A Long-Pulse H-mode Regime with a New Coherent Mode Providing Continuous Transport across Pedestal in EAST

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Outline

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1. Motivation
2. Long-pulse ELM-free H-mode
3. Edge Coherent Mode (ECM)
4. GYRO code simulations
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Target: Long-pulse H-mode without large ELMs

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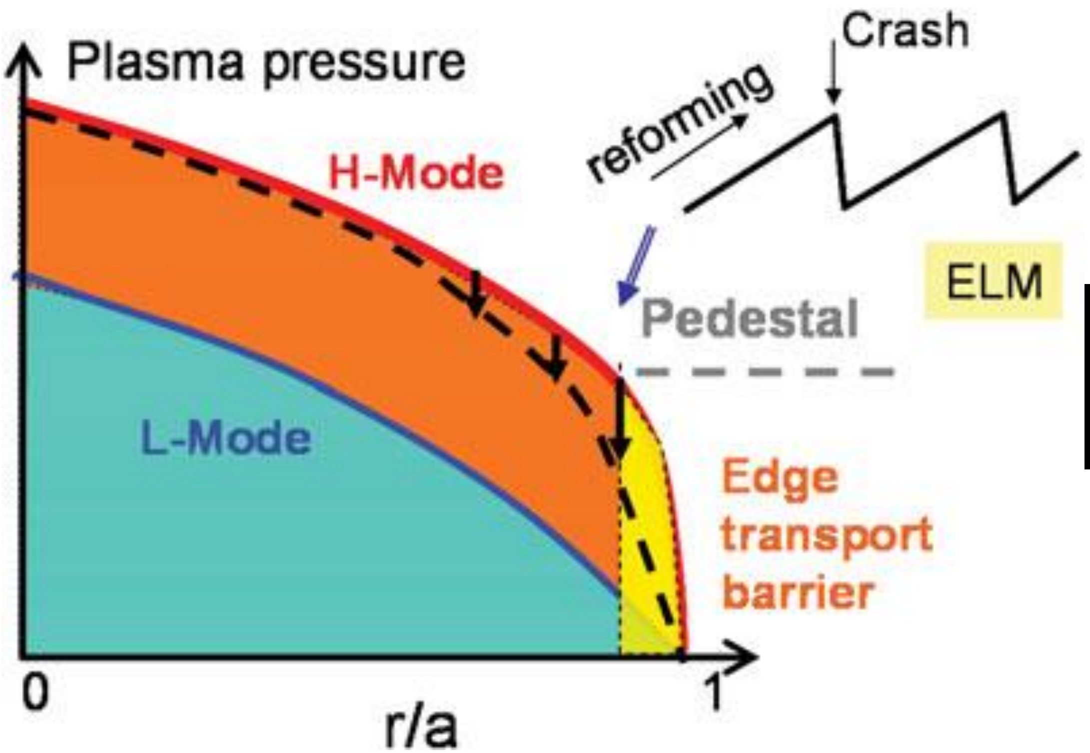

One solution:

long-lived coherent modes or turbulence

Question: Can we use the micro-instabilities, like TEM, to avoid large ELMs?

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Long-pulse nearly non-inductive ELM-free H-mode > 200 τ_E , H_{98} ~ 1.2 , sustained by LHCD

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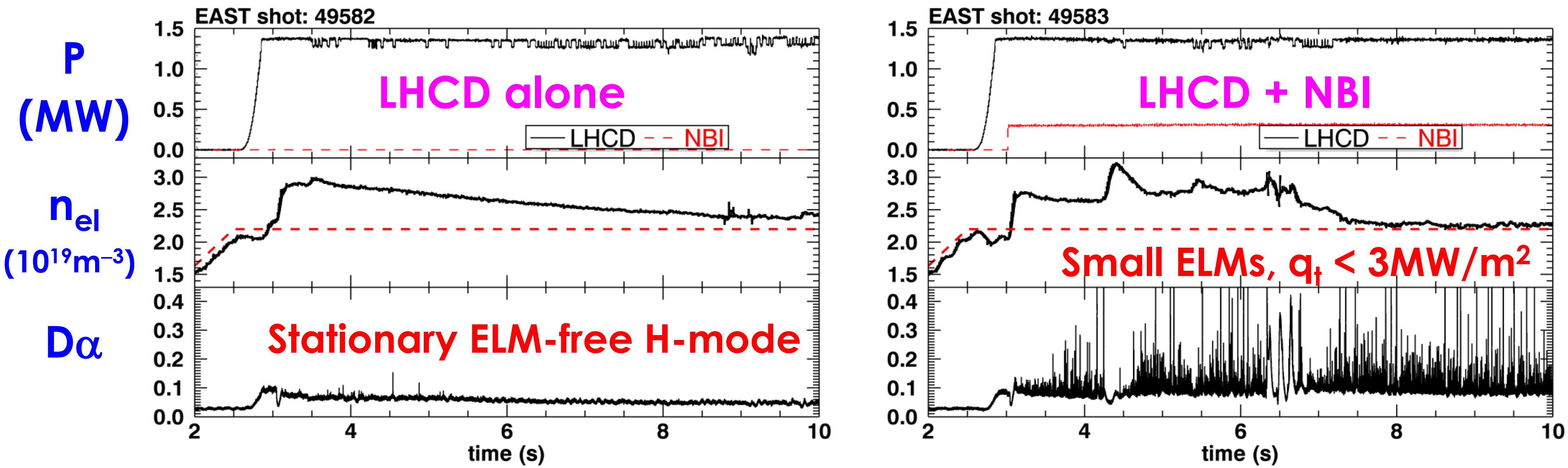
- With intensive lithium wall coating. The accumulated amount of lithium injection is more than 1 kg with 15-45 grams for each day.

LHCD	4.6 GHz	3MW(6MW)
LHCD	2.45 GHz	2MW(4MW)
NBI	co-I_p	3MW(4MW)
ICRF	2 antennas	2MW(12MW)

- Stationary ELM-free H-modes have been obtained only with LHCD alone.
- Additional power from NBI or ICRF or outgap↑ (κ↑) brings small ELMs back.



Long-pulse nearly non-inductive ELM-free H-mode > 200 τ_E , sustained by LHCD alone

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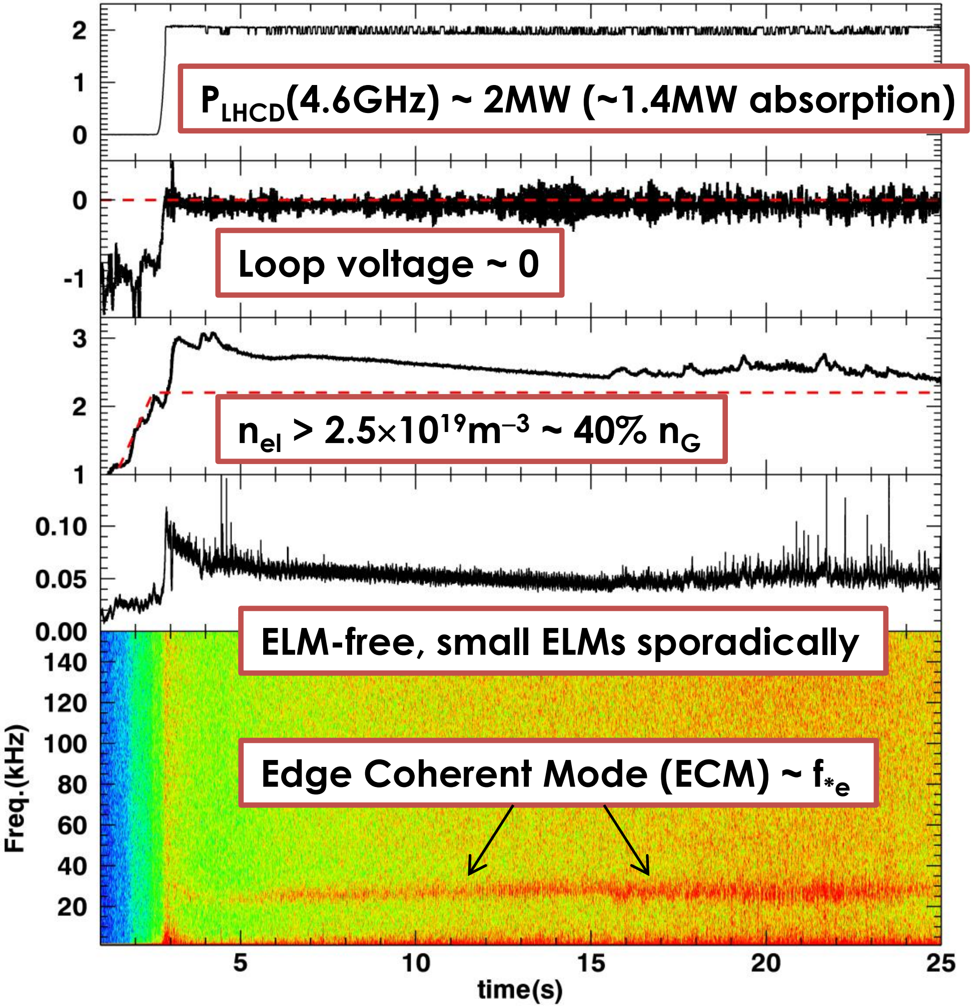

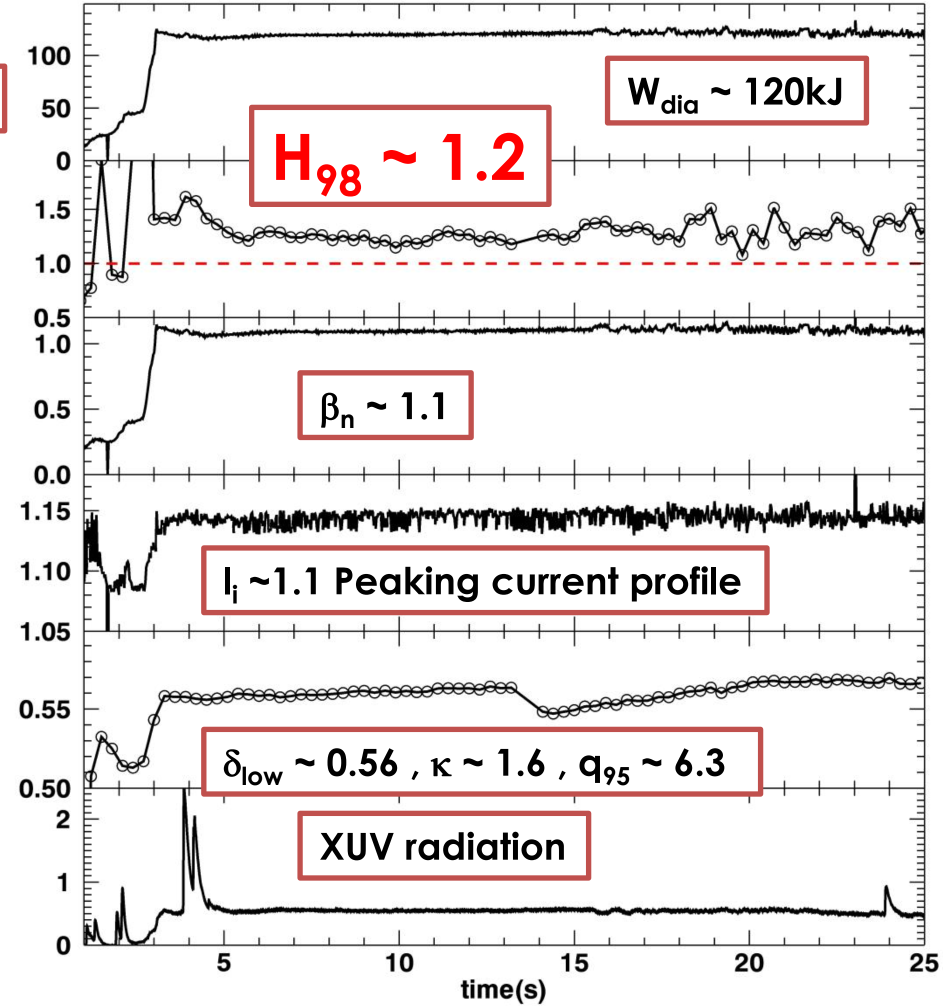

Measured by edge tangential Helium line emission

I_p = 0.38 kA, B_t = 2.3T, R_0 = 1.9m, a = 0.44m

Collisionality at pedestal top is still high $\nu^*_e \sim 1$

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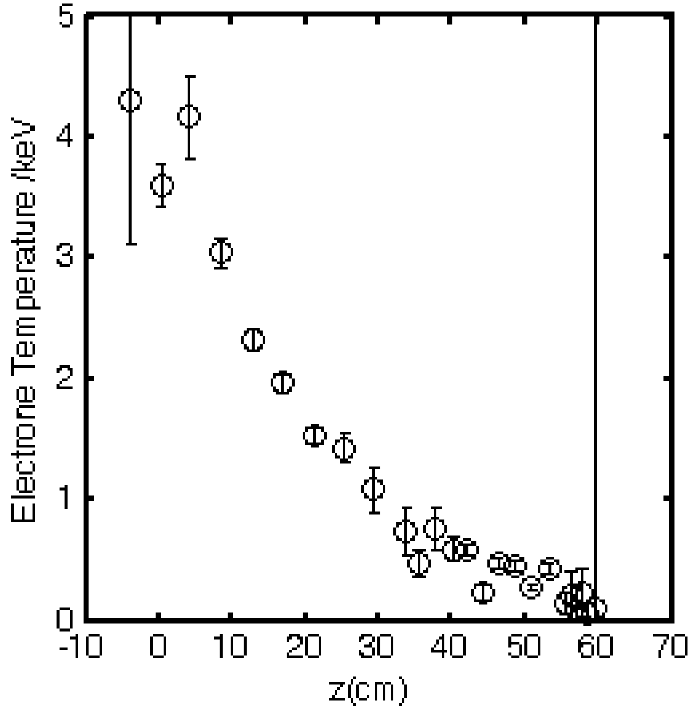
This scenario has rather hot core plasma:

T_{e0} up to 4.5 keV, T_{eped} ~ 0.4 keV



LHW deep penetration at high B_{t0} = 2.3 T ⇒ hot core plasma

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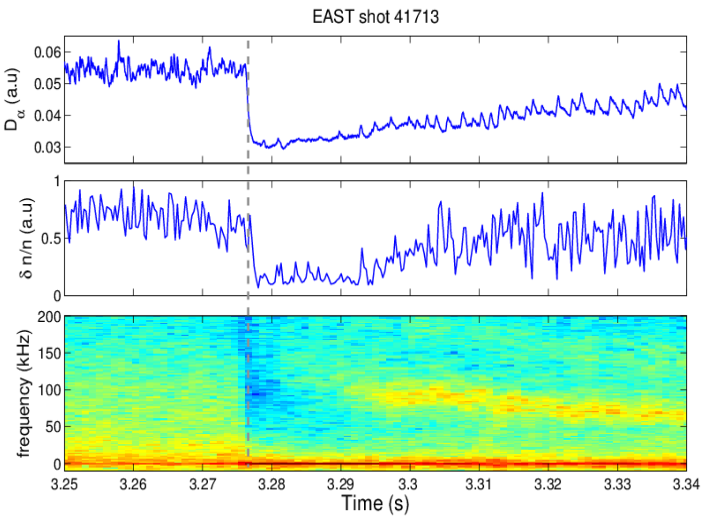
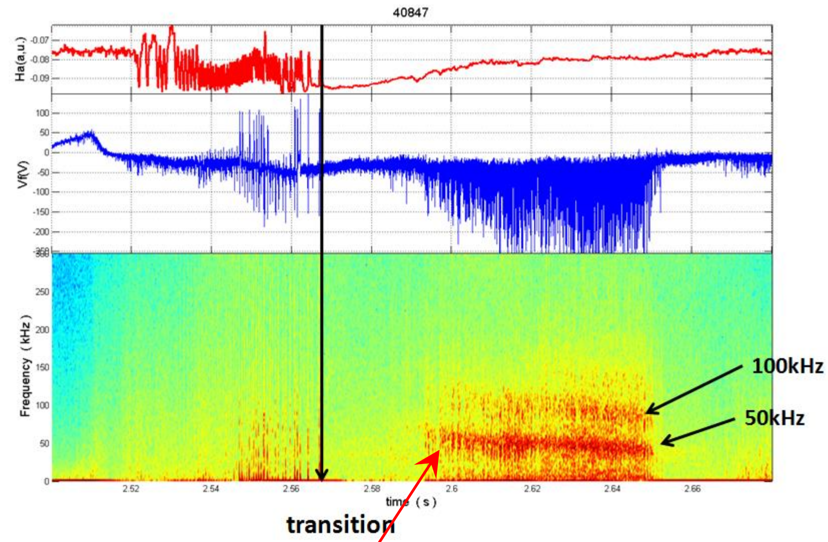
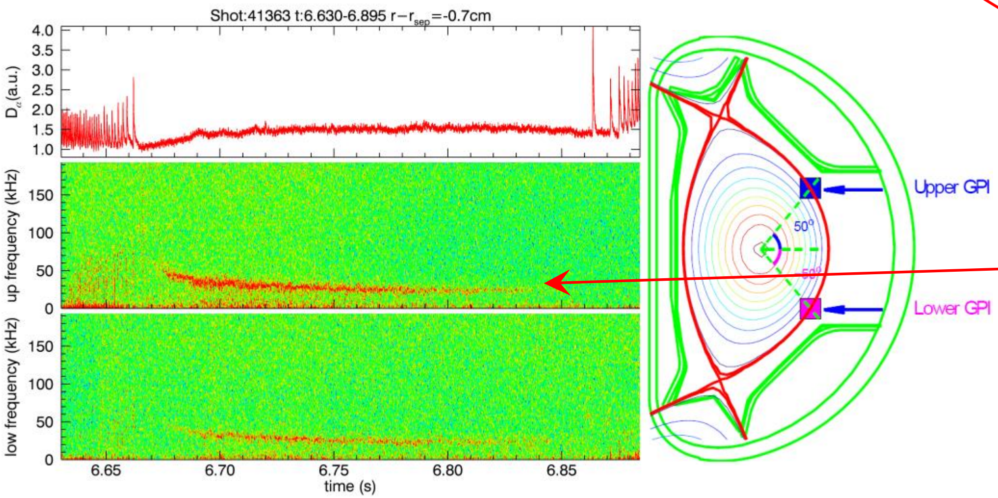
Edge Coherent Mode (ECM) has been detected by several pedestal fluctuation diagnostics







- Reflectometer
- Reciprocating probes
- Gas puff imaging (GPI)
- Thermal Helium beam emission spectroscopy (THeBES)

ECM has weak magnetic component at $\beta_n \sim 1$

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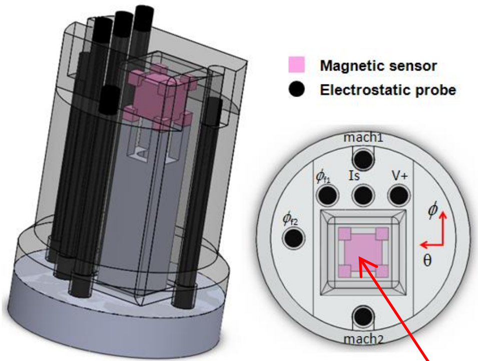

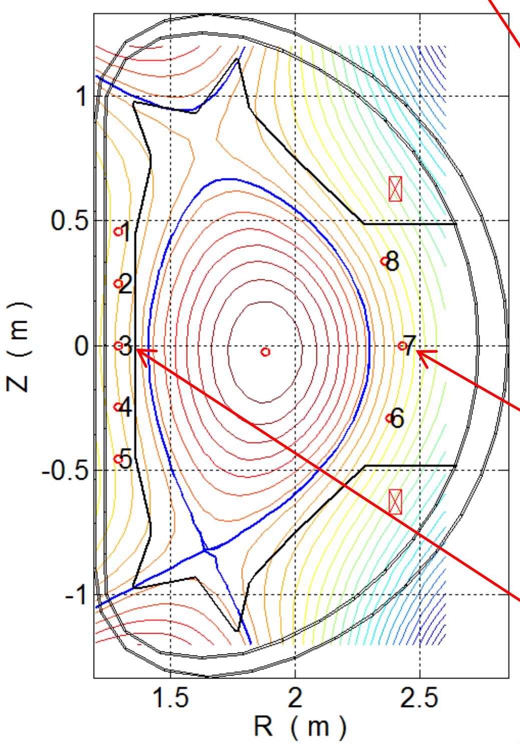

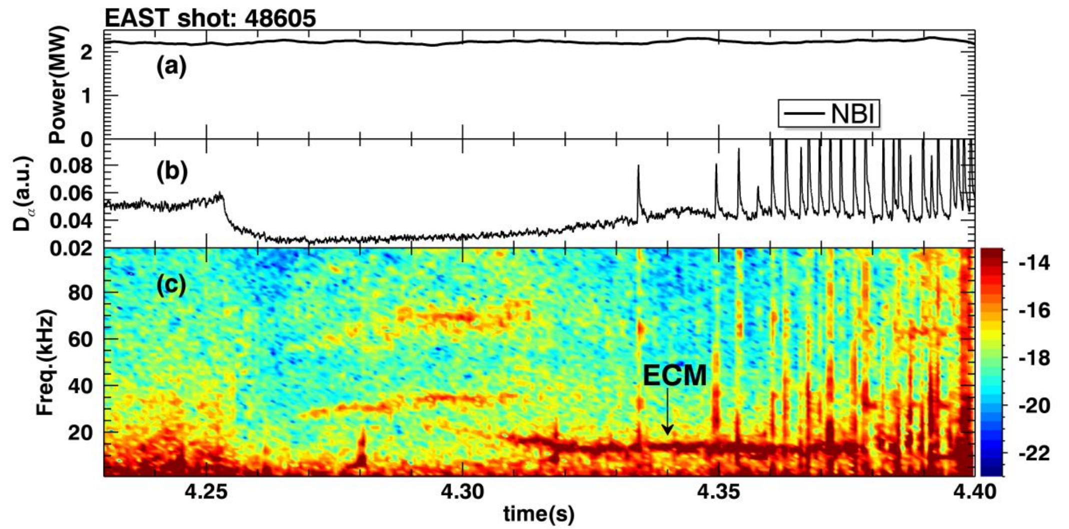

- ECM has a rather weak magnetic component, $\delta B \sim 0.2$G ($\delta B/B_p \sim 1\times10^{-4}$), as measured directly by small magnetic coils mounted on the reciprocating probe at the mode location.
- Also detectable by the fast Mirnov coils localized on the low-field side, but only when the plasma boundary moves close to the outer wall.
- Undetectable by fast Mirnov coils on the high-field side.

Promote particle transport, evidenced by Dα↑, especially with higher density

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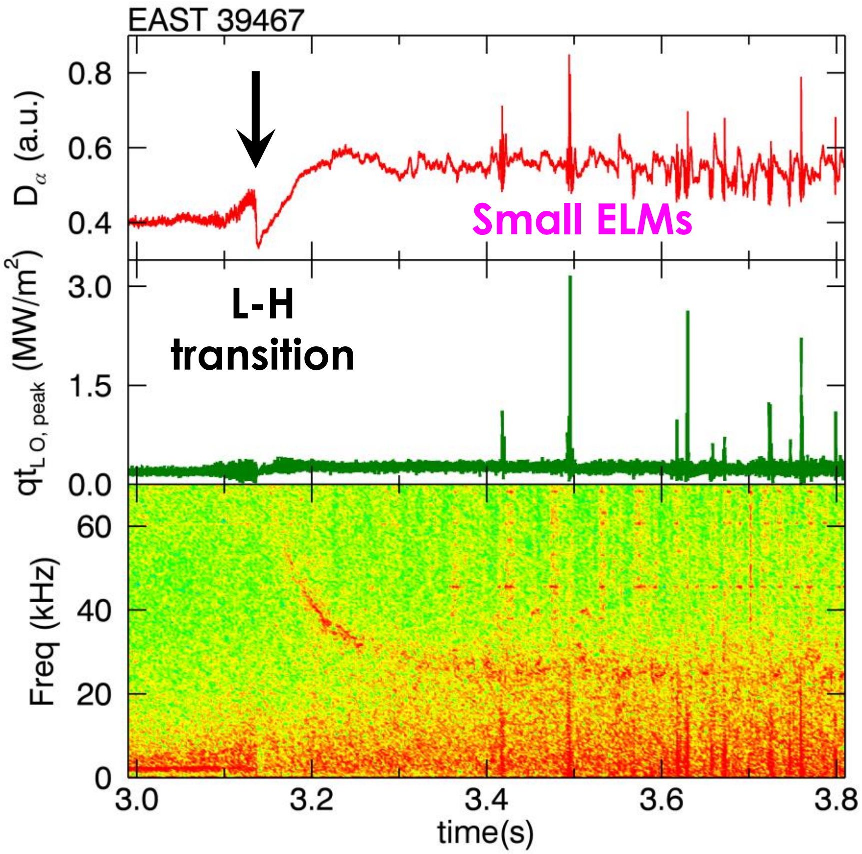
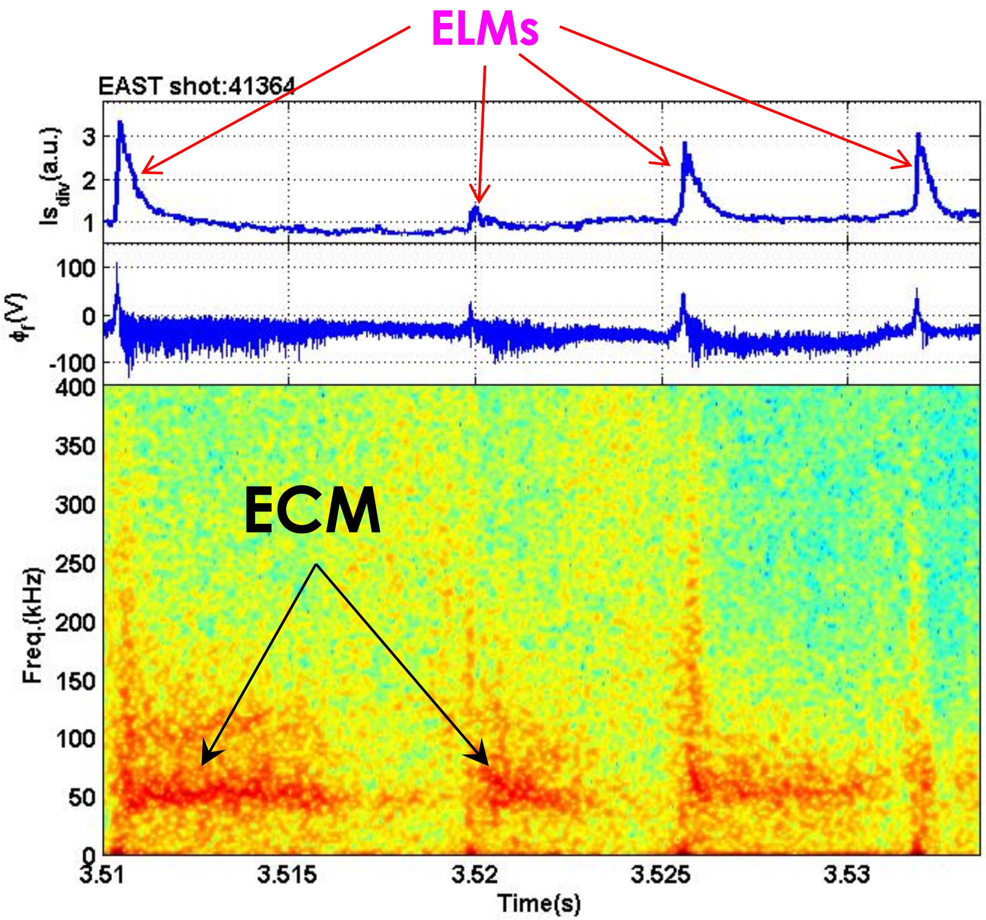


Sometimes, it also appears immediately following ELM events



Usually starts to appear during pedestal buildup shortly after an L-H transition or a transition from ELMy to ELM-free phase

The appearance of ECM is independent of LHCD, ICRF or NBI heating schemes

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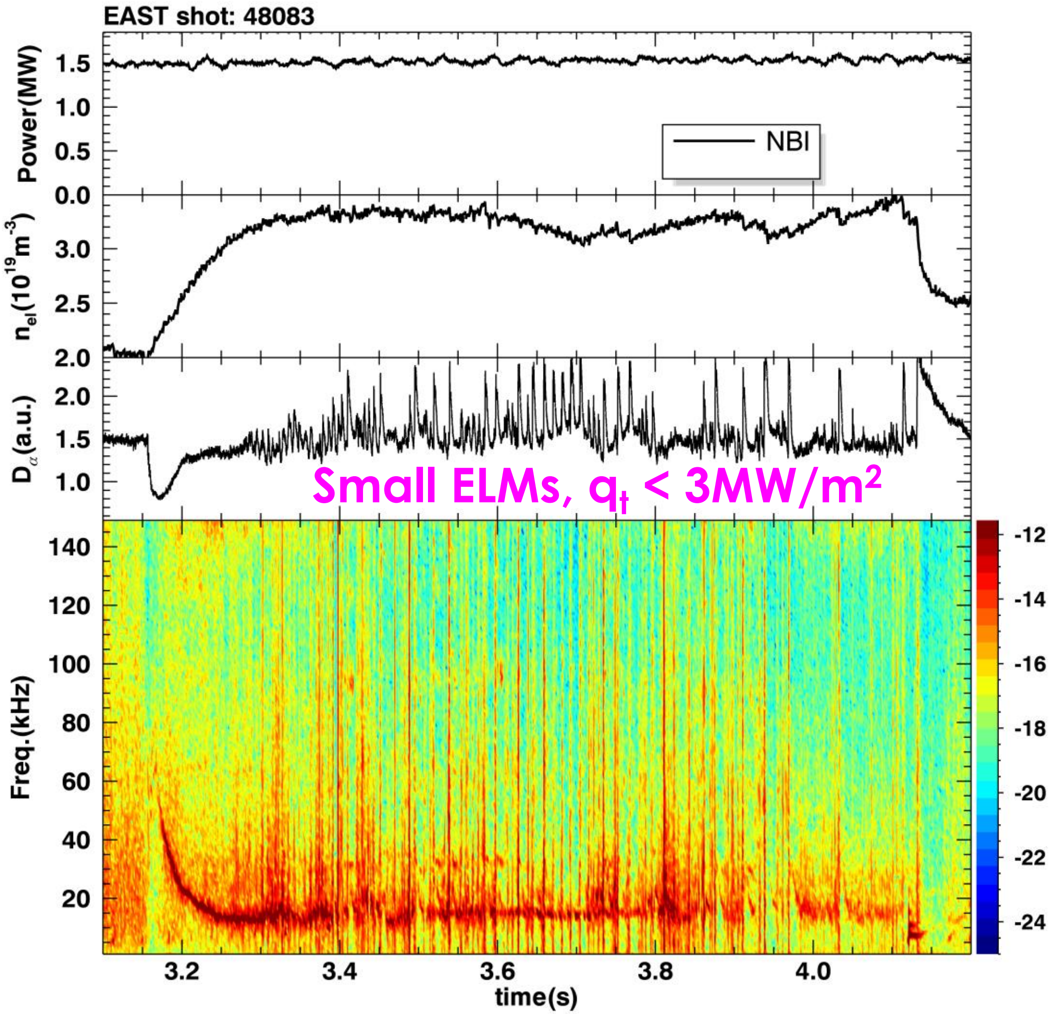
Pure NBI H-mode, 3MW (~1.5MW absorption)



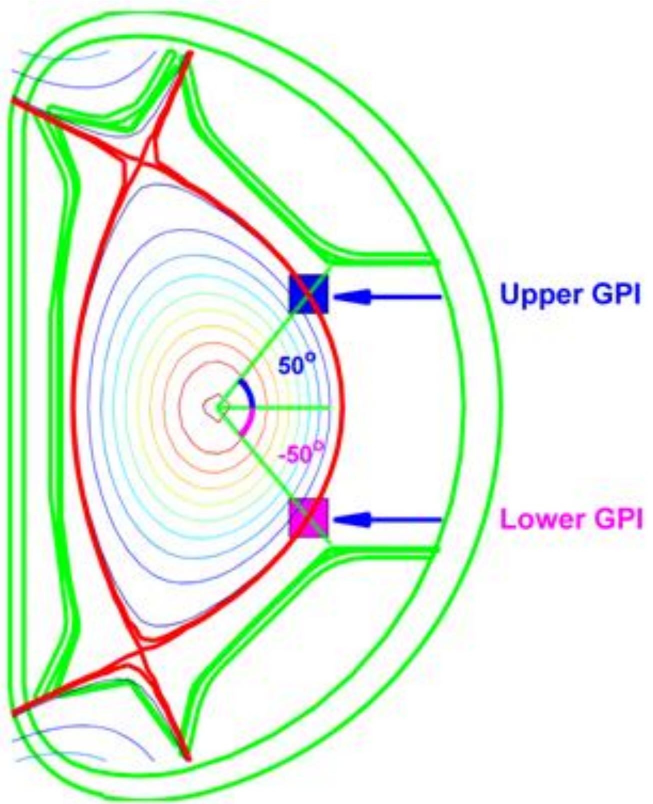
NBI H-mode typically has small ELMs when the ECM appears.

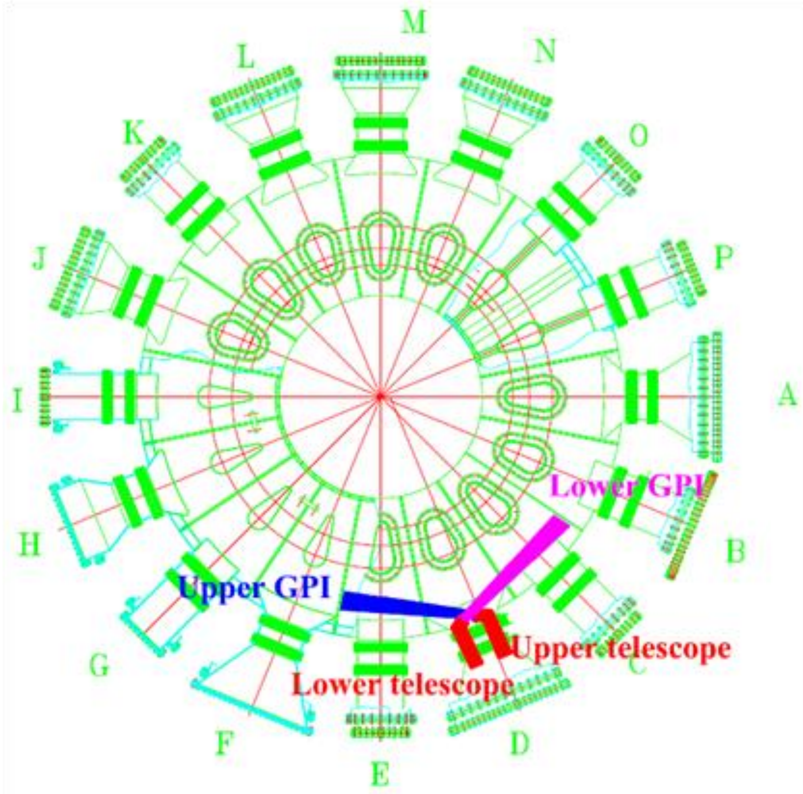
Initial frequency chirping down phase of tens of ms, due to Doppler shift induced by cocurrent toroidal rotation increase.

The frequency downshift is strongest in the NBI case, due to the strong toroidal rotation driven by NBI.

Since ECM propagates in the electron diamagnetic direction.

ECM 2D structure has been measured by a Dual Gas-Puff-Imaging (DGPI) system





Two 13×13 cm square areas up-down symmetrically about the midplane, separated toroidally by 66.6°. We use Helium gas puffed into Deuterium plasmas. HeI line emission at 587.6 nm. two fast cameras at a frame rate of 391 kHz and a resolution of 64×64 pixels with 12-bit dynamic range.

DGPI show up-down-symmetric tilted structures

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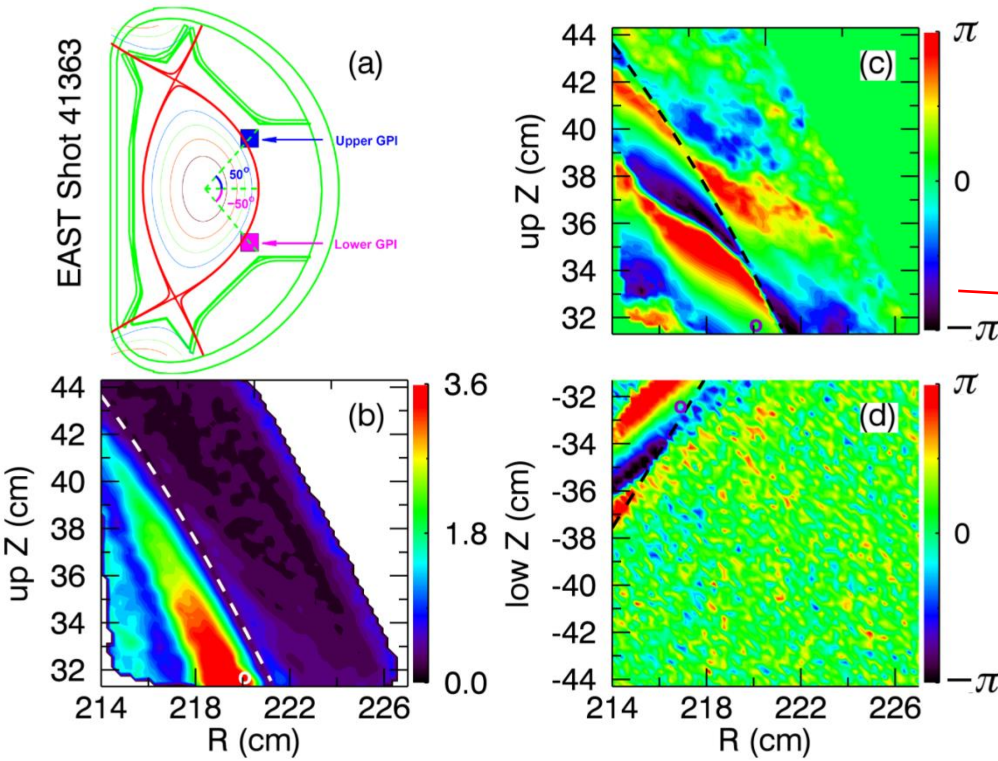
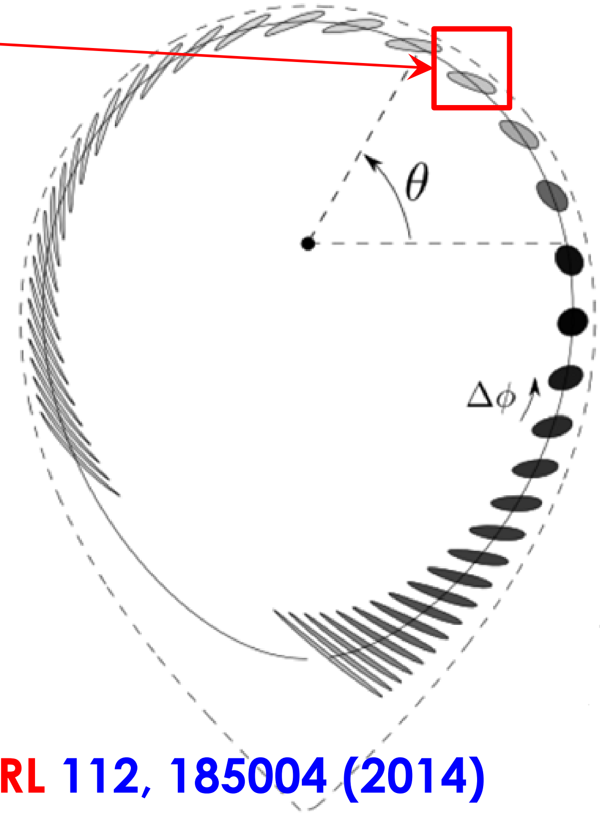


Flow shear would tilt the structures in the same direction.

Magnetic shear can tilt the structures in the opposite directions.



Localized in the steep-gradient pedestal region, peaking at 1-2 cm inside the separatrix with a radial spread of ~1 cm.

Poloidal wave length λ_θ ~ 8 cm, n = 16-19

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A ELM-free period with ECM detected by DGPI

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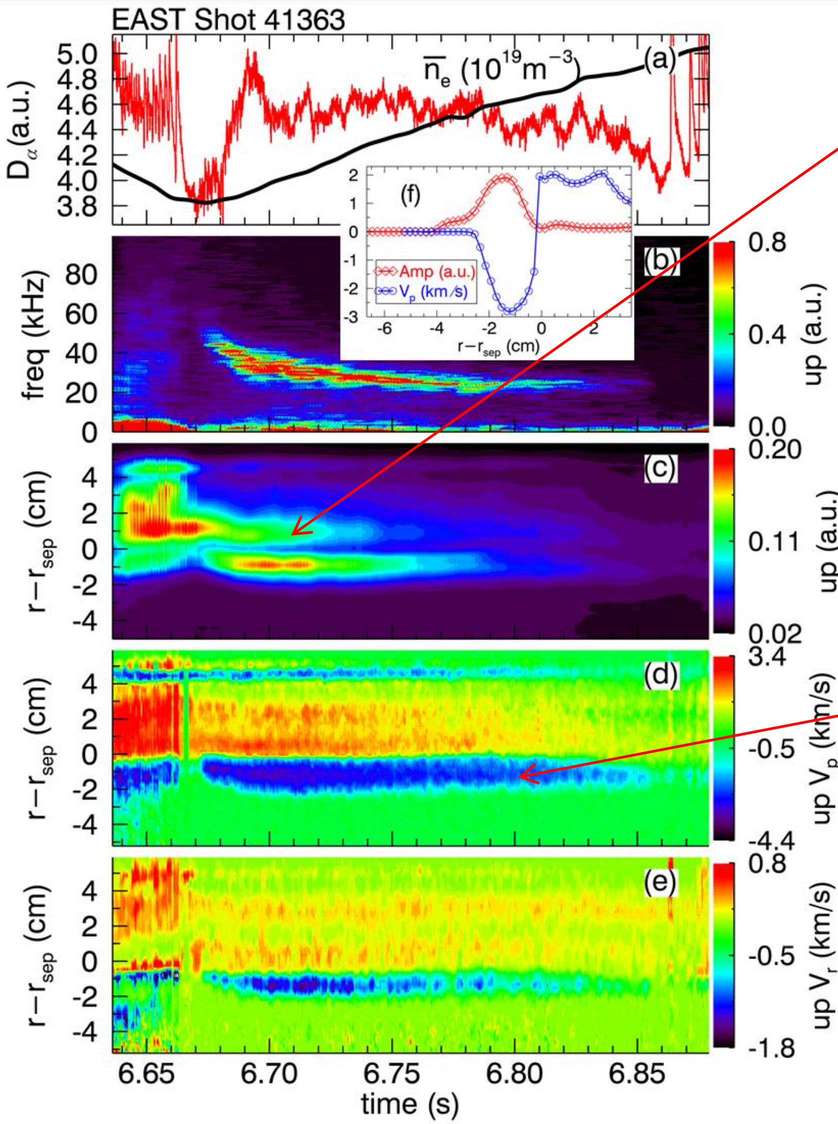


The associated fluctuations are also seen in the SOL near the separatrix, due to convective transport across the separatrix driven by the ECM.

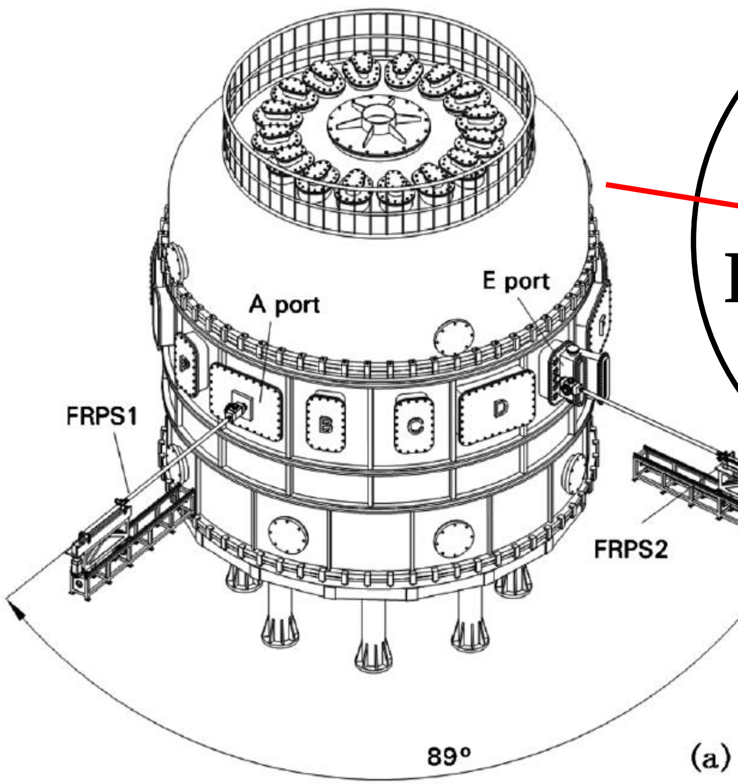
Poloidal and radial phase velocities estimated based on a modified TDE technique.

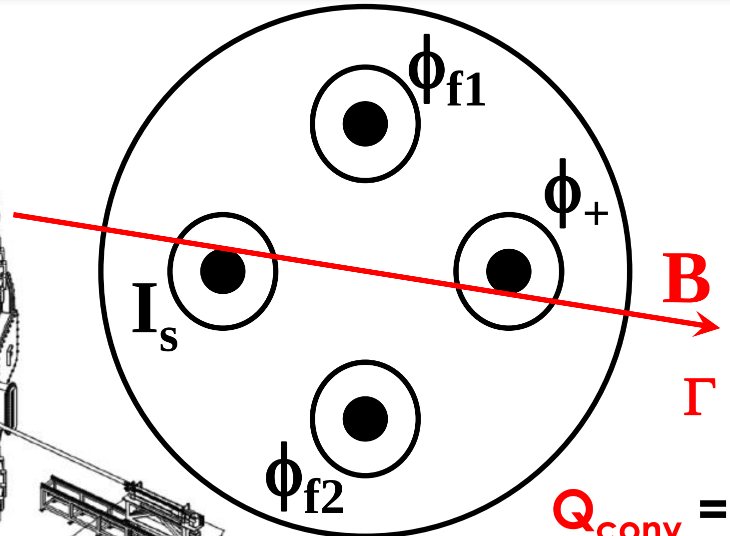
ECM propagates in the electron diamagnetic direction in the lab frame.

The fluctuations in the SOL propagate in the ion diamagnetic direction.

So, there is a strong phase velocity shear near the separatrix.

New diamond-coated 4-tip probe array





$\phi_f = (\phi_{f1} + \phi_{f2})/2$

$\phi_p = \phi_f + 2.8T_e$

$T_e = (\phi_+ - \phi_f)/\ln 2$

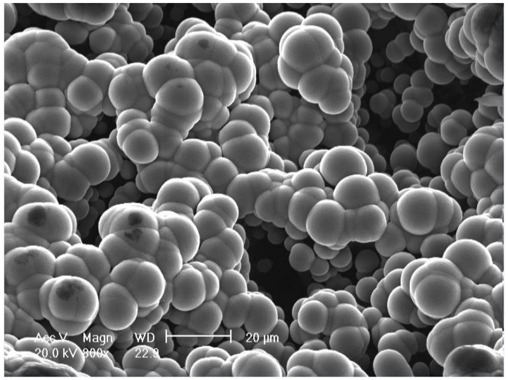
$n_e = I_s/(0.5eA_{eff}C_s)$

$\Gamma = \langle \delta n_e \delta \phi_p k_\theta \sin(\alpha) \rangle / B$

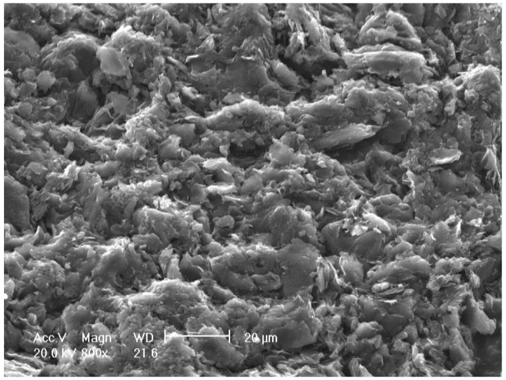
$Q_{conv} = (3/2)T_e\Gamma$

$Q_{cond} = \langle \delta T_e \delta \phi_p k_\theta \sin(\alpha) \rangle n_e / B$

With diamond coating

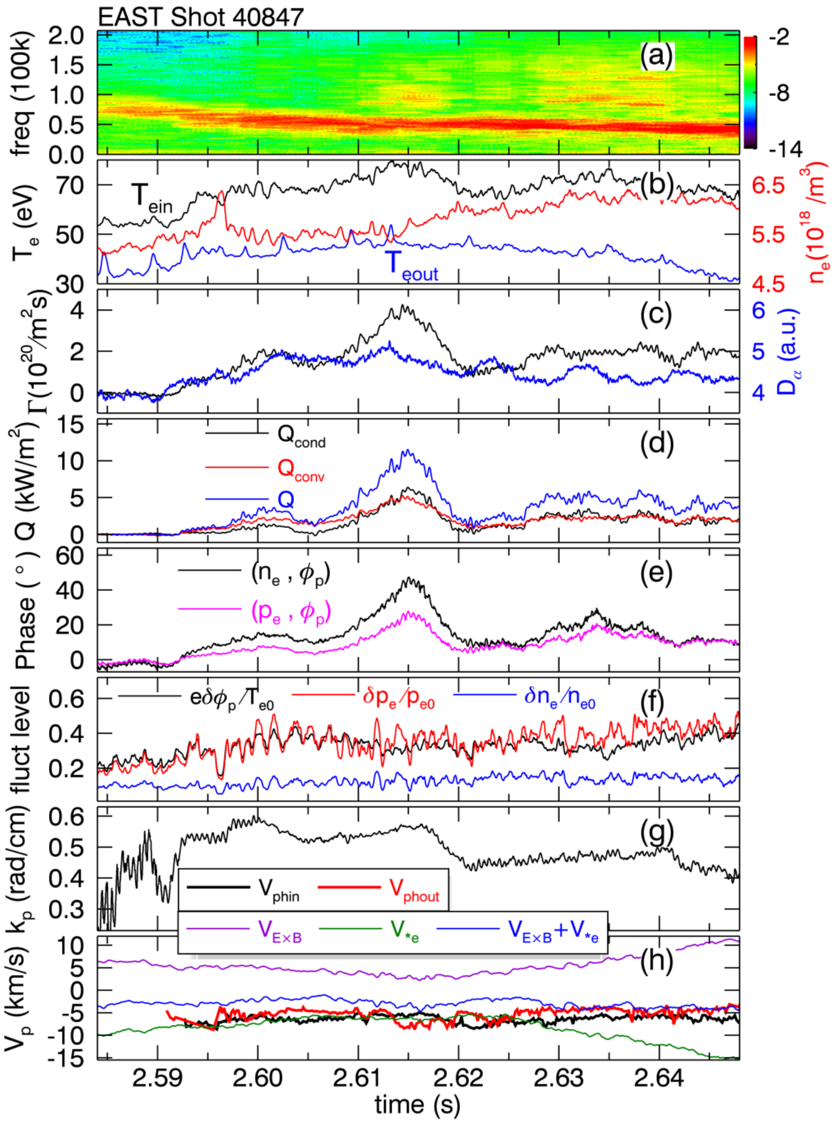


W/O diamond coating



R. Schrittwieser et al., 40th EPS, (Espoo, Finland, 1-5 July 2013) P6.017

Evidence of particle and heat exhaust by ECM



ELM-free period just following an L-H transition, probes at –8mm and –3mm

The time evolutions of the phases and fluxes appear to be correlated with the edge T_e gradient.

QS = 0.2-0.4 MW ~ 15%-30% P_{loss}

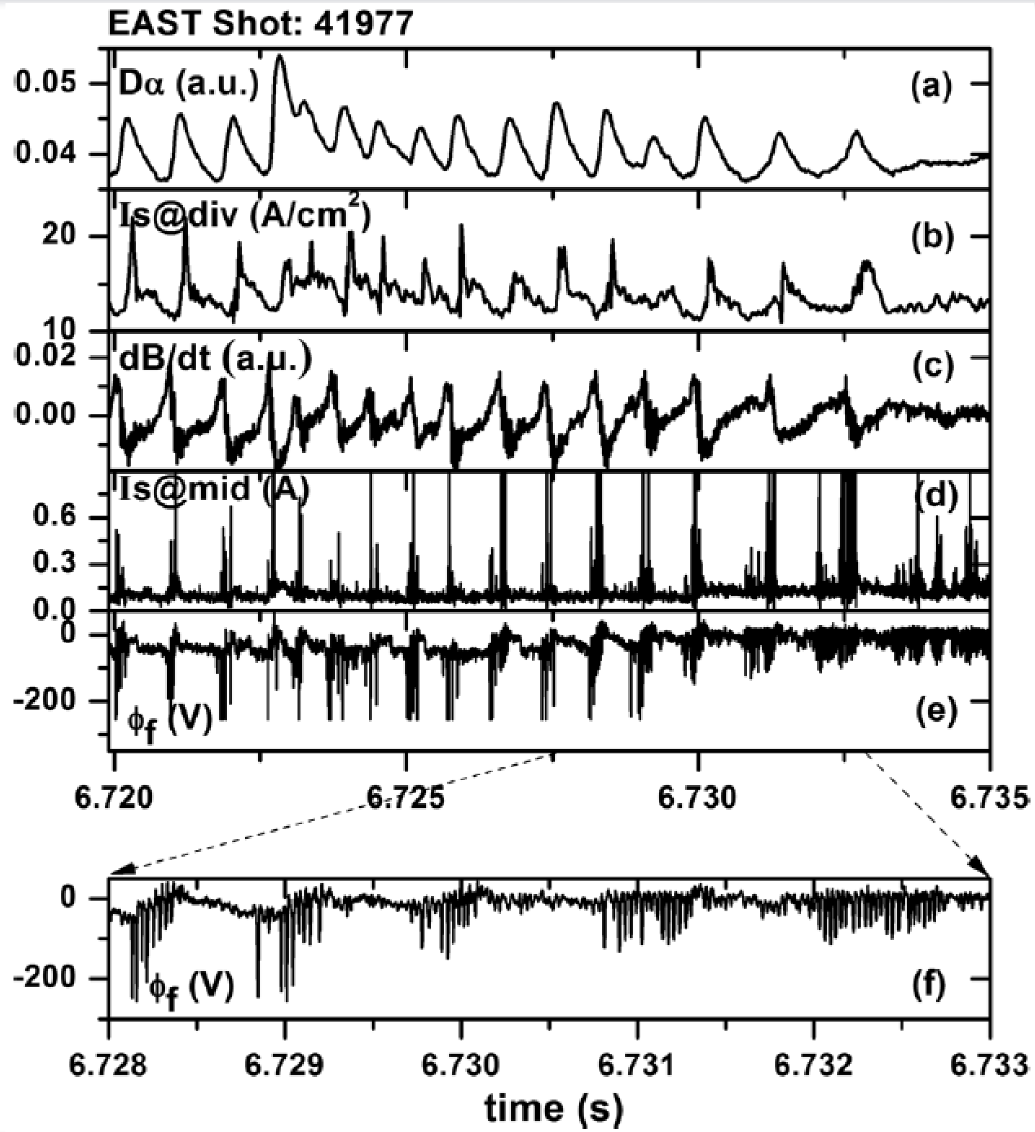
Cross phase: $\alpha(p_e,\phi_p) \sim 10°$, $\alpha(n_e,\phi_p) \sim 20°$

$\delta p_e / p_{e0} \sim e\delta\phi_p / T_{e0} \sim 40\% > \delta n_e / n_{e0}$

V_{phin} (–8mm) = V_{phout} (–3mm) ~ $V_{E\times B} + V_{*e}$

Propagates in the electron diamagnetic direction in the plasma frame

Sometimes, ECM evolves into a small-ELM-like cycle state



It usually appears when the pedestal saturates

Induced by ECM amplitude modulation

Probe measurements at the mode location show the oscillations in E_r and ∇p are nearly in-phase, suggesting this cycle state is very likely a limit-cycle oscillation due to a predator-prey interaction between ECM and local ∇p

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GYRO code simulation in the pedestal region

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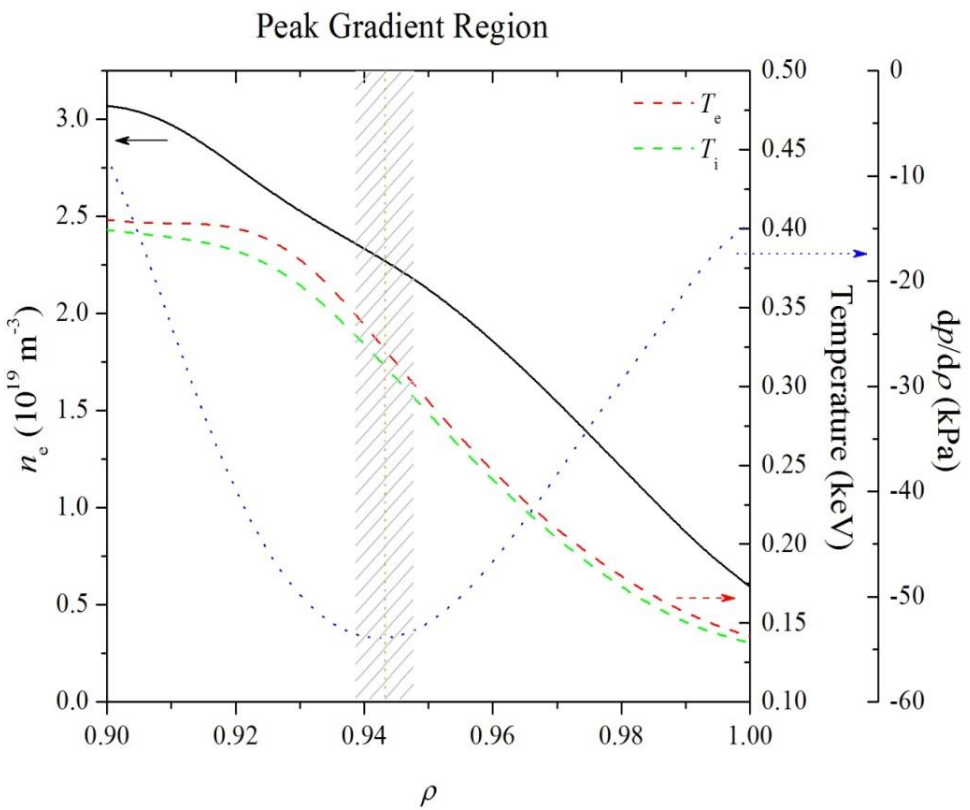

q = 4.6 n_e = 2.3×10^{19}m^{-3}

ν_e^* = 1.5 T_e = 0.33 keV

V$_t$ ~ 0.4 km/s T_i = 0.96 T_e

- ✓ Use GYRO eigenvalue solver
- ✓ Flux-tube near the peak gradient pedestal region
- ✓ With realistic geometry from EAST kinetic EFIT and experimental profiles
- ✓ Full Gyrokinetic species
- ✓ Full electromagnetic effects
- ✓ Collision and rotation

GYRO shows dissipative trapped electron mode

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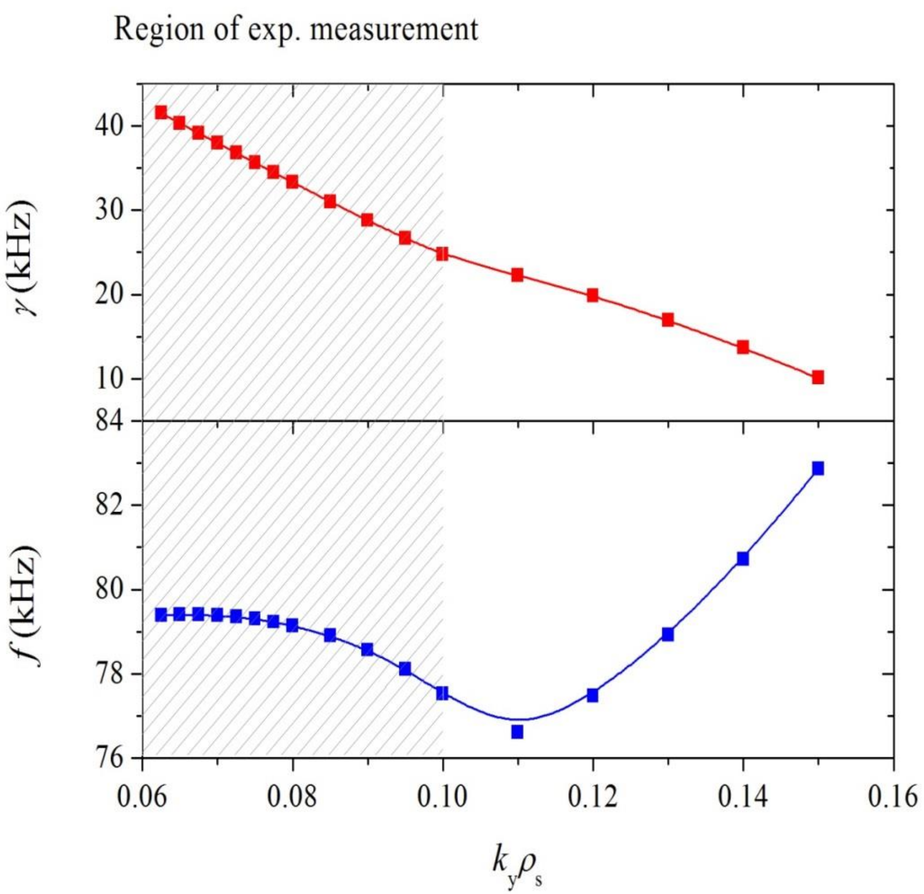
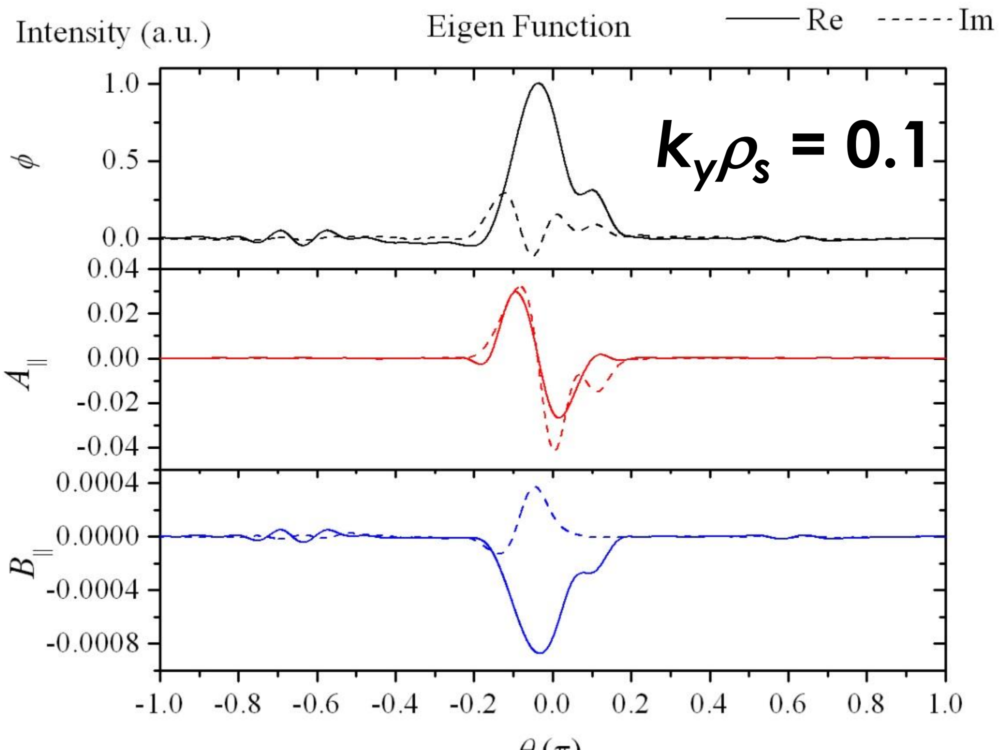
$k_y\rho_s$ scan



The most unstable mode in the steep-gradient pedestal region shows the nature of dissipative trapped electron mode (DTEM), with characteristics consistent with ECM.

- **Propagate in the electron diamagnetic direction**
- **At a frequency of 70-80 kHz near local f_{*e}, similar to the observed frequency at the onset of ECMs**
- **The growth rate of this mode peaks in the same $k_y\rho_s$ range of measurements ($0.06 < k_y\rho_s < 0.1$), decreases towards the high k_y region**

Eigenfunctions of the mode



- Show typical ballooning structure with an even parity in $\delta\phi$ and $\delta B_{||}$, odd parity in $\delta A_{||}$.
- The real and imaginary components of $\delta A_{||}$ exhibit the same sign of proportionality as expected for TEM.
- The amplitude of $\delta A_{||}$ is about 30 times smaller than $\delta\phi$.

Collisionality and T_e gradient dependence

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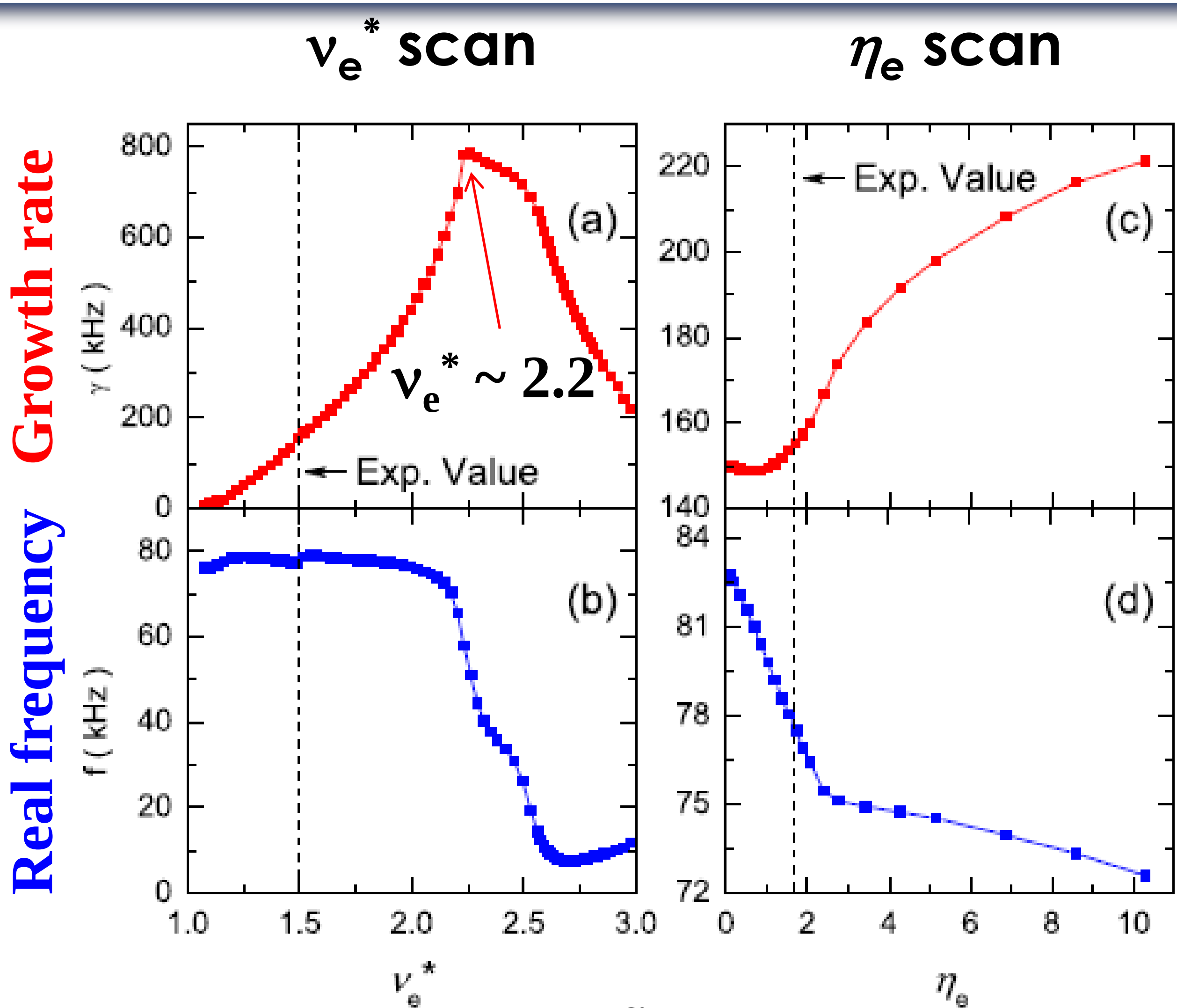

$k_y\rho_s$ fixed at 0.1

- Strongly depends on collisionality
- Unstable in the same collisionality range of the experimental observation $0.5 < \nu_e^* < 5$
- Growth rate peaks at $\nu_e^* \sim 2.2$
- Mainly destabilized by the T_e gradient
- Not sensitive to T_i gradient or β_e

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Summary

- Long-pulse nearly non-inductive ELM-free or small-ELM H-mode plasmas with duration > 200 τ_E and good energy confinement with H_{98} ~ 1.2 have been achieved in EAST, sustained by LHCD with intensive lithium wall coating.

- A new Edge Coherent Mode (ECM) at a frequency near the local f_{*e} has been observed in the steep-gradient pedestal region continuously throughout the long-pulse H-mode period, providing significant particle and heat exhaust across the pedestal, as evidenced by the direct probe measurements of the ECM-driven particle and heat fluxes, which allows the long-pulse operations of stationary ELM-free or small-ELM H-mode plasmas.

- This mode shows the nature of dissipative trapped electron mode (DTEM), as evidenced by the GYRO code simulations.

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Thank you very much for your attention!

Acknowledgements

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[1] H.Q. Wang, G.S. Xu* et al., Phys. Rev. Lett. 112, 185004 (2014).

[2] H. Q. Wang, G. S. Xu et al., Phys. Plasmas 21, 092511 (2014)

[3] J. Li, H.Y. Guo* et al., Nature Physics 9, 817 (2013)

[4] H.Y. Guo, J. Li et al., Phys. Plasmas 21, 056107 (2014)

Summary of ECM characteristics

f = 15-90 kHz, near local electron diamagnetic frequency f_{*e}
Electrostatic, with weak magnetic component $\delta B \sim 0.2$ G, $\delta B/B_p \sim 1\times10^{-4}$
In the steep-gradient pedestal region, peak at 1-2 cm inside the separatrix
Propagate in the electron diamagnetic direction in the plasma frame
Toroidal mode number n = 16-19
Poloidal wave length $\lambda_\theta \sim 8$ cm, poroidal mode number m > 50, $k_\theta \rho_s \sim 0.1$
Starts to appear during pedestal buildup with an initial frequency chirping down phase of tens of milliseconds
Central-line-averaged density $\bar{n}_e = 1.9 - 5\times10^{19}\,\mathrm{m}^{-3}$ $\bar{n}_e/n_G = 0.28 - 0.7$
Collisionality at the top of pedestal $\nu_e^* = 0.5 - 5$
Parameter space $q_{95} > 3.7$, $\delta = 0.4$-0.7
Cross phase of fluctuations $\alpha(p_e,\phi_p) \sim 10°$, $\alpha(n_e,\phi_p) \sim 20°$, $e\delta\phi_p/T_{e0} \sim 40\%$
Drive significant outward particle and heat transport
Sometimes, ECM evolves into a small-ELM-like cycle state

Comments and contact information