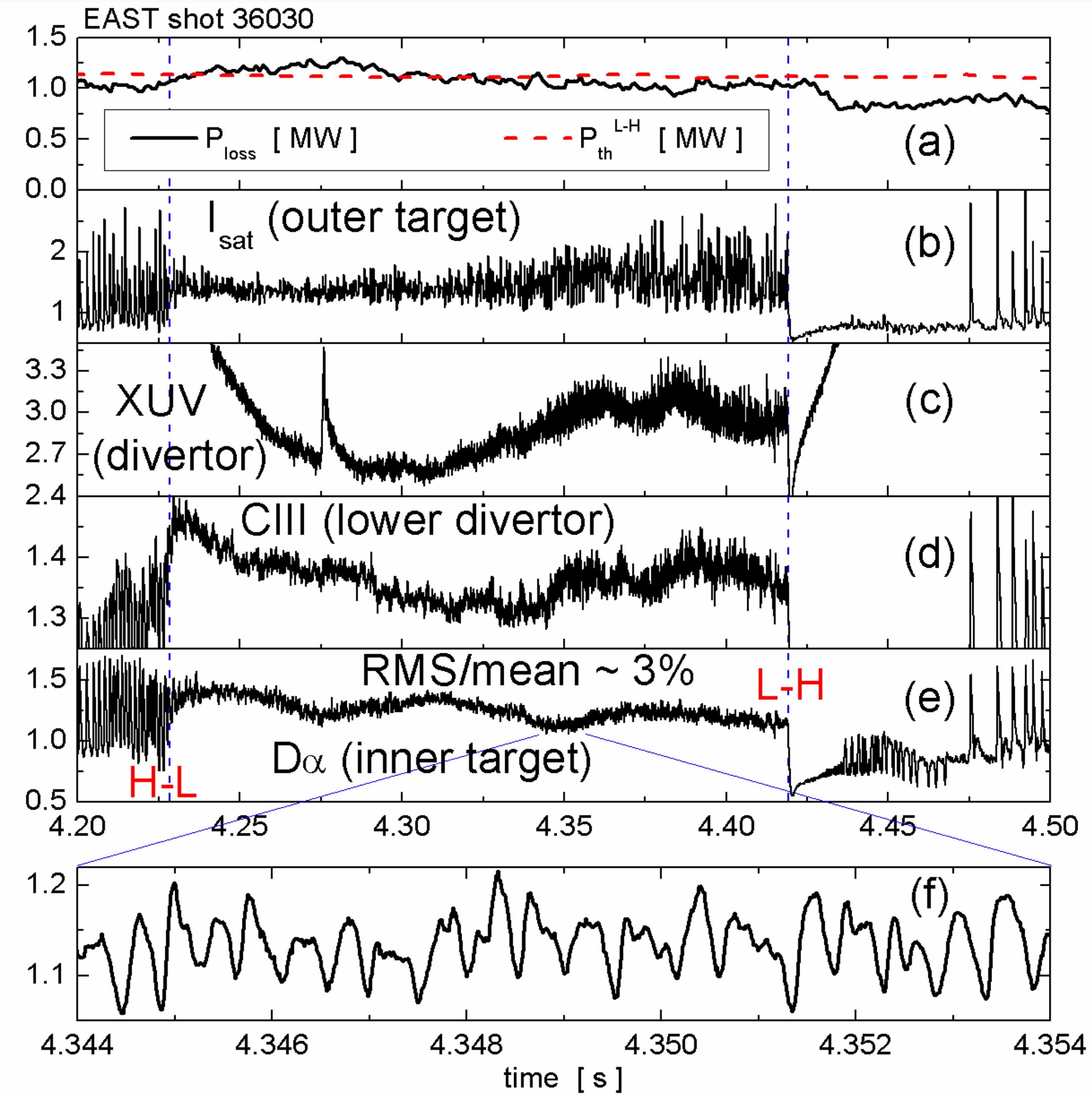

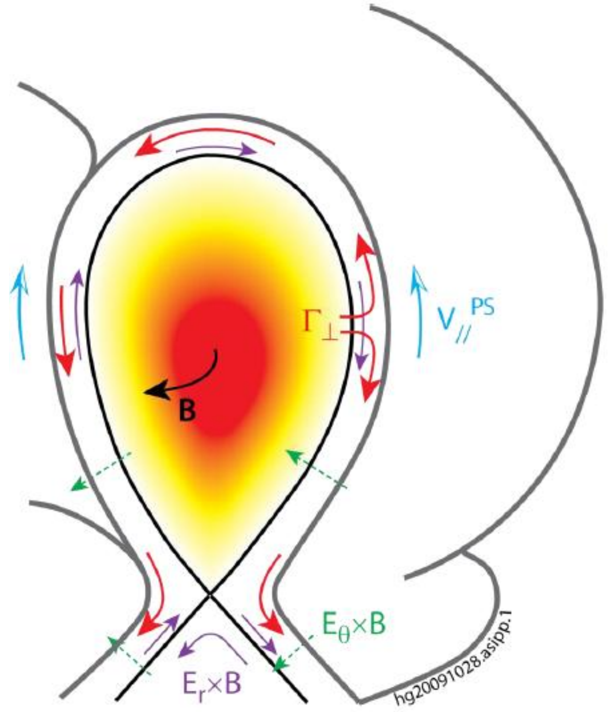

A oscillation in edge Er shear modulates cross-field transport and therefore the divertor Dα emission from recycling neutrals.

Direct measurements of Er, turbulent fluctuations and turbulent Reynolds stress at the plasma edge

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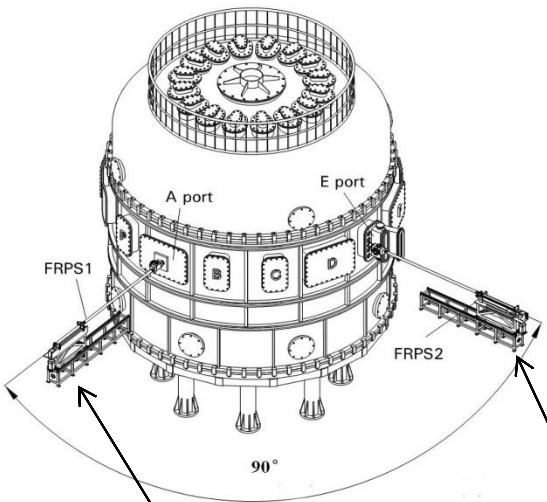

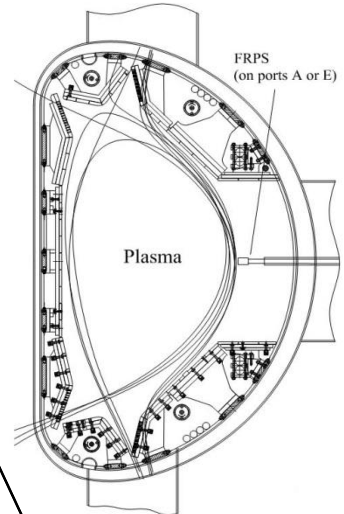

$$E_r = [\Phi_{f1} - (\Phi_{f2} + \Phi_{f3})/2]/\delta r$$

$$E_p = (\Phi_{f2} - \Phi_{f3})/\delta p$$

Reynolds stress

$$\langle \tilde{v}_r \tilde{v}_p \rangle = \langle \tilde{E}_r \tilde{E}_p \rangle / B^2$$

Modulation in edge turbulence, strongly correlated with the turbulence-driven Reynolds stress

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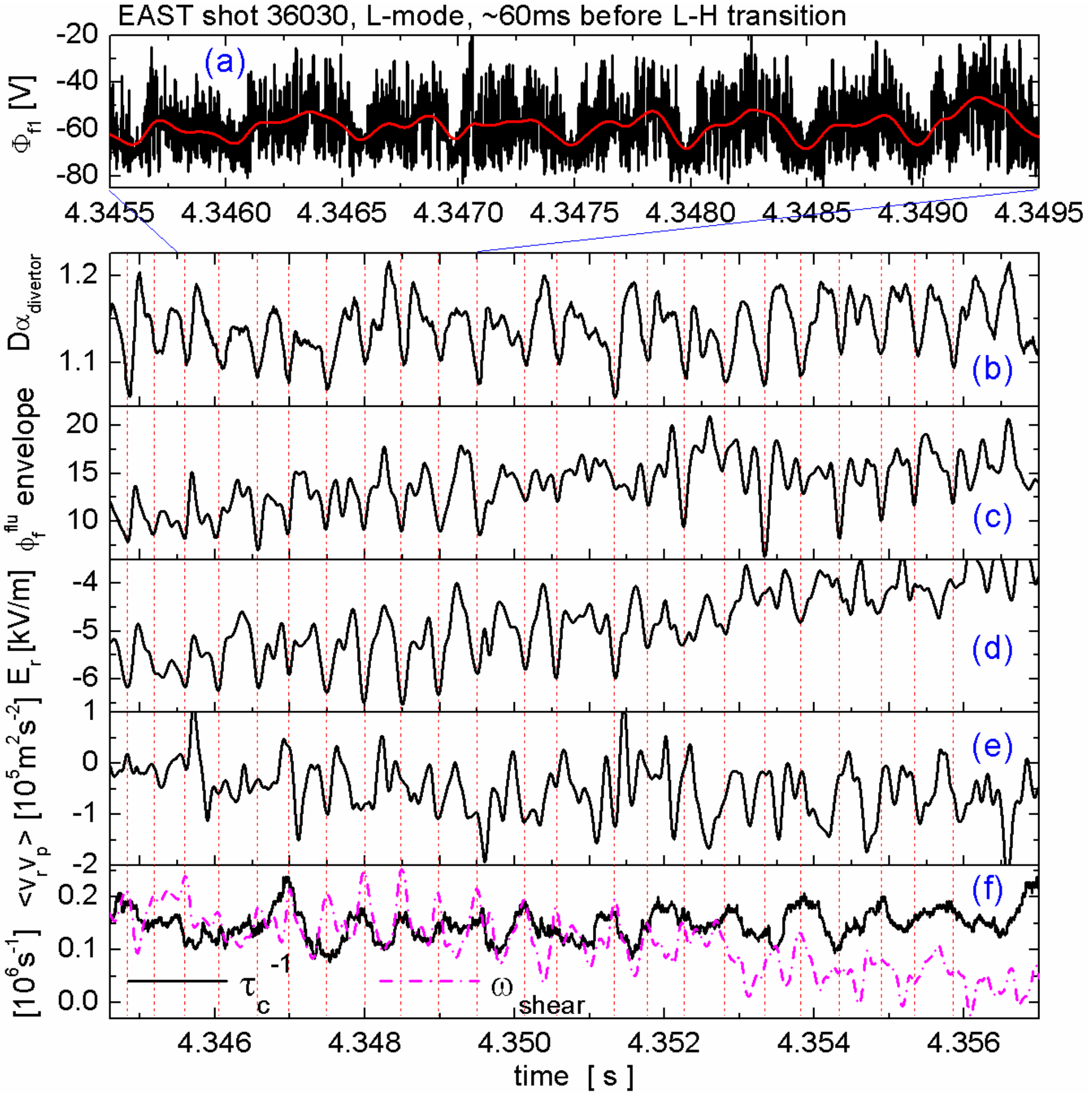

Energy transfer rate from turbulence to zonal flows

$$\gamma \equiv \langle v_p \rangle \langle \tilde{v}_r \tilde{v}_p \rangle / (\Delta r \langle \tilde{v}_p^2 \rangle)$$

$$\sim 2 \times 10^4 \ \mathrm{s}^{-1}$$

Zonal flow damping rate

$$v_{\mathrm{thi}}/qR_0 \qquad \tau_{ii}^{-1}$$

$$1 \times 10^4 \ \mathrm{s}^{-1}$$

The Reynolds force is strong enough to overcome the damping force, thereby driving the zonal flows.

Wavelet bicoherence analysis shows three-wave coupling between the turbulence in the frequency range of 30–100 kHz and the 2 kHz oscillations.

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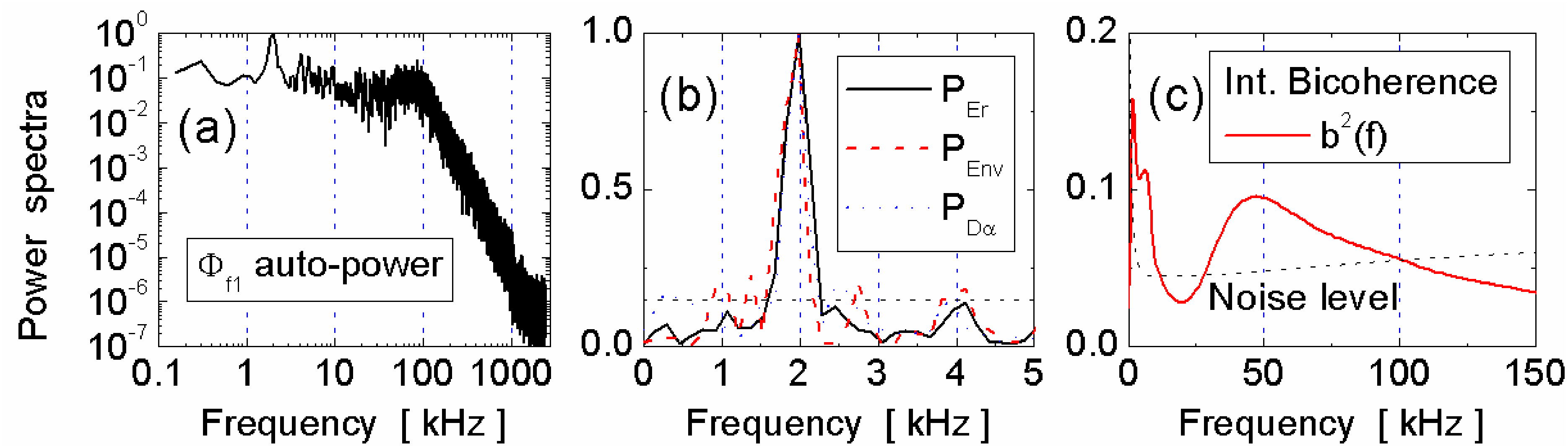

Just prior to the L-H transition, the Er oscillation often evolves into intermittent negative Er spikes

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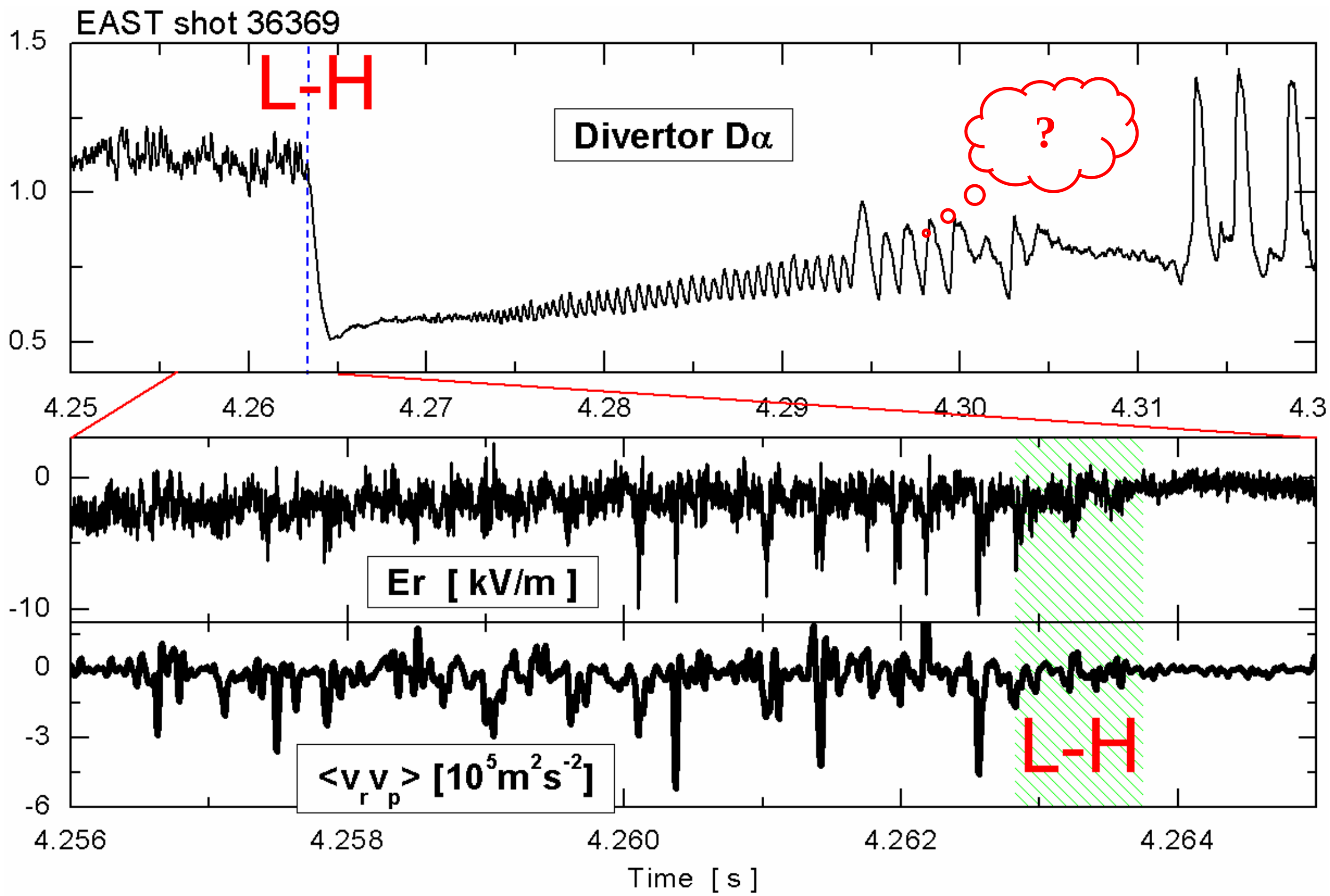

Avalanches arrive at the plasma edge → drive turbulence and zonal flows → transiently enhance the shear → may trigger the L-H transition

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The H modes with frequent small ELMs and good confinement are highly desired for ITER and beyond

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- **Not all ELMs are related to MHD activity. Some ELMs, especially the small and frequent ones, often occur far below the boundary of MHD instabilities.**
- **The small ELM has ever been proposed as a limit-cycle solution in the transport equation [Itoh, 91 PRL].**
- **Recent work in several devices has shown that the dithering at the L-H transition is related to the zonal flows. However, most of the observations are before or during the transition to the H modes. There is little direct experimental evidence that turbulence-zonal flow interactions also exist in the H-mode pedestal, well after the transition, or is associated with small ELMs.**

A new small-ELM regime has been observed on EAST with good confinement at marginal power

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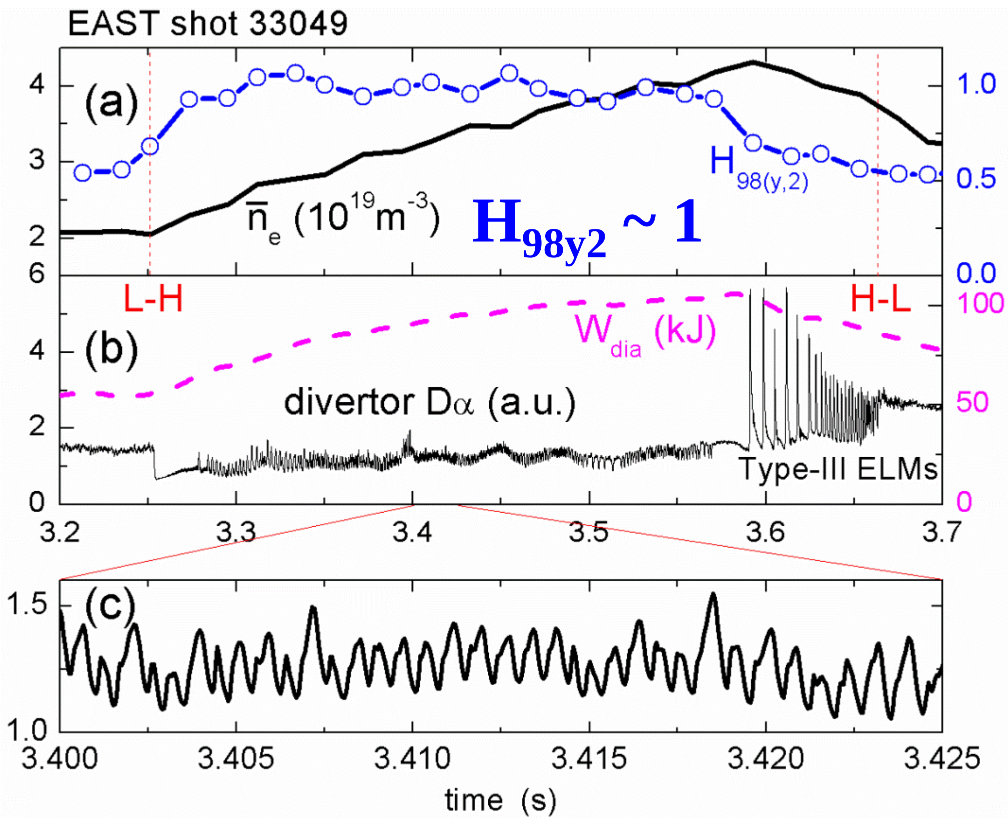
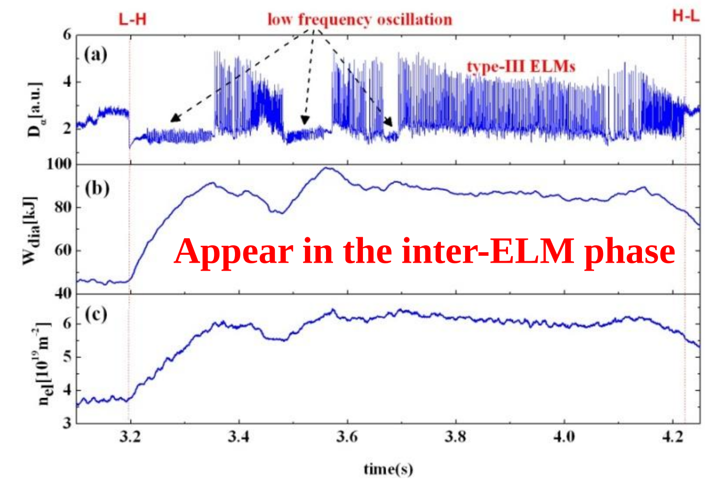
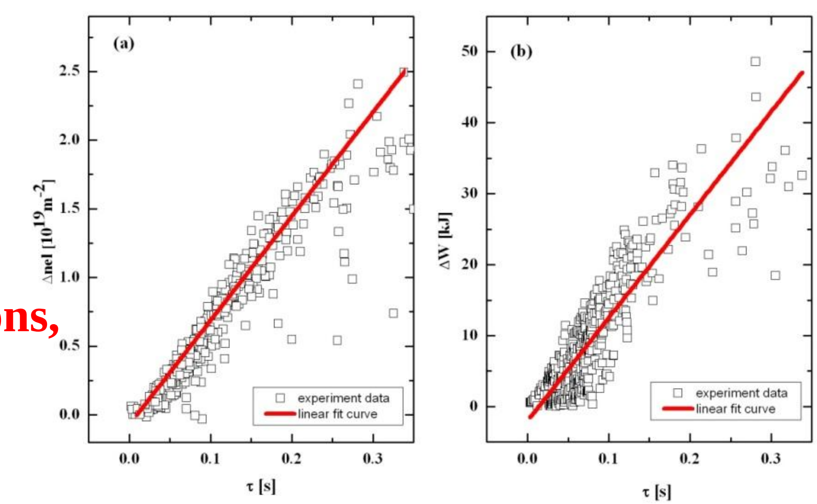




Statistics of 300 shots



Frequently appear shortly after the L-H transitions, and also appear in the inter-ELM phase

The $\bar{n}_e$ and W_{dia} continue to increase with time

Appear to originate from the plasma edge

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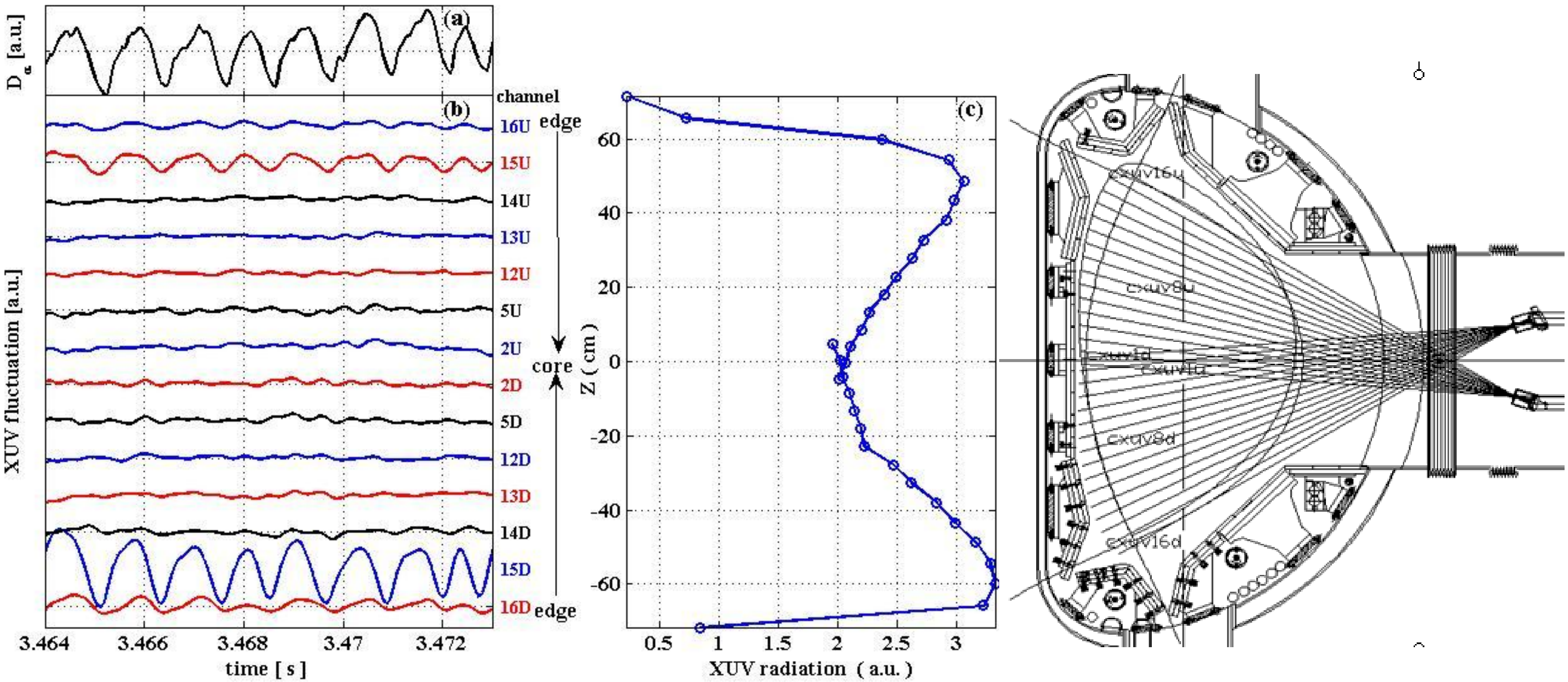

Strong perturbations were only seen in the XUV chords passing through the pedestal region, demonstrating that it is an edge localized activity.

Such a mall-ELM regime has been obtained under a rather wide range of operation conditions

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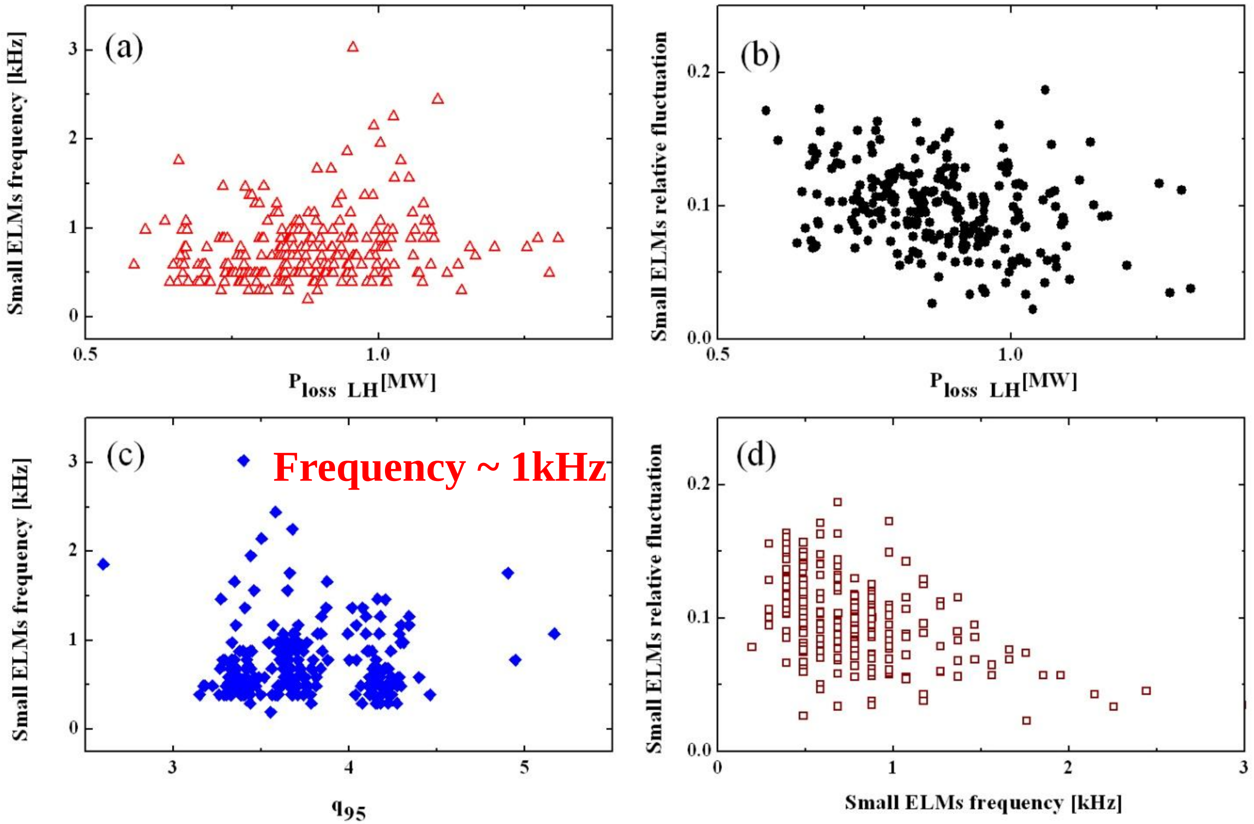

a) **Frequency has no clear dependence on heating power**

c) **Frequency has no dependence on q_{95}**

b) **Amplitude in Dα has no clear dependence on heating power**

d) **Amplitude in Dα decreases with increasing frequency**

B_t = 1.4~2 T, I_p = 0.4~0.8 MA, $n_e = 2\sim6\times10^{19}m^{-3}$, elongation κ = 1.64~1.94, lower triangularity δ_{low} = 0.44~0.58, q_{95} = 2.7~5.0, double null or single null configuration, relative high collisionality at pedestal top $\nu^*_e \sim 1$

Evidence of zonal-flow potential structure at plasma edge has been obtained with two reciprocating probes

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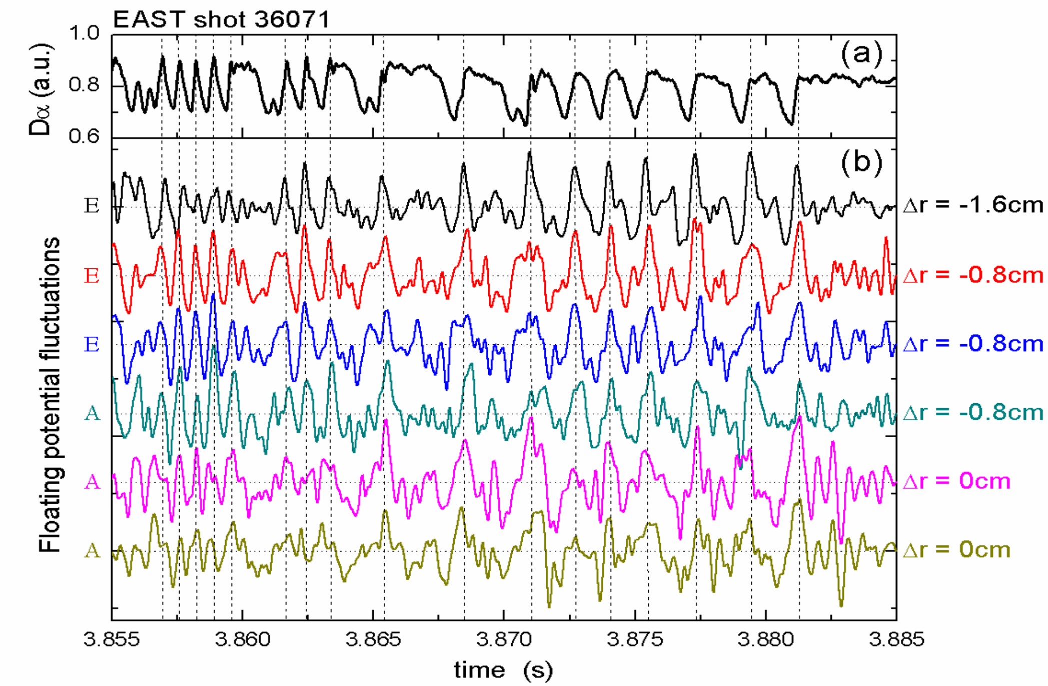

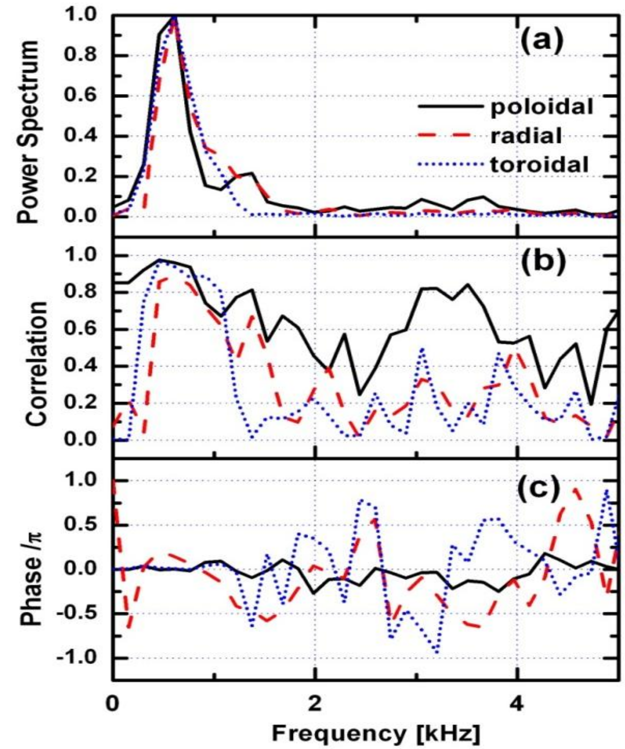

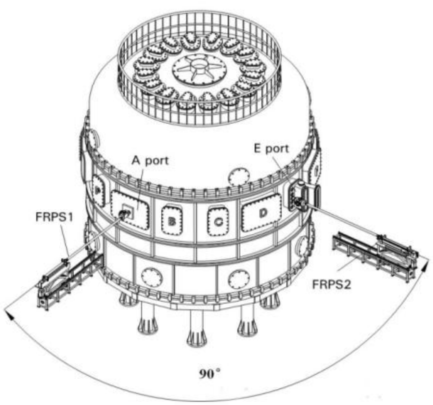

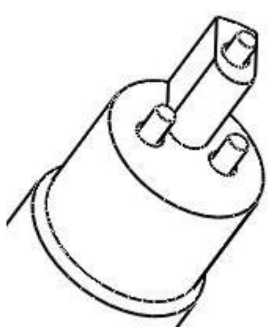

The detailed correlation analysis shows that the fluctuations at different toroidal, poloidal and radial locations are strongly correlated with each other, with nearly no phase differences poloidally and toroidally, but with finite phase difference radially, propagating outward.

At the pedestal a high-frequency-broadband (50-500 kHz) turbulence modulated by oscillatory zonal flows

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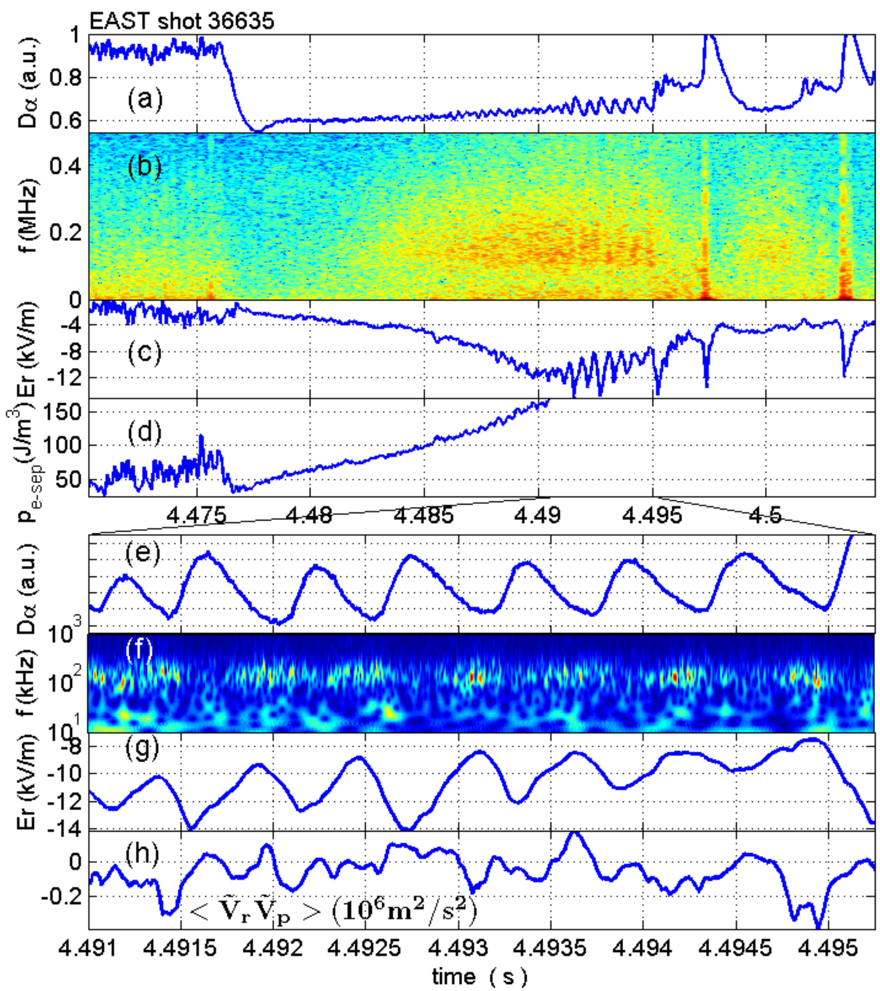

- **The high-frequency turbulence appears shortly after the transition when the edge pressure gradient has been enhanced.**
- **The growth, saturation and disappearance of the zonal flows are correlated with those of the high-frequency turbulence.**
- **The energy gain of the zonal flow is estimated to be of the same order as the energy loss of the high-frequency turbulence, thus strongly suggesting the casual link between them.**

$$e|\Delta\Phi| \quad , \quad \tfrac{1}{2}m_i\left(\tilde{E}_p/B\right)^2 \quad \sim \quad \tfrac{1}{2}m_i\left(E_r/B\right)^2\left(1+2q_{95}^2\right) \sim 3\times10^{-19}\,J$$

Very small-amplitude ($B_{flu}/B_0<1\times10^{-5}$) axisymmetric magnetic perturbations associated with small ELMs

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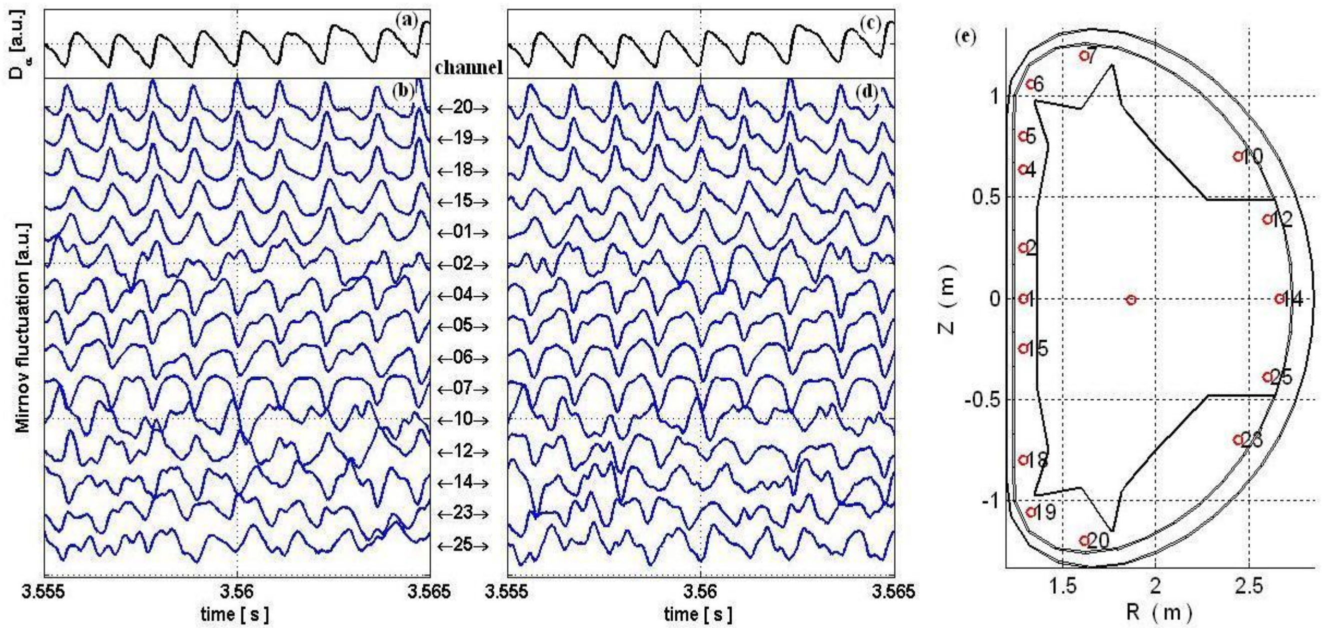

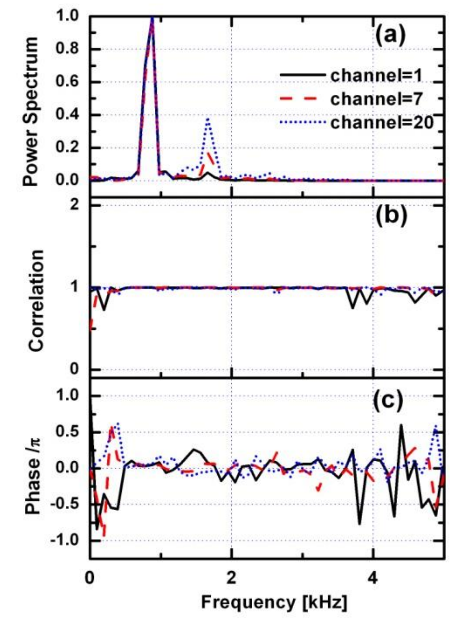

In contrast to usual ELMs with finite mode number, axisymmetric magnetic perturbations were detected by Mirnov coil arrays inside the vacuum chamber.

The magnetic perturbations, measured by two Mirnov coil arrays toroidally separated by 180°, are nearly in phase for all poloidal locations.

The magnetic perturbations are very small, suggesting more electrostatic nature. It could be induced by an oscillation in bootstrap current.

A novel predator-prey model based on turbulence-zonal flow competition reproduced this regime

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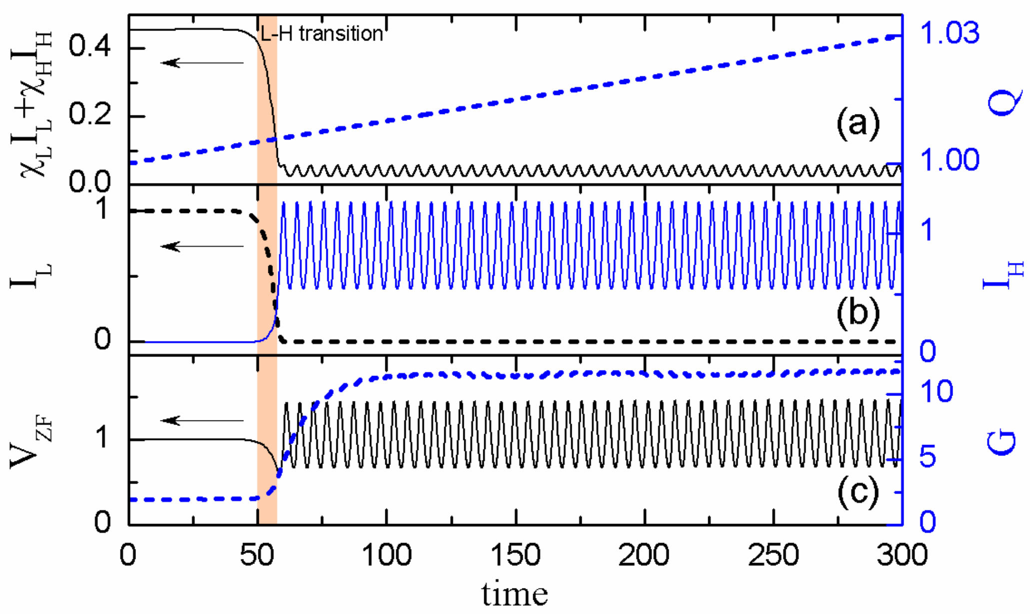

Incorporating the evolution of zonal flows, pressure gradient and turbulences at two different frequency ranges

Successfully reproduced the key features of this newly observed small-ELM regime.

$$\partial_t I_L = \gamma_L Q I_L - \alpha_L V_{ZF}^2 I_L - \nu_L V_{MF}^2 I_L$$

$$\partial_t I_H = \gamma_H Q I_H - \alpha_H V_{ZF}^2 I_H$$

$$\partial_t V_{ZF}^2 = \nu_L V_{MF}^2 I_L + \alpha_L V_{ZF}^2 I_L + \alpha_H V_{ZF}^2 I_H - \mu V_{ZF}^2$$

$$\partial_t G = Q - \chi_L I_L G - \chi_H I_H G - \tau^{-1} G$$

Variable	Physical quantity
V_{ZF}	Zonal flows shear $\propto \partial_r \tilde{V}_E$
$V_{MF} = G$	Mean flow shear $\propto \partial_r \langle V_E \rangle$
I_L	Low-frequency turbulence
I_H	High-frequency turbulence
G	Pressure gradient
Q	Input heating power

Summary

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- Dedicated experiments were carried out on EAST to study the transition dynamics near the power threshold.
- A small-amplitude dithering near the transition threshold has been observed in EAST, which is different from the usual dithering transition by smaller amplitude and more electrostatic in nature. Probe measurements show zonal flow characteristics and turbulence modulation at the plasma edge associated with this small-amplitude dithering.
- A new small ELM regime and a high-frequency-broadband turbulence have been observed, for the first time, in the H mode of the EAST tokamak. The high-frequency turbulence was modulated by the zonal flows, resulting in small-ELM-like transport events. Good confinement ($H_{98y,2} \sim 1$) was achieved in this “small-ELM” regime, even with heating power close to the transition threshold. A novel predator-prey model based on turbulence-zonal flow competition successfully reproduced this regime.

Thank you very much for your attention!

Sawtooth heat pulses appear to periodically enhance the dithering, sometimes trigger the L-H transition

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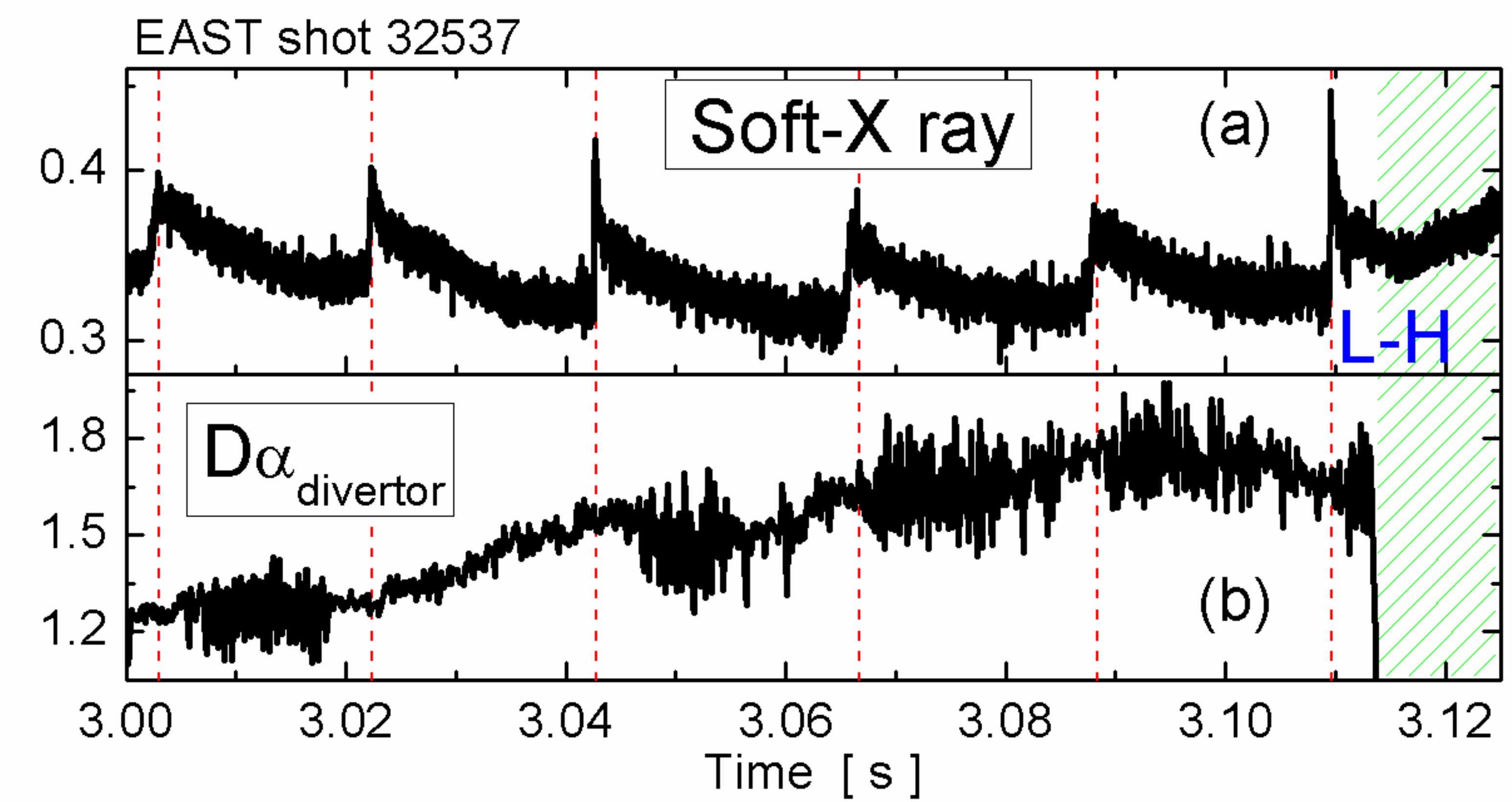

Near the power threshold the dithering amplitude is periodically enhanced by the sawtooth heat pulses, finally triggering the L-H transition after a big sawtooth crash.

Wavelet bicoherence analysis shows strong coupling between the h-freq turbulence and the zonal flows

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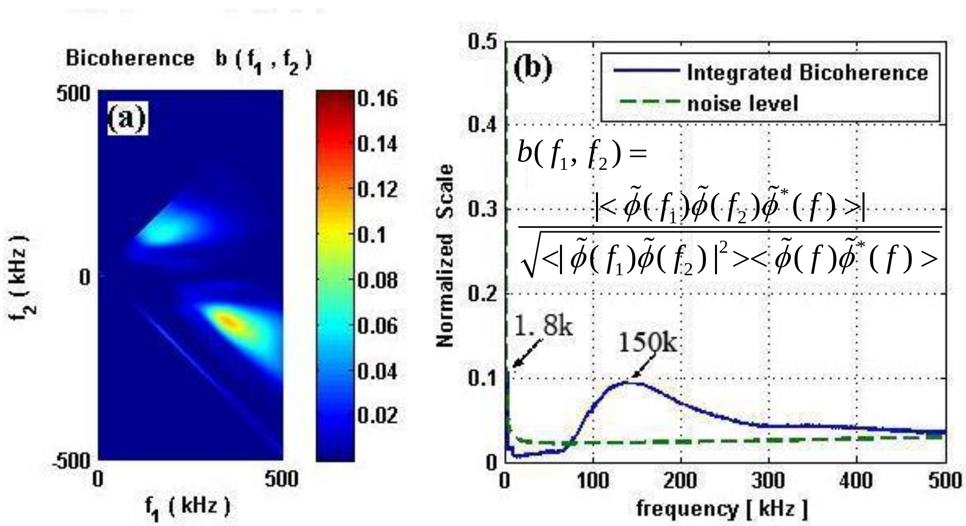

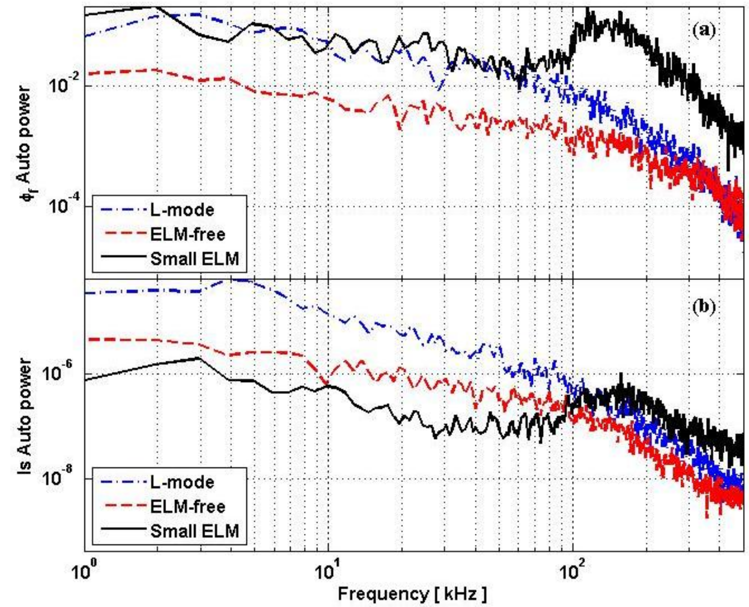

The high-frequency turbulence can be seen in both potential and density fluctuations

Usual dithering transitions have axisymmetric magnetic perturbations

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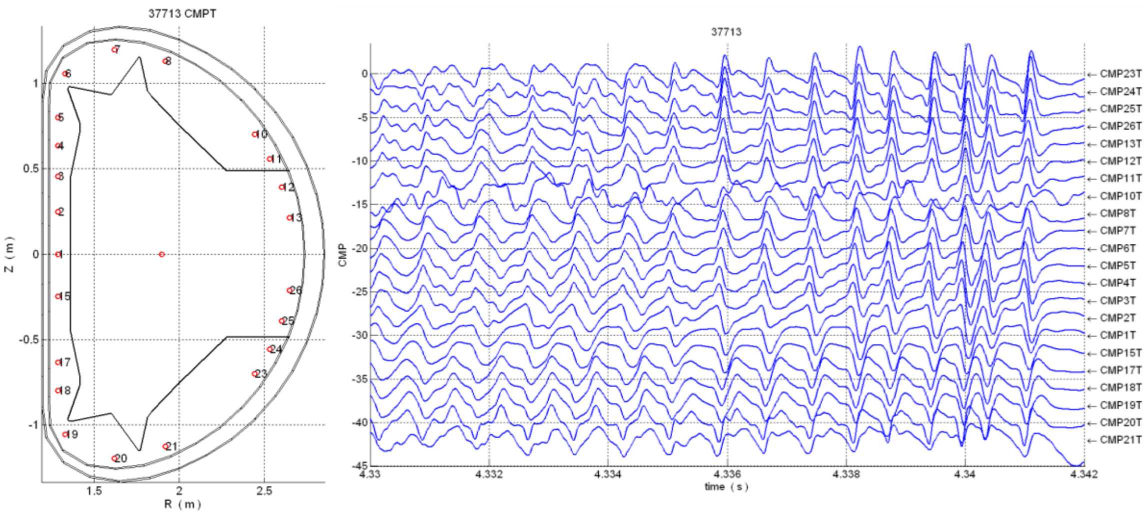
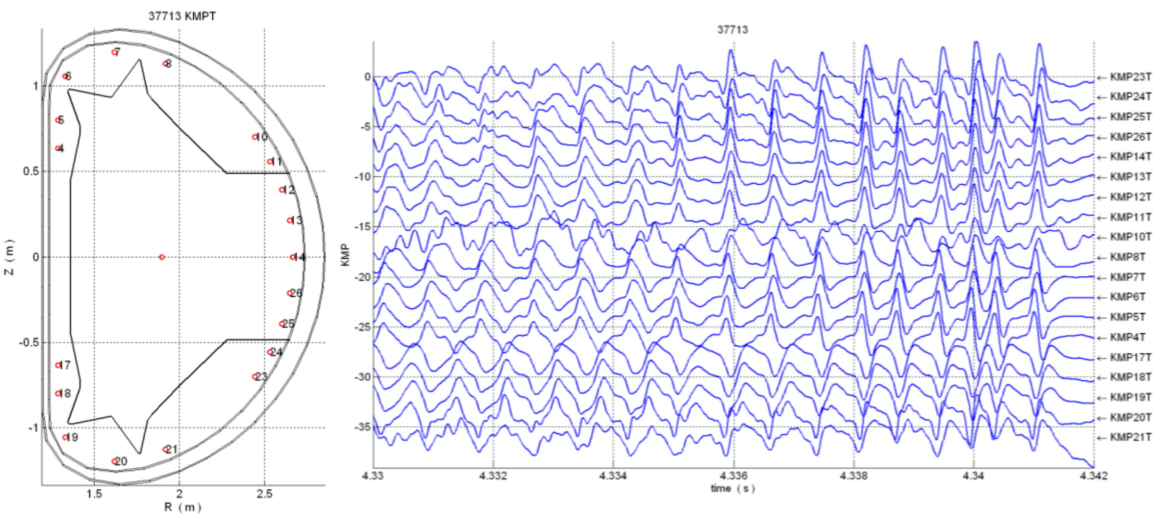
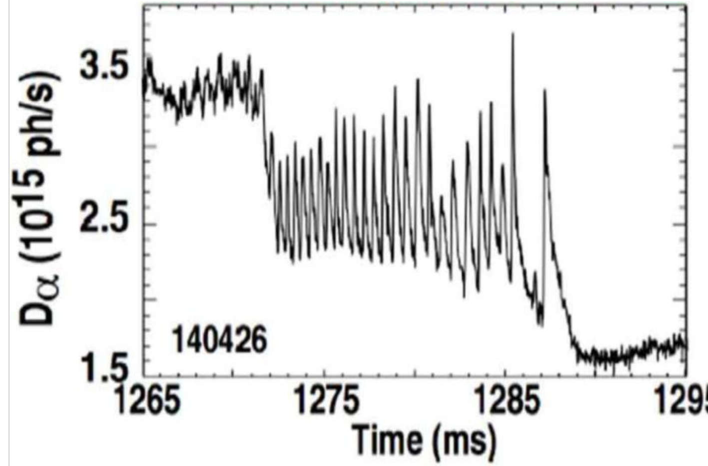
Two Mirnov arrays toroidally separated by 180°

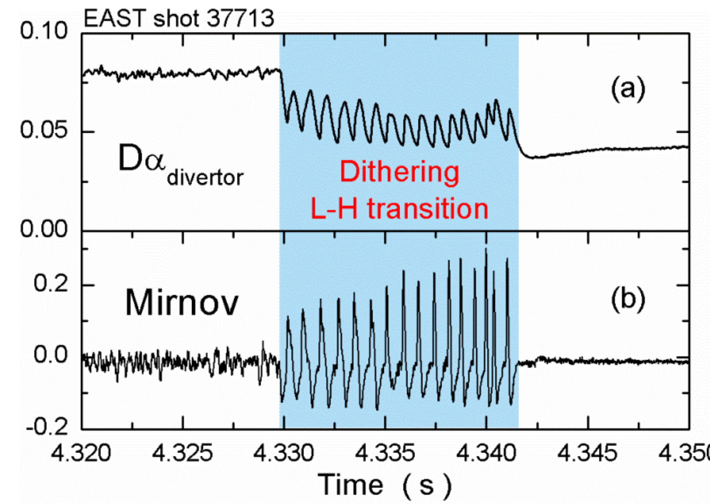




Dithering transition in DIII-D
L. Schmitz 11 TTF



Dithering transition in EAST



I-phases between H-L and L-H in EAST