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 $\rho^*$

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
Scan Experiment to Study Pedestal Fluctuation Characteristics

- \( \rho^* \) is scanned by a factor of \( \sim 2 \) while keeping \( \beta, q, \nu^*, M \) and \( T_i/T_e \) constant at the pedestal top

Low triangularity ELMing H-mode

5x6 2D BES array

BES

\( B_t = 2.1T, 1.37T & 1.0T \)
Phase-lock Averaging Used to Study Dynamics at Different Times During inter-ELM Cycle

- Fluctuation characteristics averaged over hundreds of ELM cycles

BES 2D array spans $0.88 < r/a < 1.0$

$B_t = -2.1T$
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 $\rho^* \sim 0.4\%$ density fluctuations saturate within $<10$ ms
- Higher frequency band fluctuation does not change with time

$\rho^* \sim 0.4\%$

$r/a \sim 0.94$
Lower Frequency Band (50 kHz - 150 kHz) Fluctuation Dynamics Correlated with Pedestal Pressure and Density Gradient

Normalized density fluctuation and pedestal profiles (%)

\[ \nabla P_e \]

\[ \nabla n_e \]

\[ \rho^* \approx 0.4\% \]

\[ \nabla \text{Normalized pedestal profiles} \]

\[ r/a \approx 0.96 \]
Lower Frequency Band (50 kHz - 150 kHz) Fluctuation Dynamics Correlated with Pedestal Pressure and Density Gradient

- KBM is expected to scale with pressure gradient

\[ \rho^* \approx 0.4\% \]

\[ \frac{\tilde{n}}{n_{\text{max}}} \]

\[ \Delta \text{Normalized pedestal profiles} \]

\[ r/a \approx 0.96 \]
Lower Frequency Band (50 kHz -150 kHz) Fluctuation Dynamics Correlated with Pedestal Pressure and Density Gradient

- KBM is expected to scale with pressure gradient

\[ \rho^* \sim 0.4\% \]

\[ \frac{\tilde{n}}{n_{\max}} \]

\[ \nabla T_e \]

Normalized density fluctuation and pedestal profiles (%)

Not well correlated with electron temperature evolution

\[ r/a \sim 0.96 \]

Normalized pedestal profiles

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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

\[ V_{\theta, turbulence} = V_{EXB} + V_{mode} \]

\[ V_{mode} \approx V_D \]

Turbulence velocity \( V_\theta \) measured by cross correlation time lag

\( \rho^* \approx 0.4\% \)
The higher frequency mode extends to higher $k$

$\rho^* \sim 0.4\% \quad r/a \sim 0.94$

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

\[ \rho^* \approx 0.4\% \]

\[ 0-10\% \quad 80-99\% \]
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

\[ S = \frac{\tilde{n}^3}{\bar{n}^{2.5}} \]
No Dependence of Radial Correlation Length on $\rho^*$

- Radial correlation length for lower frequency band fluctuation (50-150 kHz) exhibits no dependence on $\rho^*$
- Poloidal correlation length has small dependence on $\rho^*$
- Previous analysis showed that the pedestal width has no or weak dependence on $\rho^*$ [1]
- Different for core L-mode turbulence for which $L_c^r \sim \rho^*$

\[ L_r \sim 2 \text{cm} \]

\[ r/a \sim 0.94 \]

**Radial correlation length**

\[ \rho^* \sim 0.4\% \]
\[ \rho^* \sim 0.6\% \]
\[ \rho^* \sim 0.8\% \]

**Poloidal correlation length**

\[ \rho^* \sim 0.4\% \]
\[ \rho^* \sim 0.6\% \]
\[ \rho^* \sim 0.8\% \]

No PSF Deconvolution

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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

- $B_\tau = -2$ 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 $k_\theta$ measurements and comparison with ELITE mode structure)
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, $\Delta f \sim 8$ kHz
- No measurable phase coherence between individual modes

![HFC amplitude profile](image.png)
High Frequency Coherent Modes: \( k_\theta \approx 0.17-0.4 \text{ cm}^{-1} \)

- \( k_\theta \approx 0.17-0.4 \text{ cm}^{-1} \), somewhat lower than ITG mode.
- \( n \approx 10-25 \), dominant toroidal mode number \( n \approx 19 \)
- Not shown in the magnetic probe measurements
  - Needs localized magnetic fluctuation measurements

\[ r/a \approx 0.96 \]

BES spectrum @ \( r/a \approx 0.96 \)

Magnetic fluctuation spectrum
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

\[ V \text{ (km/s)} \]

\[ \Psi \]

\[ V_{\theta} \text{ from BES} \]

\[ V_{\text{ExB}} \text{ Ion direction} \]

\[ \text{electron direction} \]
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

Typical ExB shearing rate in edge barrier

General Behavior

![Diagram showing General Behavior](image)

![Diagram showing Typical ExB shearing rate](image)
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 ExB 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