Fluctuation Analysis Techniques for Detection of Zonal Flow Features in the DIII-D Tokamak

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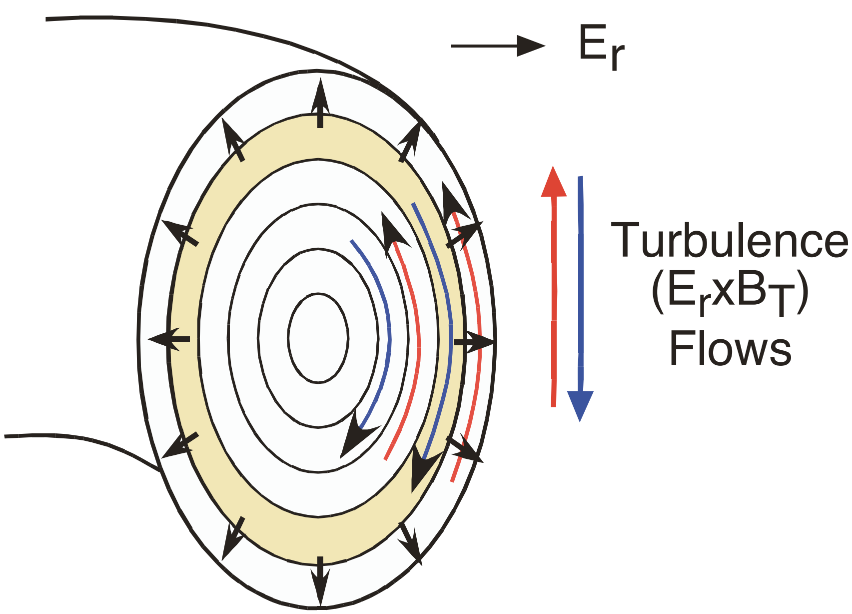
The University of Wisconsin Madison

DIII-D National Fusion Facility San Diego

Self-Regulating Zonal Flows Thought Crucial to Mediating Fully Saturated State

- Predicted theoretically to regulate turbulence through time-varying $E_r x B_T$ (v_θ) flows
  - observed in simulations of core and edge turbulence
- n=0, m=0, radially-localized electrostatic potential structures (linearly stable). Zonal flows have two dominant branches:
  - Low-frequency residual (Rosenbluth-Hinton) mode (f < 10 kHz)
  - Higher-frequency Geodesic Acoustic Mode (10-200 kHz)

  $\tilde{n}/n|_{ZF} << e\tilde{\phi}/T_e|_{ZF}$



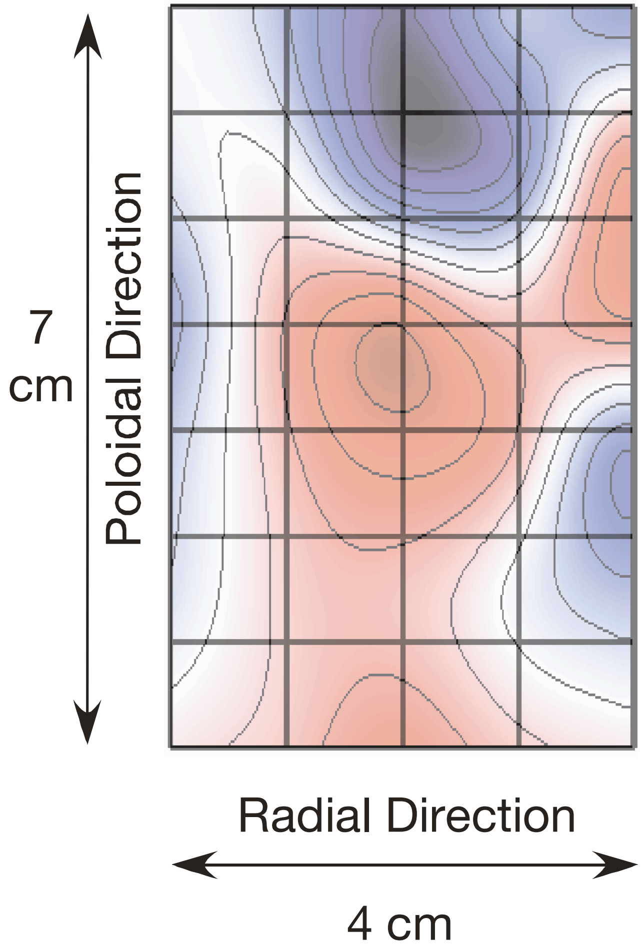
(tokamak cross-section)

Present Work:

- *Look directly at the turbulence flow field to experimentally observe such flows.*
- *Apply time-delay estimation techniques to density turbulence: measure $v_\theta(t)$*
- *Observe coherent structures in $v_\theta(t)$ with many of predicted properties: GAMs*

Time-Varying Turbulence Flows Measured via 2D Density Fluctuation Measurements with BES

Turbulence imaged with discrete channels deployed on 2D grid



Time Delay Estimation between poloidally-adjacent channels:

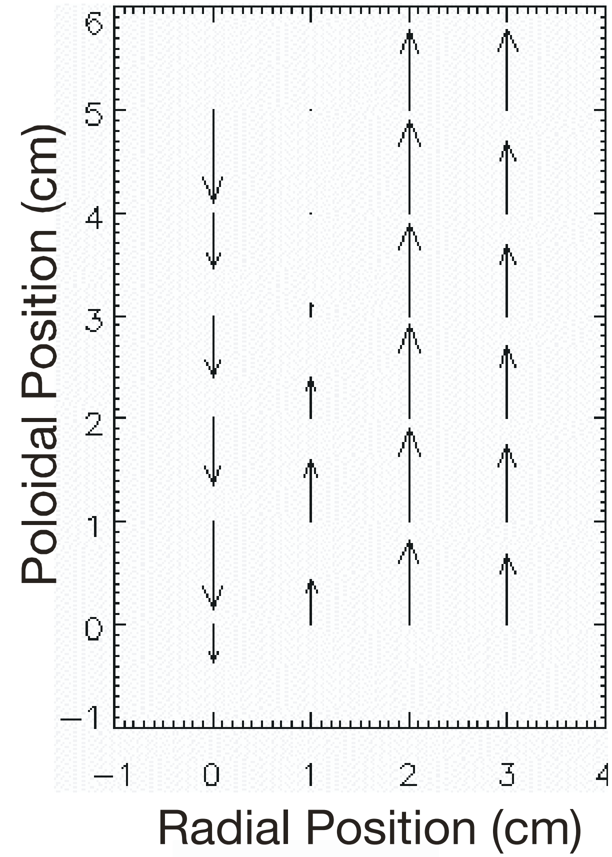
1) Wavelet-based cross-phase (□□(t))

2) Time-resolved cross-correlation (□$_{□,max}$(t))

v$_□$(t)

on relevant time scale (0 < f < 200 kHz)

Snapshot of time-dependent turbulence poloidal flow-field:



Spectral and spatial analysis of v$_□$ to search for flow features

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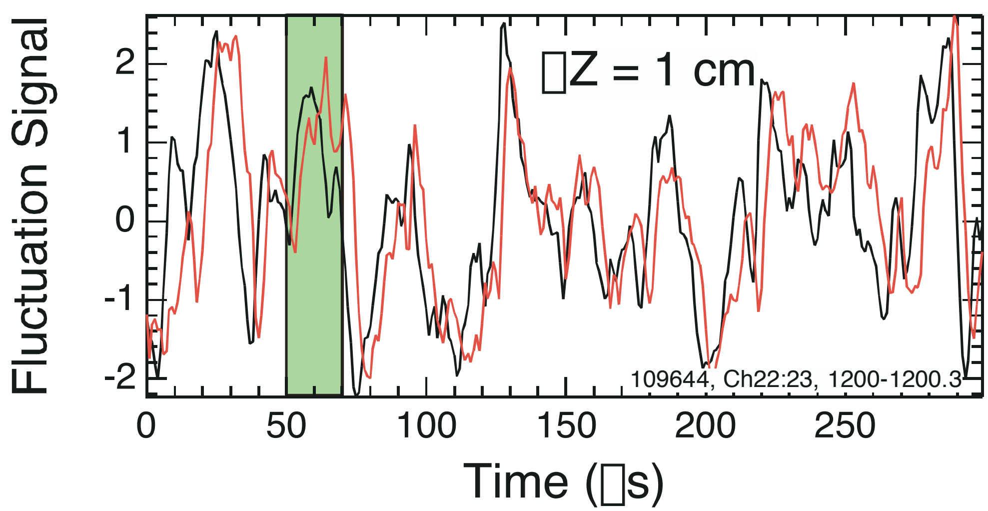
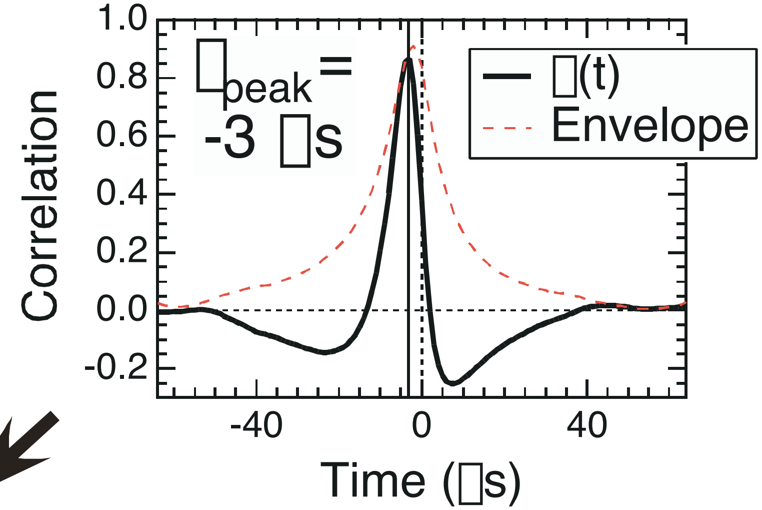
Time-Resolved Cross-Correlation to Perform Time-Delay-Estimation Analysis

- Map poloidal displacement of density eddies

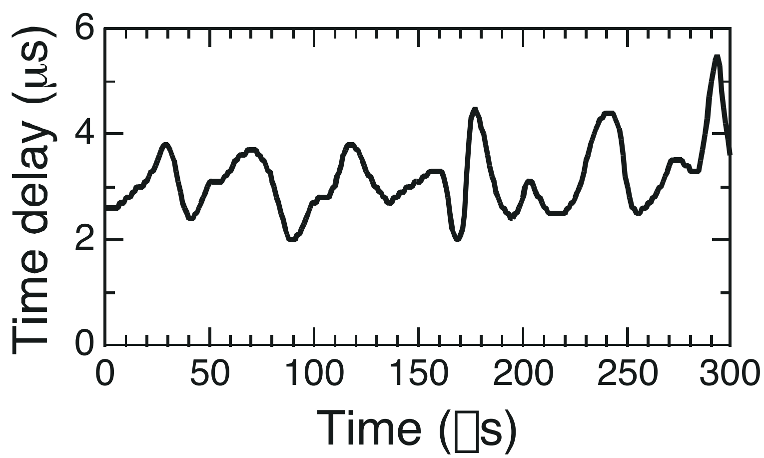
Raw data: Poloidally separated Channels



Time-lag Correlation



Calculated Time-resolved time-delay



$v_\theta(t) = \Delta Z / \Delta\tau(t)$

for $\Delta\tau < \tau_{correlation}$

Wavelet Time-Delay-Estimation Analysis Provides High Frequency Response

Wavelet-based Cross-Correlation yields temporally and frequency-resolved analysis

Complex Wavelet Transform

$$W(a,\tau) = \int_{-\infty}^{+\infty} f(t)\,\psi_{a\tau}^{*}\,dt,$$

$$\psi(t) = e^{i\omega_o t} e^{-t^2/2}$$

Cross Scale-o-gram

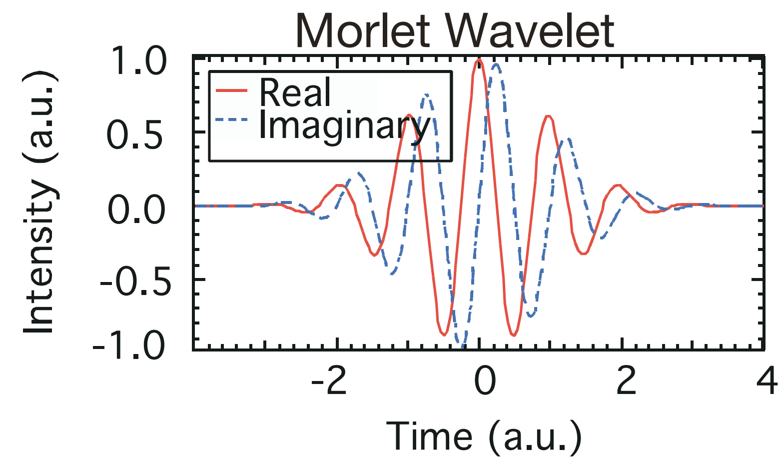
$$W_{ab}(f,\tau) = W_a^{*}(f,\tau)\,W_b(f,\tau)$$

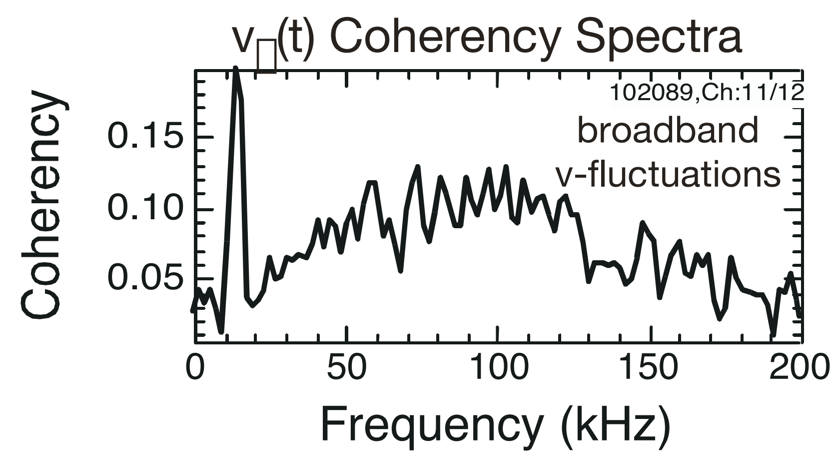
Time-dependent cross phase

$$\phi(f,\tau) = \tan^{-1}\left[\frac{im(W(f,\tau))}{re(W(f,\tau))}\right]$$

Time-dependent time-delay

$$\tilde{\tau}(t) = \Delta\phi_f(t)/2\pi f$$





- Three TDE methods yield equivalent results
  - *Wavelet correlation: high frequency response*
  - *Time-shift maximum overlap: improved S/N (low-f)*
  - *Cross-correlation: maximum S/N @ low-f*
- Cross-correlation used for most data presented here

M. Jakubowski, Ph.D Thesis

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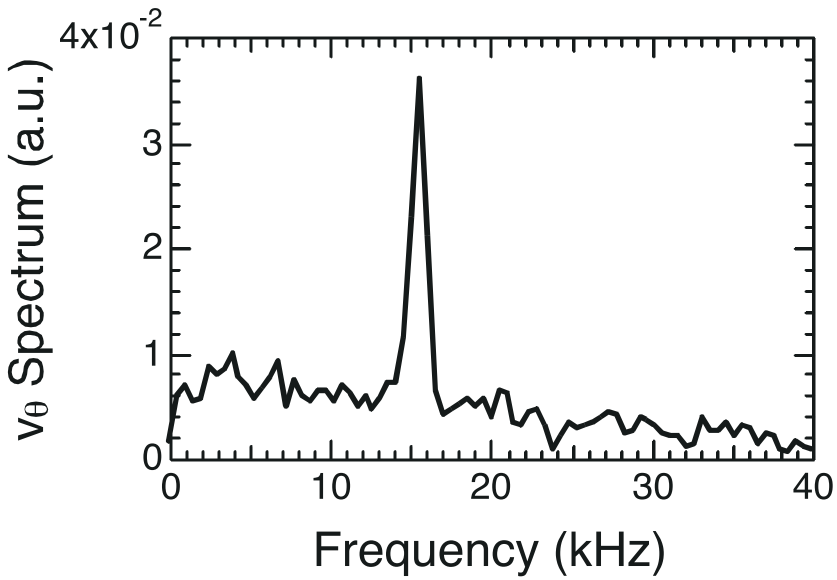
Coherent v_θ Feature Observed: Exhibits Poloidally Extended, Radially Localized Structure

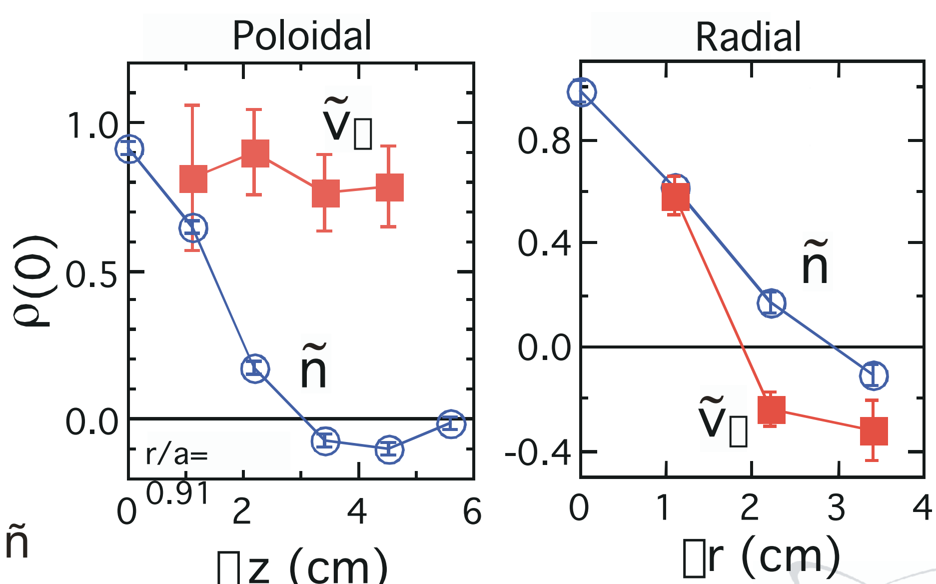
- Measurements obtained in outer region (0.85 < r/a < 1.0) of L-mode discharge



- Spectrum exhibits nearly coherent feature near 15 kHz on top of broadband weak velocity turbulence
- Not associated with any MHD activity

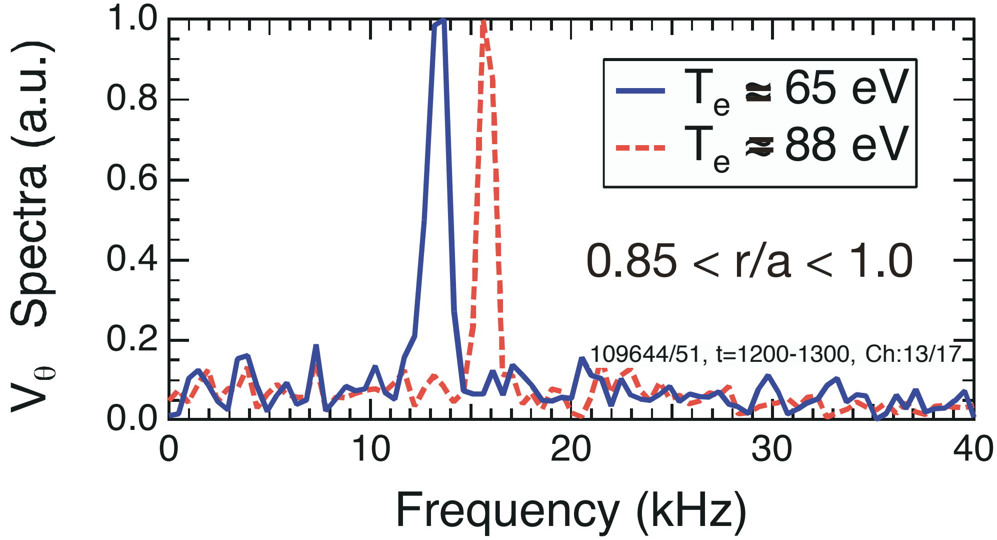
Correlation properties of v_θ feature:

- **Poloidal**
  - Extended, unlike decaying ñ
  - ~ no measurable phase shift, (m ≤ 2, consistent with m=0)
- **Radial**
  - Scale is length comparable to ñ
  - Radially, 180° shift over ~3 cm



Coherent V$_\theta$ Feature Observed:
Frequency Scales with Local Temperature

- Semi-coherent feature near 14 kHz on broadband weak velocity turbulence



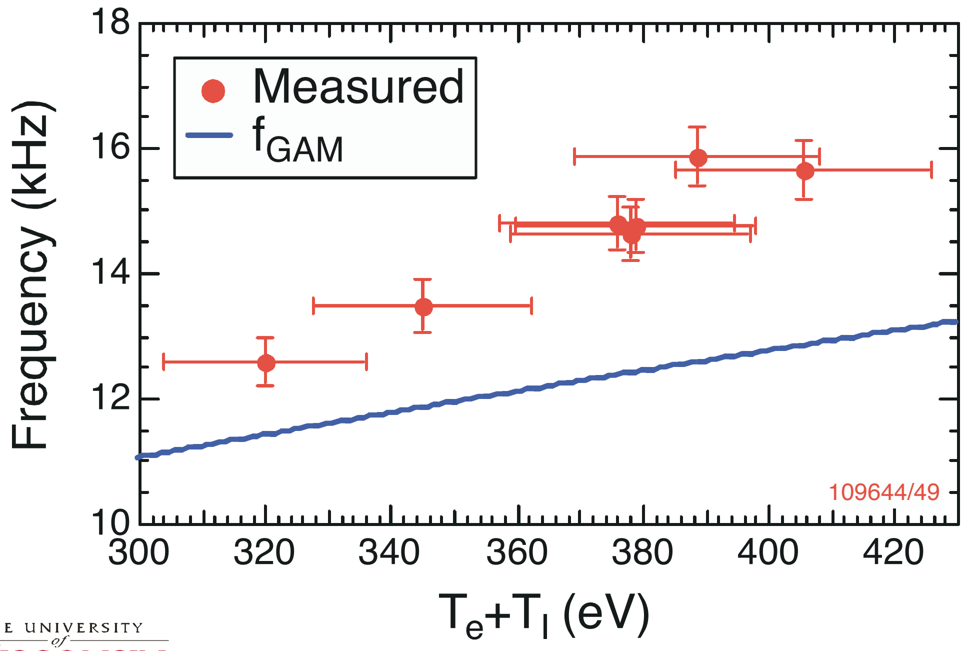
- Mode frequency increases with edge T_e:

  - suggests oscillation is a *Geodesic Acoustic Mode:*

    $f_{GAM} = c_s/2\pi R = 12$ kHz

$$c_s = \sqrt{(T_e + T_I)/M_I}$$

($T_I \sim 240$ eV, R = 1.73 m)



- Average frequency of mode scales with local T_e+T_I

- Not associated with any MHD activity

K. Hallatchek, D. Biskamp, Phys. Rev. Lett. ***86****, 1223 (2001), Fig. 1(a)*

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Effective Shearing Rate of v_θ Oscillation Can Affect Turbulence

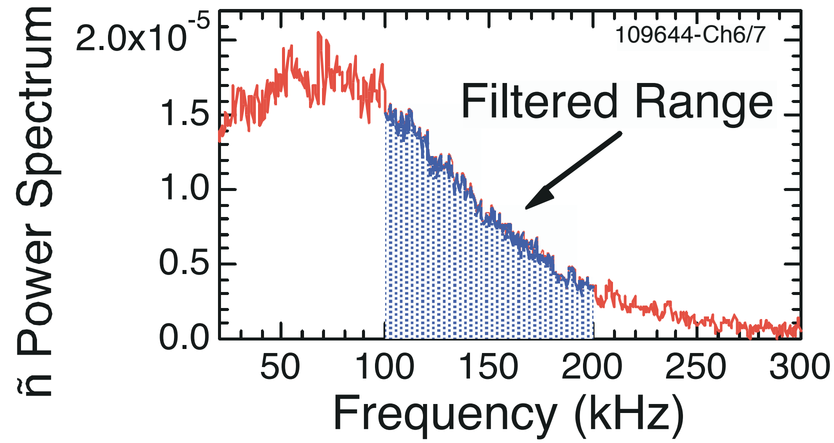
- Approximate RMS magnitude of oscillation: $\tilde{v}_\theta \approx 500\mathrm{m}/\mathrm{s}$
- Estimate shearing rate: $\omega_s \approx \dfrac{d\tilde{v}_\theta}{dr} \approx \dfrac{2(500m/s)}{0.03m} = 0.3\times10^5\ s^{-1}$
- Measured turbulence decorrelation rate: $\Delta\omega \sim 1/\tau_c \sim 1\mathrm{x}10^5\ \mathrm{s}^{-1}$
- Comparison: $\omega_s|_{\text{“GAM”}} < \Delta\omega$, but values are comparable

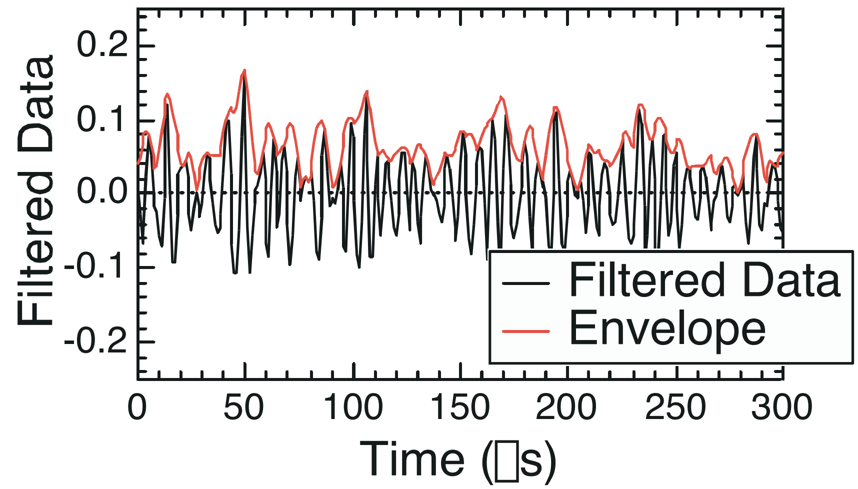
Oscillation can affect turbulence and reduce amplitude

V□ Oscillation Modulates Turbulence Amplitude

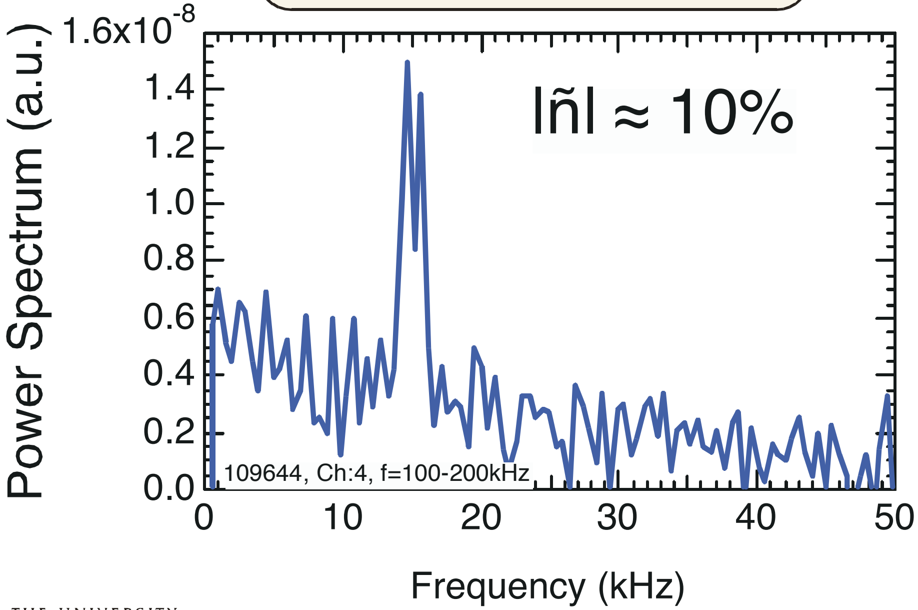
- Density fluctuations frequency-filtered: 100 < f < 200 kHz (f >> v□)

- Amplitude envelope power spectrum shows peak at coherent feature frequency





Power Spectrum of Fluctuation Amplitude



- Suggests energy exchange between waves/fluctuations and GAM flow

(Diamond et al., Nuclear Fusion 2002)

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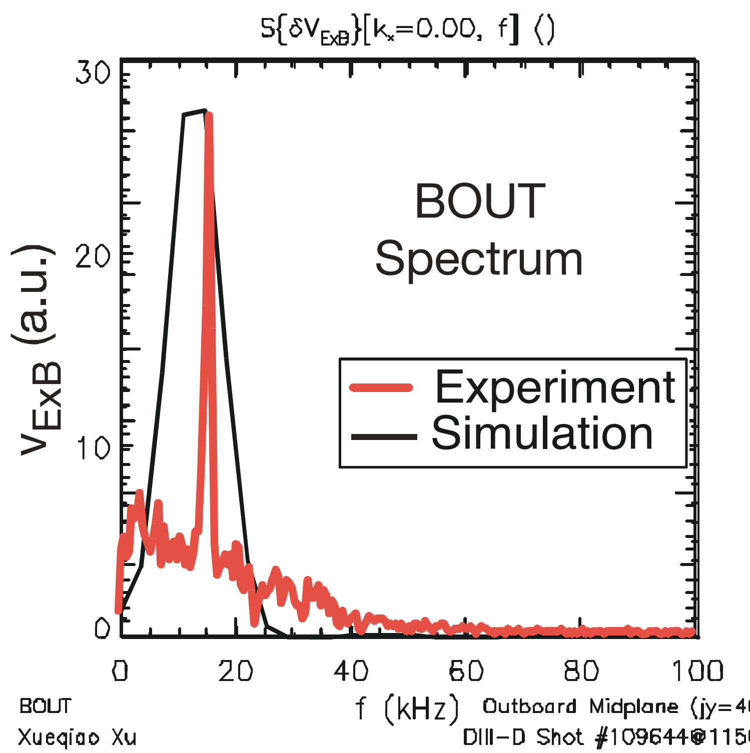
BOUT Simulation Exhibits Geodesic Acoustic Mode at Similar Frequency to Measured V□ Oscillation

- BOUT models boundary-plasma turbulence with Braginskii equations in realistic geometry
- Simulation performed with experimental edge profiles from these discharges
- Coherent GAM observed in simulation as m=0, localized potential fluctuation

GAM oscillation in BOUT at very similar frequency to measured flow oscillation

(BOUT frequency resolution limited by finite computational time window)



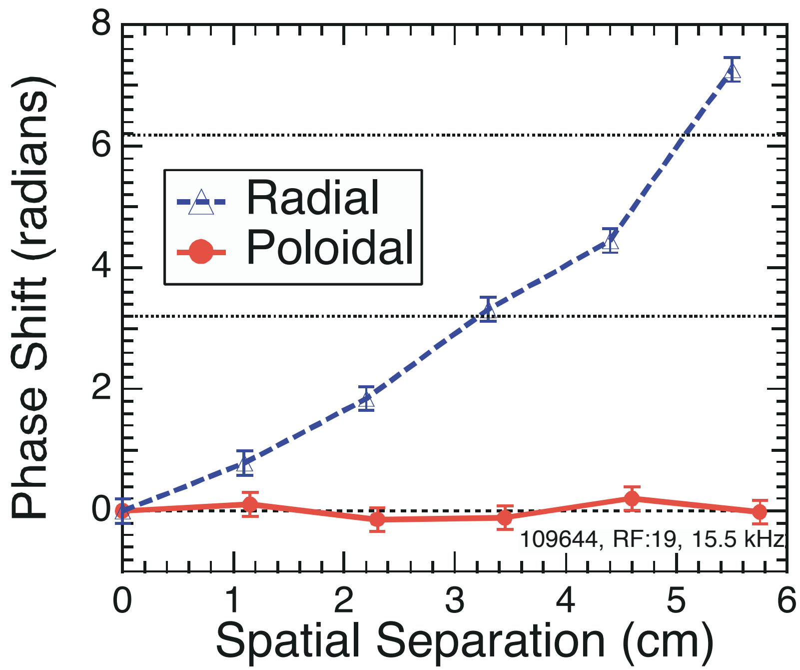
Summary

- Time-varying turbulence flows measured by applying TDE to 2D BES data:
  - *exhibits characteristics of zonal flows (GAMs) crucial to regulating turbulence*
- Characteristics of these observed flows (seen $0.85 < r/a < 1.0$):
  - *Coherent oscillation near 15 kHz, frequency scales with local temperature*
  - *No measurable poloidal phase shift: $|m| < 2$*
  - *180° radial shift over 3 cm, k_r□$_I < 0.2$*
  - *□$_S$ < 1/□$_c$, but of same order of magnitude: can affect turbulence*
  - *Modulates density fluctuation amplitude*
- Analysis of these plasmas performed with BOUT edge turbulence simulation code
  - *Predict geodesic acoustic mode (GAM) ExB oscillation seen at same frequency as observed experimentally*
- Next step: Improving density fluctuation diagnostic sensitivity to measure time-dependent flows more deeply in the plasma core

More detailed discussion, data, and theory in invited talk:
G. McKee, Talk UI2.005, Friday Morning

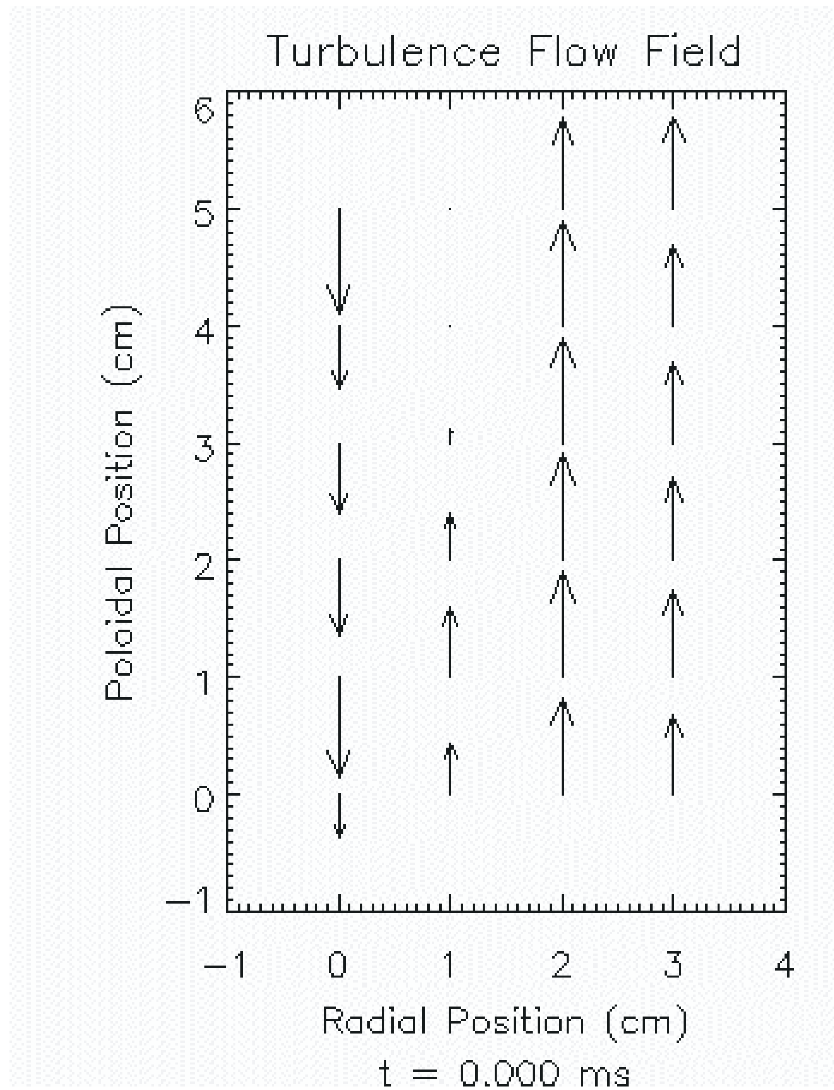
Phase Relationship Suggests Radially-Sheared Flow Action

Phase shift between radially and poloidally separated v_{θ} measurements



- Poloidally, little or no measurable phase shift, (m < 2, consistent with m=0)
- Radially, 180º shift over ~3 cm

Visualization of spatial flow field:



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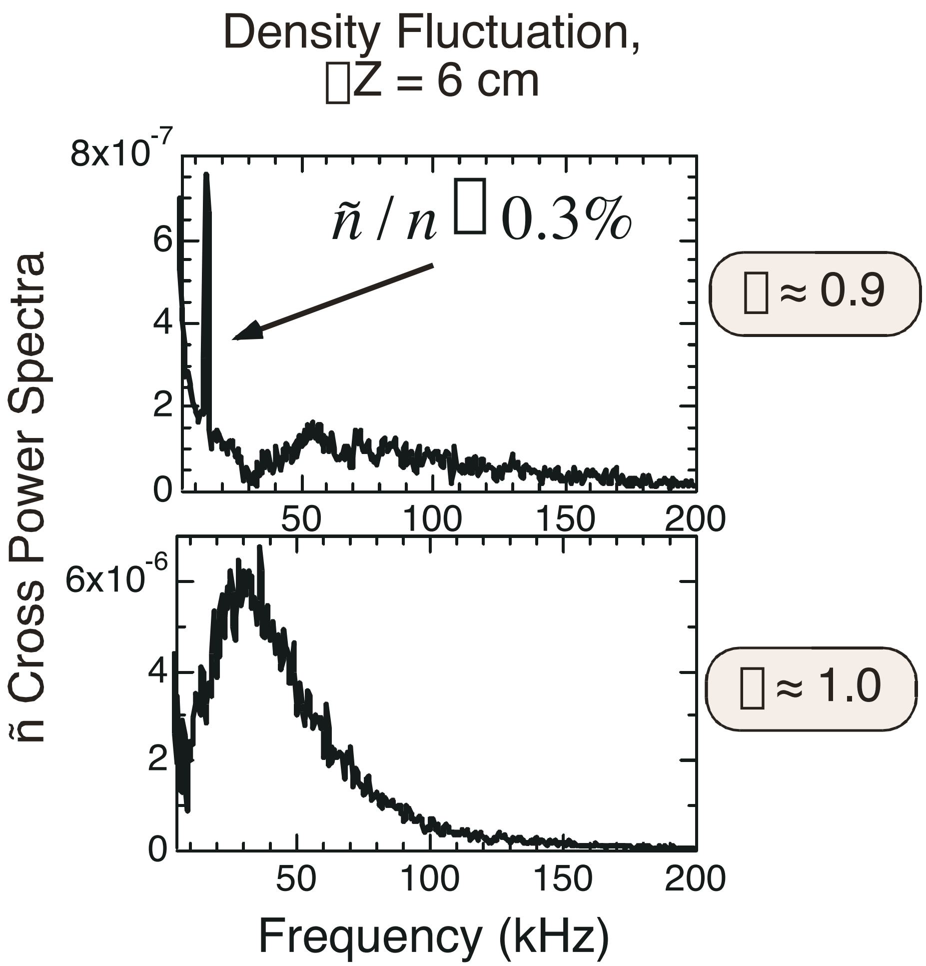
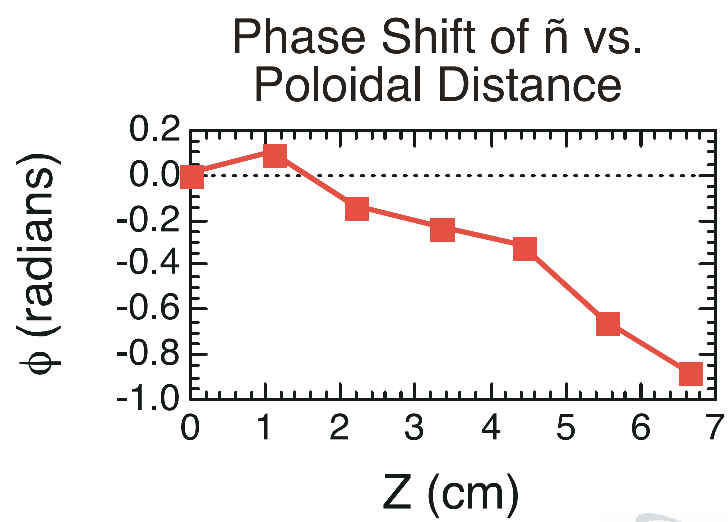
SMALL BUT FINITE DENSITY FLUCTUATION ASSOCIATED WITH COHERENT V_θ OSCILLATION



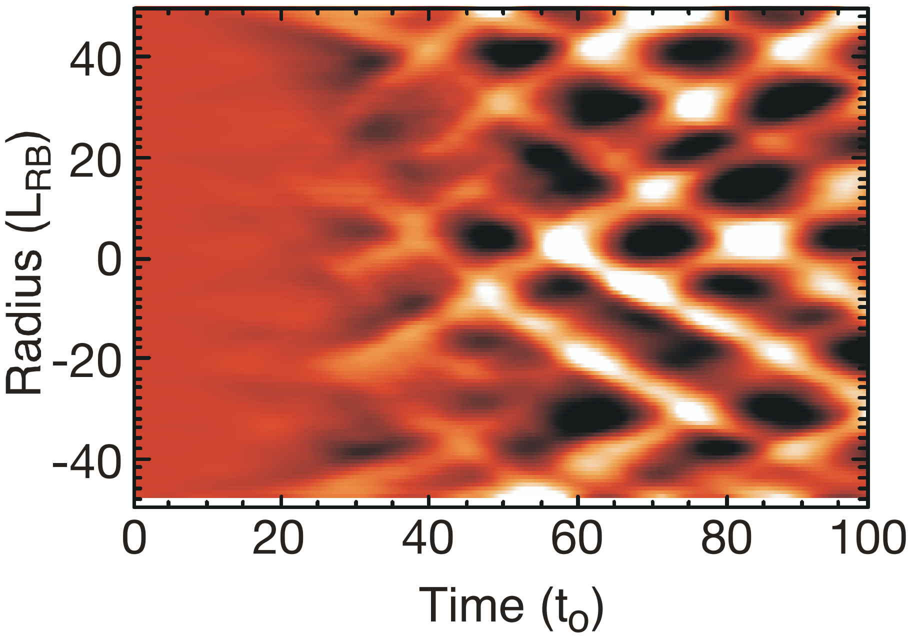
- Density fluctuation at same frequency, coherence as v_θ oscillation observed at very small normalized amplitude
- Not observable when ambient turbulence is high, near separatrix
- ñ phase shift suggests moderately high m ~ 10 (based on limited poloidal sampling)



3D Braginskii Simulations Exhibit Geodesic Acoustic Modes: Characteristics very similar to Flow Oscillation

- Flow spectrum near edge/core transition region evolves to steady coherent oscillation (GAM)

ExB Flow Profile

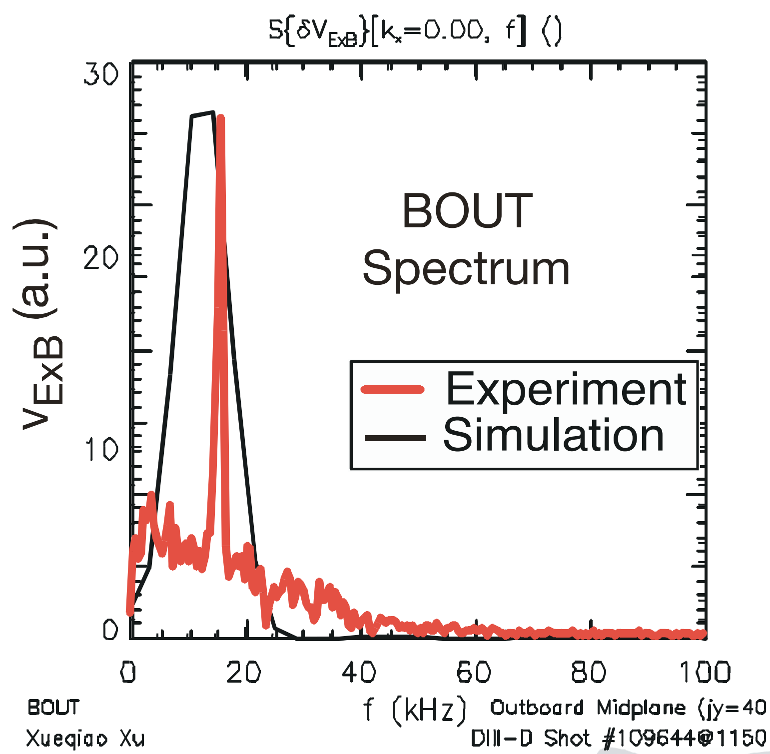


$t_o = \sqrt{RL_n/(2c_s)^2}$

R_{LB}, Resistive Balooning Scale Length (~mm)

K. Hallatchek, D. Biskamp, Phys. Rev. Lett. ***86****, 1223 (2001), Fig. 1(a)*

- BOUT simulation performed with experimental edge profiles
- v_{ExB} oscillation observed at similar frequency to measured flow oscillation, in excellent agreement with measurements



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