Pressure-Gradient-Limiting Instability Dynamics in the H-mode Pedestal on DIII-D

by

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with

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Motivation and Goals

- **Motivation**
  - Pedestal height is a key factor influencing plasma performance and fusion power in ITER and burning plasmas
  - Understanding instability mechanisms that limit the pedestal height and width is essential to obtaining a predictive model for the H-mode pedestal
- **Method**
  - Characterize the properties and dynamics of the pedestal turbulence to provide insights into the underlying instabilities and their role in the formation of pedestal structure.
  - Can we search for turbulence characteristics with the predicted wave-number and frequency?
- **Goal**
  - Ultimately, test and validate theoretical models and nonlinear simulations of H-mode pedestal. For example, EPED1 model based on peeling-ballooning and kinetic ballooning mode (KBM) has successfully predicted pedestal height and width in many experiments

Overview

- **Related pedestal turbulence properties observed in two different experimental configurations**

A) Dual-band long-wavelength broadband density turbulence observed in ELMing H-mode plasmas

– 2 modes propagate in different poloidal directions
– Lower frequency band evolves significantly with time during inter-ELM cycle, but higher frequency band shows little variation
– Lower frequency band exhibits some KBM-like features and turbulence scale length has little or no dependence on ρ^*

B) High Frequency Coherent Modes (HFC) are observed in ELM-free Quiescent H-mode (QH) plasmas

– Multiple weakly driven (non-turbulent) coherent modes
– Mode localized to the pedestal region
– Also exhibit KBM-like features

Dual-band Long Wavelength Density Fluctuation Dynamics in ELMing H-mode Pedestal

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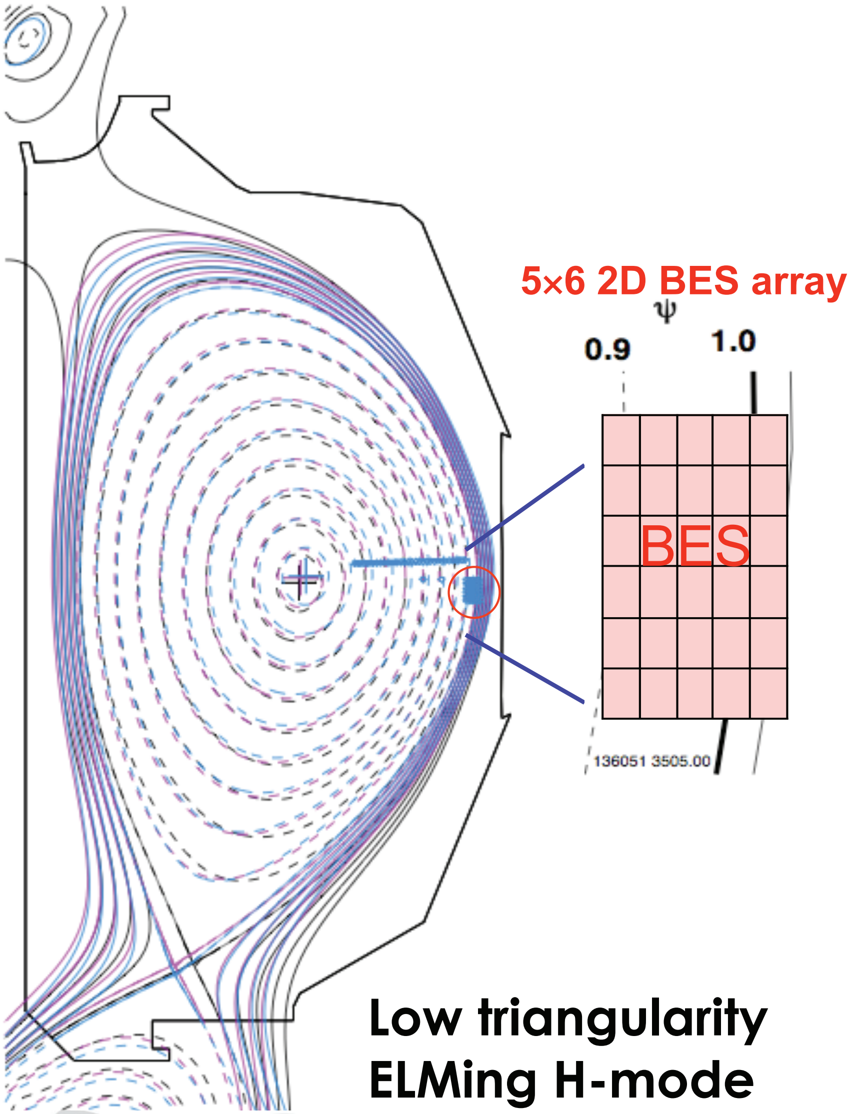
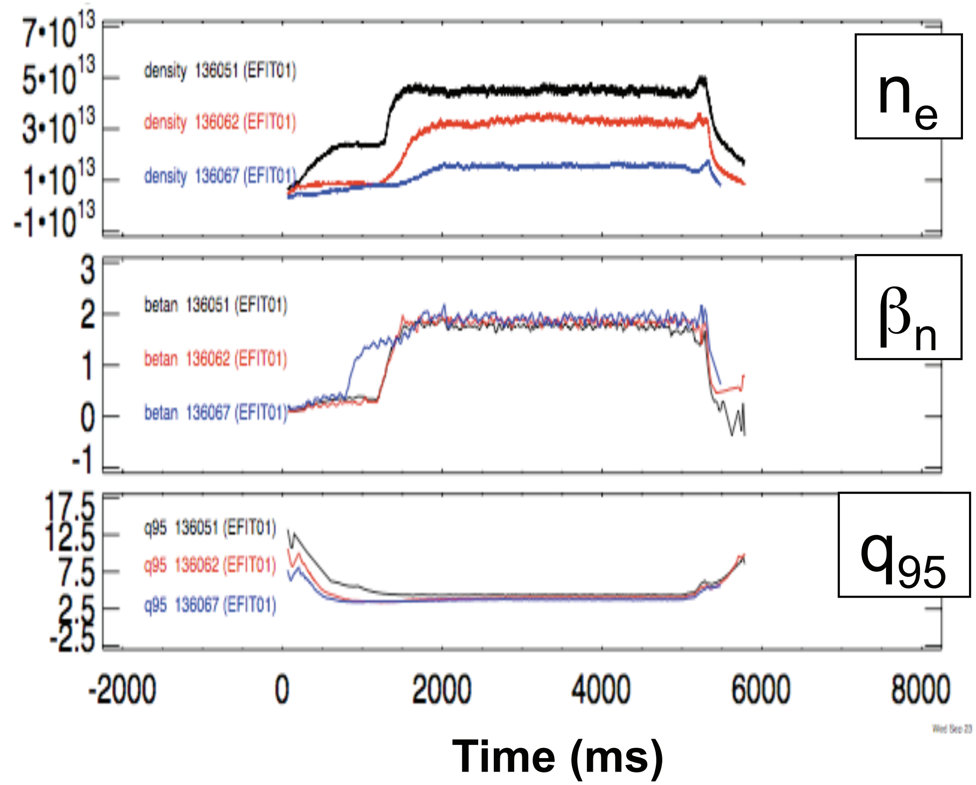
ρ^* Scan Experiment to Study Pedestal Fluctuation Characteristics



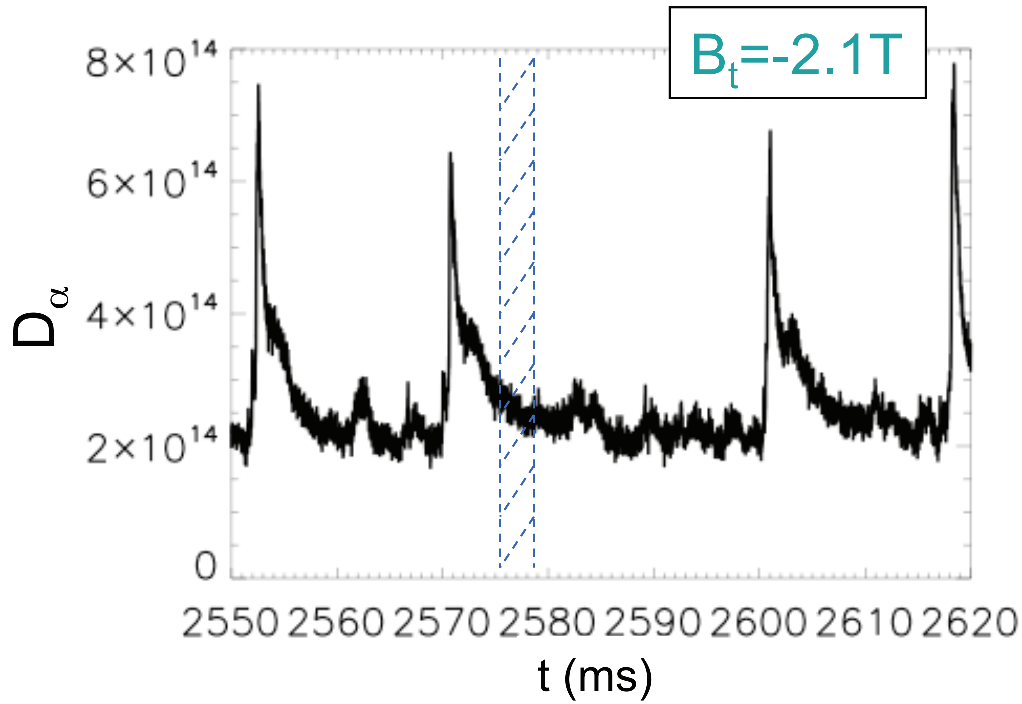
Low triangularity ELMing H-mode

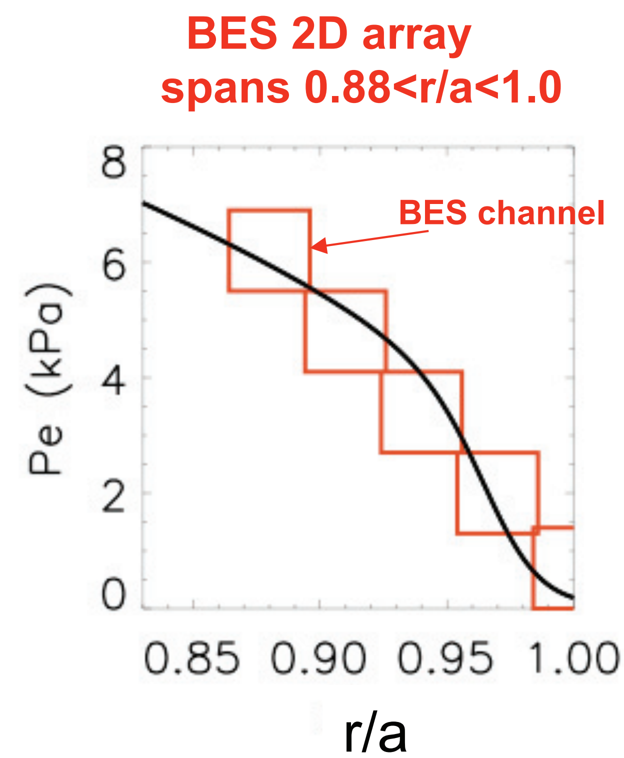
B_t=2.1T, 1.37T & 1.0T



- ρ^* is scanned by a factor of ~ 2 while keeping β, q, ν^*, M and T_i/T_e constant at the pedestal top

Phase-lock Averaging Used to Study Dynamics at Different Times During inter-ELM Cycle

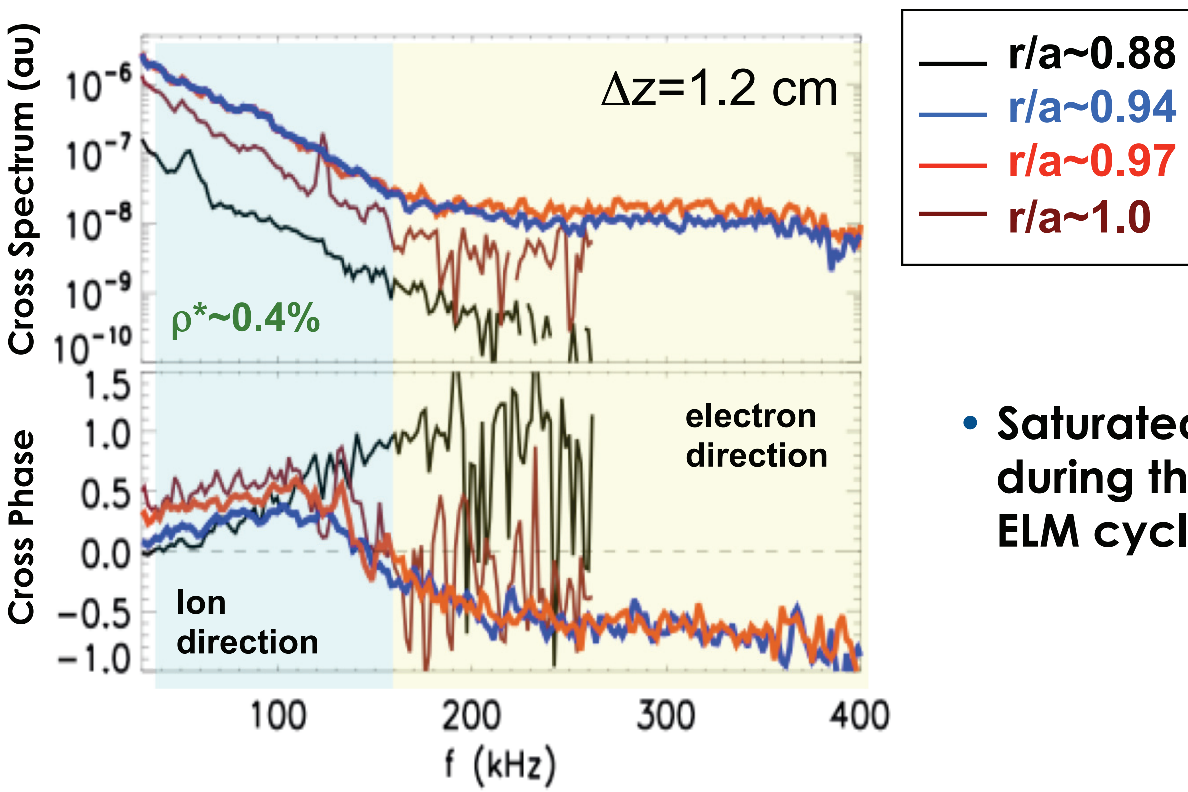




- **Fluctuation characteristics averaged over hundreds of ELM cycles**

Two Broadband Fluctuation Structures Observed Near Maximal Pedestal Pressure Gradient

- **Two bands of fluctuations 1) 50-150 kHz, 2) 200 kHz-400 kHz propagate in different directions (i.e., e/i diamagnetic drift)**
  - Different underlying instabilities?
  - Qualitatively similar to behavior seen previously in TFTR and DIII-D L-modes
- **Limited to maximal pressure gradient location**



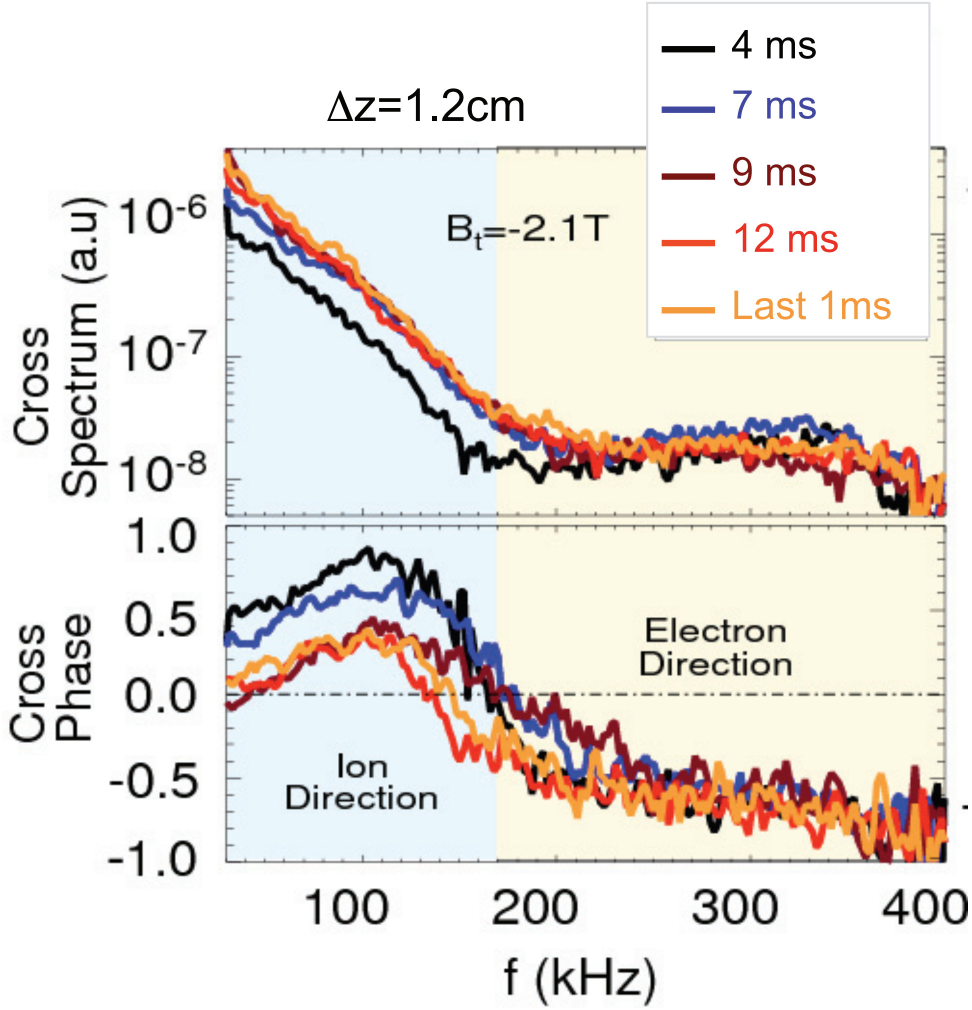
- **Saturated phase during the inter-ELM cycle**

Lower Frequency Band Density Fluctuations Build Up Quickly after ELM Crash

- **At ρ*~0.4% density fluctuations saturate within <10 ms**
- **Higher frequency band fluctuation does not change with time**

ρ*~0.4%

r/a~0.94



296/ZY/rs

Note: Using test data in besmenu. Dc normalized

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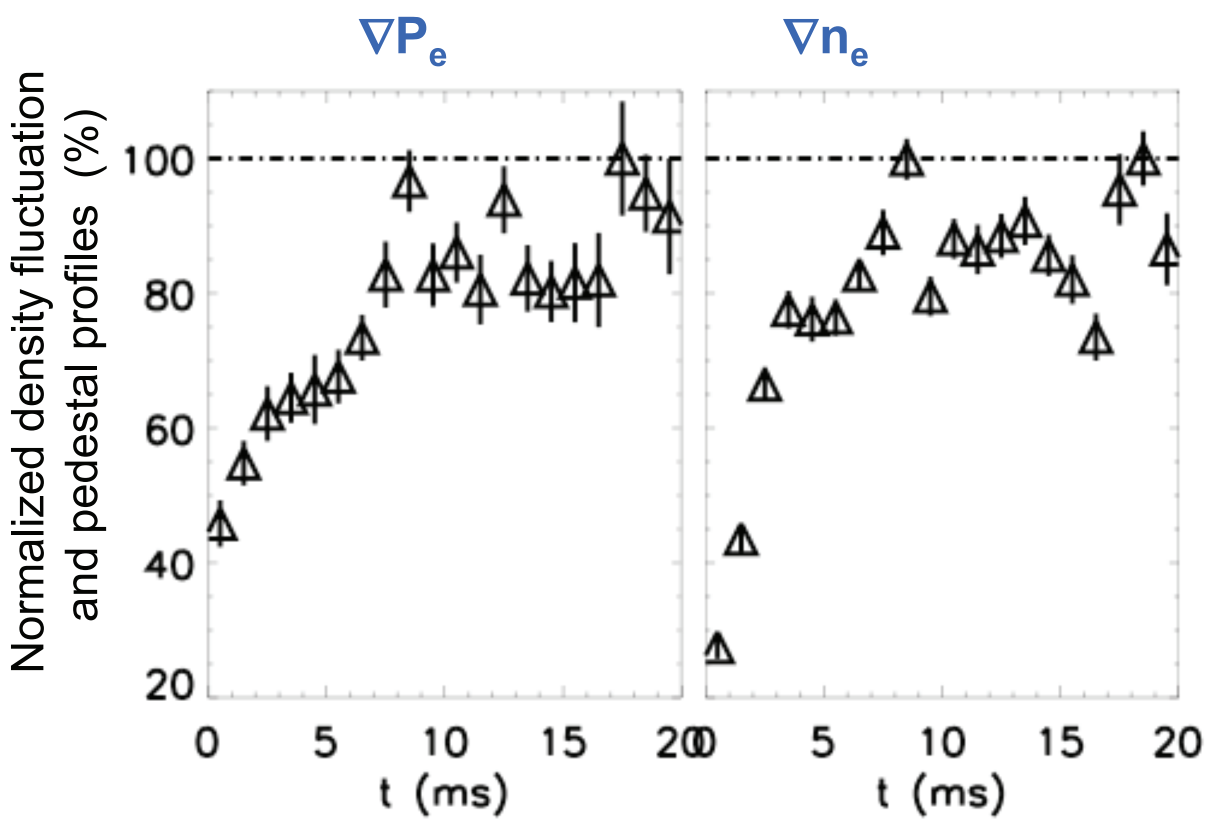
Lower Frequency Band (50 kHz -150kHz) Fluctuation Dynamics Correlated with Pedestal Pressure and Density Gradient



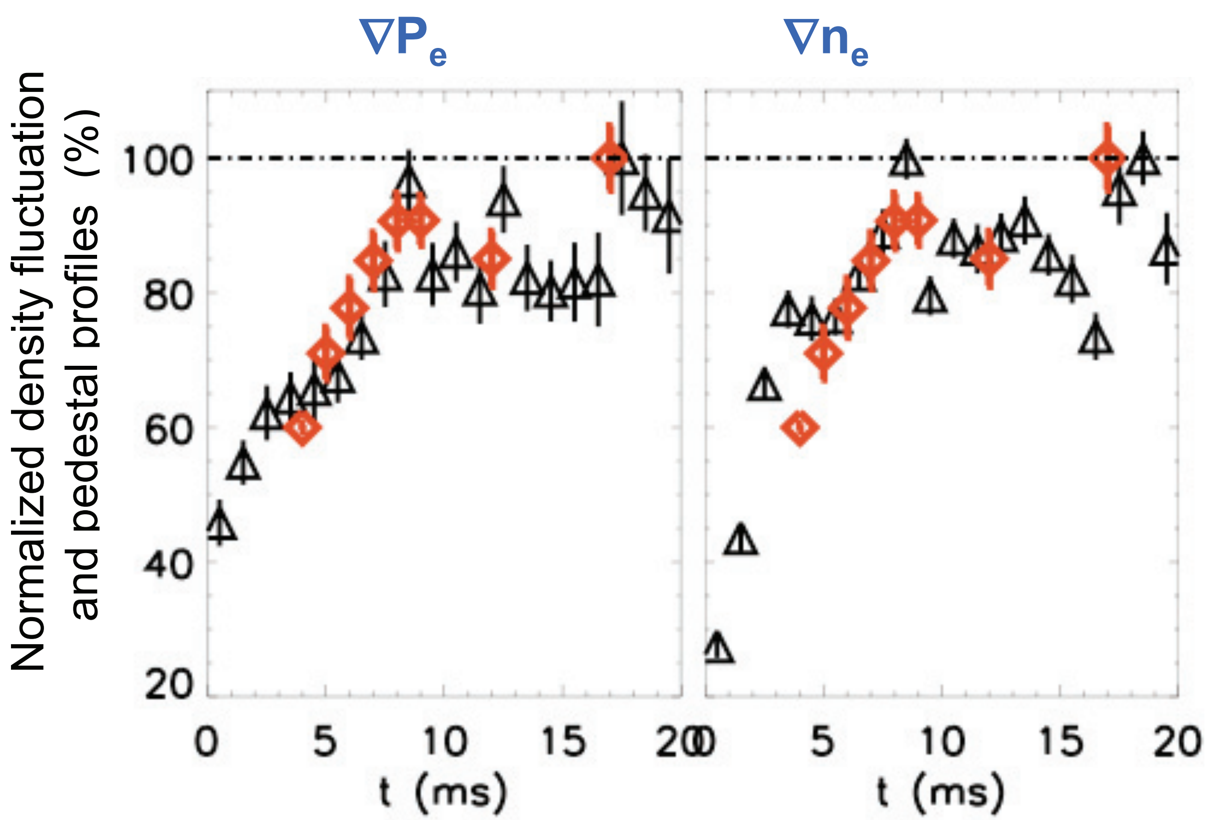
ρ*~0.4%

Δ Normalized pedestal profiles

r/a~0.96

Lower Frequency Band (50 kHz -150 kHz) Fluctuation Dynamics Correlated with Pedestal Pressure and Density Gradient

- **KBM is expected to scale with pressure gradient**



ρ^*~0.4%

◊ $\left.\frac{\tilde{n}}{n}\middle/\frac{\tilde{n}}{n}\right|_{max}$

Δ Normalized pedestal profiles

r/a~0.96

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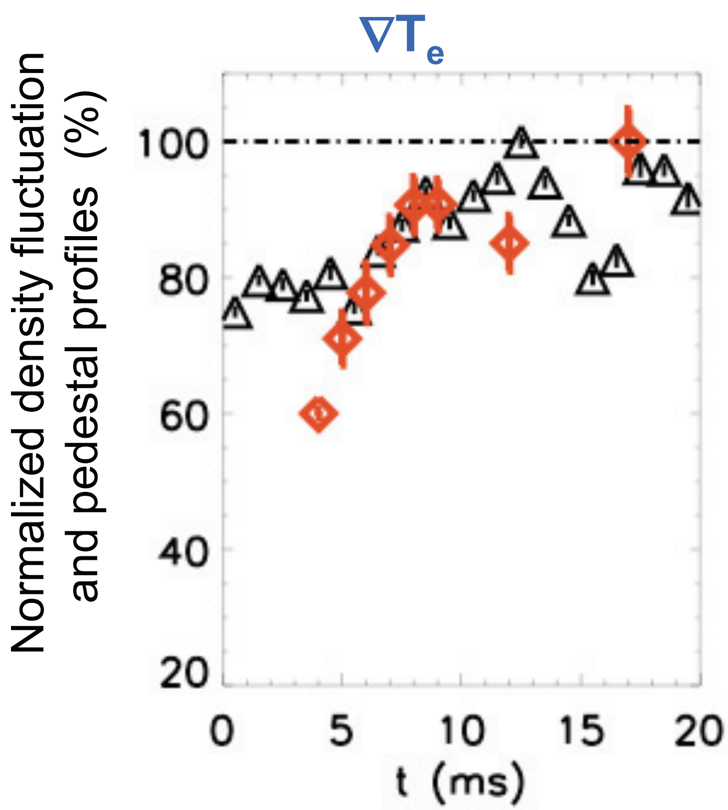


$\rho^* \sim 0.4\%$

◊ $\left.\frac{\tilde{n}}{n} \middle/ \frac{\tilde{n}}{n}\right|_{max}$

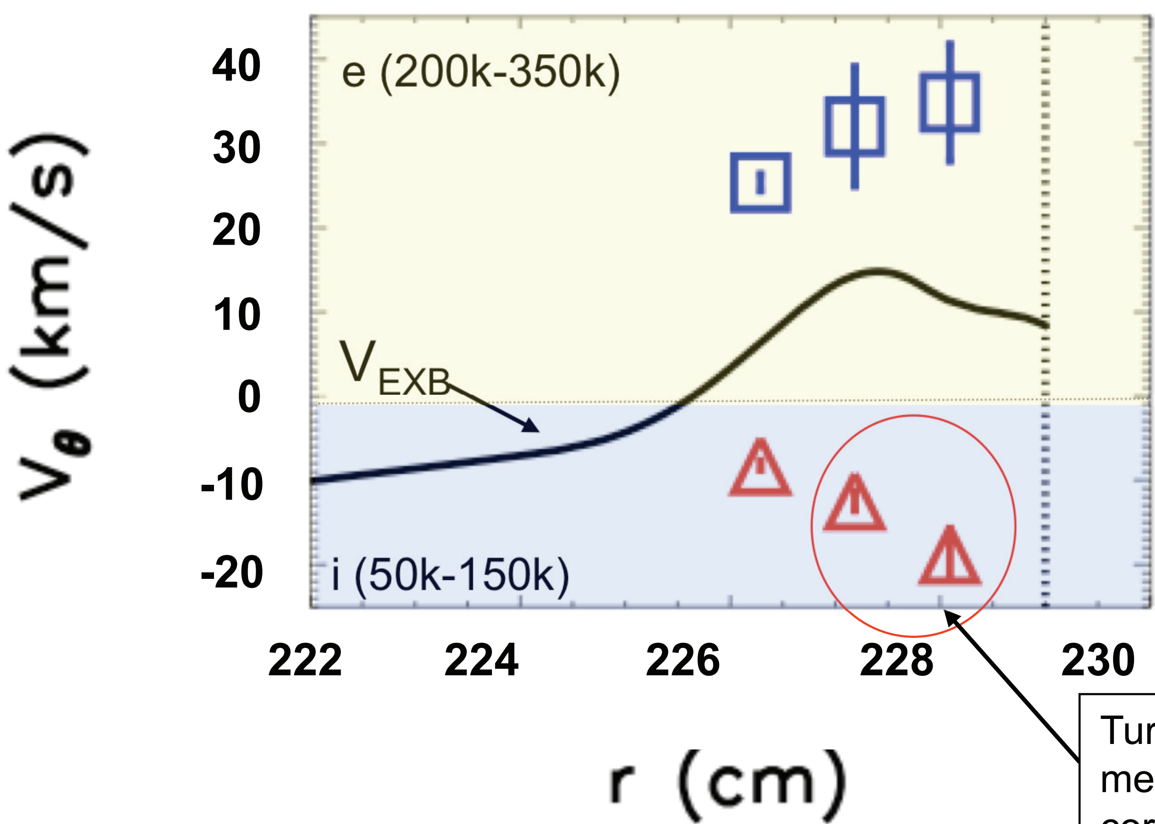
Δ **Normalized pedestal profiles**

r/a~0.96

Not well correlated with electron temperature evolution

Two Modes Propagate in Different Directions in Plasma Frame

- **Dual bands do not individually match EXB velocity**
- **Lower frequency band propagate in the ion diamagnetic direction in the plasma frame - one of the features predicted for KBM**



$\rho^* \sim 0.4\%$

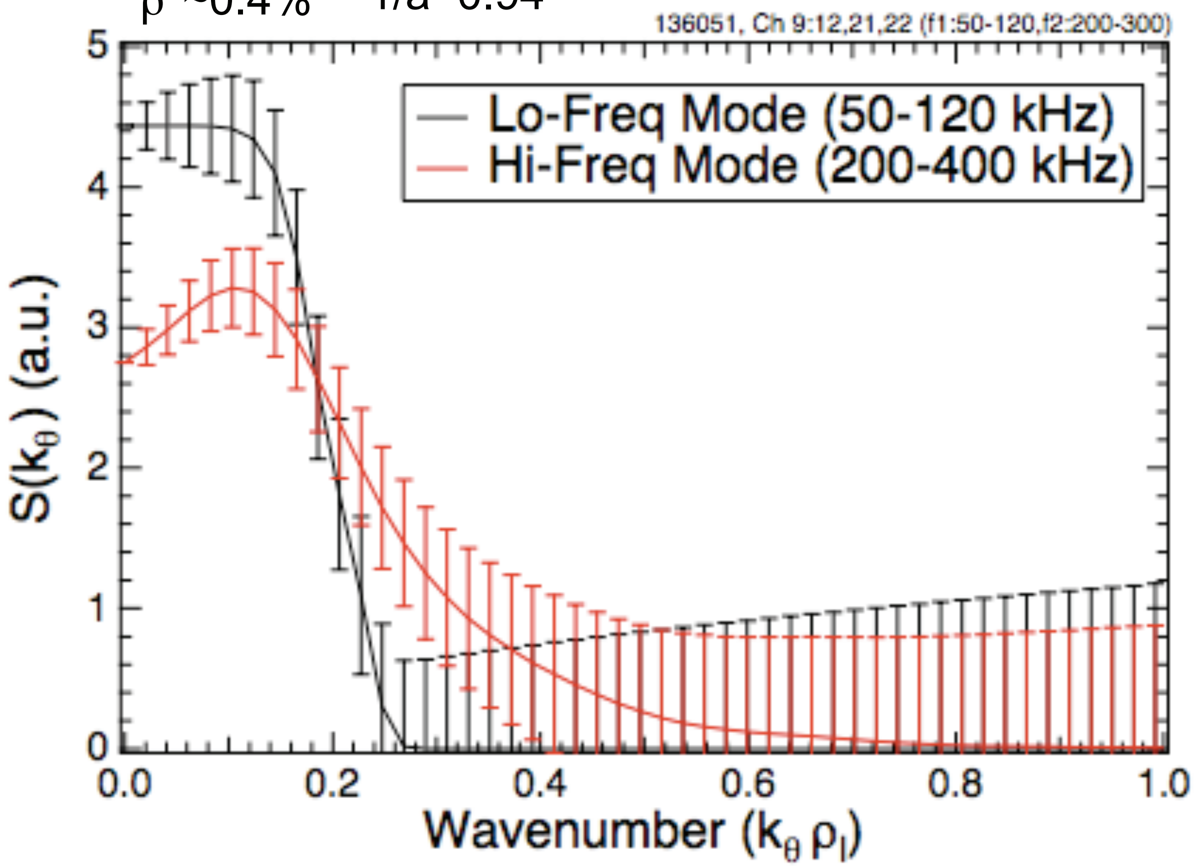
$V_{\theta,turbulence} = V_{EXB} + V_{mode}$
$V_{mode} \sim V_D$

Turbulence velocity V_θ measured by cross correlation time lag

Wave-number Spectrum of Dual Band Structure

- **The higher frequency mode extends to higher k**

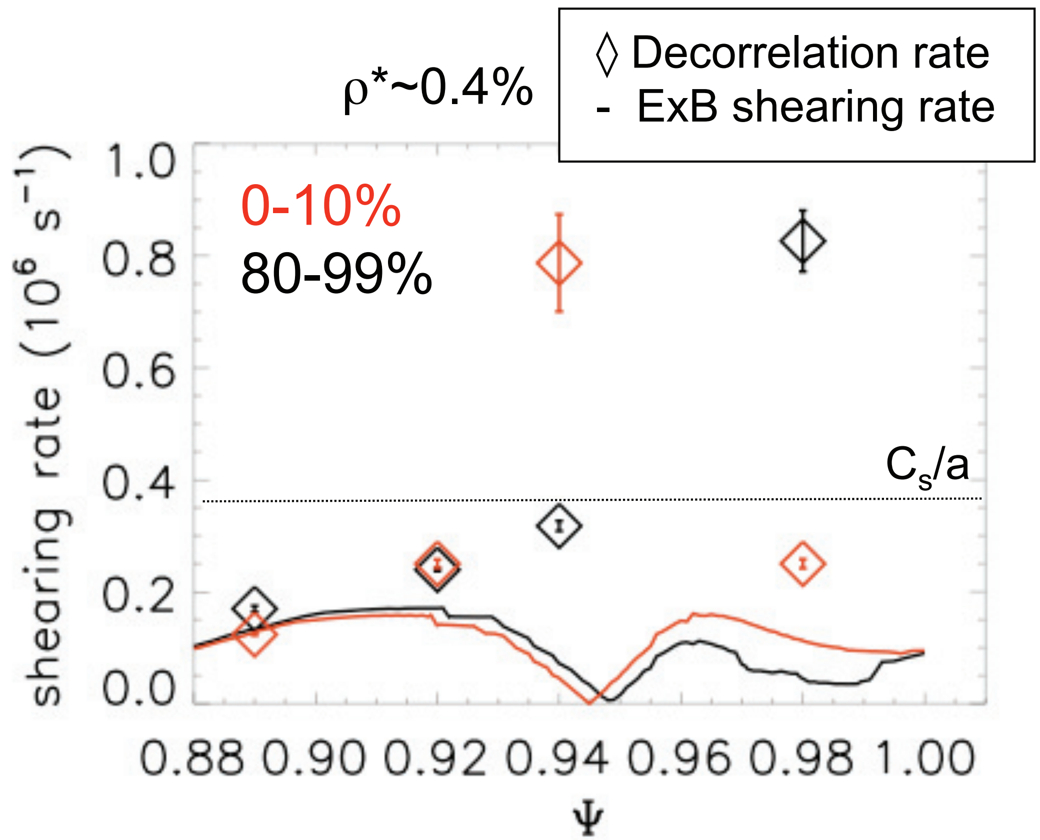
ρ^*~0.4% r/a~0.94



- **Higher frequency band exhibits features of TEM**

Decorrelation Rate Exceeds ExB Shearing Rate

- **Decorrelation rate is larger than the ExB shearing rate**
  - One of the features predicted for KBM
- **Decrease of decorrelation rate at later time, but no change in ExB shear**
  - Suggests turbulence saturation mechanism other than equilibrium ExB shearing rate, eg. zonal flow?
  - Need more sets of data and studies before drawing a conclusion



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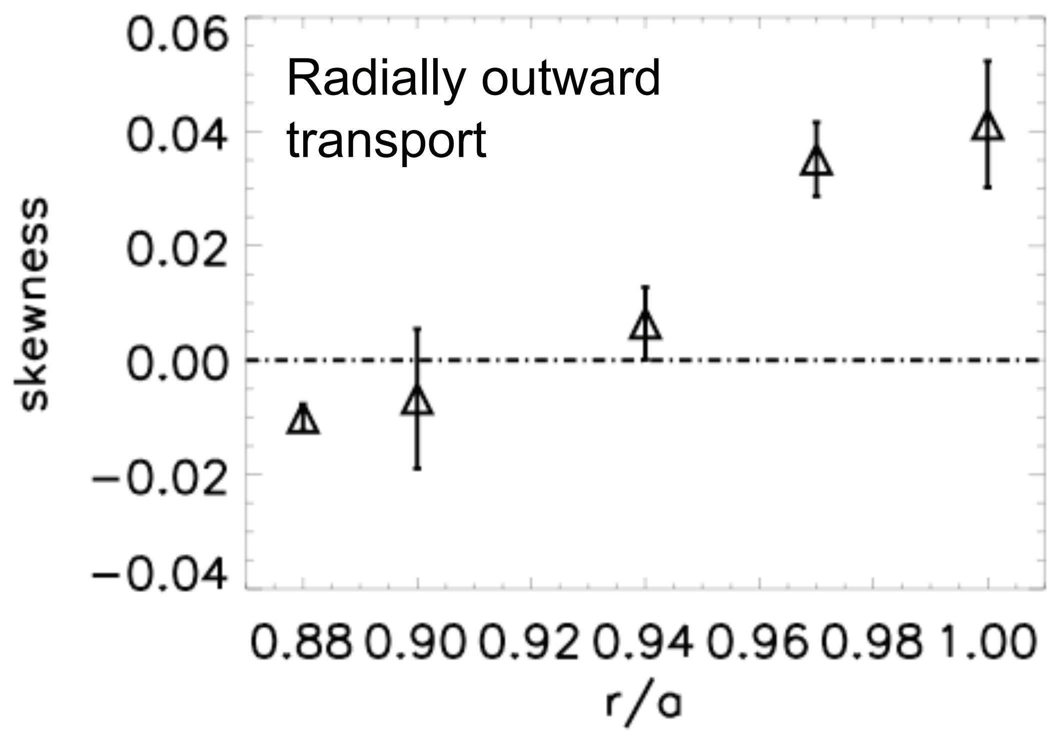
Skewness of Density Fluctuation (50 kHz-150 kHz) Changes Sign across Pedestal

- **Particles transport outwards to SOL**
- **No significant time evolution of skewness during inter-ELM cycle**
- **Contrasts with the increasing turbulence amplitude**



$$S = \overline{\tilde{n}^3} \Big/ \overline{\tilde{n}^2}^{1.5}$$

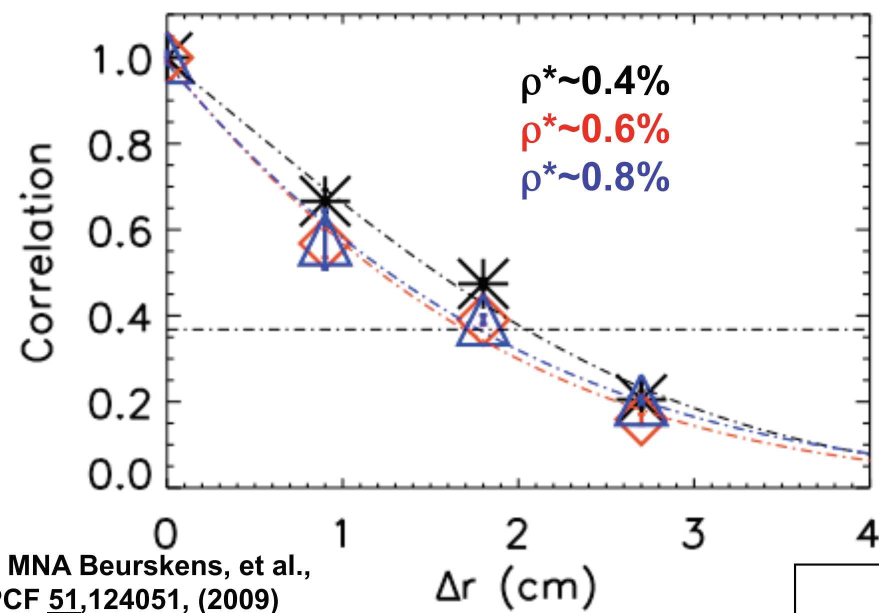
No Dependence of Radial Correlation Length on ρ*

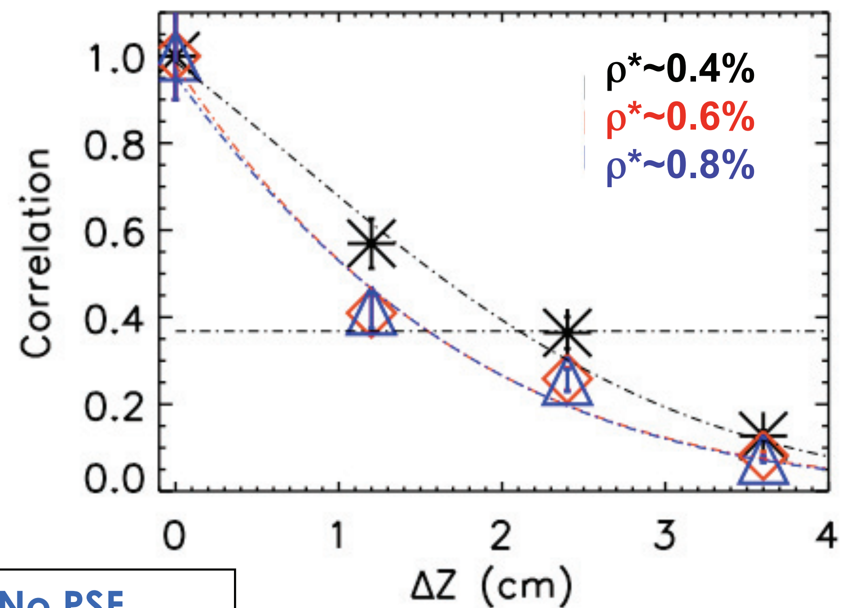
- Radial correlation length for lower frequency band fluctuation (50-150 kHz) exhibits no dependence on ρ*
- Poloidal correlation length has small dependence on ρ*
- Previous analysis showed that the pedestal width has no or weak dependence on ρ* [1]
- Different for core L-mode turbulence for which L_{cr}~ρ*

Radial correlation length

r/a~0.94

Poloidal correlation length





L_r~2cm

No PSF Deconvolution

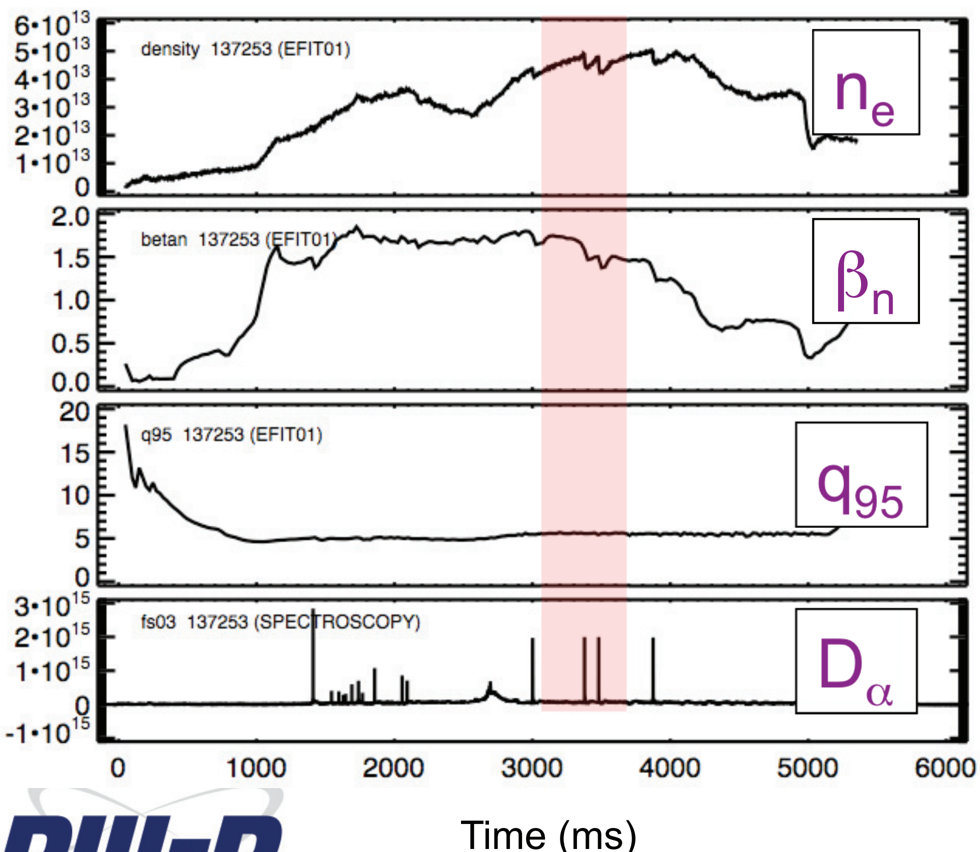
ρ*~0.4% : L_θ~2cm
ρ*~0.6%&0.8% : L_θ~1.5cm

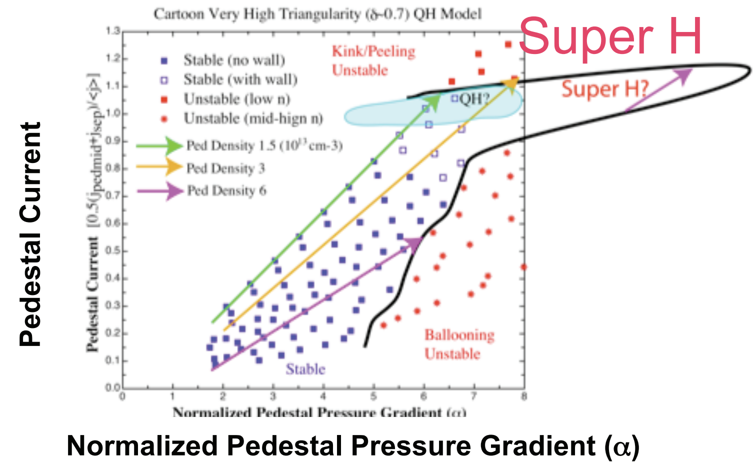
[1] MNA Beurskens, et al., PPCF 51,124051, (2009)

High Frequency Coherent Modes Observed in High-Density ELM-Free QH Plasmas

Edge Electron Pedestal Pressure Rises with Density Increase in QH-mode Plasmas

- **High pedestal pressure may yield high core plasma performance in Q-mode plasmas**
  - ELM-free operation
  - Strongly shaped DND plasma
  - Density increased to achieve higher pressure

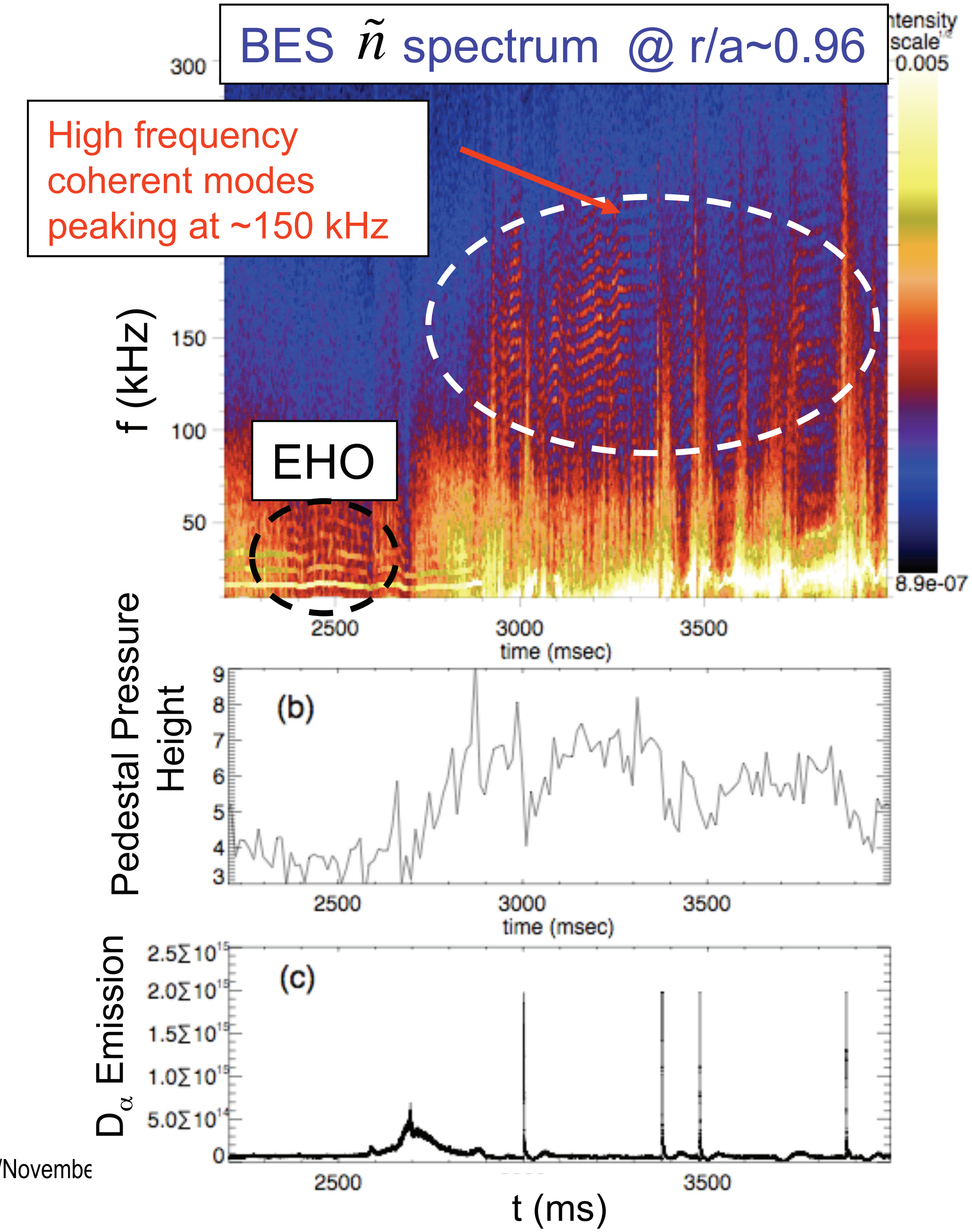




- **B_t = -2 T, I_p=-1.2 MA**
- **X-point geometry changed to increase density**
- **Long ELM-free window**

High Pedestal Pressure QH-mode Discharges Exhibit High Frequency Coherent Modes

- **Several QH shots exhibit high frequency coherent (HFC) modes peaking ~150 kHz**
- **HFC modes appear when Edge Harmonic Oscillation (EHO) disappears**
- **Transition from EHO to HFC occurs as electron pedestal pressure increases**
- **Pedestal pressure saturates when modes appear**
- **4 discrete ELM events occur, widely separated in time. HFC modes disappear at ELMs and rapidly reappear afterwards**
- **EHO: n~1-3 — magnetics**
- **HFC mode: n~10-25 — (inferred from k_θ measurements and comparison with ELITE mode structure)**



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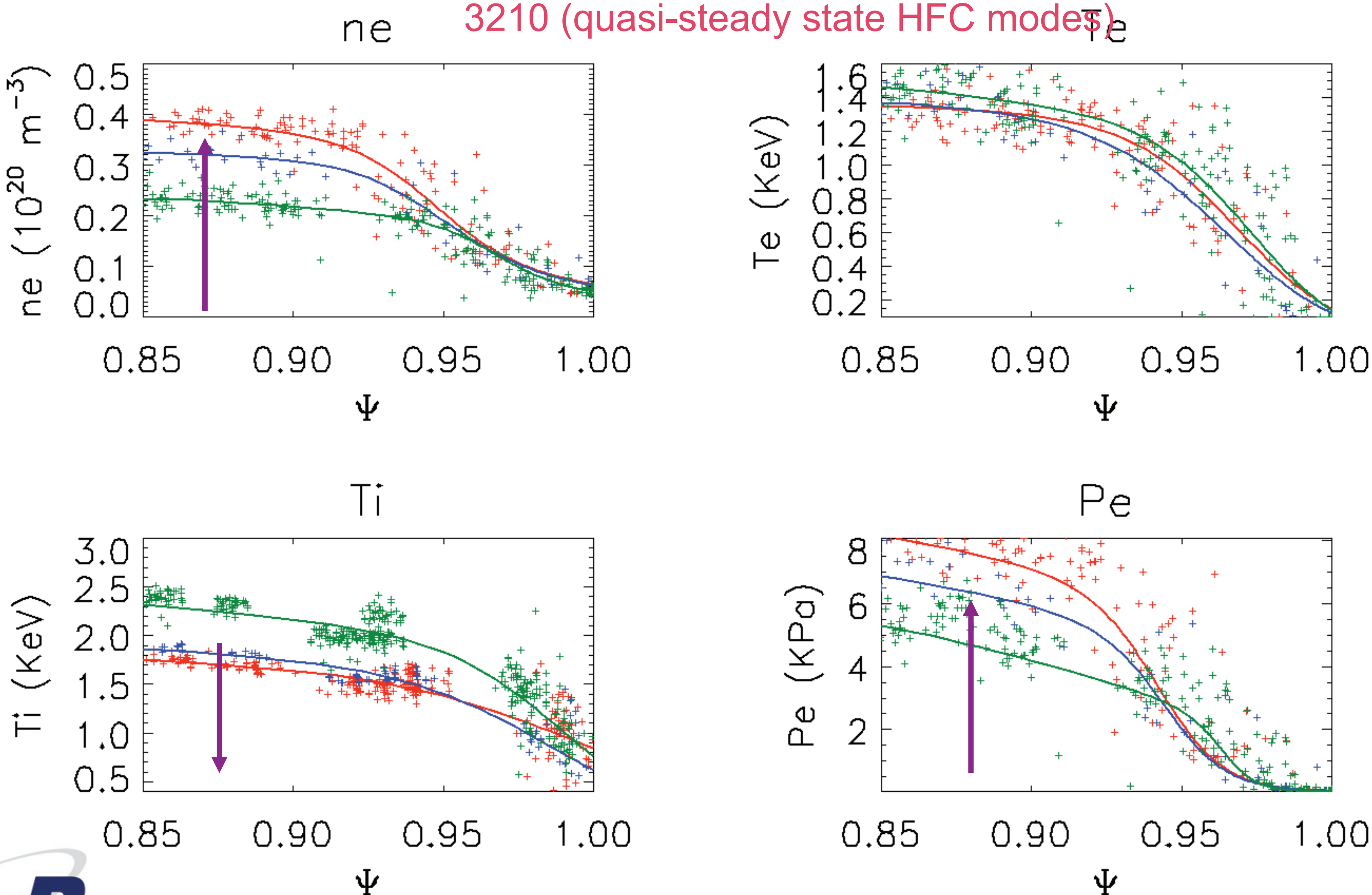
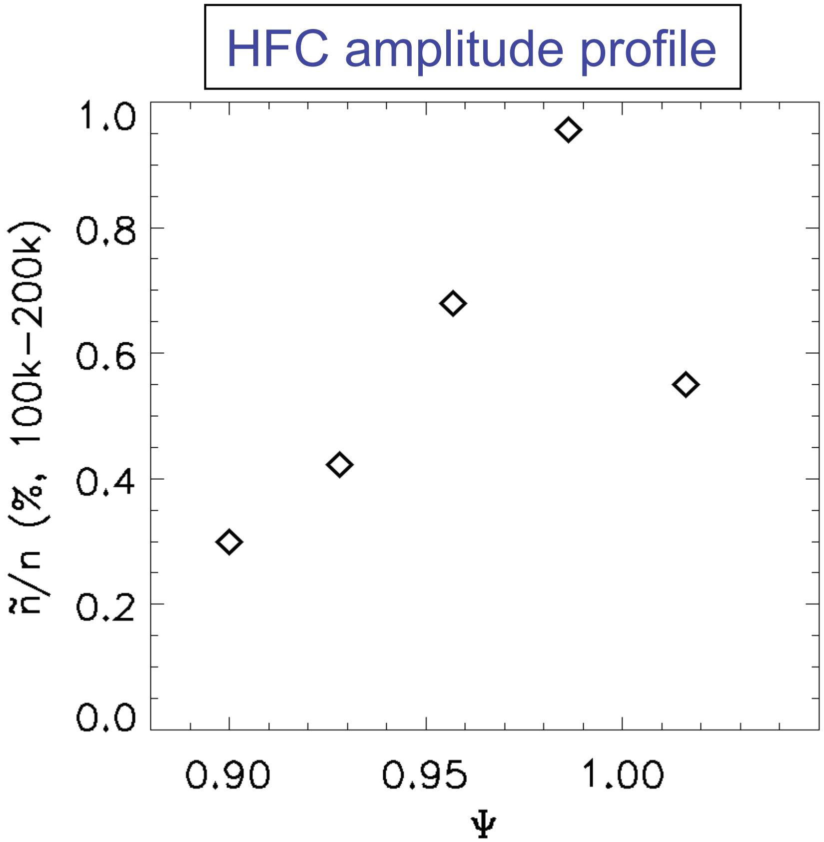
Edge Electron Pedestal Pressure Rises with Density Increase

t = 2400 (standard QH edge pressure: EHO)
2800 (early high pressure)
3210 (quasi-steady state HFC modes)



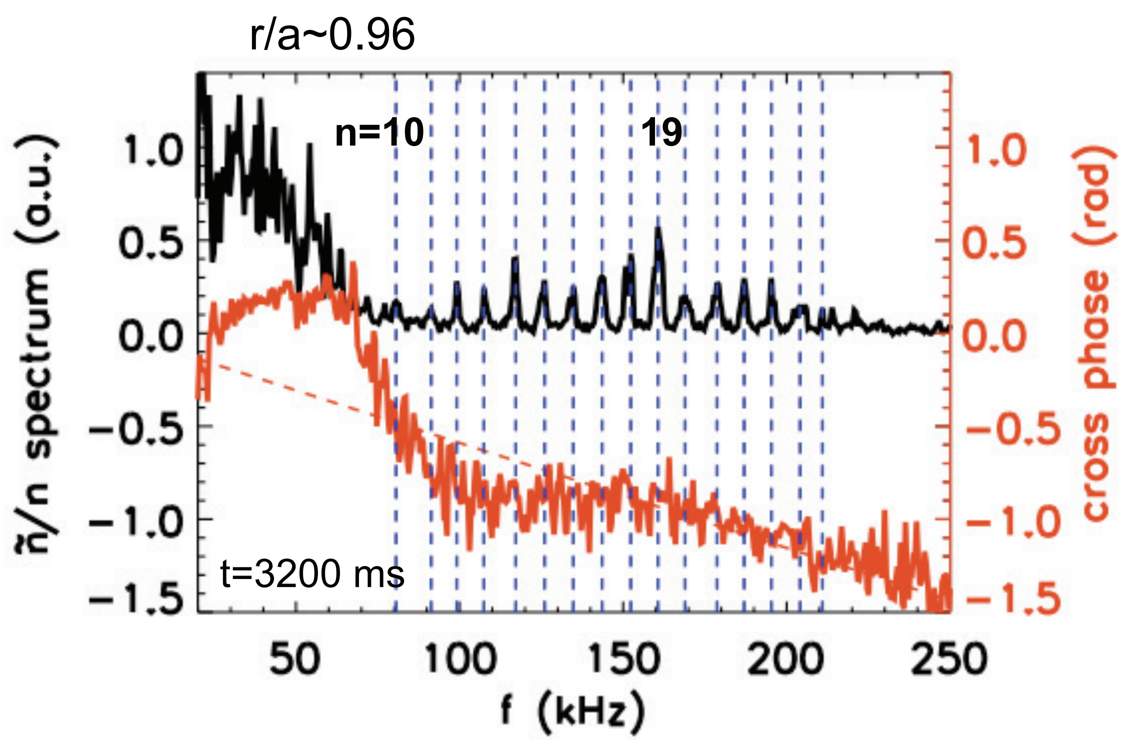
High Frequency Coherent Modes Localized in the Pedestal Region and Peak just inside Separatrix

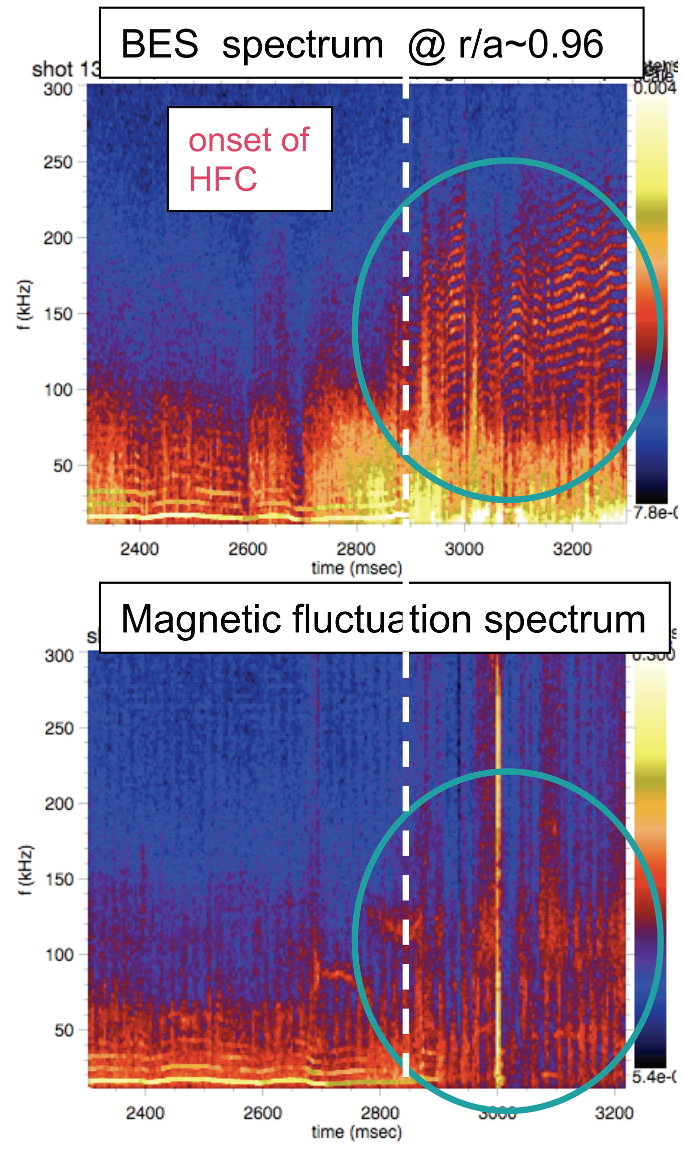
- **Modes not observed deeper in plasma**
  - BES radial array extends from 0.3 < r/a < 0.9
- **Extend from 100-220 kHz, Δf~8 kHz**
- **No measurable phase coherence between individual modes**



High Frequency Coherent Modes: k_θ~0.17-0.4 cm^{-1}

- k_θ~0.17-0.4 cm^{-1} , somewhat lower than ITG mode.
- n~10-25, dominant toroidal mode number n~19
- Not shown in the magnetic probe measurements
  - Needs localized magnetic fluctuation measurements





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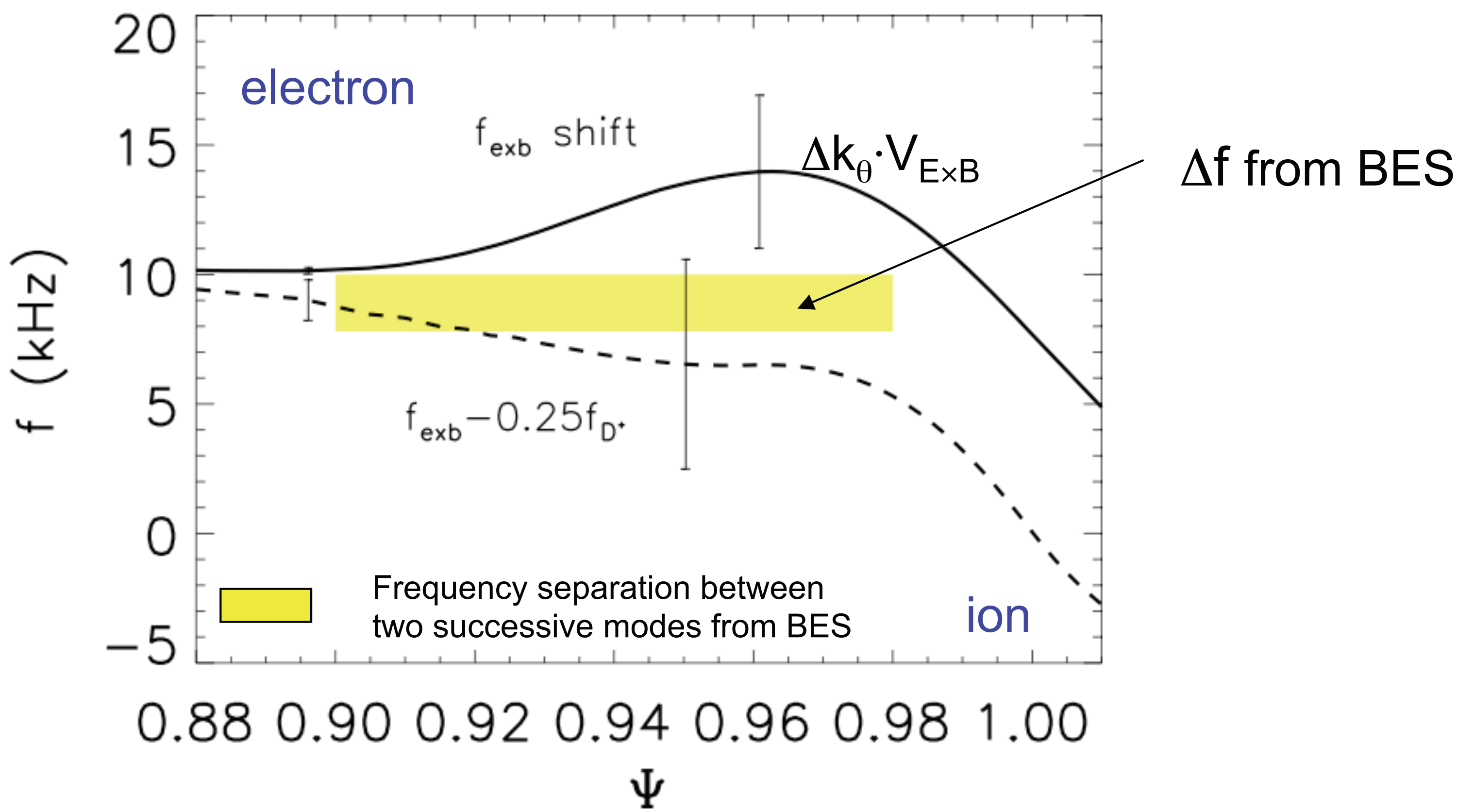
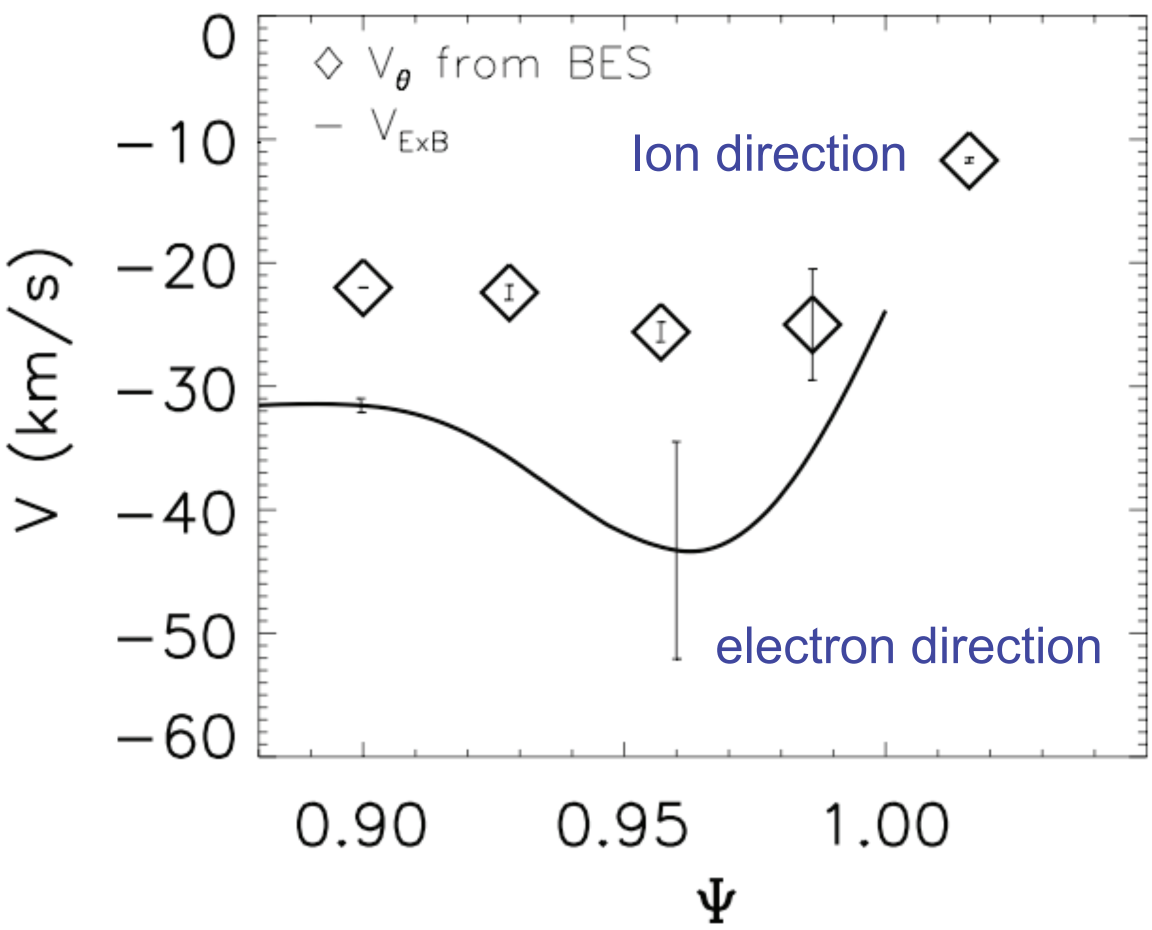
Mode Frequency Consistent with the KBM Predicted Frequency

- **Intrinsic mode frequency ~0.2-0.3 times ion diamagnetic frequency**
- **KBM frequency predicted to be ~0.5 f_{D+}**

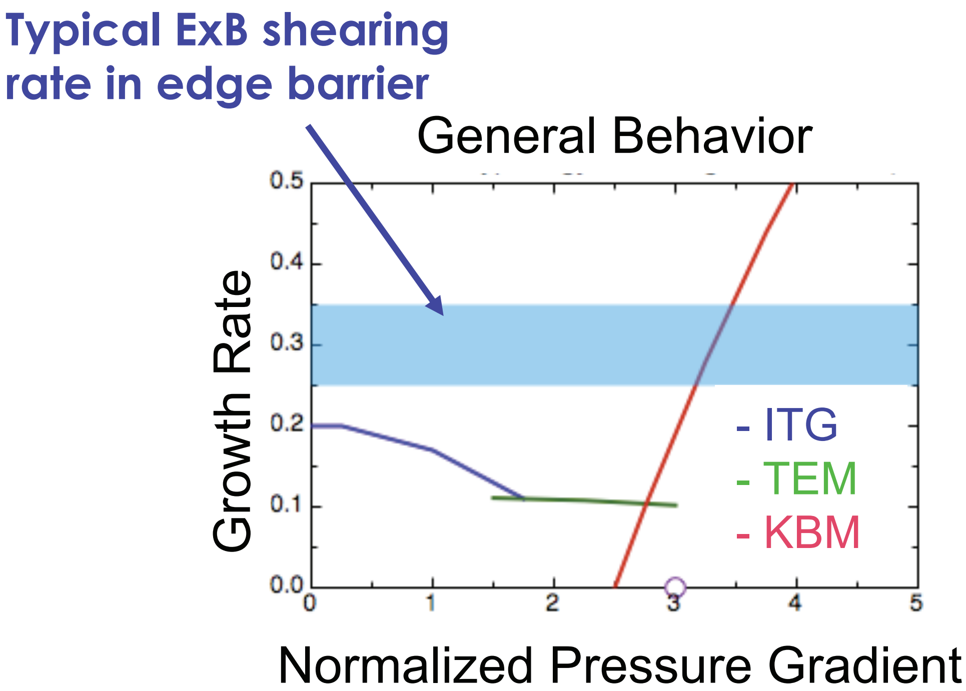


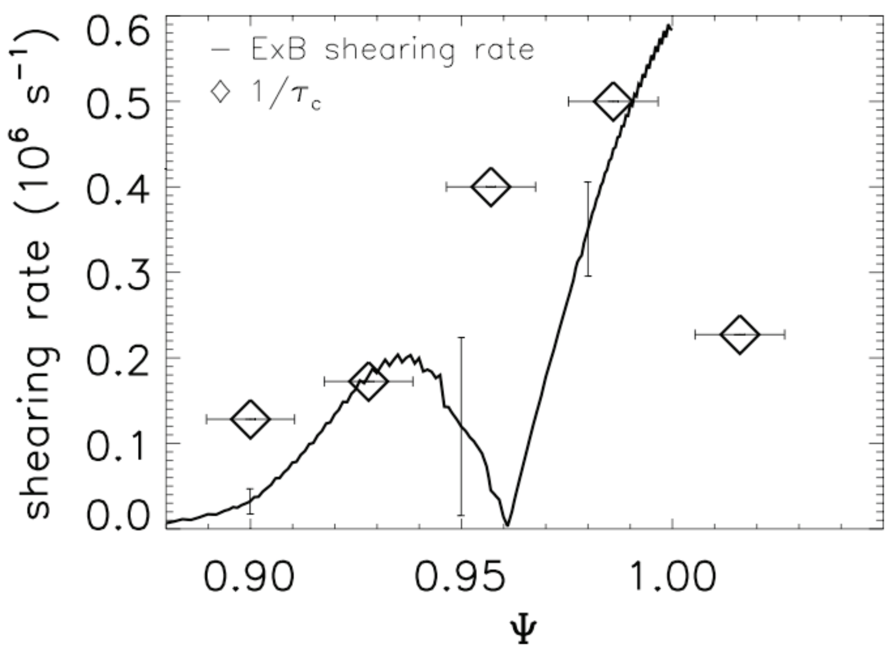
Modes Propagates in Ion Diamagnetic Direction in Plasma Frame



Mode Decorrelation Rate ($1/\tau_c$) Comparable to ExB Shearing Rate in the Edge Barrier

- **High ExB shearing rate expected to quench ITG, TEM**
- **At high pedestal pressure gradient, KBM expected to be driven unstable**
- **HFC $1/\tau_c$ comparable to ExB shearing rate at the edge barrier**
  - Similar regime as KBM: high growth rates can exceed ExB shear and potentially saturate pressure gradients



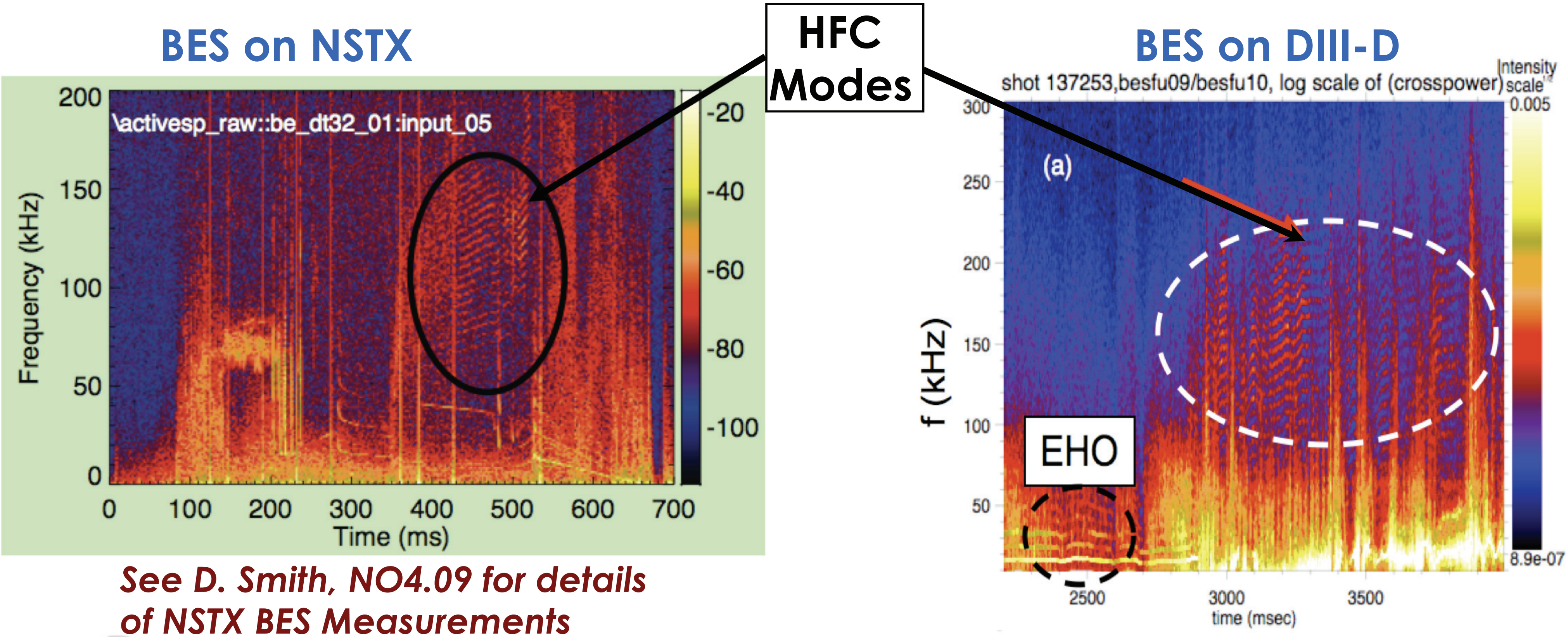


HFC Modes Observed Recently in Pedestal of NSTX Plasmas

- **Similarities to HFC modes observed on DIII-D**

- Multiple highly coherent modes; similar frequency range
- Localized to pedestal region (r/a~0.95)
- Not observed in magnetic spectrum

- **Suggests a universality to underlying pedestal instability**



See D. Smith, NO4.09 for details of NSTX BES Measurements

Summary

- **Long wavelength density fluctuations in two different experimental regimes are characterized and show KBM-like features**
- **Dual-band broadband turbulence in ELMing H-mode plasmas**
  - Modes propagate in opposite poloidal direction in plasma frame
  - Lower frequency band (50-150 kHz) dynamics correlated with pedestal electron pressure and density gradient time evolution during inter-ELM cycle
  - Lower frequency band exhibits several KBM-like features: propagating in the ion diamagnetic direction in the plasma frame; decorrelation rate exceeding E×B shearing rate
- **High Frequency Coherent Modes (HFC) in ELM-free QH-mode plasma**
  - Localized in pedestal
  - KBM like features: mode frequency close to 0.2-0.3 ion diamagnetic frequency; propagating in the ion diamagnetic direction in the plasma frame; mode decorrelation rate exceeding EB shearing rate; medium-n structure (n=10-25)
- **The experimental observation of the pedestal turbulence properties shows a qualitative correlation with the KBM-like features: However, to obtain a definitive comparison, nonlinear simulations are required and being developed to assess nature and identification of modes**