Direct observations of the onset of a coherent continuous edge instability limiting the pedestal gradient between ELMs

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Summary of key observations

- Inter-ELM fluctuation measurements show evidence of the onset of coherent density and magnetic fluctuations with frequency in the range of 300 kHz and spatial poloidal scale $k_\theta \rho_s \sim 0.04$.

- Results clearly show that the mode is consistent with an edge localized mode; the mode ***onset*** points to the kinetic ballooning mode (KBM).

- Edge stability analysis using ELITE and BALOO indicate that the experimental point is close to the peeling-ballooning limit and that the pedestal region is infinite-n-ballooning unstable, all consistent with measurements.

Leverage the β-dependence of the linear growth rate to investigate the edge transport between ELMs

Alcator C-Mod

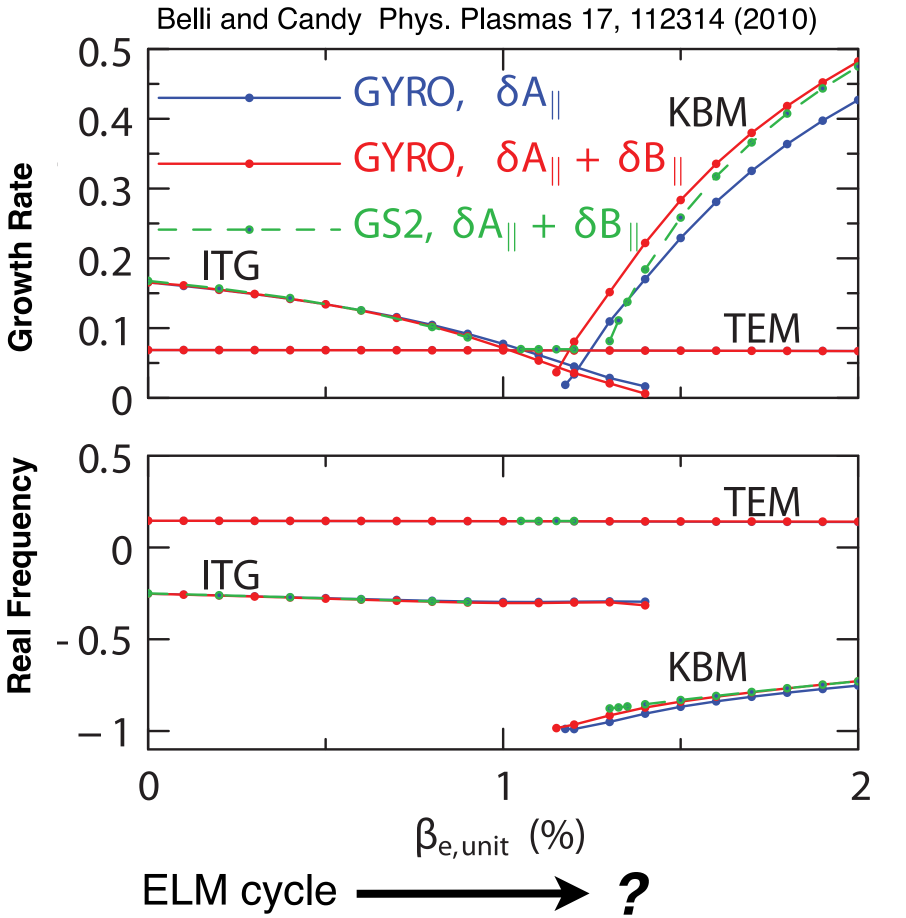
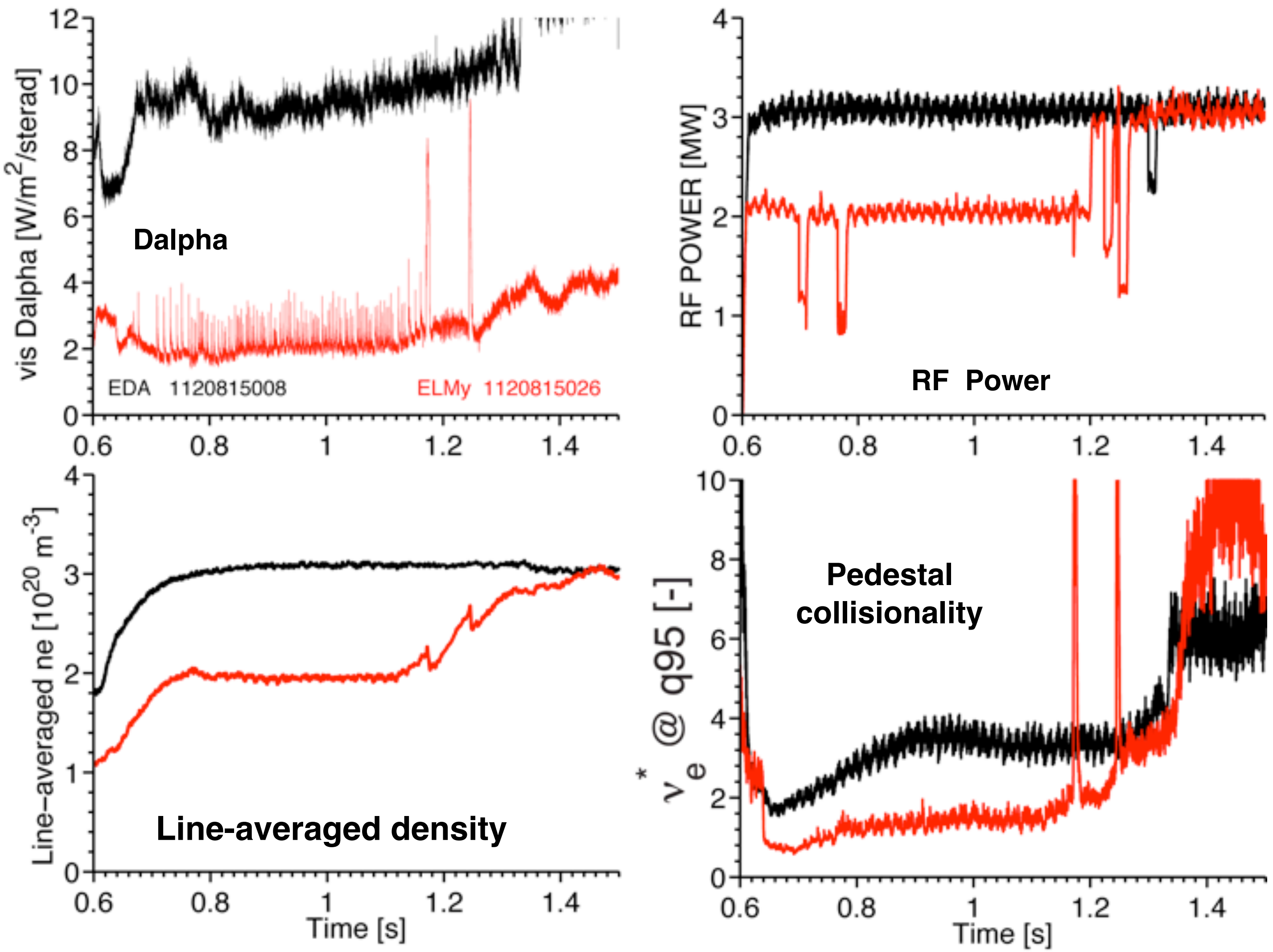


FIG. 1. (Color online) Cyclone base case scan comparing GYRO against GS2 results including both $\delta A_{\parallel}$ and $\delta B_{\parallel}$. The linear growth rate γ and real frequency ω_r are compared as functions of the electron beta $\beta_{e,\mathrm{unit}}$. Also shown are GYRO results for $\delta A_{\parallel}$ only.

- The goal is identify the fluctuation amplitude during the ELM cycle
  - One approach is to track the fluctuation amplitude during the β evolution.
- The hard onset of KBM will leave signatures in all transport channels.
- Expected characteristics
  - Intermediate-n and electromagnetic mode
  - Sudden change in growth rate
  - Ion spatial scale ($k\rho_s < 1$)
  - Propagates in ion diamagnetic direction
  - Even parity ballooning mode structure in ES potential.

Test the KBM hypothesis in the EPED predictive model

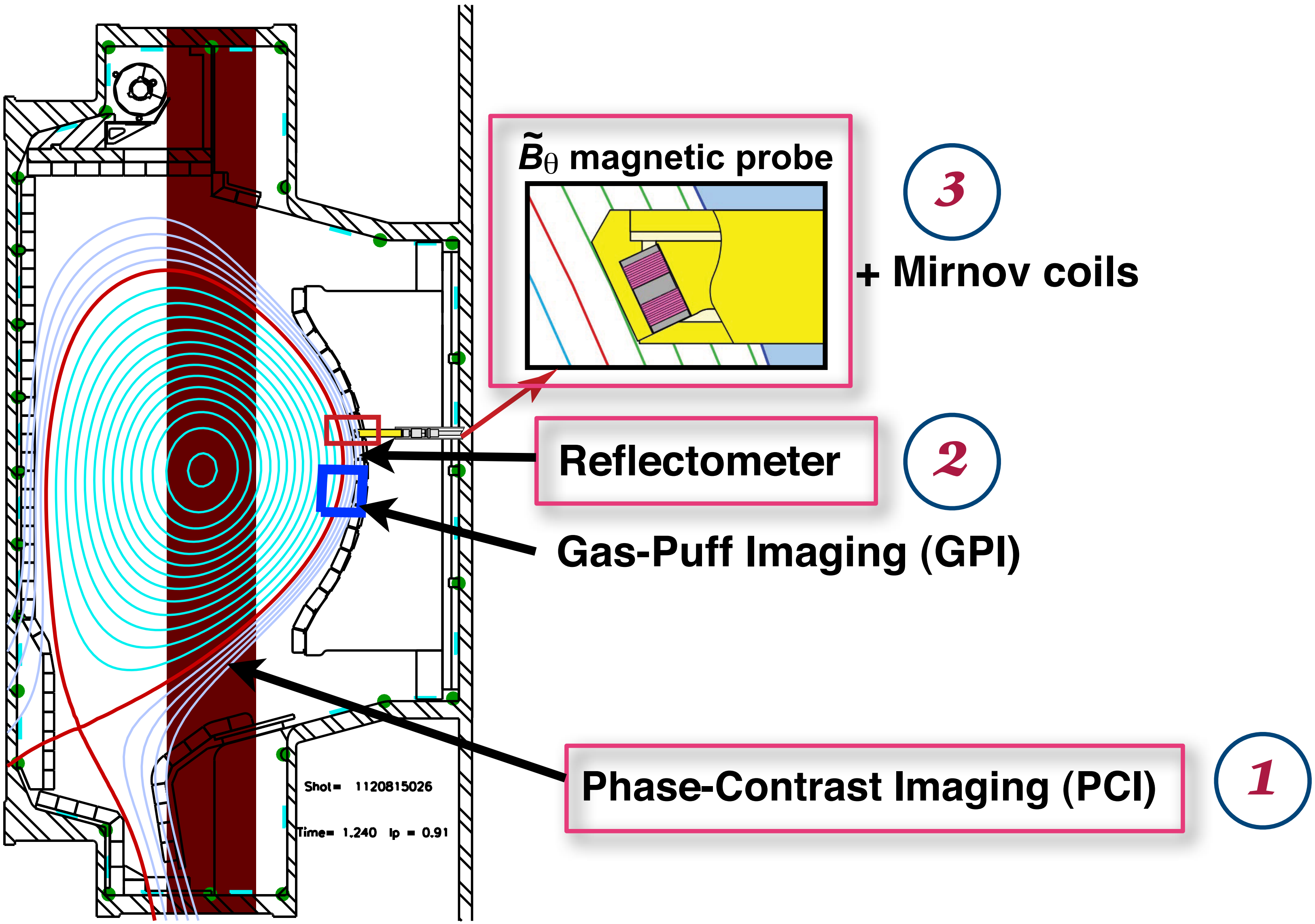
Dedicated Alcator C-Mod experiments examine the pedestal turbulence between ELMs



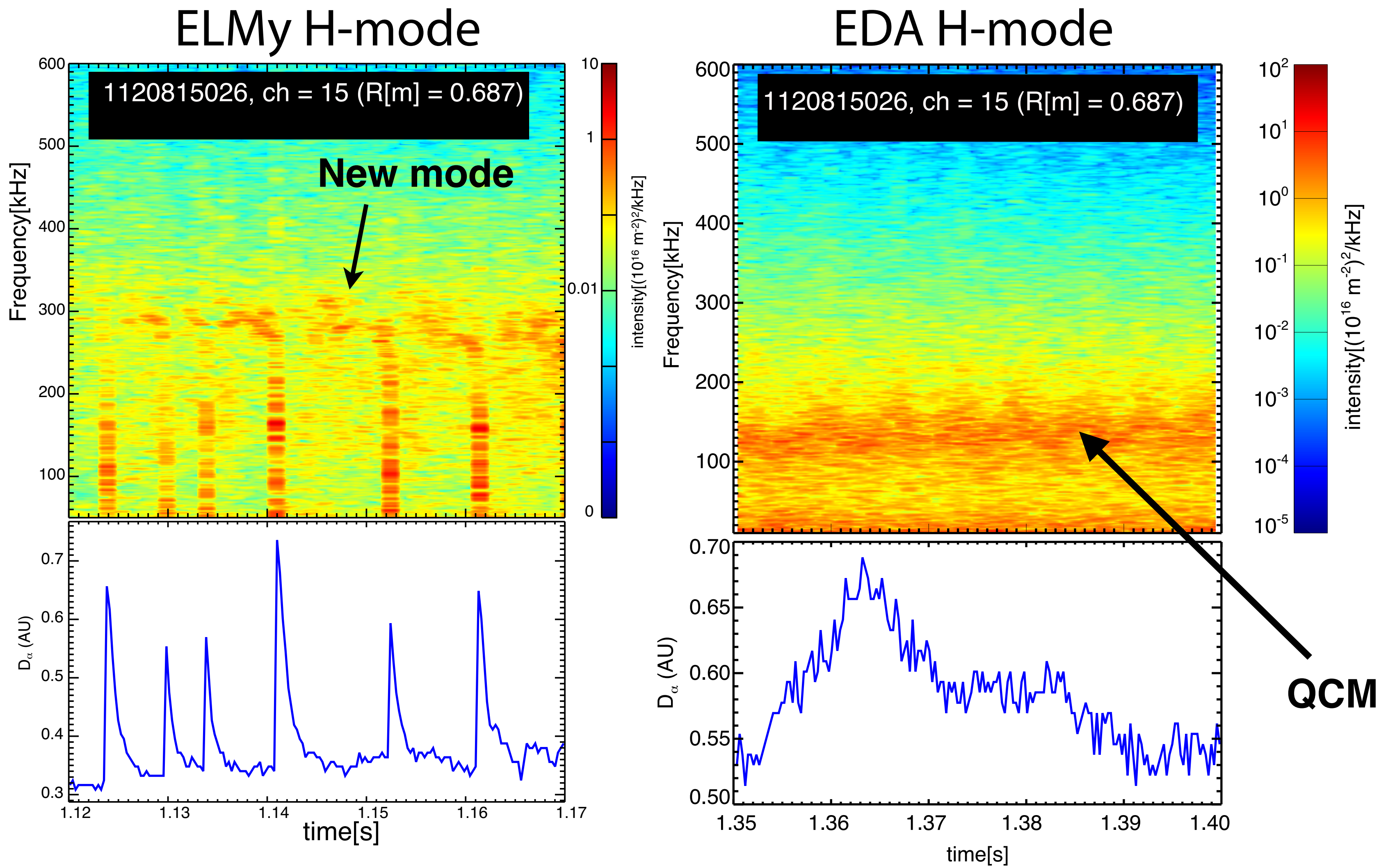
- In C-Mod, EDA are obtained at higher collisionality. ELMy regimes are achieved using reduced target density.

Various poloidally separated diagnostics provide edge fluctuations measurements between ELMs

Alcator C-Mod

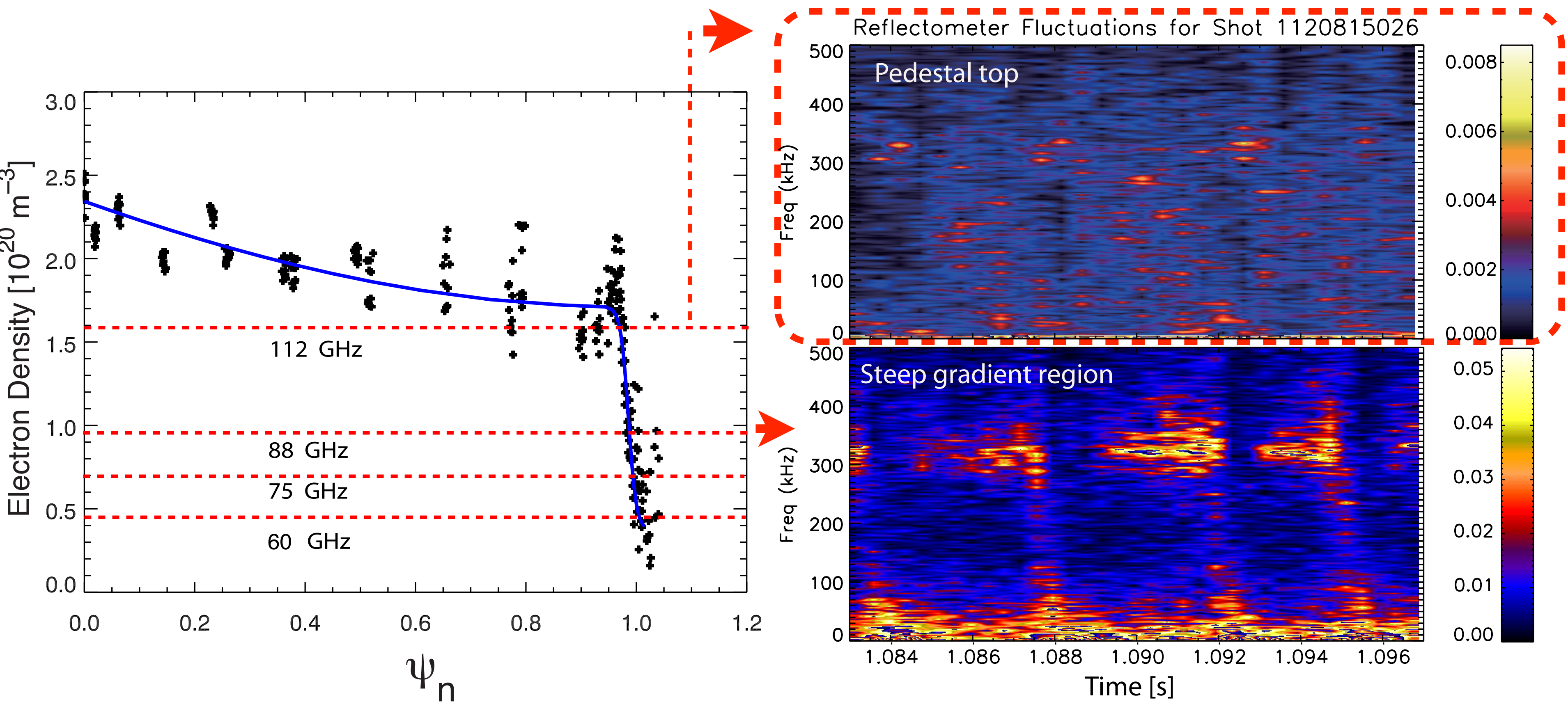


PCI spectrogram of inter-ELM fluctuations contrasts those of EDA H-mode



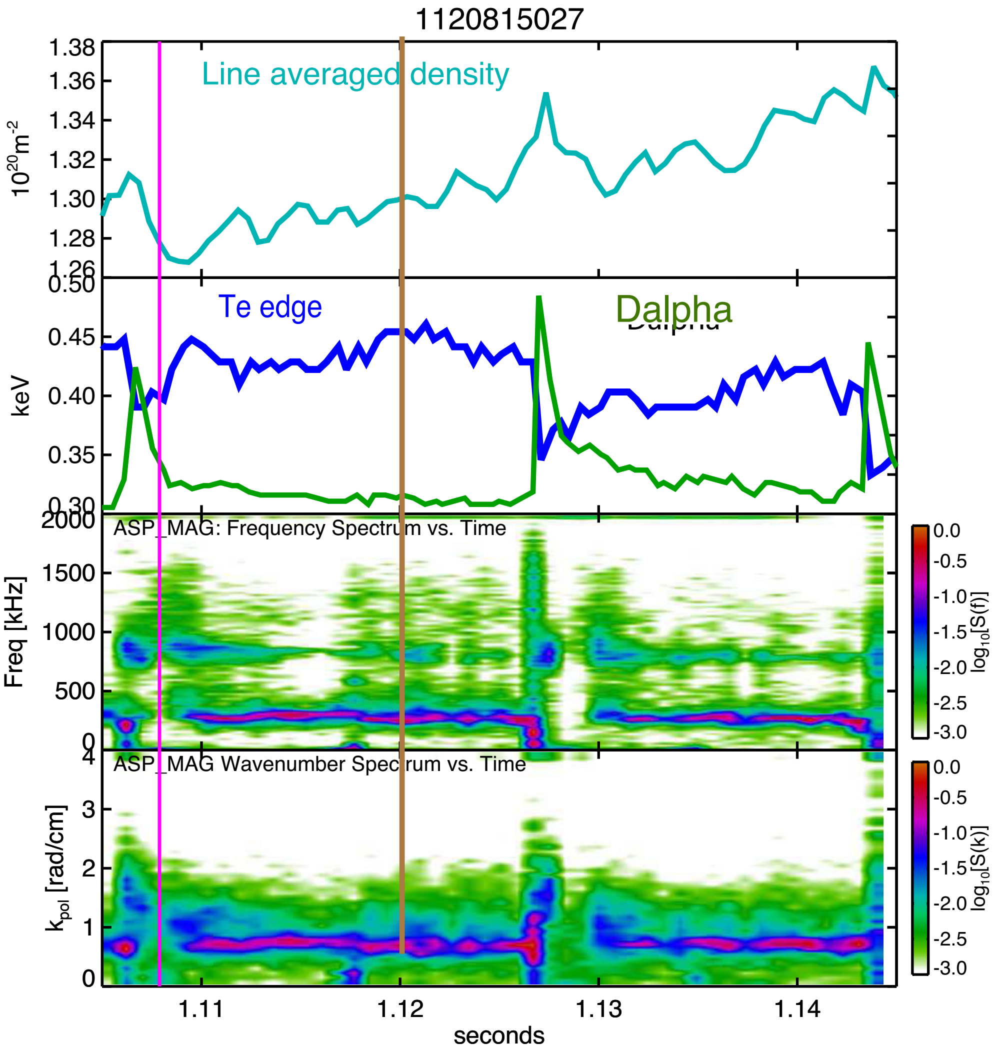
- PCI provides an upper bound on the radial component wavevector $k_R \Rightarrow k_\theta$ when mode is edge localized.

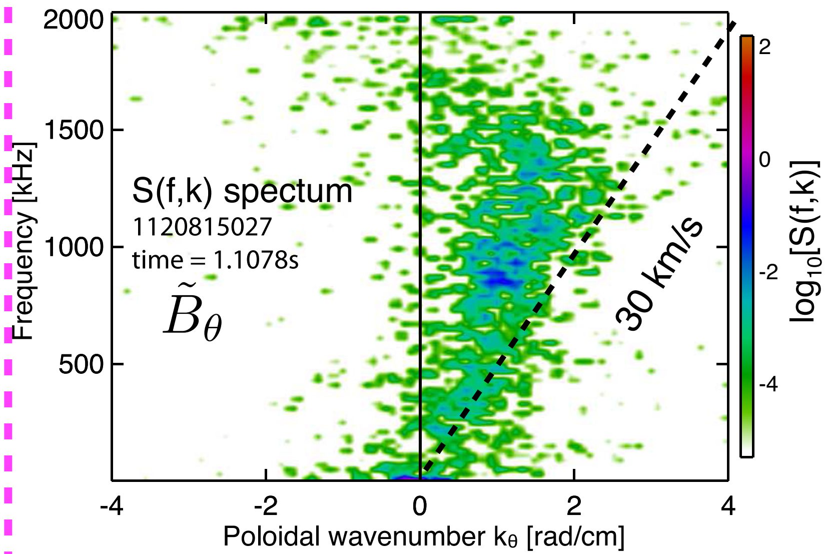
Density fluctuations from reflectometry point to an edge localization of mode

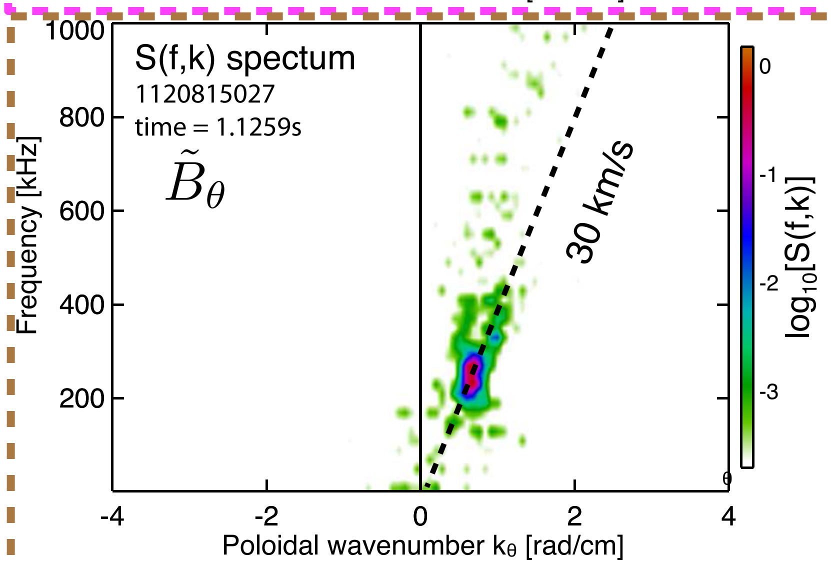


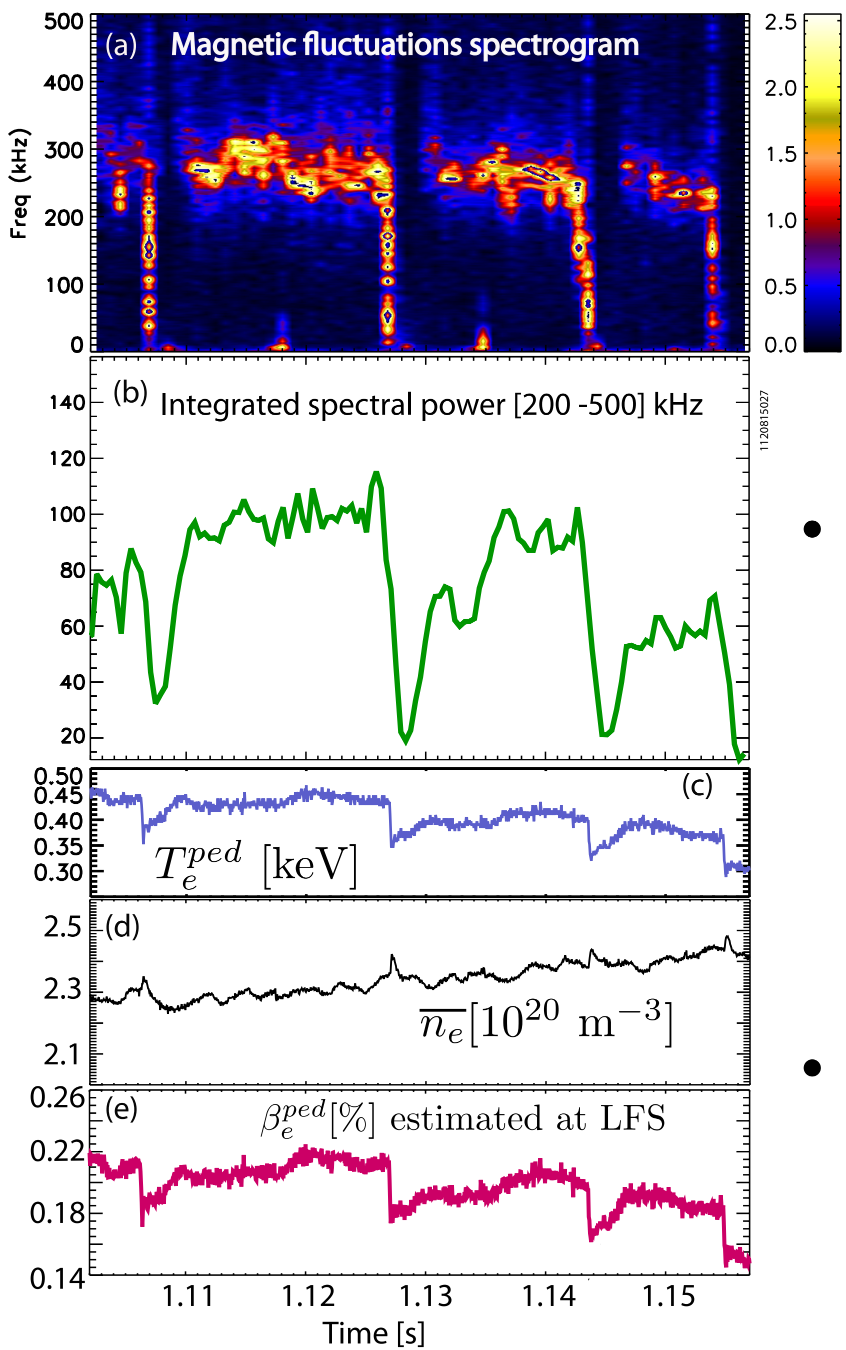
- The edge localization of the mode is also observed with GPI.

Low $k_\theta \rho_s$ magnetic fluctuations between ELMs propagate in electron diamagnetic direction (lab frame)









Magnetic fluctuations between ELMs develop/onset as the edge electron temperature increases and subsequently saturate

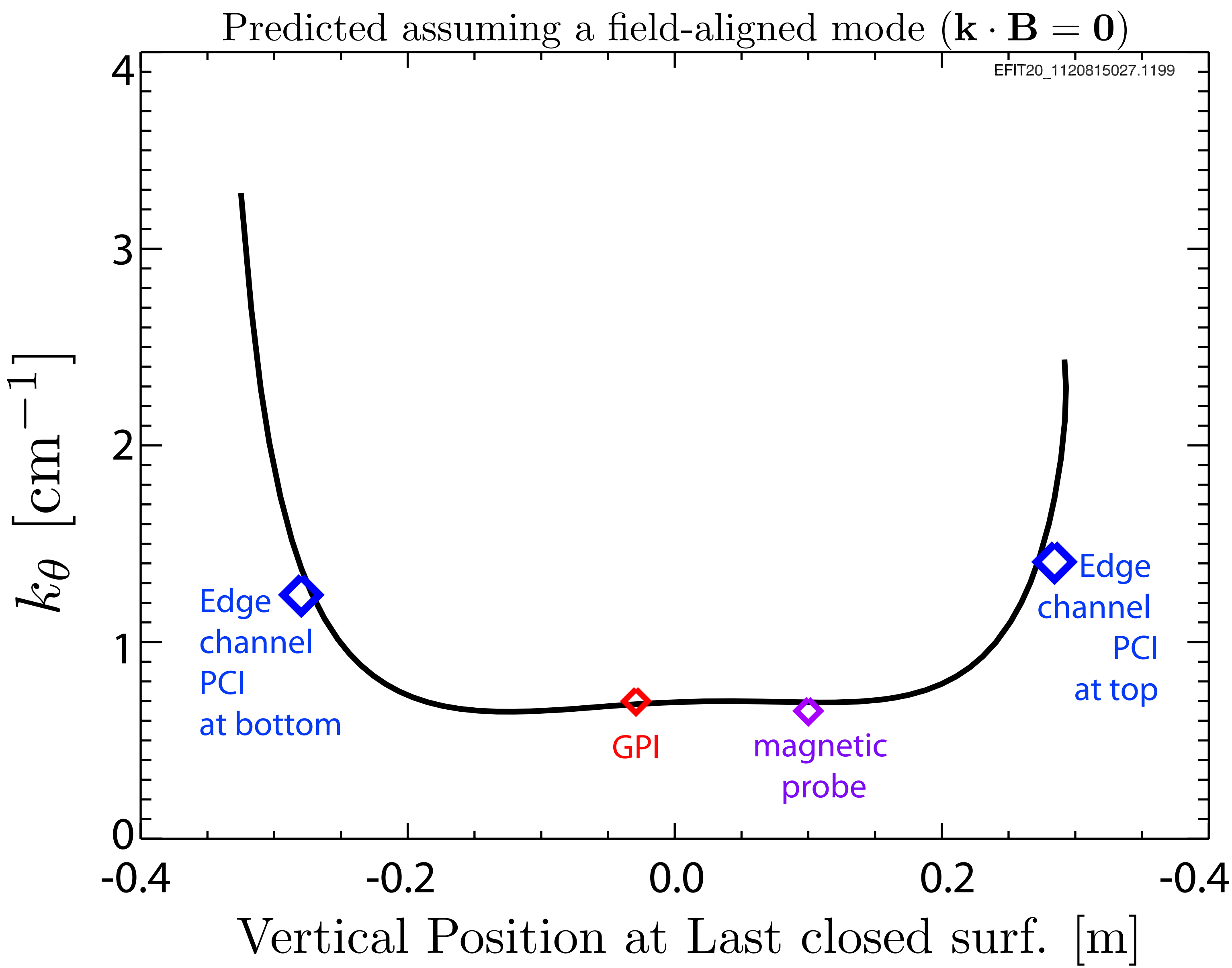
Alcator C-Mod

- Edge temperature increase leads to the *onset* of the fluctuations; in turn leading to a clamping of the edge temperature

- β-limit is consistent with the expected KBM dependence.
  - Expected threshold from gyrokinetic calculations are being determined.

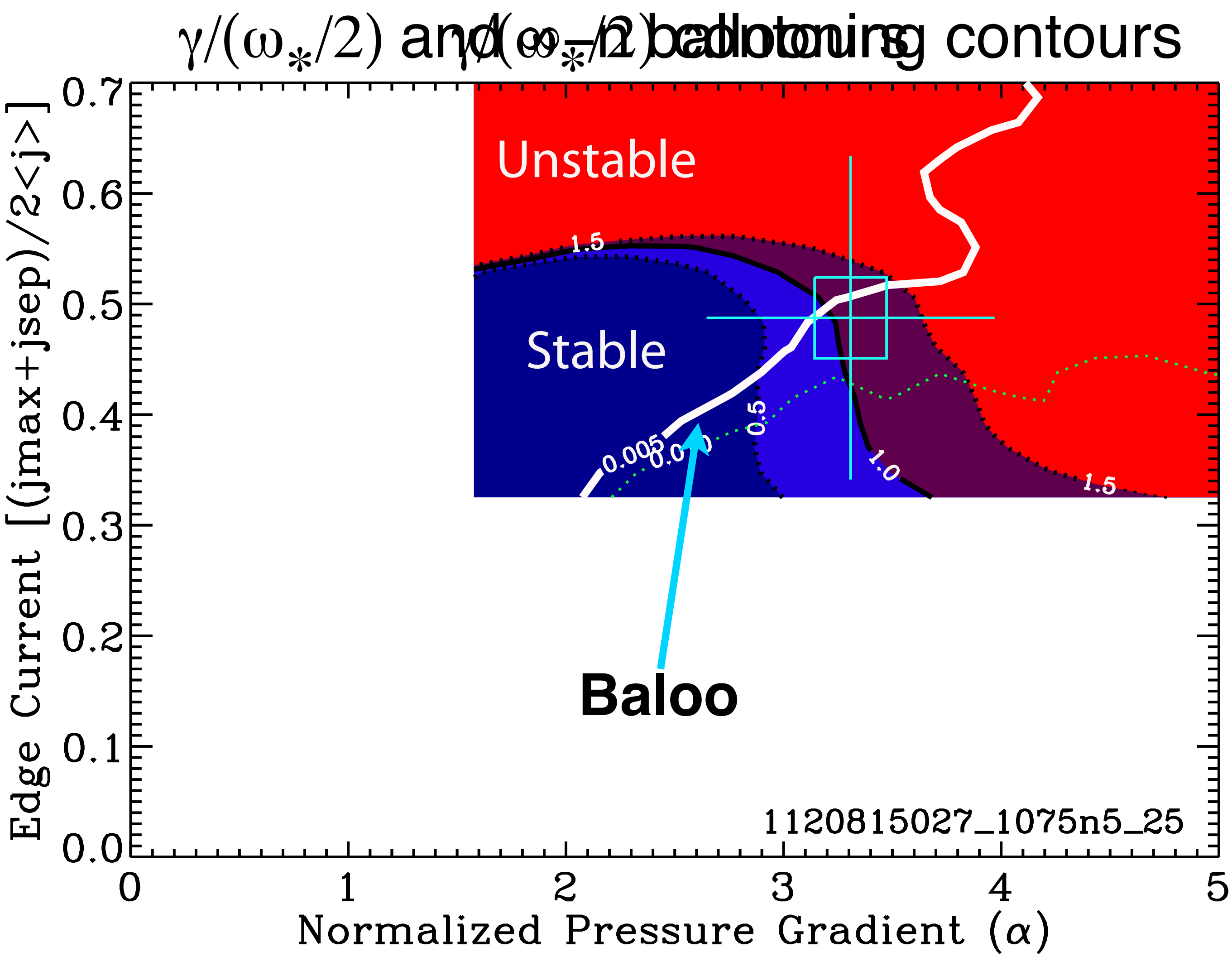
Wavenumber measurements from various diagnostics compared with field-aligned perturbation predictions show good agreement

Alcator C-Mod



From ELITE, the pedestal is ballooning unstable; from infinite-n calculations most of the pedestal is unstable

Alcator C-Mod



- Experimental point is near both the nominal P-B and KBM thresholds.

Summary of key observations and future work

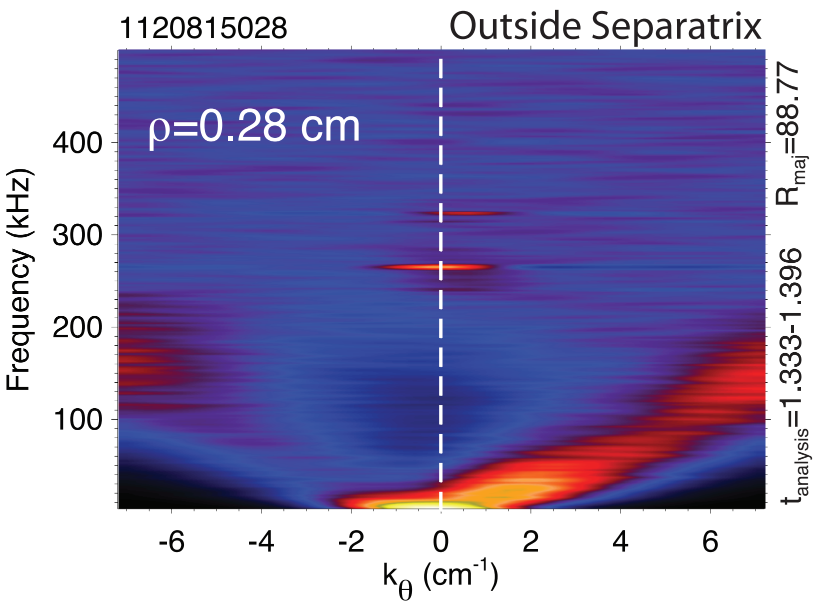
- We observed the onset of coherent density and magnetic fluctuations with frequency in the range of 300kHz and spatial poloidal scale $k_\theta \rho_s \sim 0.04$.
  - ☑ The mode is observed on various poloidally separated edge diagnostics pointing to a **field-aligned-edge mode** with a ballooning character.
  - ☑ Mode has magnetic signature and is n=10 as observed with array of Mirnov (not shown here)
- Results clearly show characteristic features of KBM-like:
  - ☑ Mode turns on and its amplitude saturates prior to an ELM
  - ☑ Mode **onset** is associated with monotonic increase of the edge temperature (suggesting that the gradient is destabilizing)
  - ☑ Onset subsequently leads to a clamping of the edge gradient.
  - ☑ Ion spatial scale $k_\theta \rho_s \sim 0.04$ and aligned with the pedestal buildup via ELM cycle.
  - – Collisions appears to be playing a role in determining dominant instability growth rate.
  - ■ **Missing piece: propagation direction in the plasma frame.**

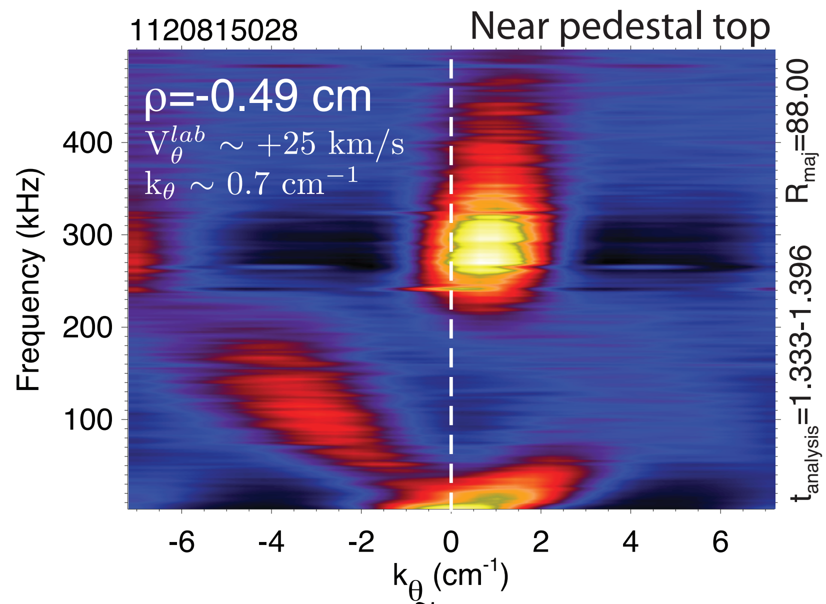
First evidence of KBM-like mode limiting the pedestal gradient

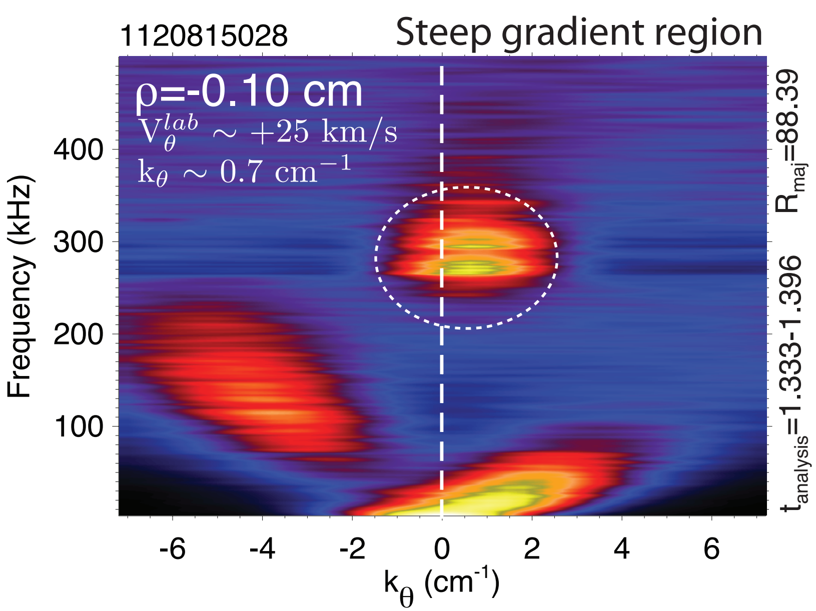
- Future and ongoing work:
  - Resolve the propagation direction of the mode
  - Perform linear gyrokinetic simulations in the edge pedestal to check for dominant mode

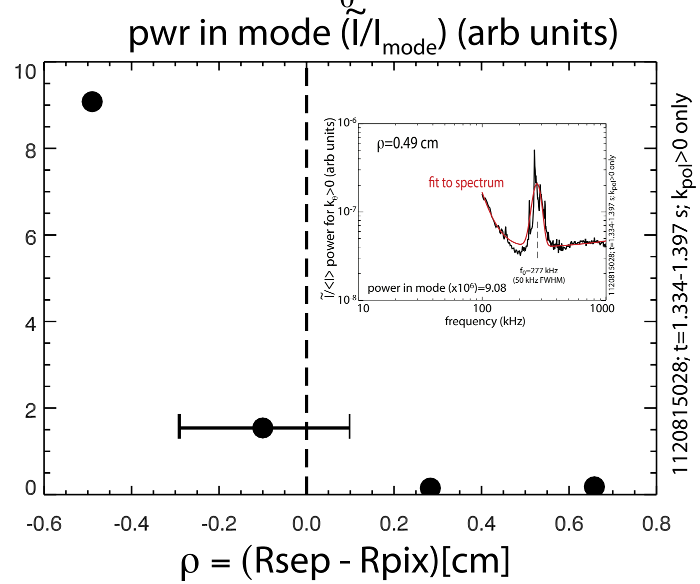
Backup

HeI GPI measurements confirm the presence of the mode in the edge region propagation in the electron diamagnetic direction but its localization remains unclear

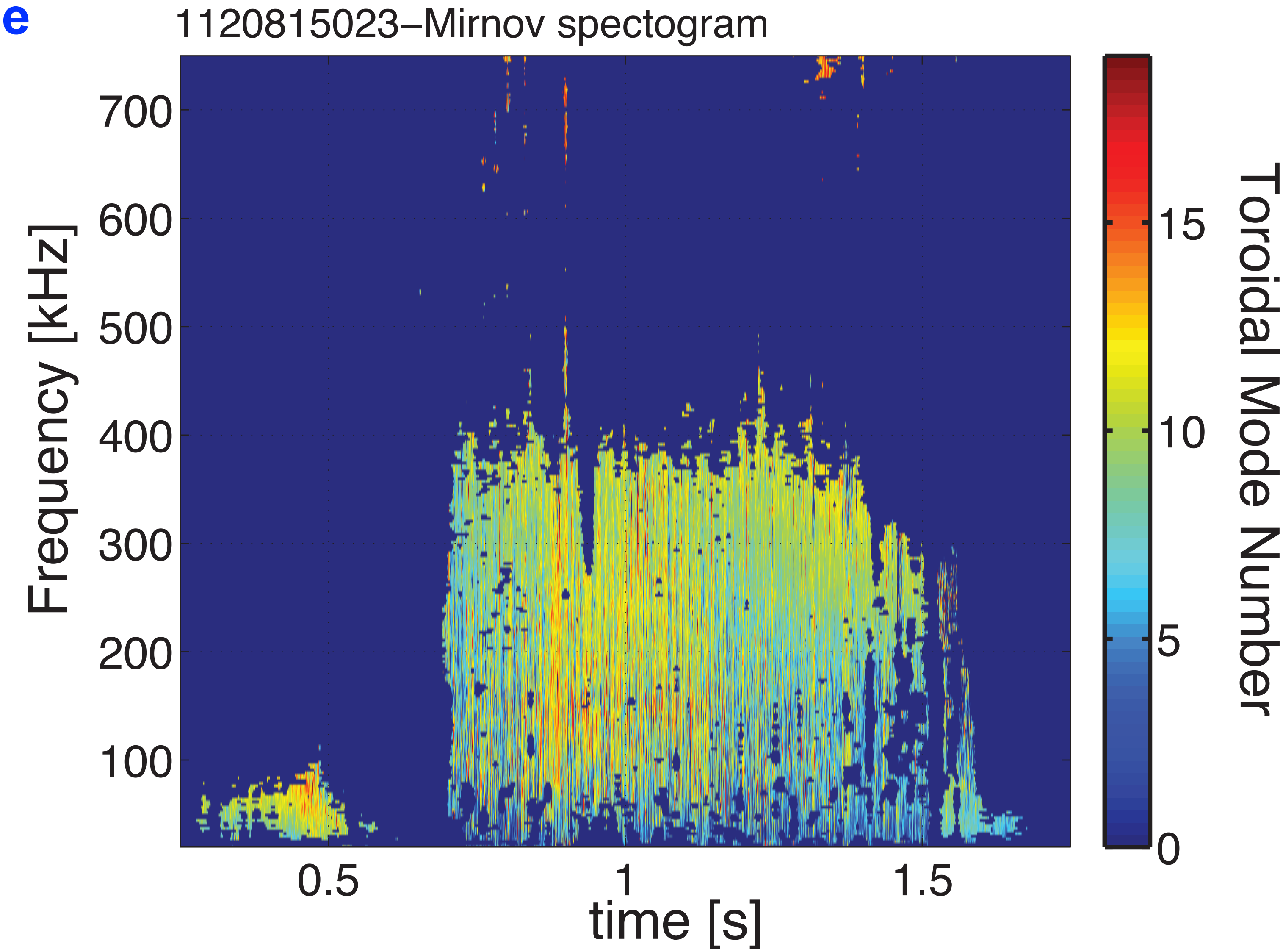






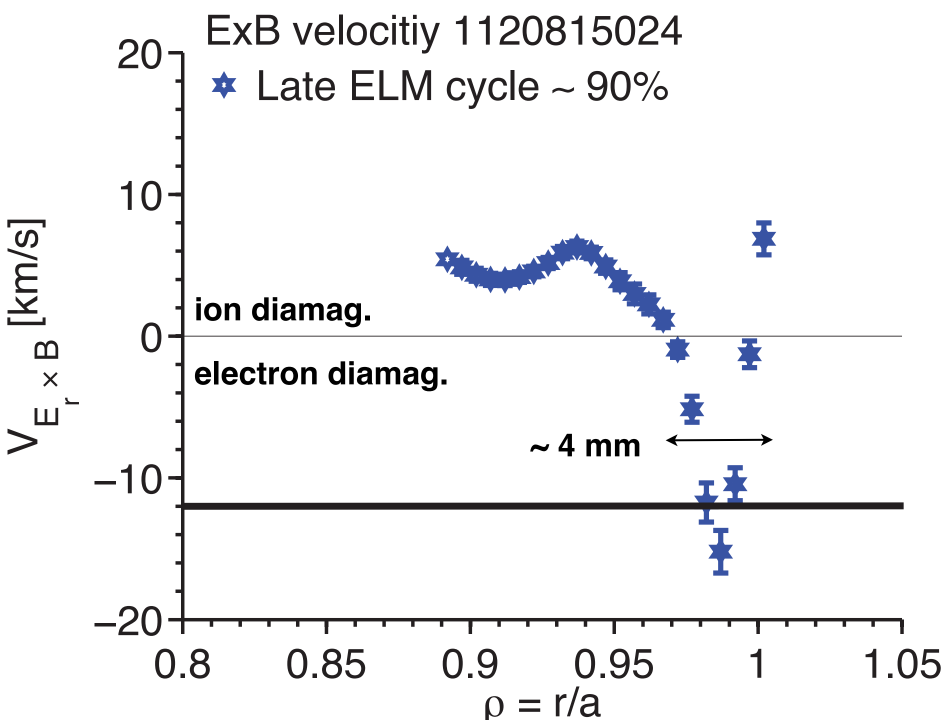


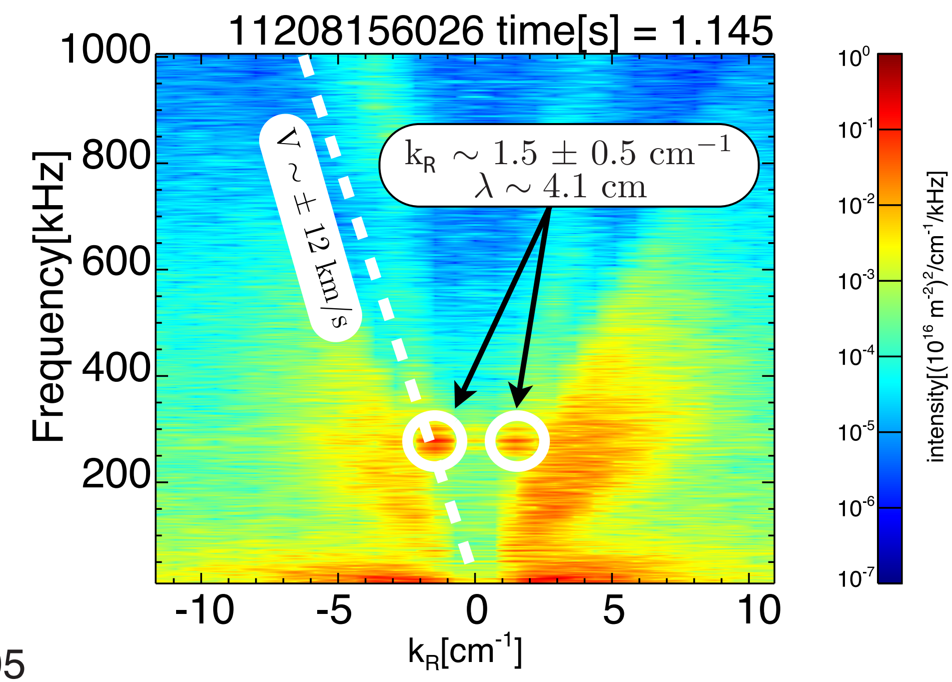
Analysis of Mirnov coils indicates the presence of a broadband n=+10 mode characteristics of a ballooning mode



- n=10 yields k_θ ~ 0.7 cm^{-1} (note that QCM is a n=20 mode)

The determined propagation velocity enables the localization of the radial structure in the edge region





Note: For otherwise two equivalent discharges

- Based on the ExB velocity profile the radial structure is localized in the edge region.

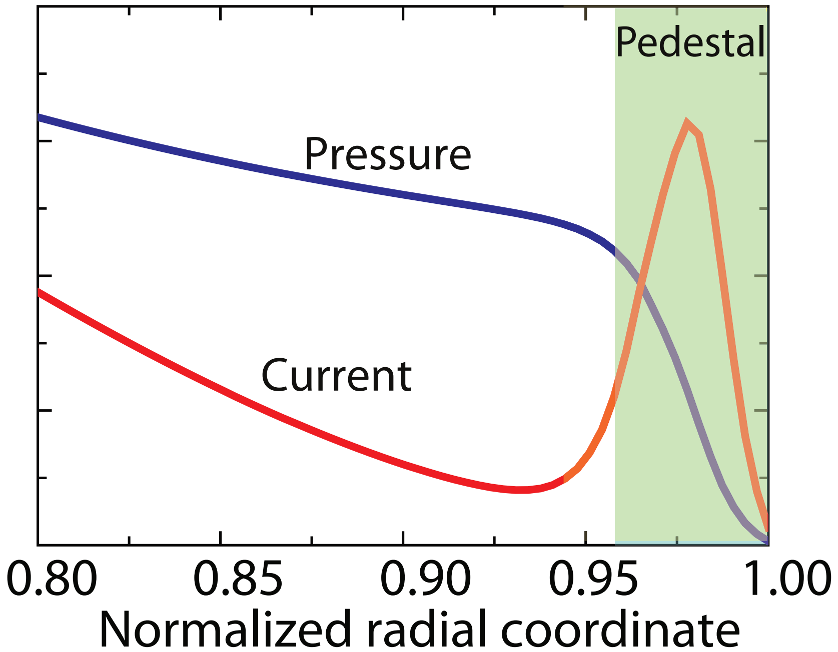
Magnetic signature

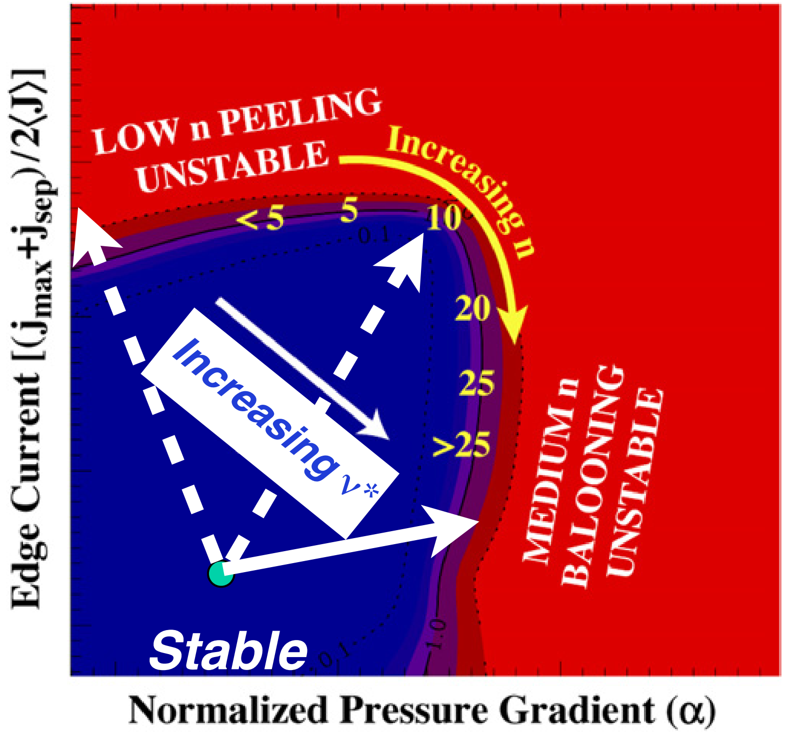
Fluctuations analysis: Global and local

Phase contrast imaging PCI
O-mode Reflectometer
Gas puff imaging
Magnetic probes
Mirnov coils

Peeling ballooning theory is the leading model for providing the threshold for the edge localized modes (ELM)

Alcator C-Mod



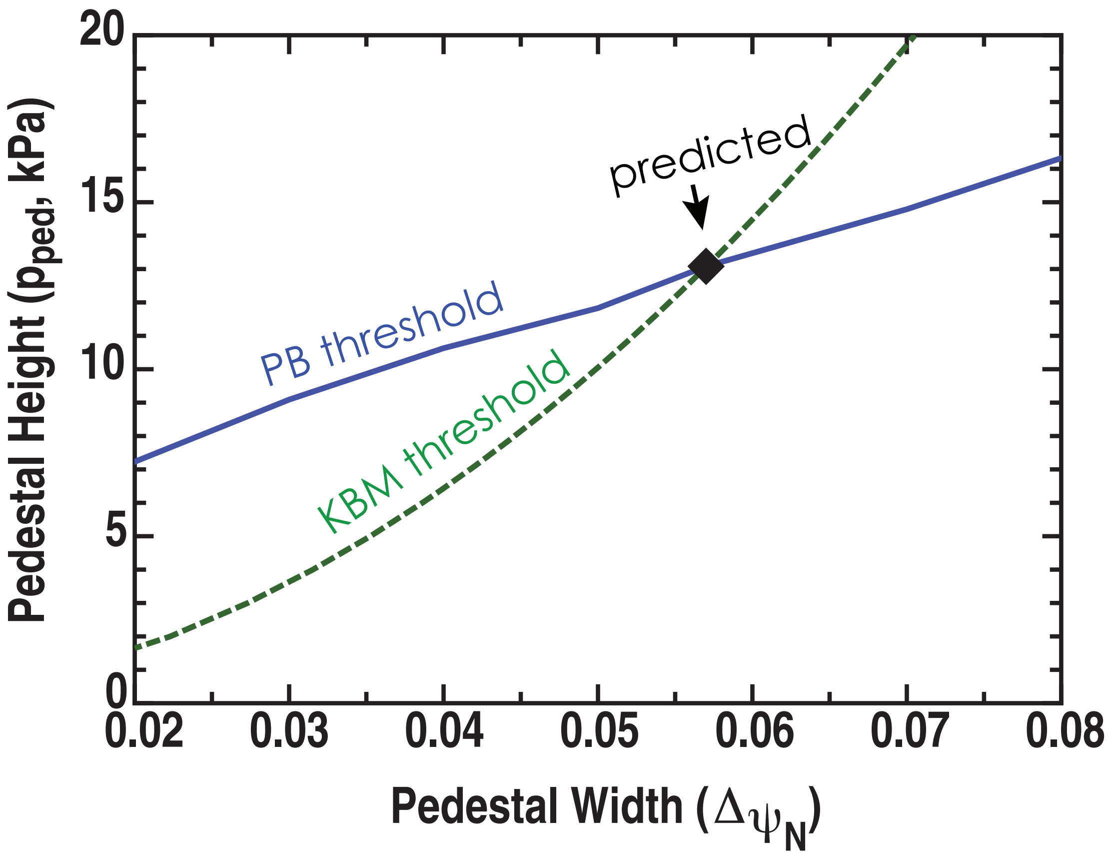


Connor, PoP (1998)
Wilson, PoP (2002)
Snyder, PoP (2002)

- It is hypothesized that ELMs are triggered when the plasma edge (current and/or pressure gradient) crosses the stability boundary

Fundamental question: What sets the pedestal?

EPED -leading pedestal predictive model - combines PBM and KBM constraints to predict maximum achievable height and width



- Combined models for bootstrap current, PB stability, KBM stability
- Inputs: B_T, I_P, R, a, κ,δ, n_{ped}, β_{global}
- Outputs: Pedestal height and width (no free or fit parameters)
- Hypothesis: EPED prediction *should* match pressure height/ width observed just prior to ELM onset

Good agreement with experiment

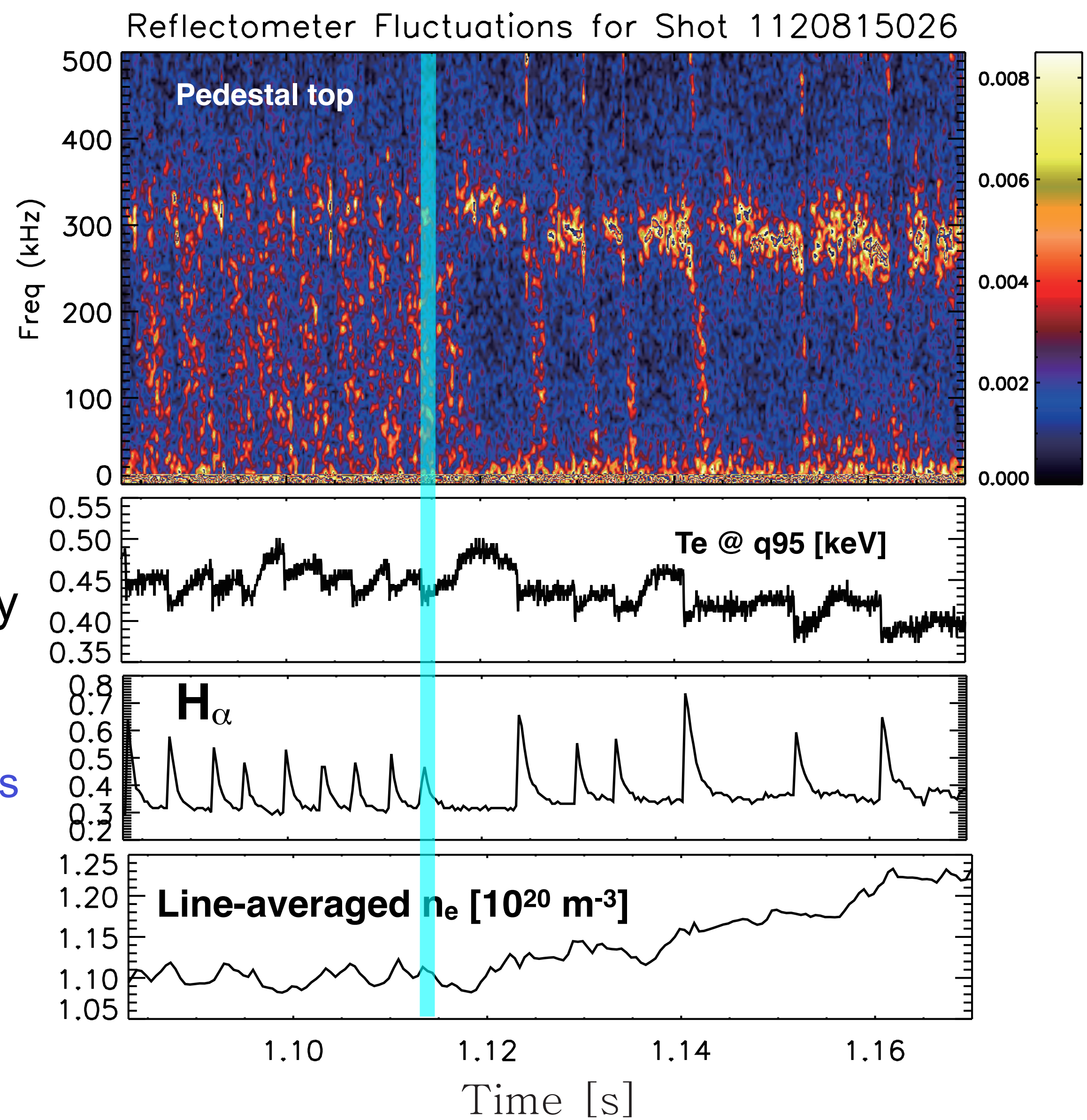
Test of the KBM argument?

Snyder, PoP (2002)

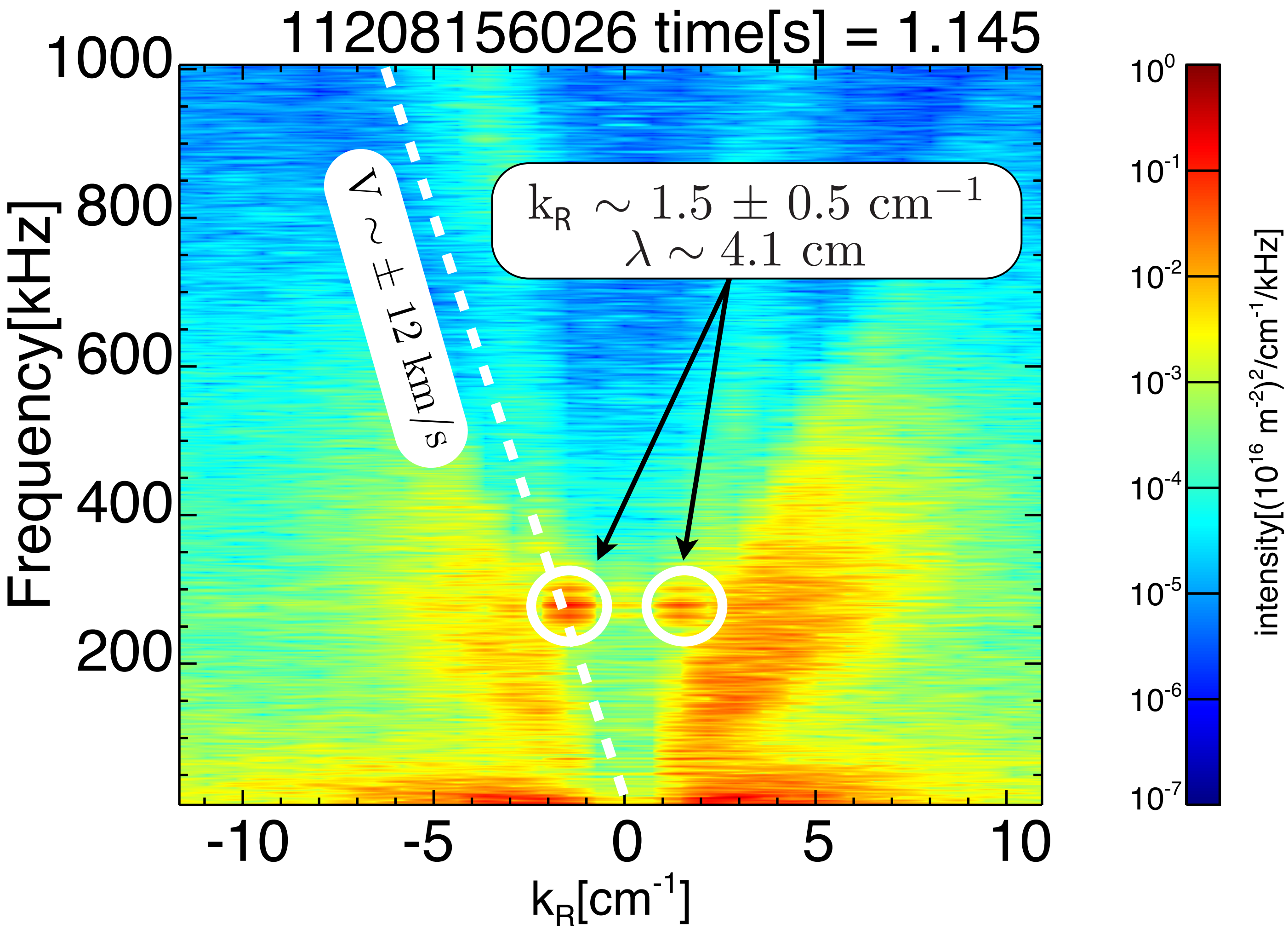
Density fluctuations at the pedestal top indicates the occurrence of the mode when the line-averaged density increases

Alcator C-Mod

- Increased line-averaged density is indicative of a higher pedestal density
  - Leading the reflectometer to probe the pedestal region
- Mode is observed observed when the density cutoff is localized near the steep gradient region
  - Suggesting that the mode is edge localized.

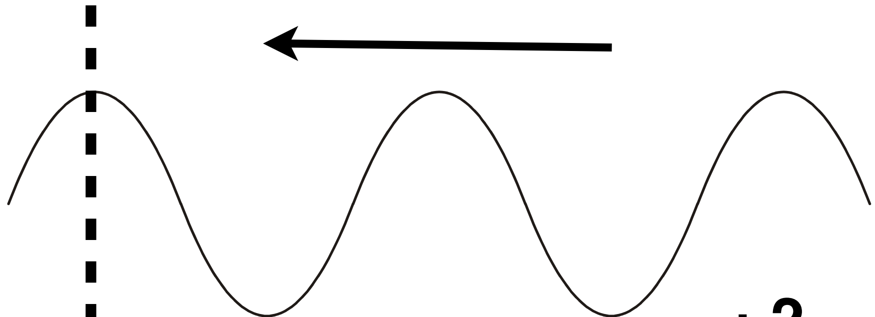


S(f,k) conditional spectrum at t=1.145s suggests that the inter-ELM mode has a radial structure



- Presence of both positive and negative radial wavenumber is due to the line integration of the measurements, which picks up top and bottom propagations.
- Evidence of asymmetry between the two propagation direction.

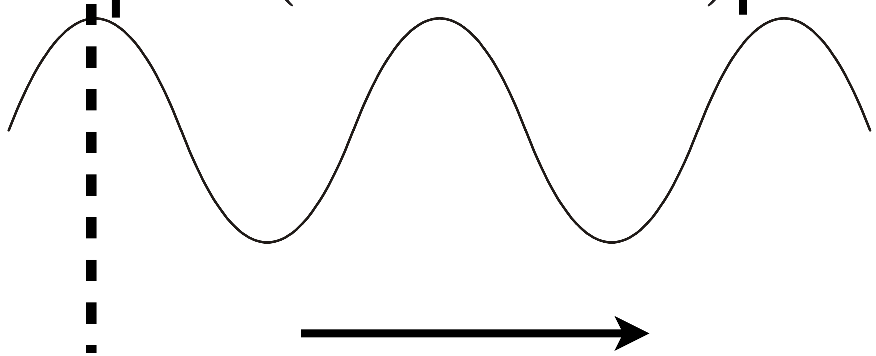
Line-integration from field aligned propagating structure would yield an apparent radial structure



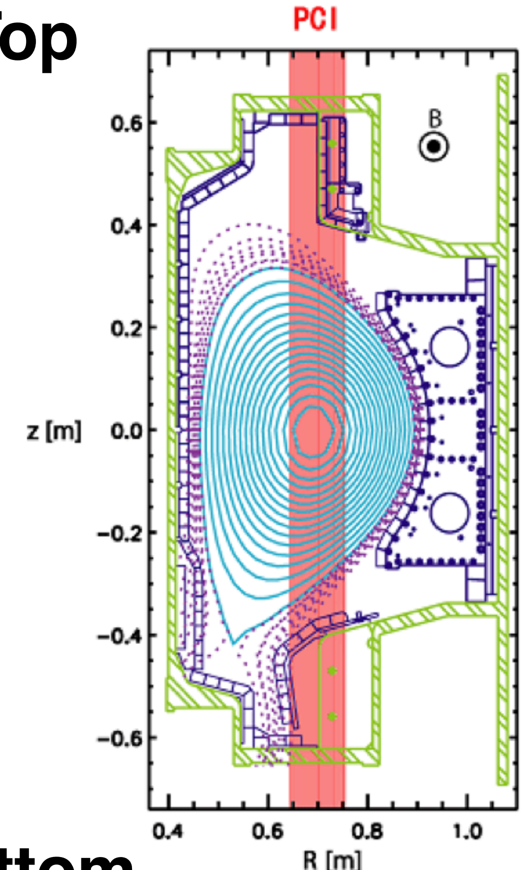
$$\left| \sin(k_R R + \omega t) + \sin(k_R R - \omega t) \right|^2 \propto \cos(2 k_R R)$$

$$\Downarrow$$

should observe 2 cm amplitude modulation



Top



Bottom

C-Mod shows temperature equilibration in both ELMy and EDA H-mode suggesting collisional plasma

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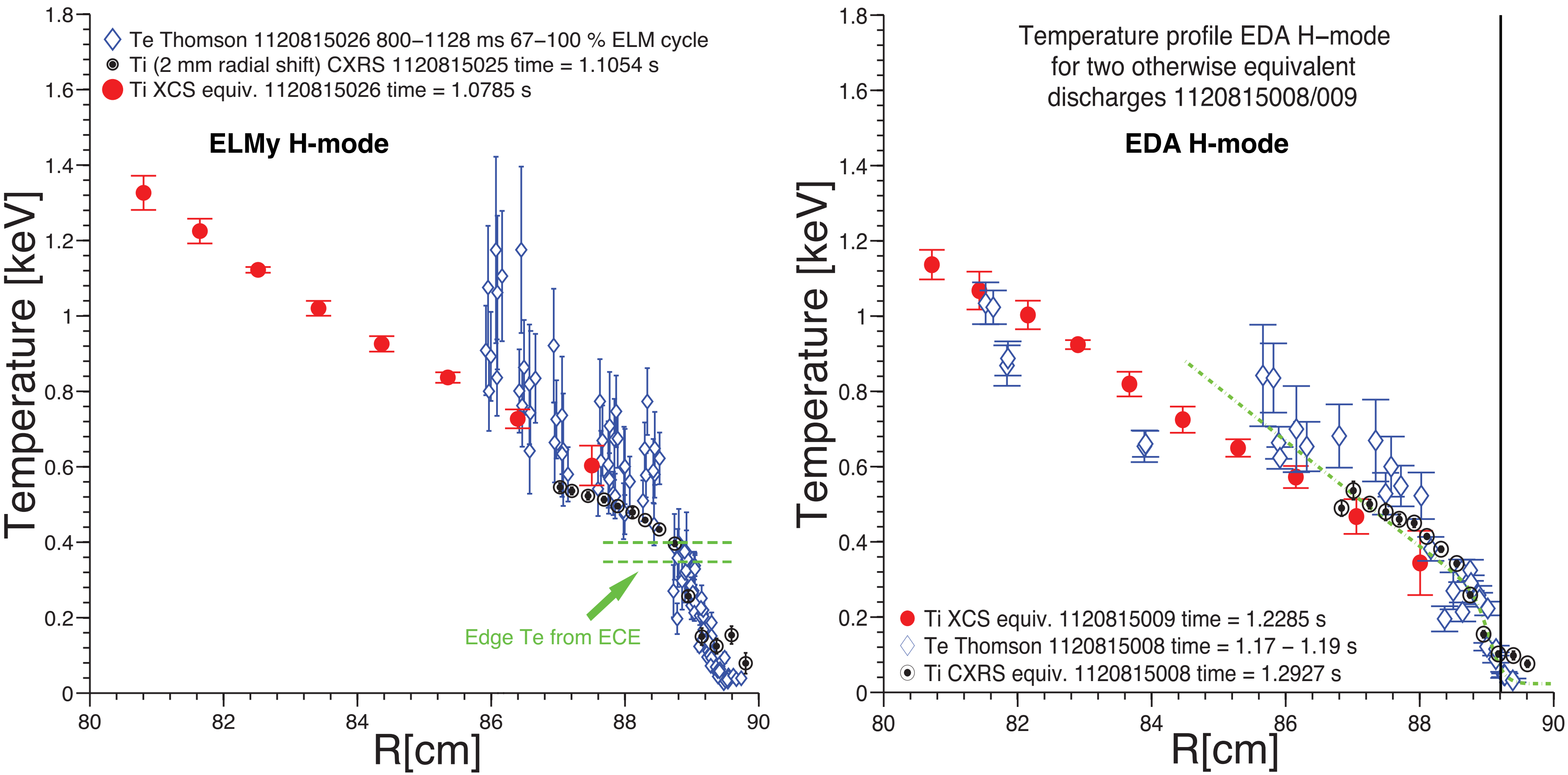
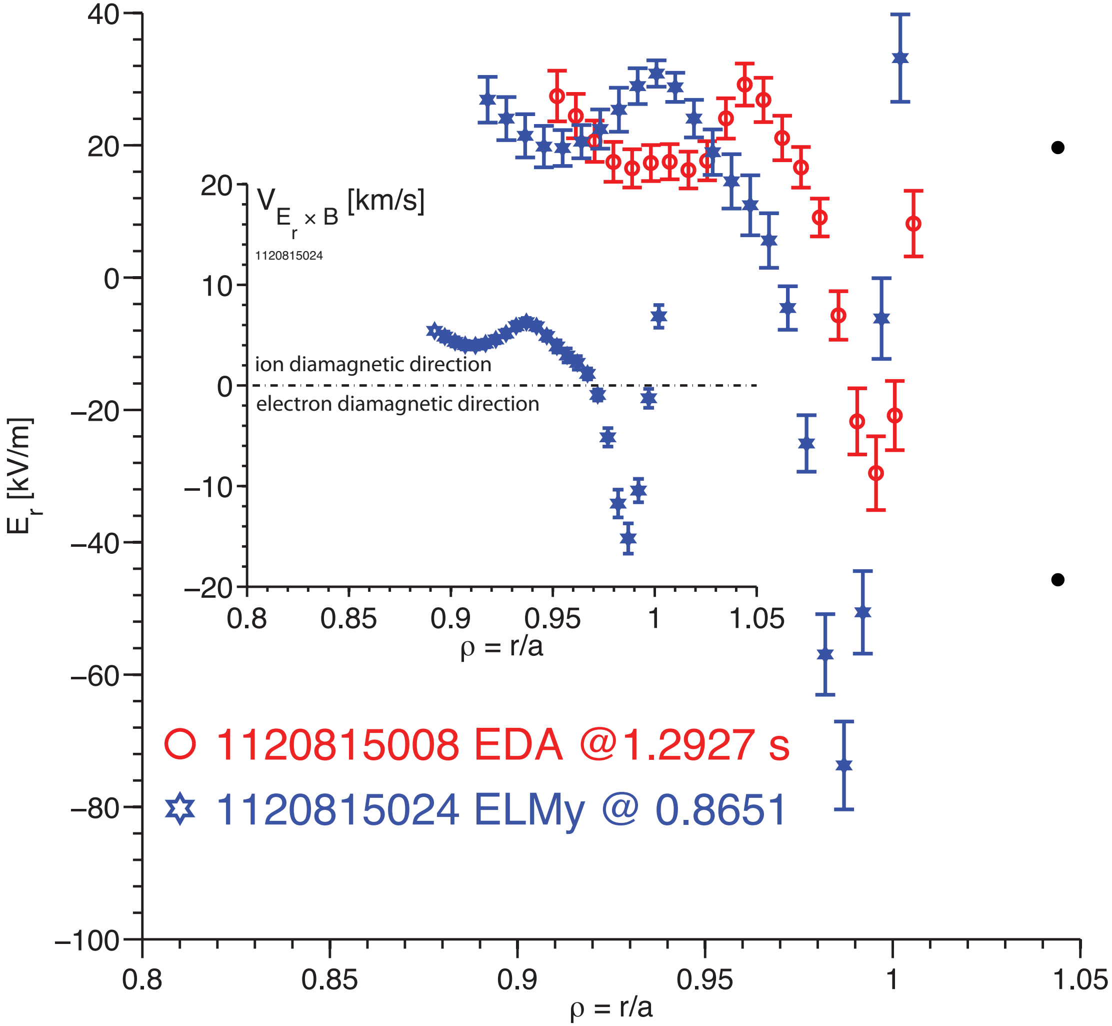


- Temperature pedestal height and width in ELMy regimes are larger than that of EDA cases.
  - Pedestal pressure height and width increases between ELMs with the gradient clamped (shown in Hughes NF 2013)

Edge radial electric field deepens from EDA to ELMy regimes



- Gas Puff (GP) CXRS provide measurements of the edge radial electric field
  - similar to McDermott previous results

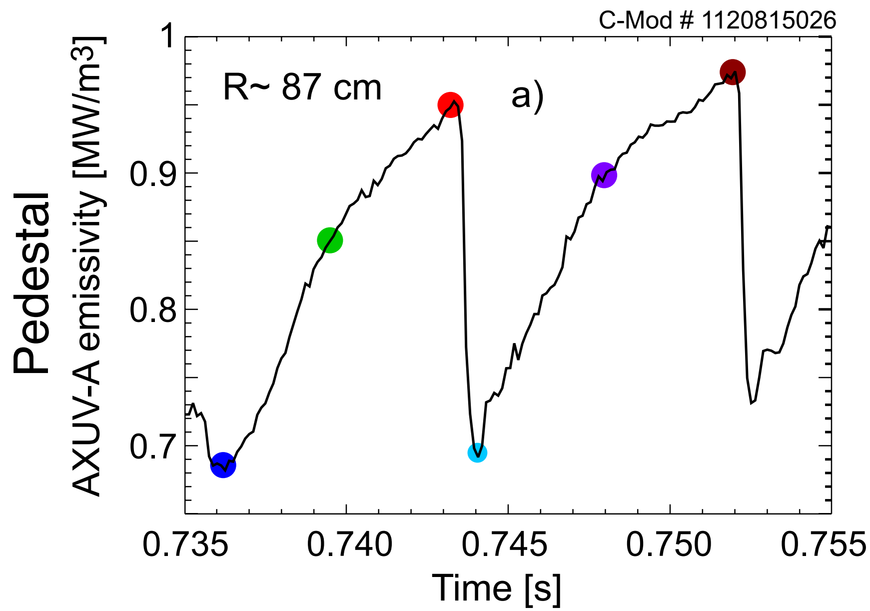
- Associated ExB velocities in ELMy regimes provide propagation direction of fluctuations in plasma frame.

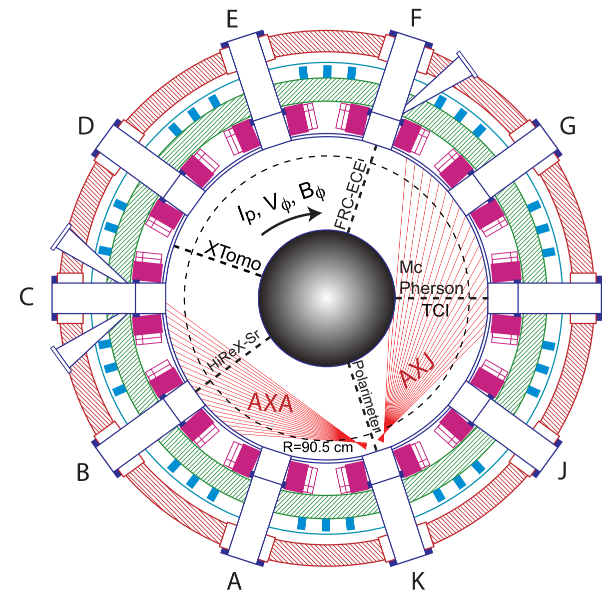
C. Theiler *et al.* TTF 2013

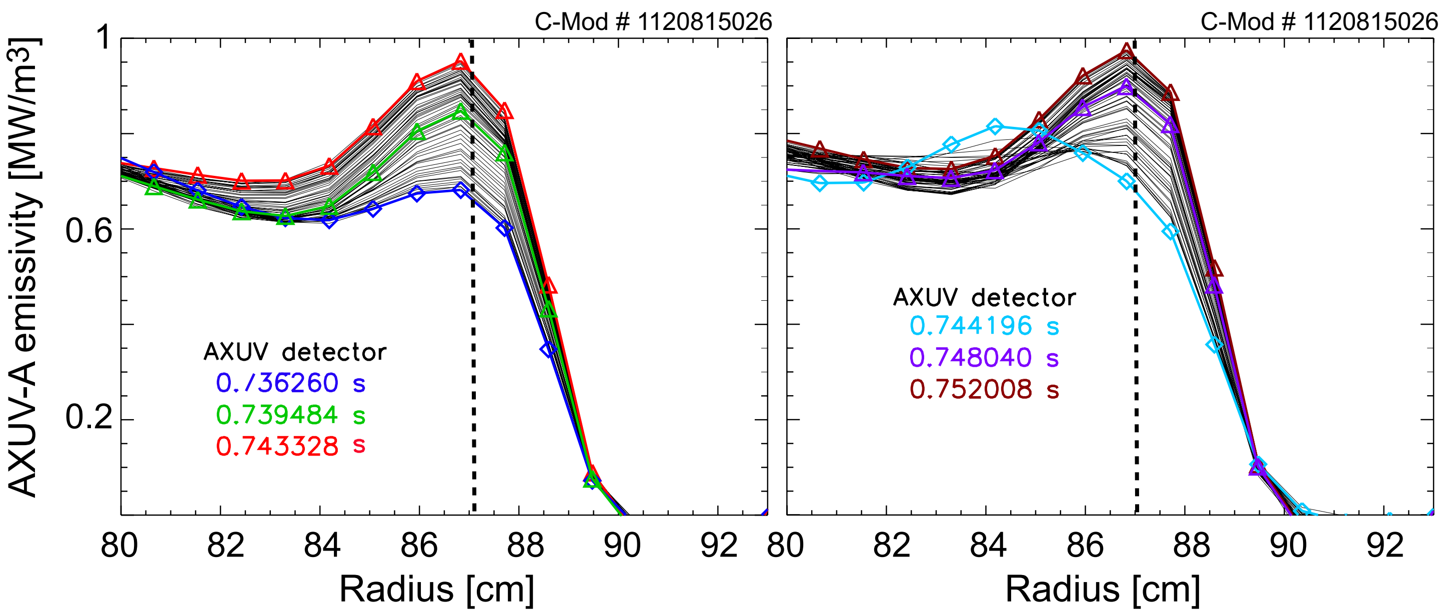
M. Churchill *et al.* to be submitted

Evidence of intrinsic impurity density buildup during ELM cycle

Alcator C-Mod







KBM has been hypothesized to provide the mechanism for setting the pedestal width-poloidal-β-scaling

Alcator C-Mod

***Argument** (for standard aspect ratio and neglecting aspect ratio dependence) used in Snyder PoP 2009*

$$\alpha = \frac{-2\partial_\psi V}{(2\pi)^2}\left(\frac{V}{2\pi^2 R_0}\right)^{1/2} \mu_0 \partial_\psi p$$

$$\Delta[\psi_n] \sim \frac{\beta_\theta^{ped}}{<\alpha>} \sim \frac{\beta_\theta^{ped}}{<\alpha_{crit}>}$$

$$\text{Note } \alpha_{crit} \sim 1/\sqrt{\hat{s}}$$

$$\hat{s} \text{ scales } < j_{bootstrap} >^{-1} \sim (\beta_\theta^{ped})^{-1}$$

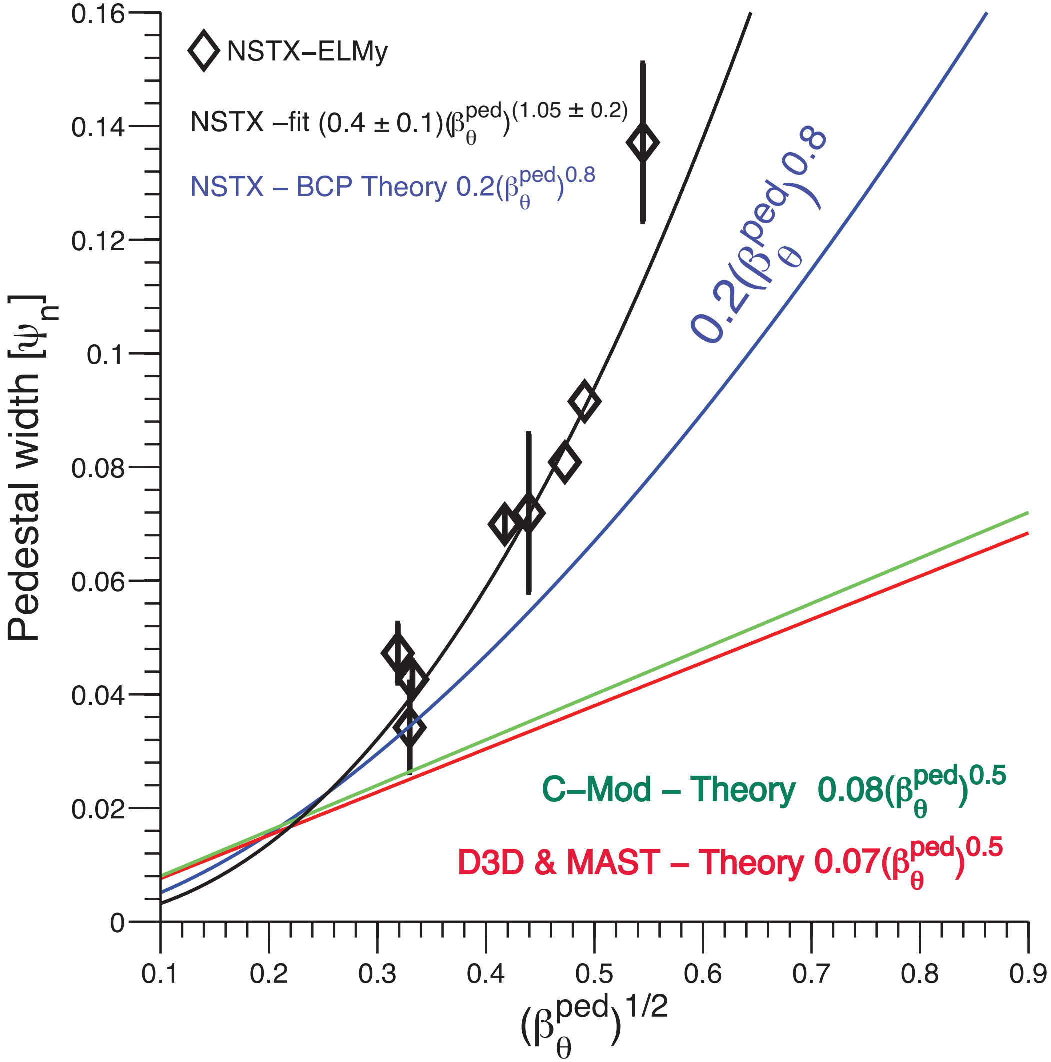
$$< \alpha_{crit} > \sim \sqrt{\beta_\theta^{ped}} \Rightarrow \boxed{\Delta[\psi_n] \sim \sqrt{\beta_\theta^{ped}}}$$

- Strong KBM onset imposes constraint on edge <u>pressure</u> gradient, which can be described when α~ α_{crit}
- Correlation between pedestal width and poloidal β has been observed on DIII-D, JET, C-Mod, JT-60U, MAST, NSTX

Urano NF 2008
Kirk PPCF 2009
OsborneJNM 2009
Beurkens NF 2011
Diallo NF 2012
Walk NF 2012

NSTX measured pedestal width scales like $(\beta_\theta)^\alpha$ with exponent ranging from 0.8 to 1 consistently larger than other tokamaks

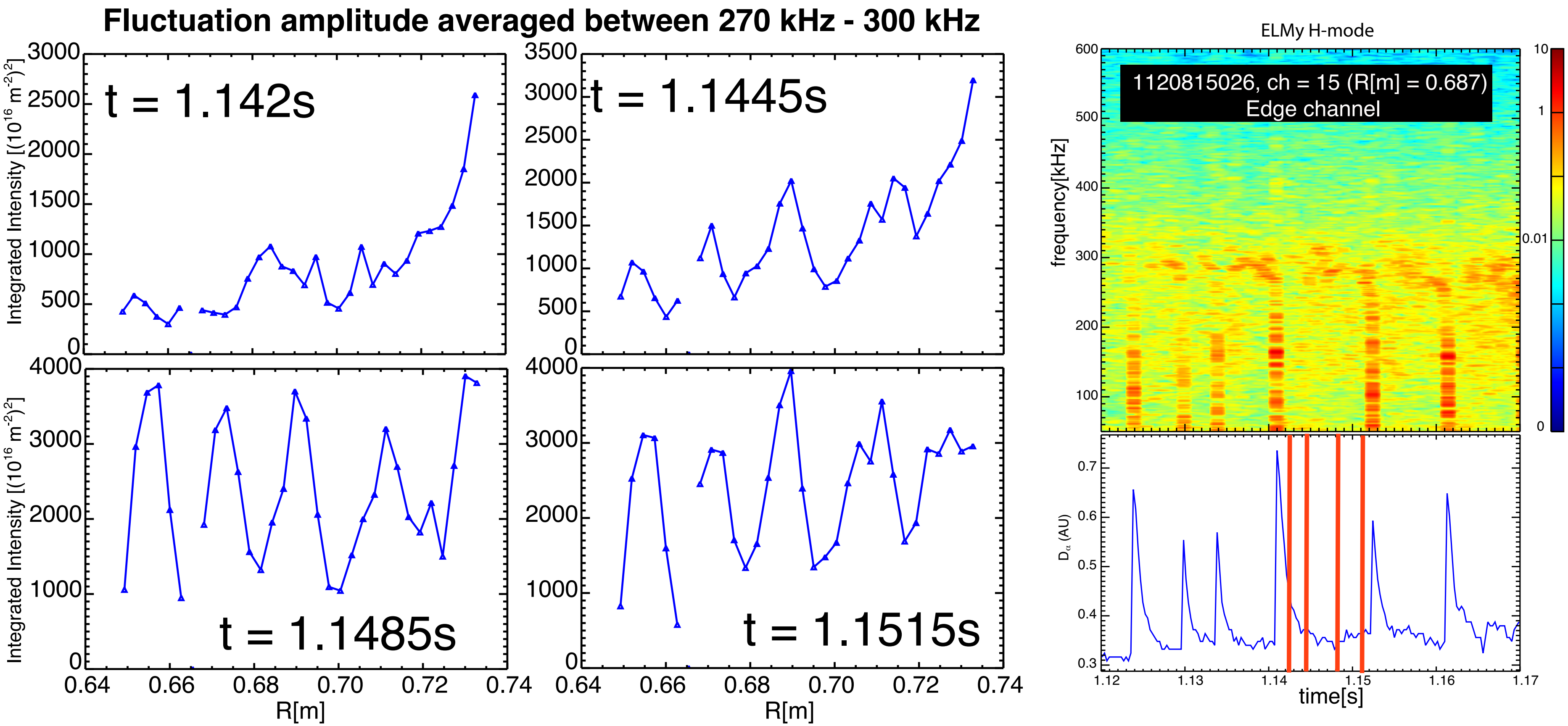
Alcator C-Mod



Diallo Submitted to NF 2013

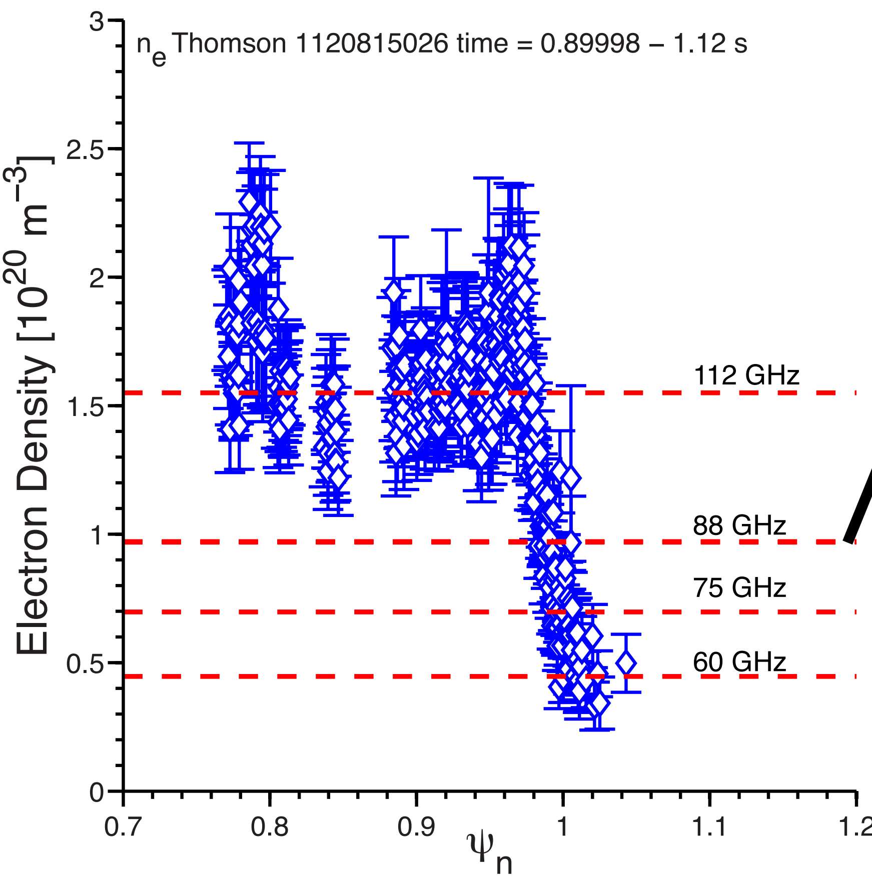
- In NSTX, the observed width is larger than conventional tokamaks
  - NSTX pedestal width is 1.7 and 2.4 larger than MAST and DIII-D & C-Mod respectively
- Pedestal width scaling is consistent with predicted width for KBM constrained pedestal
  - "ballooning critical pedestal"- BCP technique from EPED Model [Snyder Nucl. Fusion (2011)]
  - Conventional tokamaks show an exponent of 0.5 and predictions agree with data

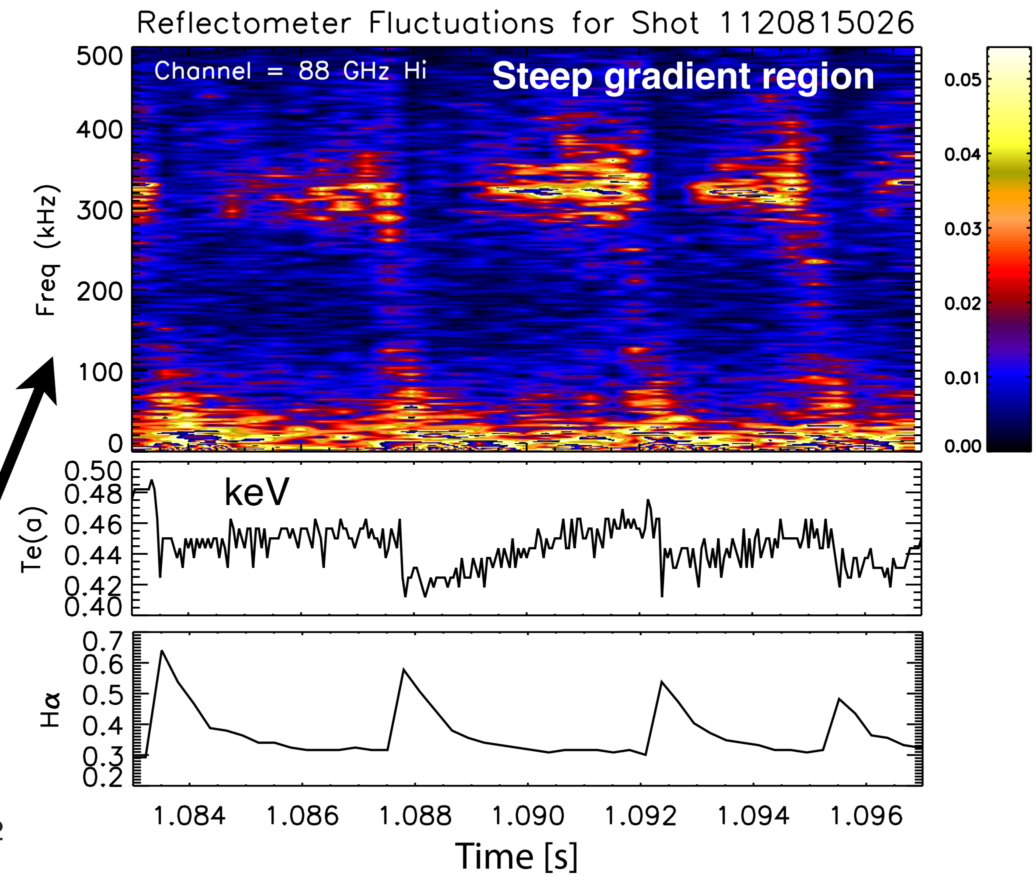
Development of the mode power radial structure after after the ELM crash with up to 60% contrast



- In the ELM early stage, the intensity is peaked at larger radii and increases and saturates during the ELM cycle.

Density fluctuation spectrogram from O-mode reflectometer show the onset of fluctuations in the steep gradient region





- Inter-ELM density fluctuations track the edge temperature increase.
- Steep density gradient is clamped but the density pedestal varies over a large range.

Motivation

- Test the hypothesis of EPED model - the leading candidate for predicting the pedestal of ITER and other future tokamaks

Snyder NF 2009

- It has been observed in many machines that the pedestal gradient is limited prior to the ELM onset.
  - EPED hypothesizes that the onset of KBM provide the necessary transport for clamping the edge gradient
  - Recent results from DIII-D, AUG, and NSTX showed the existence of ion scale mode during the ELMy regimes.

Yan PRL 2011
Boom NF 2012
Diallo PoP 2013

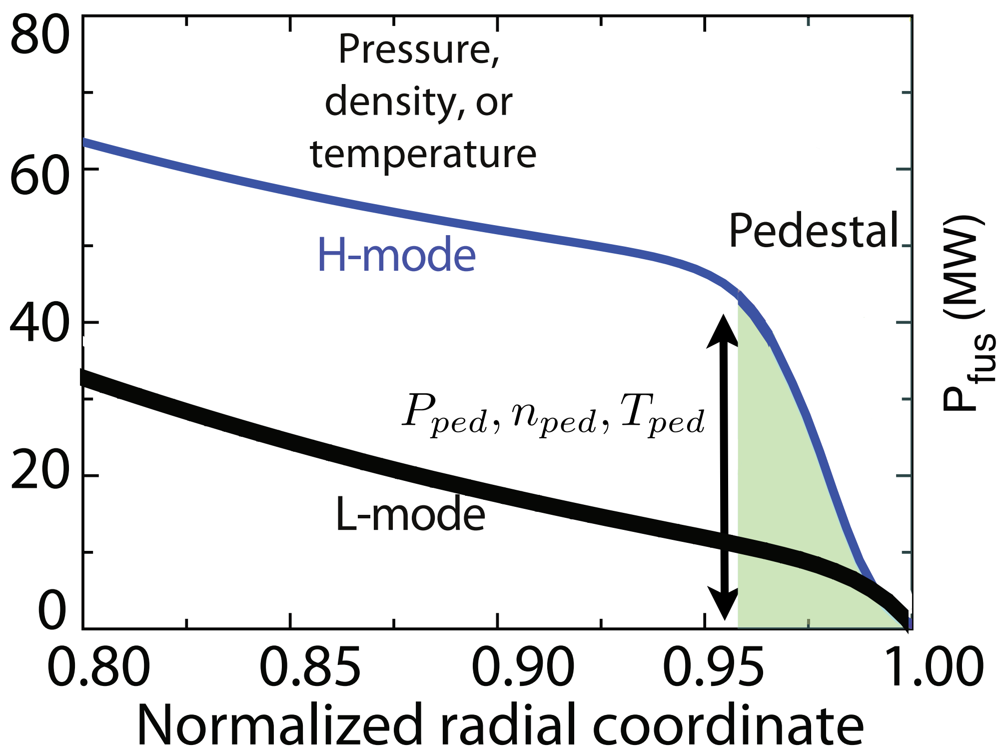
- To show that KBM provides the necessary transport for edge gradient limitation, it is necessary to show that the mode turns on in response to an increase of pressure gradient.
  - A proxy consists of observing the onset of a mode in the pedestal region
  - Characterize its properties (e.g., spatial structure, propagation direction, etc…)

Understanding the pedestal structure is crucial for performance prediction of fusion devices

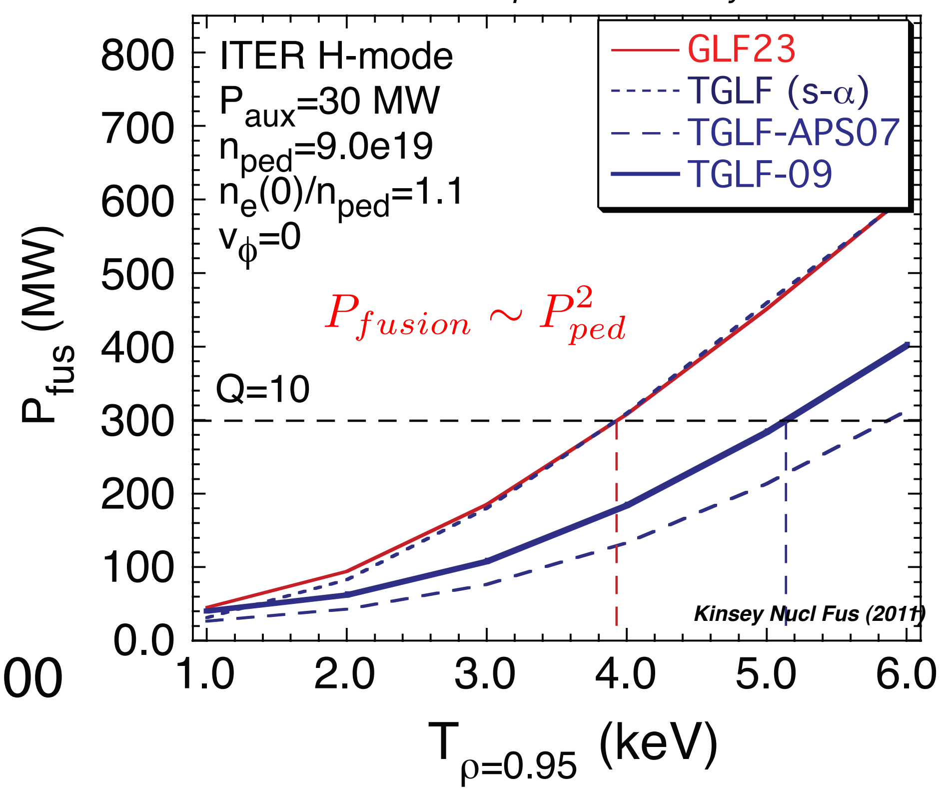
Alcator C-Mod

- Pedestal is an edge transport barrier associated with high-confinement regime (H-mode)

- Predictive models indicate that the pedestal height plays a crucial role in fusion performance

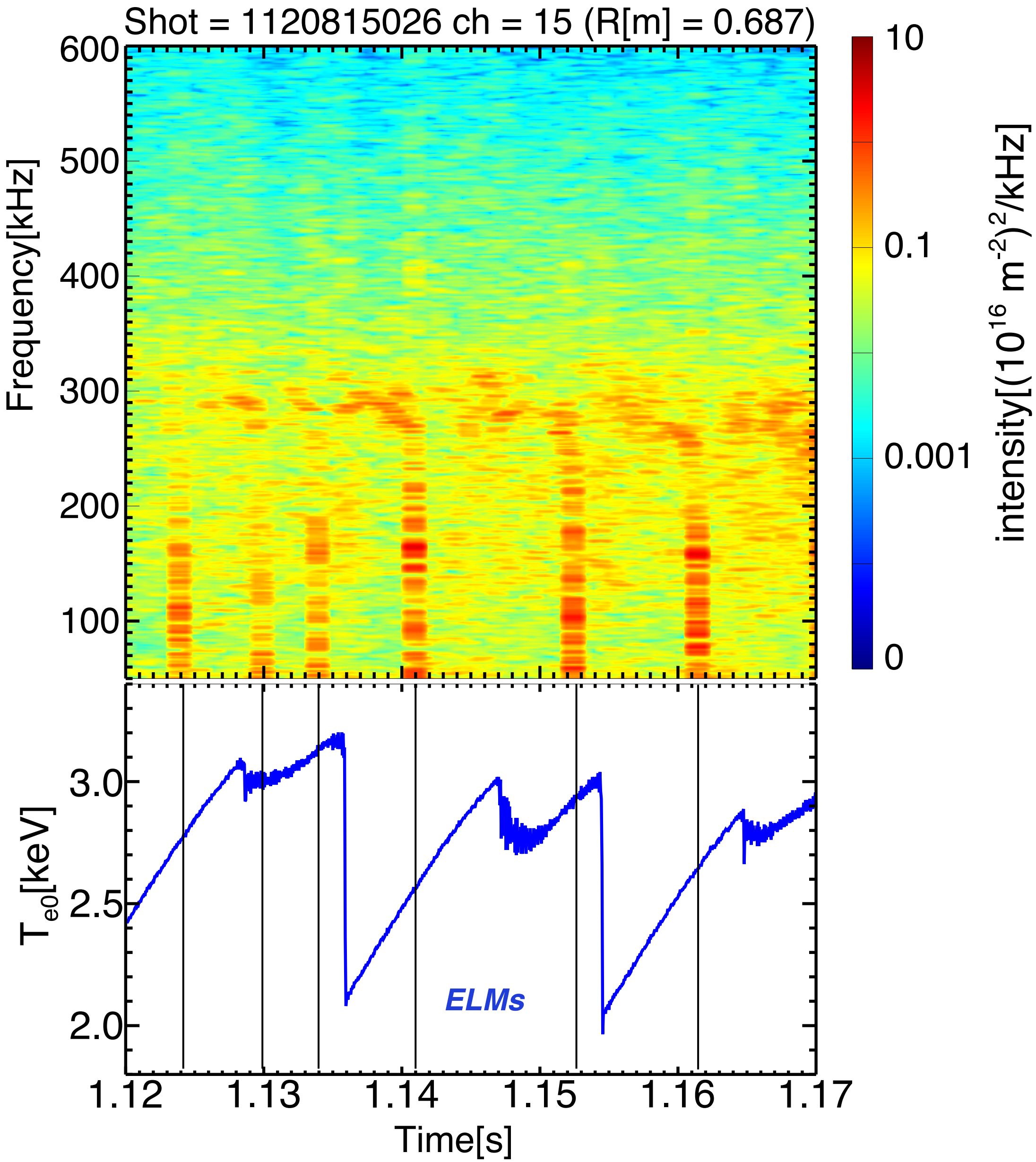


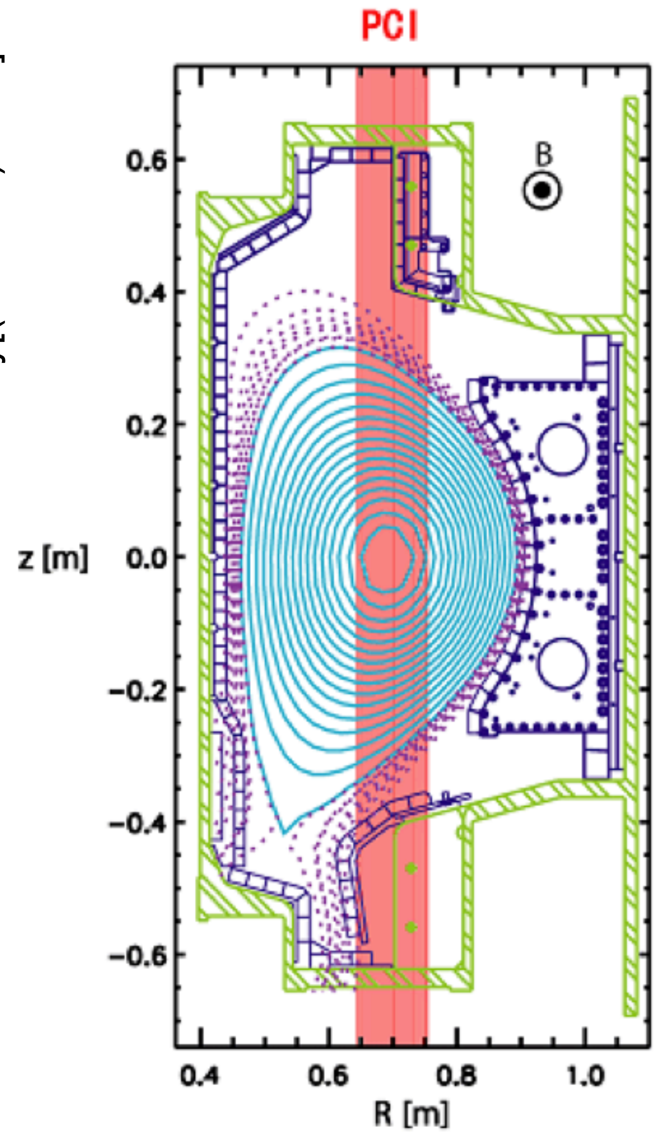
Predicted fusion power vs pedestal temperature at fixed pedestal density



PCI fluctuation indicate that the inter-ELM fluctuations are uncorrelated with sawteeth pulses

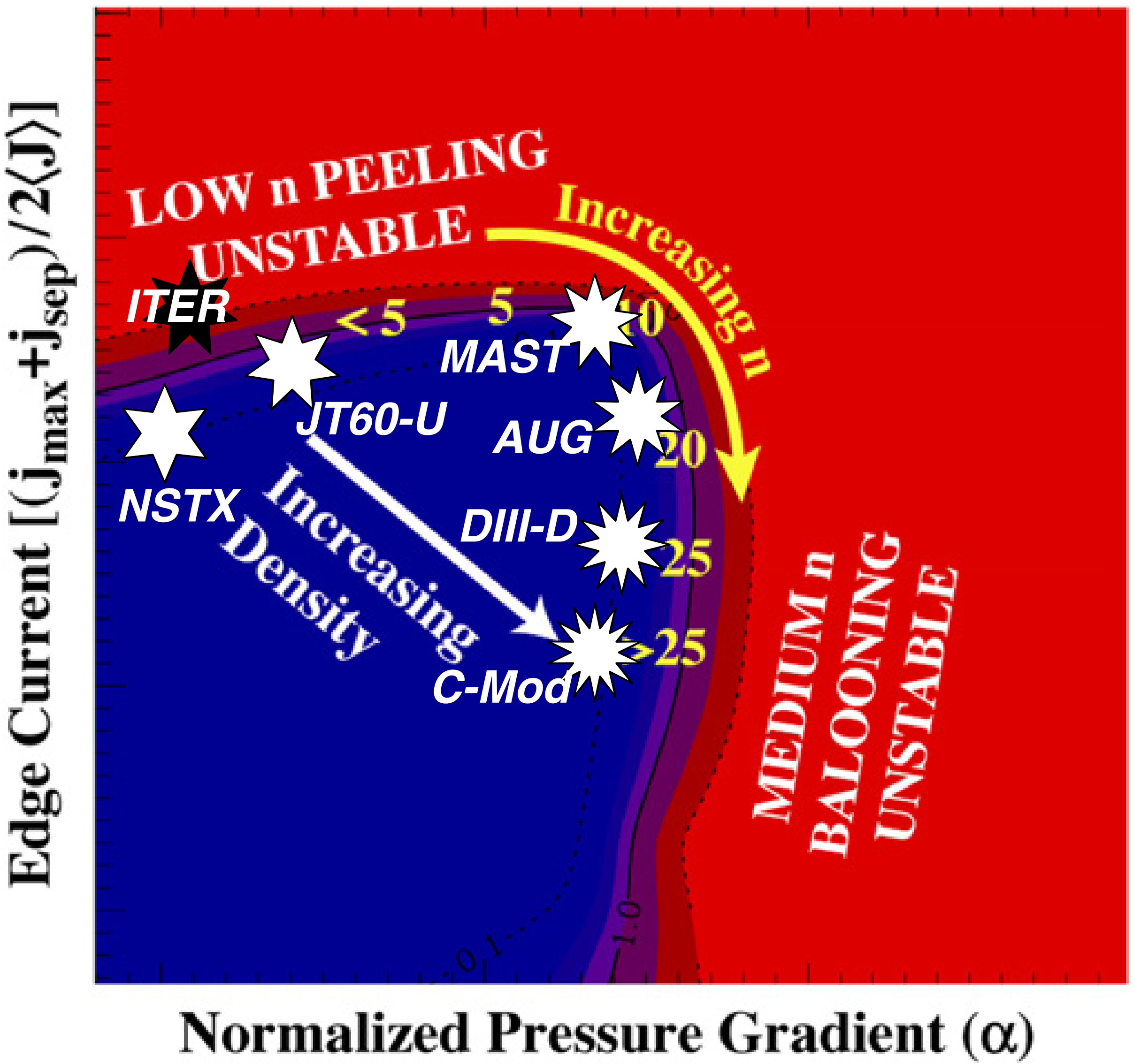
Alcator C-Mod





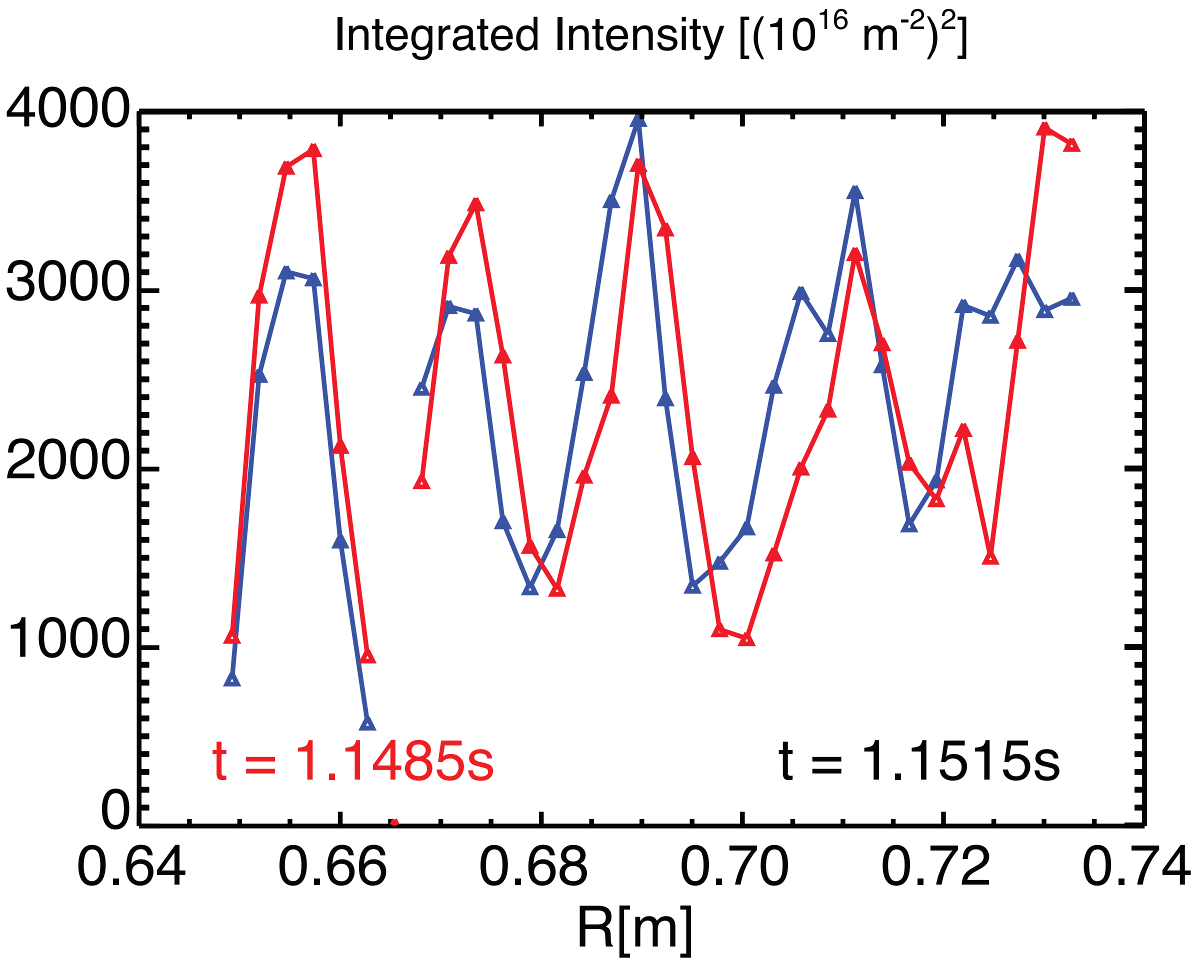
Pre-ELM-onset operating point of machines on the stability diagram

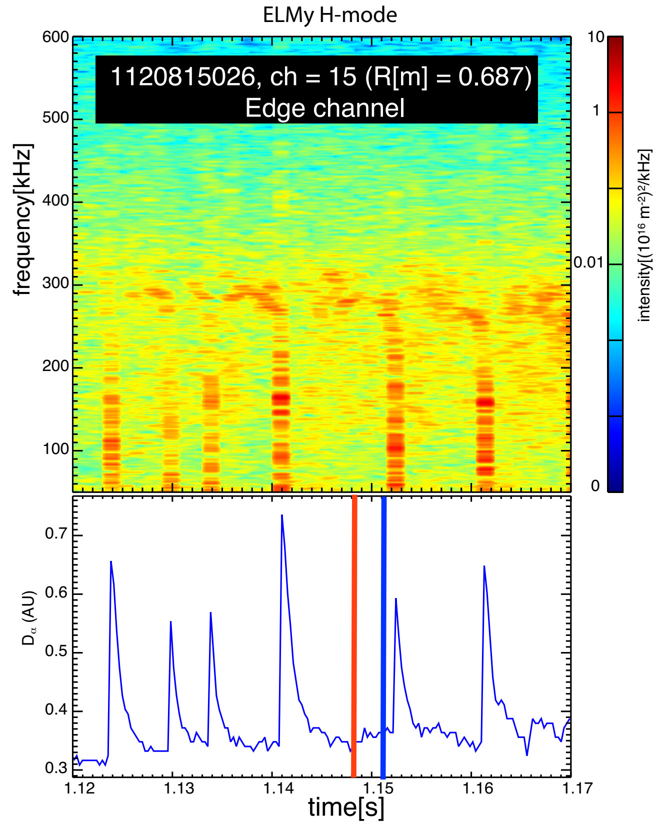
Alcator C-Mod



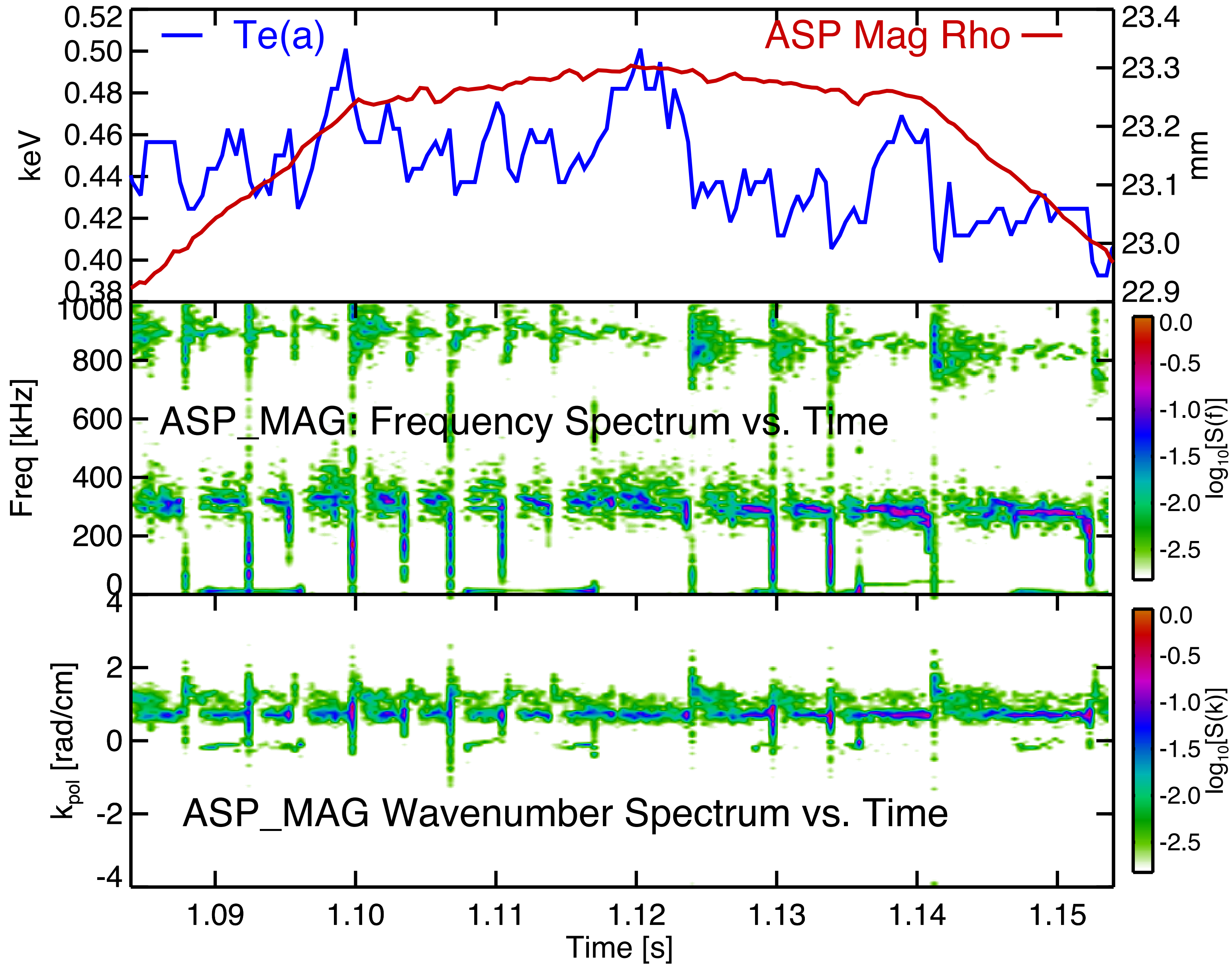
Urano NF 2008
Kirk PPCF 2009
Osborne JNM 2009
Maingi NF 2004
Walk NF 2012

Mode *power* radial structure prior to the ELM onset



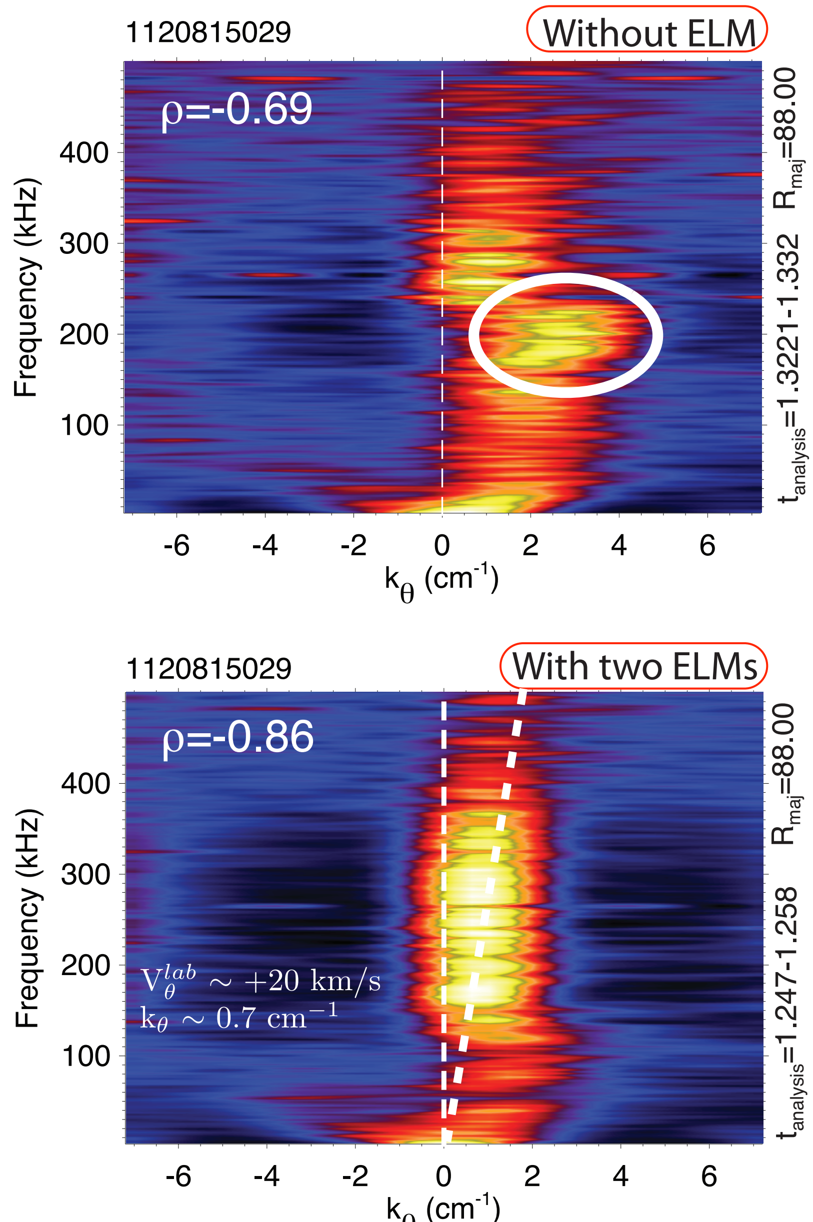


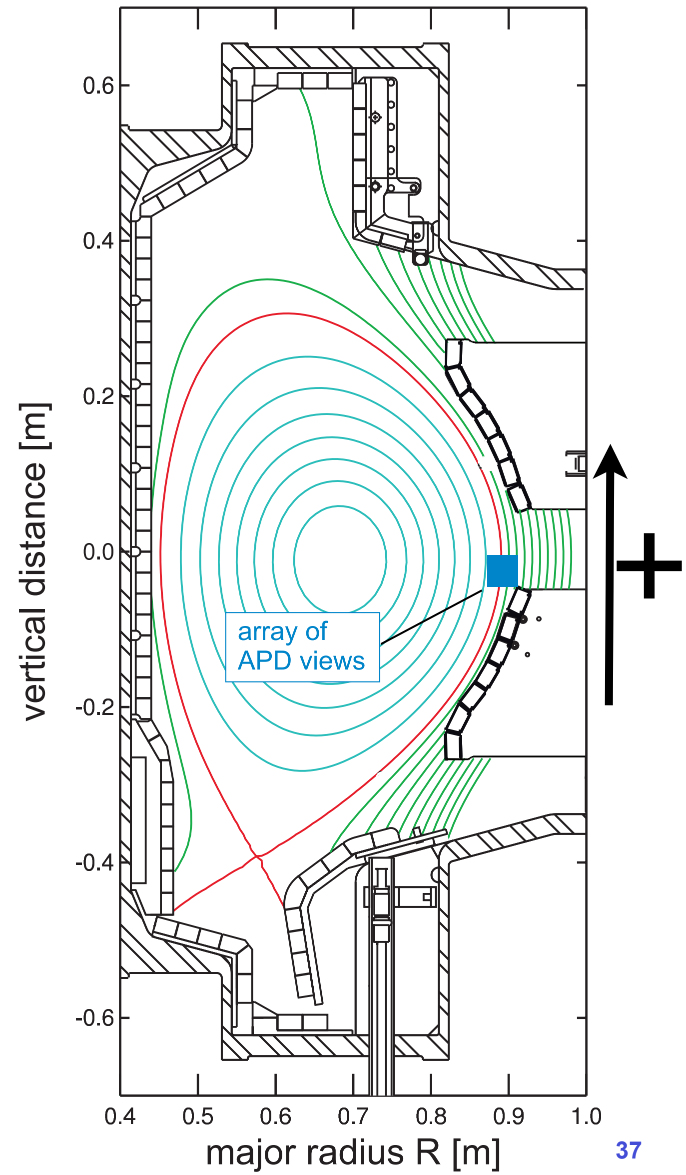
- In the saturation phase of the mode, there is evidence of phase shift that increases with large radius.
    - could be due to plasma motion…..(requires forward modeling)


Te(a)
ASP Mag Rho
keV
mm
0.52
0.50
0.48
0.46
0.44
0.42
0.40
0.38
23.4
23.3
23.2
23.1
23.0
22.9
ASP_MAG: Frequency Spectrum vs. Time
Freq [kHz]
1000
800
600
400
200
0
log10[S(f)]
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
ASP_MAG Wavenumber Spectrum vs. Time
kpol [rad/cm]
4
2
0
-2
-4
log10[S(k)]
1.09
1.10
1.11
1.12
1.13
1.14
1.15
Time [s]

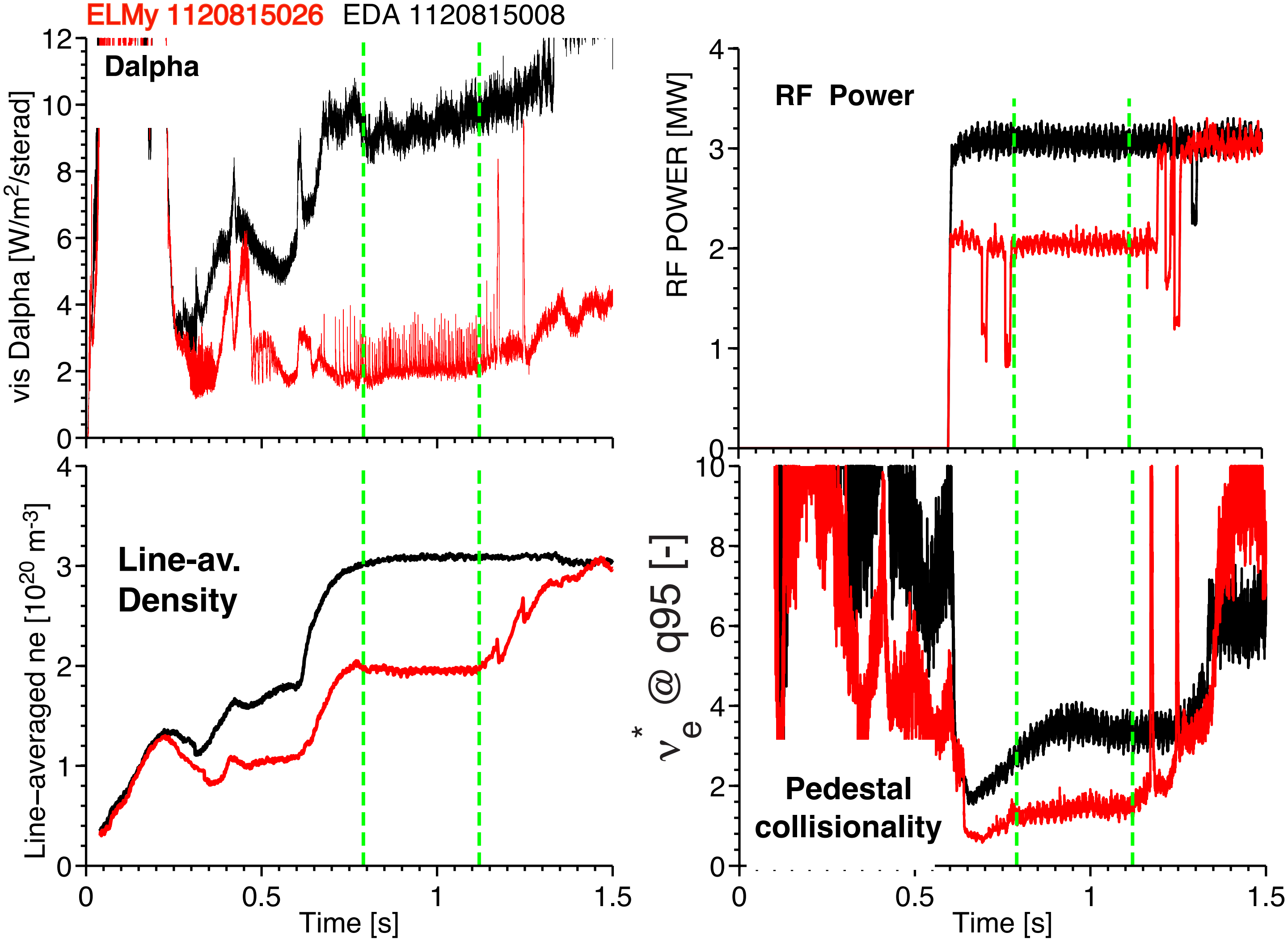
Conditional wavenumber frequency spectra of the poloidal structure of the HeI light fluctuations indicate that the mode is predominant in ELMy case

Alcator C-Mod





Dedicated Alcator C-Mod experiments examine the pedestal turbulence between ELMs



- Here EDA and ELMy regimes are contrasted
  - Reduced target density for lower collisionality