Observation and Characterization of Coherent, Radially-Sheared Zonal Flows in the DIII-D Tokamak

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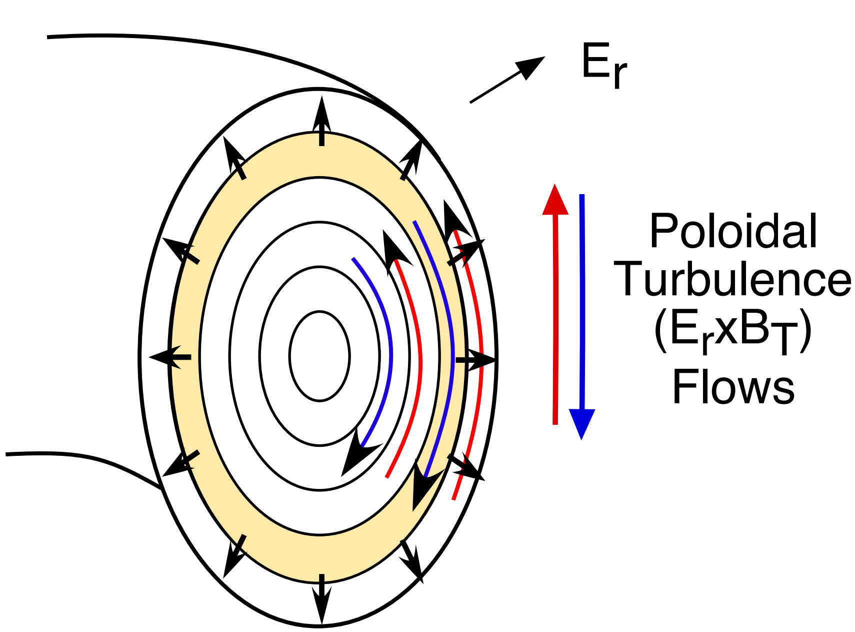
Zonal Flows Thought Crucial to Mediating Fully Saturated Turbulence in Plasmas

- Predicted to regulate turbulence via fluctuating $E_r x B_T$ (v_θ) flows
  - Observed in simulations of core and edge turbulence
  - Self-generated by turbulence through, e.g., Reynolds stress
- Structure: n=0, m=0, radially-localized electrostatic potential (linearly stable)
  - Low-frequency residual zonal flow (f < 10 kHz)
  - Higher-frequency Geodesic Acoustic Mode (10-200 kHz)



Measurement challenge:

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

Examine turbulence flow field for evidence of zonal flows:

Turbulence poloidal group velocity

$v_\theta = E_r x B_T + \nabla v_{D,i}$

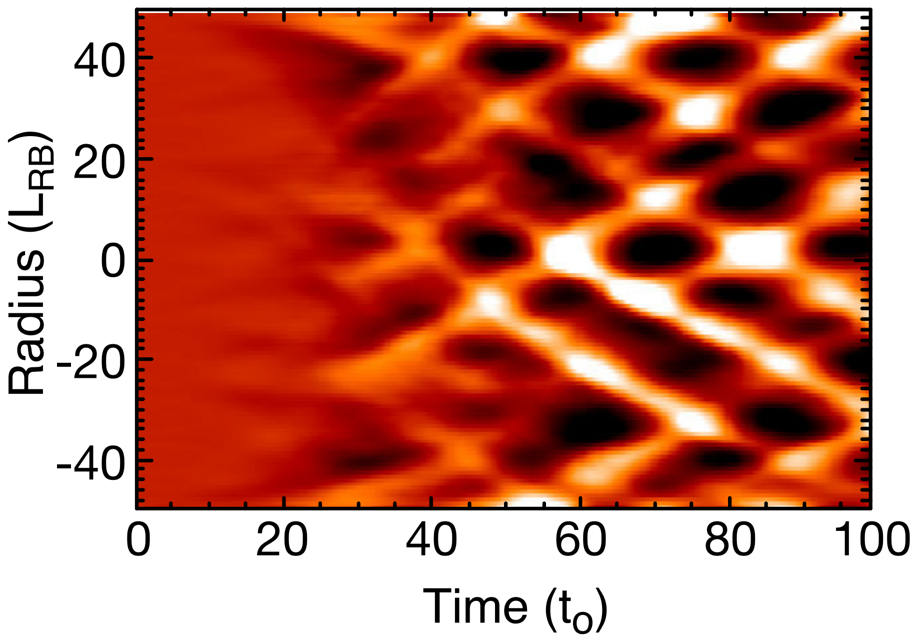
OVERVIEW AND OUTLINE

- Motivation to experimentally characterize zonal flows
- Measurement Technique:
  - Density fluctuation imaging with Beam Emission Spectroscopy (BES)
  - Time-dependent turbulence flow field:

    Time-Delay-Estimation (TDE) analysis techniques ==> $v_{\theta}(R,Z,t)$
- Flow feature observed:
  - Coherent poloidal oscillation
  - Poloidally uniform, radially sheared
  - Frequency depends on local temperature
  - Similar to Geodesic Acoustic Modes (class of zonal flows)
- BOUT simulations exhibit GAM
  - similar frequency to observed flow
- Summary

3D Braginskii Simulations of Edge-to-Core Transitional Regime Exhibit Coherent Zonal Flows

Poloidal $E_r x B_T$ Flow Contour



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

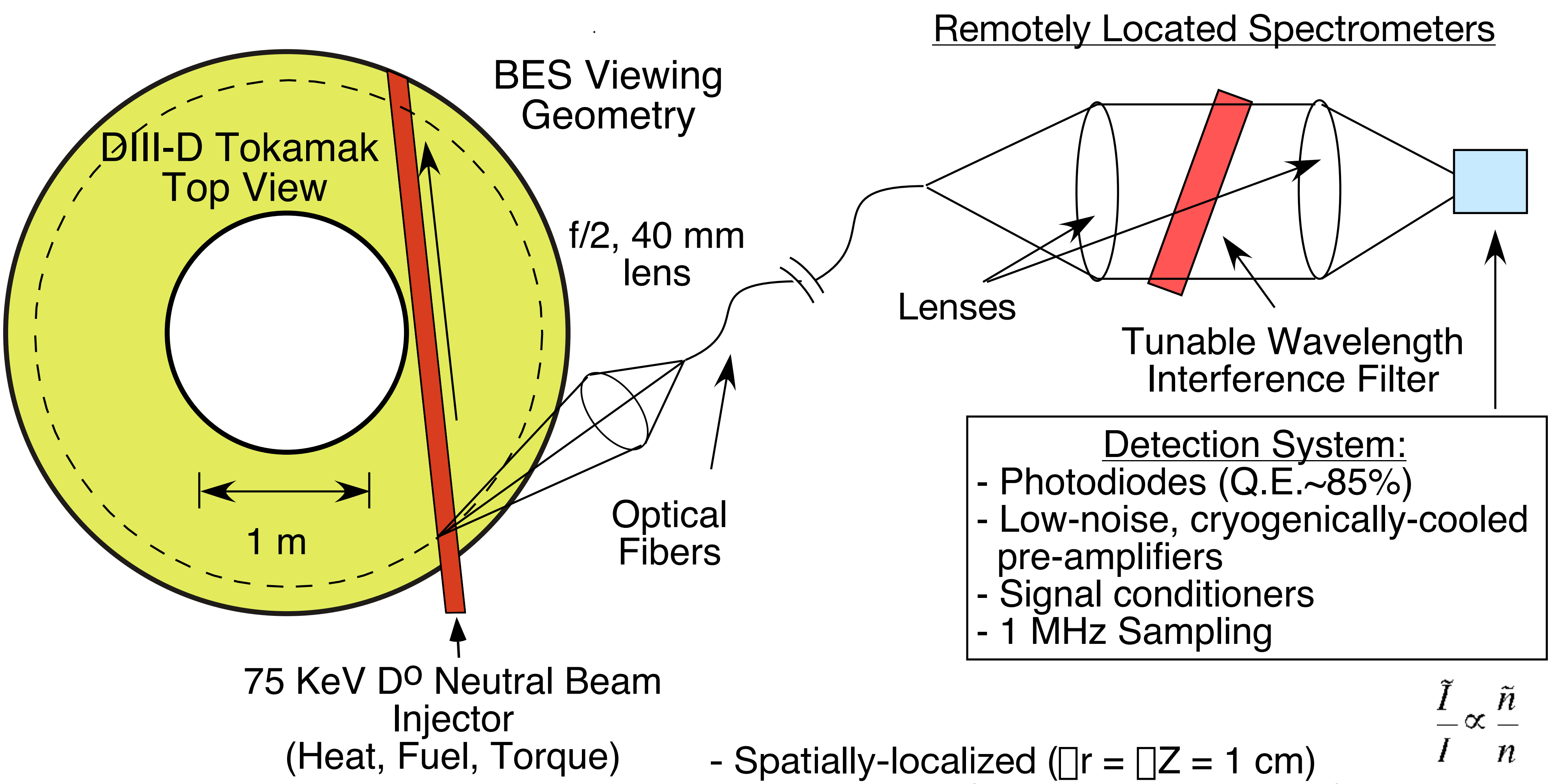
- Simulated flow profile evolves to steady, coherent oscillation
- Zonal flow specifically a: ***Geodesic Acoustic Mode (GAM)***
- Regulates turbulence and transport

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

Beam Emission Spectroscopy (BES) Diagnostic Measures Local, Long-Wavelength ($k_{\perp}\rho_{I} < 1$) Density Fluctuations

Collisionally-excited,
Doppler-shifted
beam fluorescence

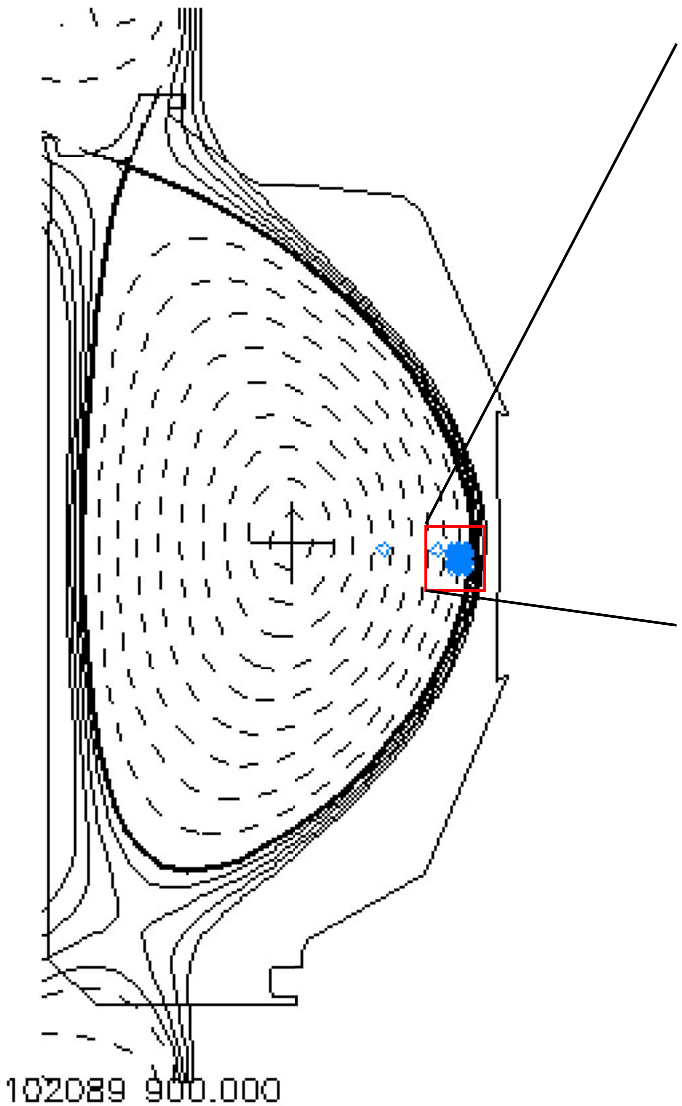
$$D^{o} + e,i \rightarrow \left(D^{o}\right)^{*} \rightarrow D^{o} + \gamma(n = 3 \rightarrow 2, \lambda_{o} = 656.1\ \mathrm{nm})$$

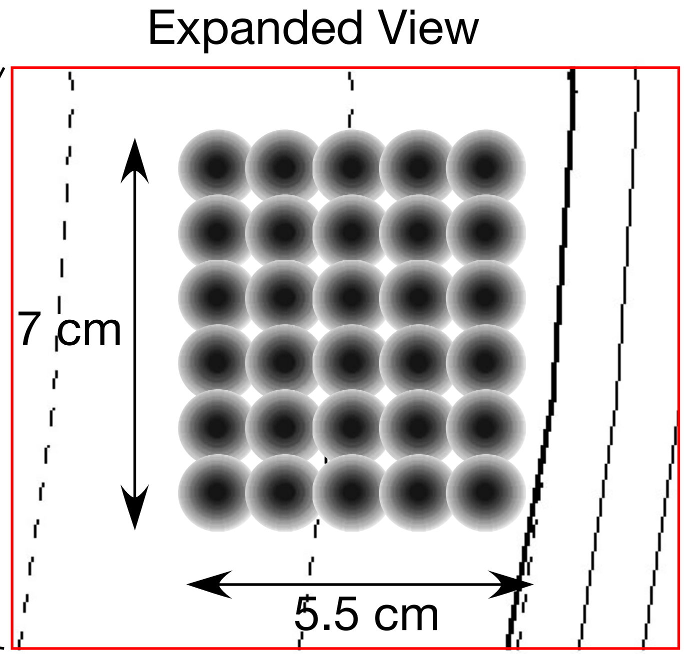


$$\frac{\tilde{I}}{I} \propto \frac{\tilde{n}}{n}$$

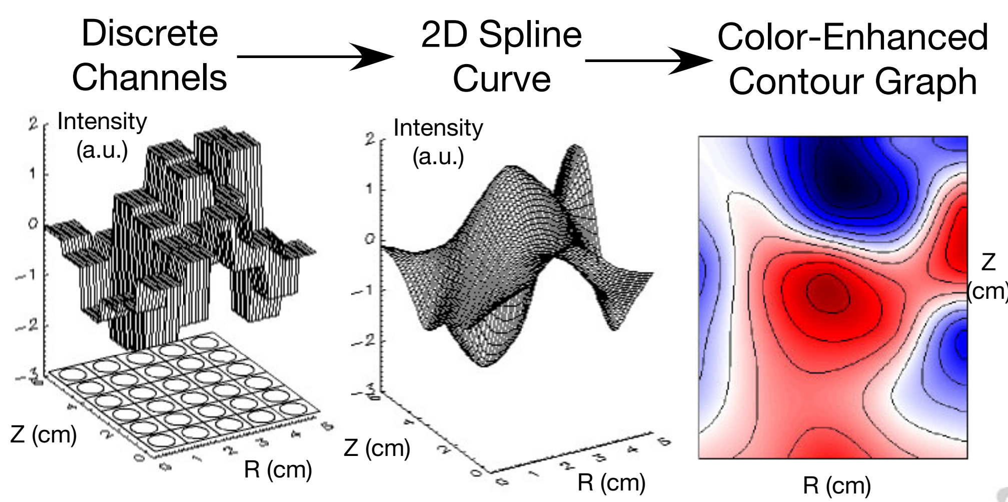
- Spatially-localized ($\Delta r = \Delta Z = 1$ cm)
- Multi-channel (32 currently deployed)
- Long-wavelength: $k_{\perp} < 3\ \mathrm{cm}^{-1}$

2D Capability of BES Allows for Imaging and Application to Turbulence Flow Measurement

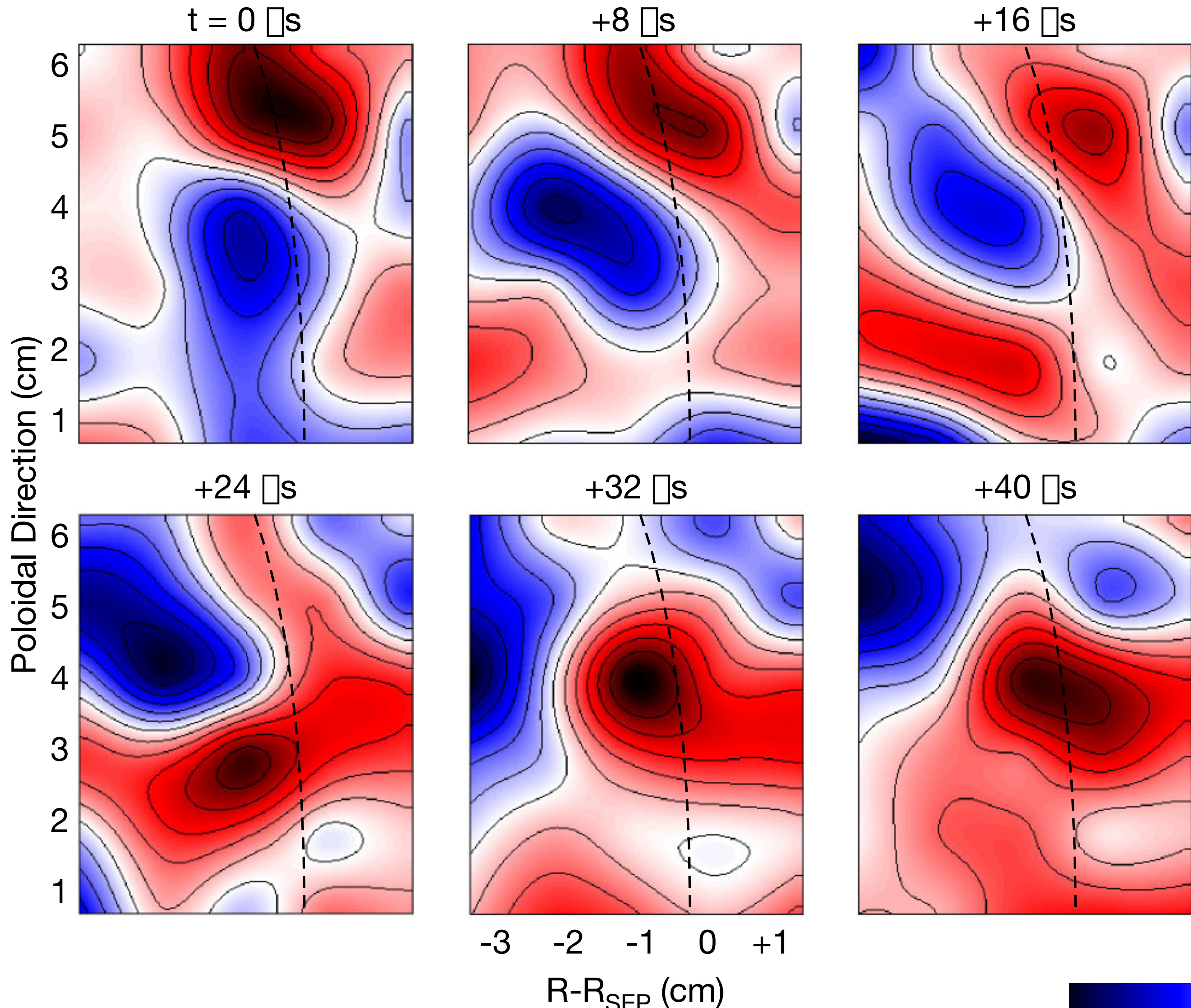




- Flexible mounting array allows for customized channel setup
- Array can be radially translated on shot-to-shot basis for spatial scanning



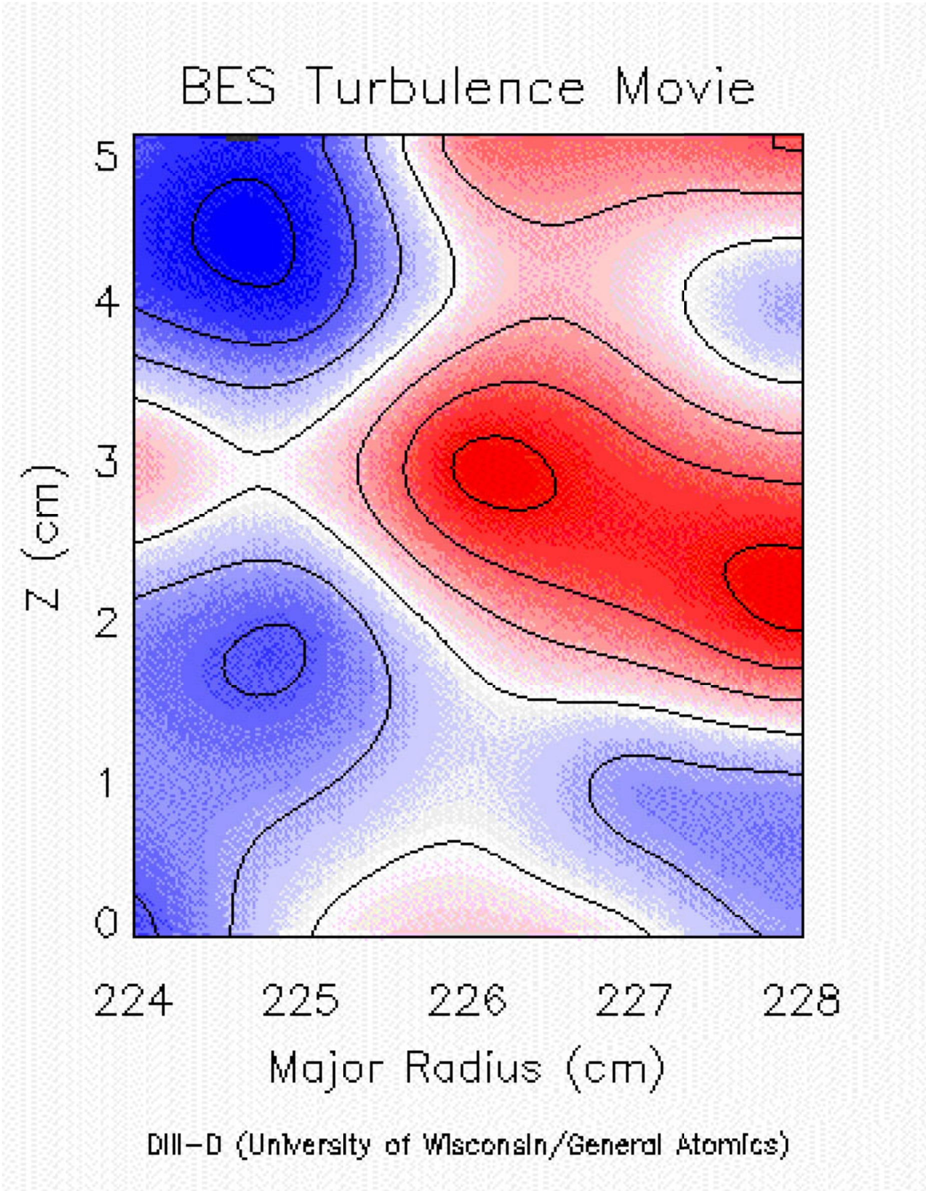
Two-Dimensional Images of Density Fluctuations Elucidate Complex, Nonlinear Interactions of Turbulent Eddies



- 1 MHz sampling
- 5 x 6 cm region near outer midplane (0.9 < □ < 1.05)
- L-mode plasma:

  5 MW neutral beams
  Upper Single Null
  $T_e \sim 75$ eV
  $T_i \sim 200$ eV
  $n_e \sim 1.5 \times 10^{19}$ m^{-3}

TURBULENCE MOVIES DEMONSTRATE EDDY INTERACTION



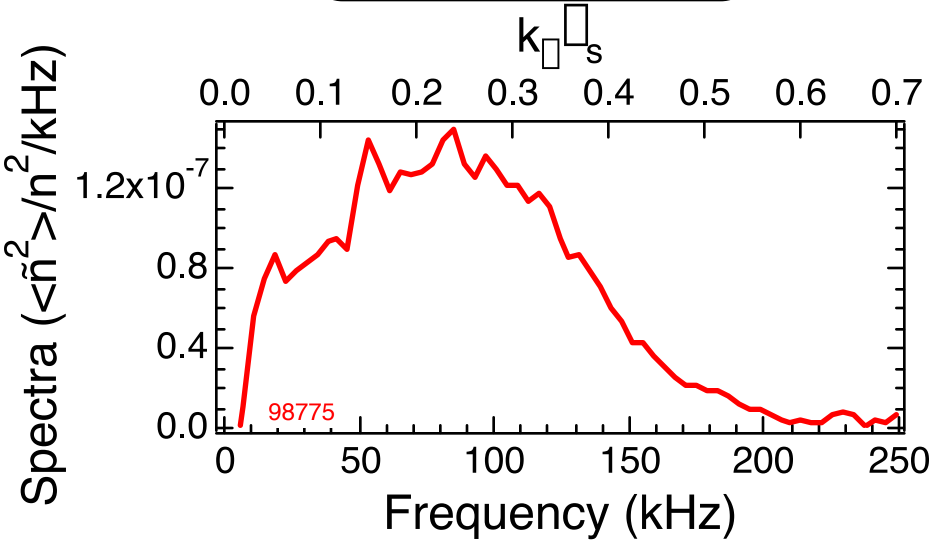
- Poloidal advection (higher inside)
- Eddy shearing from flow shear
- Net Outward particle flux
- Strong nonlinear interaction of eddies (tearing and congealing)

10 □s/sec, 1 ms record

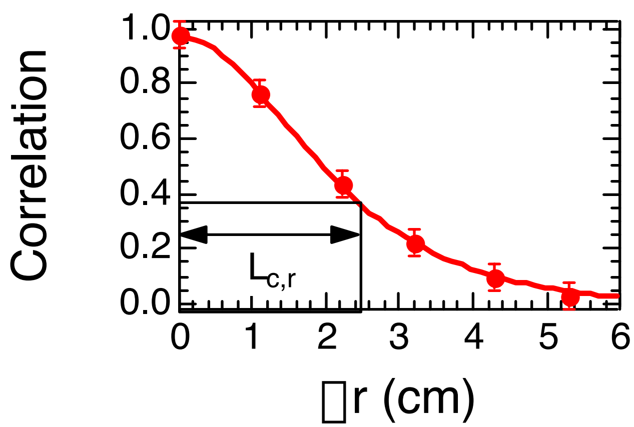
Typical Characteristics of Tokamak Plasma Turbulence

- Broadband density fluctuation spectrum
- Decaying radial and wave-like decaying poloidal correlation function
- Correlations lengths: ~ 2-4 cm

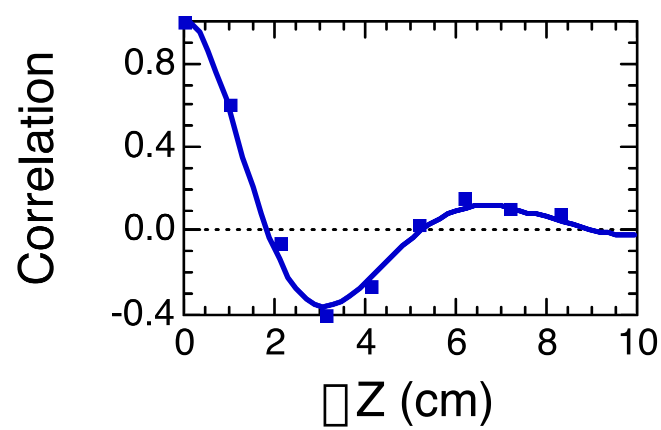
Power Spectrum



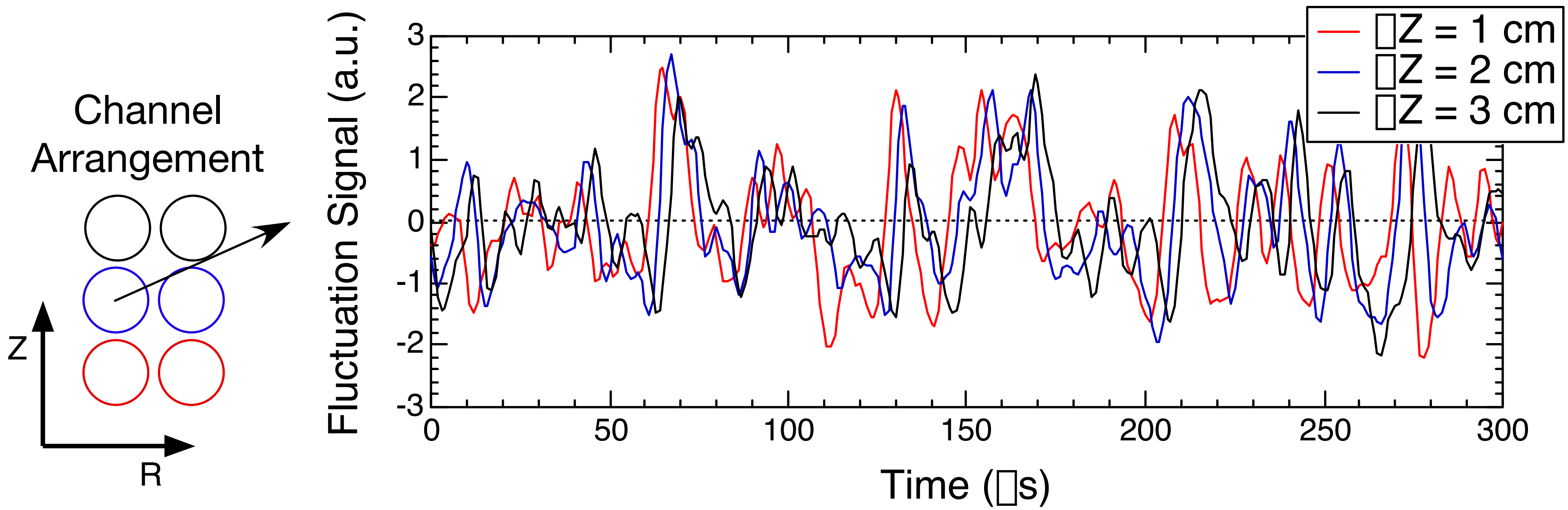
Radial Correlation Function



Poloidal Correlation Function



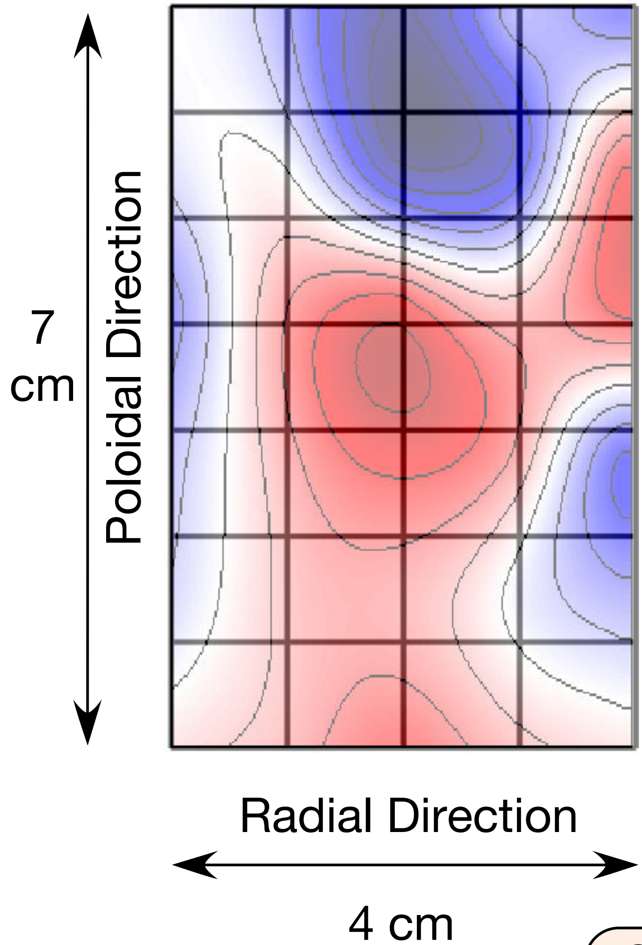
Fluctuation time series exhibits high coherence, poloidal convection



- Average Time Delay ~ 3 □s: 3.5 km/s poloidal advection of turbulence

TIME-VARYING TURBULENCE FLOWS MEASURED VIA 2D DENSITY FLUCTUATION MEASUREMENTS WITH BES

Turbulence imaged at 1 MHz
discrete BES channels
deployed on 4x7 grid



Time Delay Estimation between poloidally-adjacent channels:

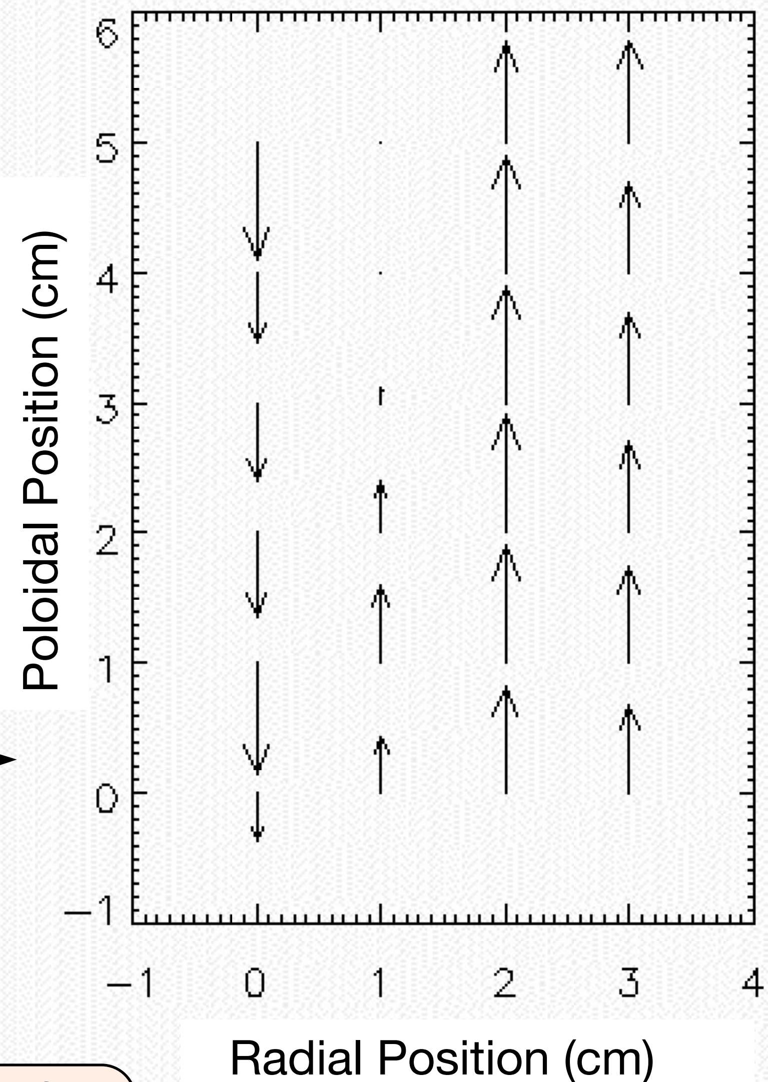
1) Wavelet-based cross-phase (□□(t))

2) Time-resolved cross-correlation ($\square_{\square,max}$(t))

$v_{\square}$(R, Z, t)

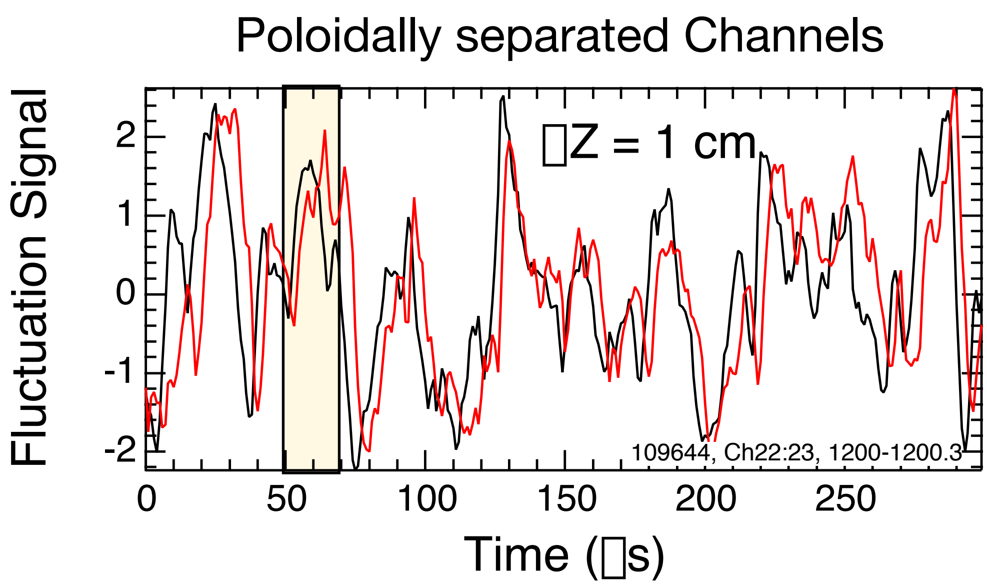
on relevant time scale (0 < f < 200 kHz)

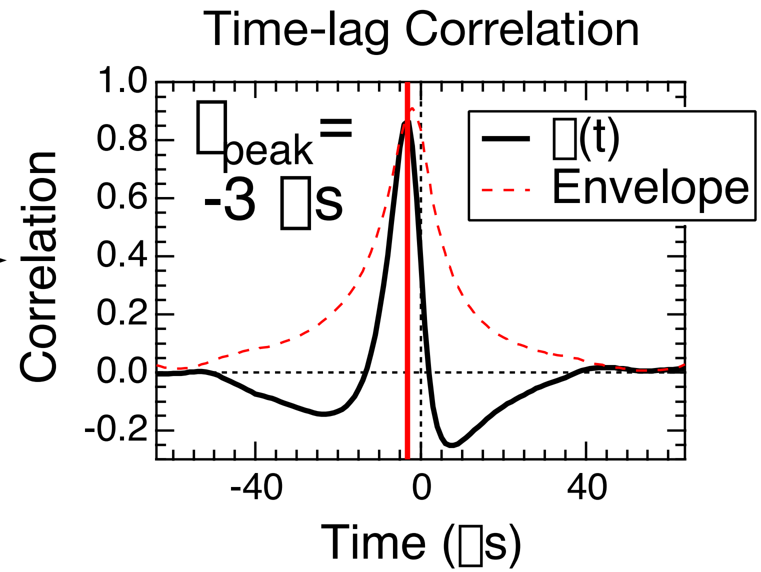
Turbulence Flow Field



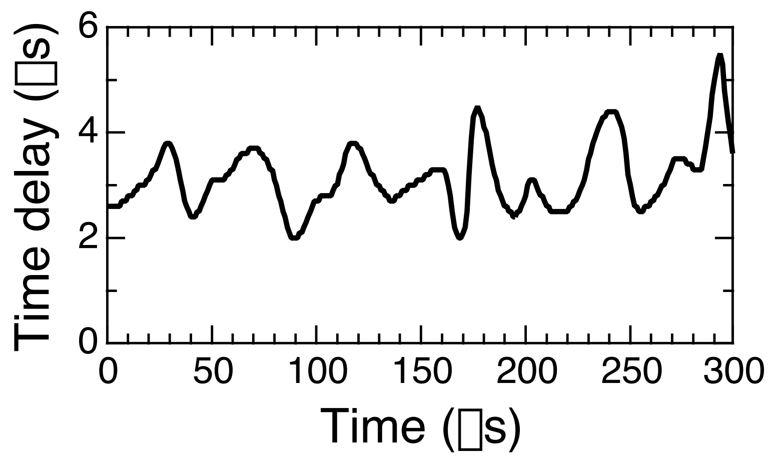
Spectral and spatial analysis of $v_{\square}$ to search for flow features

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





Calculated Time-resolved time-delay



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

WAVELET METHOD TO PERFORM TIME-DELAY-ESTIMATION ANALYSIS

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

Complex Wavelet Transform

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

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

↓

Cross Scaleogram

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

↓

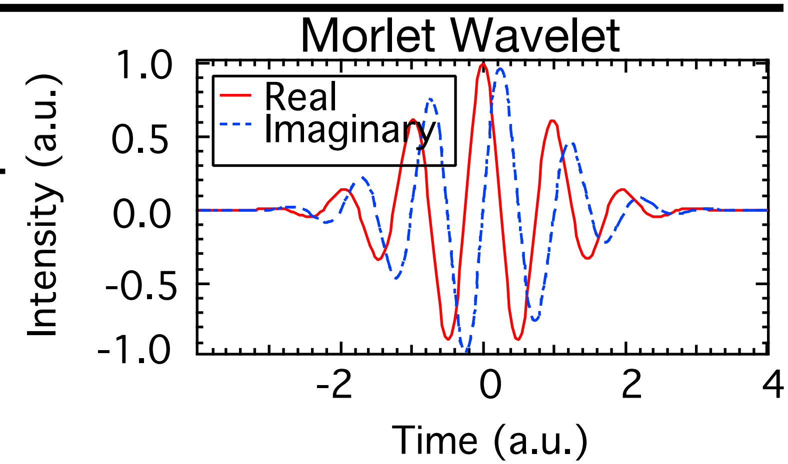
Time-dependent cross phase

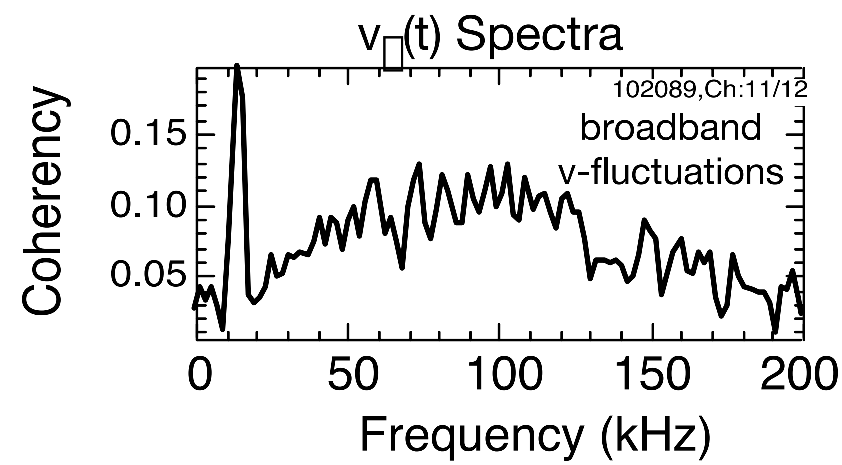
$$\phi(f,\tau) = \tan^{-1}\left(\frac{im(W(f,\tau))}{re(W(f,\tau))}\right)$$

↓

Time-dependent time-delay

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





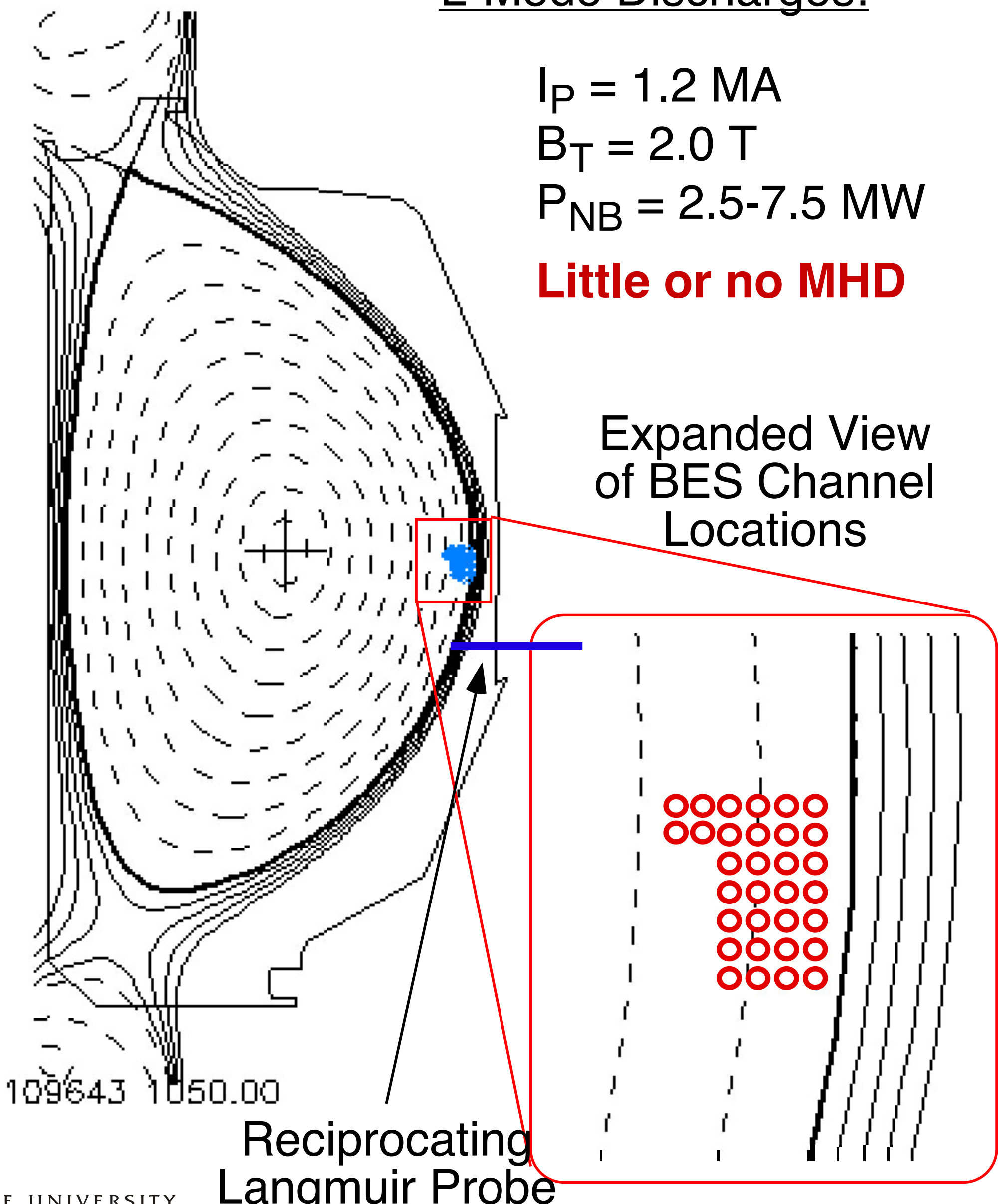
M. Jakubowski, Ph.D., Thesis
U. Wisconsin (2003)

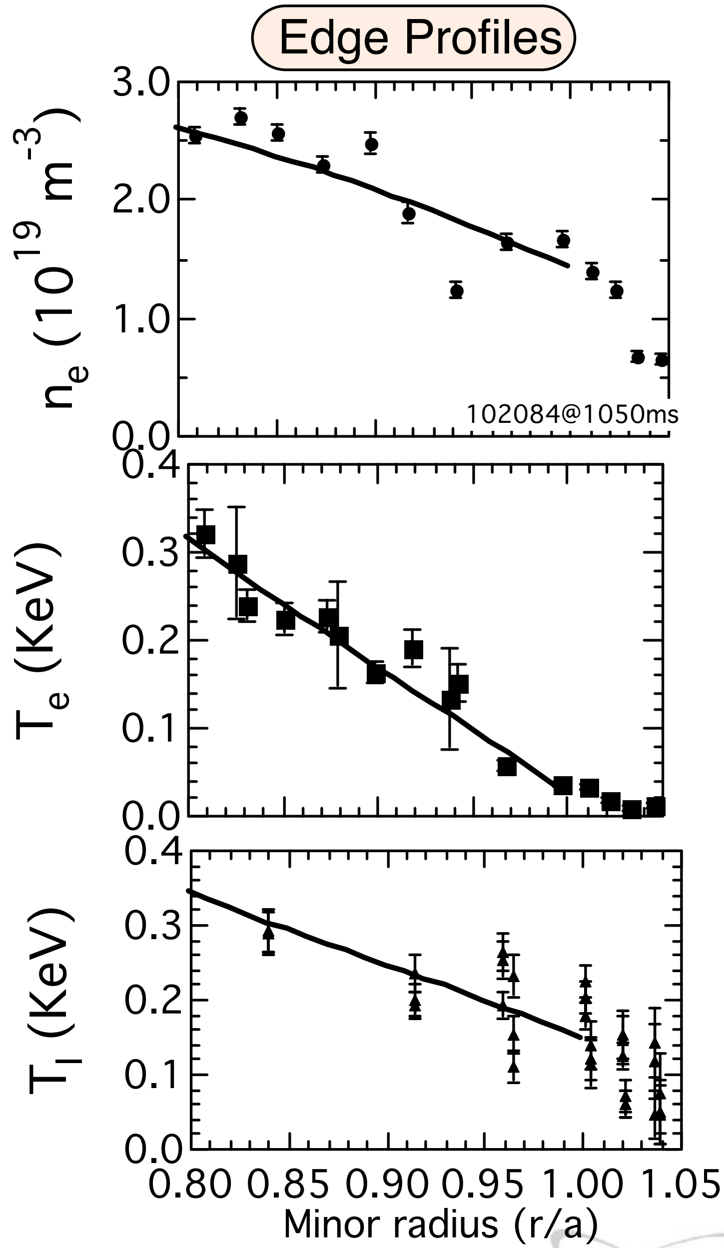
DIII-D Experiment Performed to Explore Turbulence Flows and n and T Scaling

L-Mode Discharges:

I_P = 1.2 MA
B_T = 2.0 T
P_{NB} = 2.5-7.5 MW

Little or no MHD



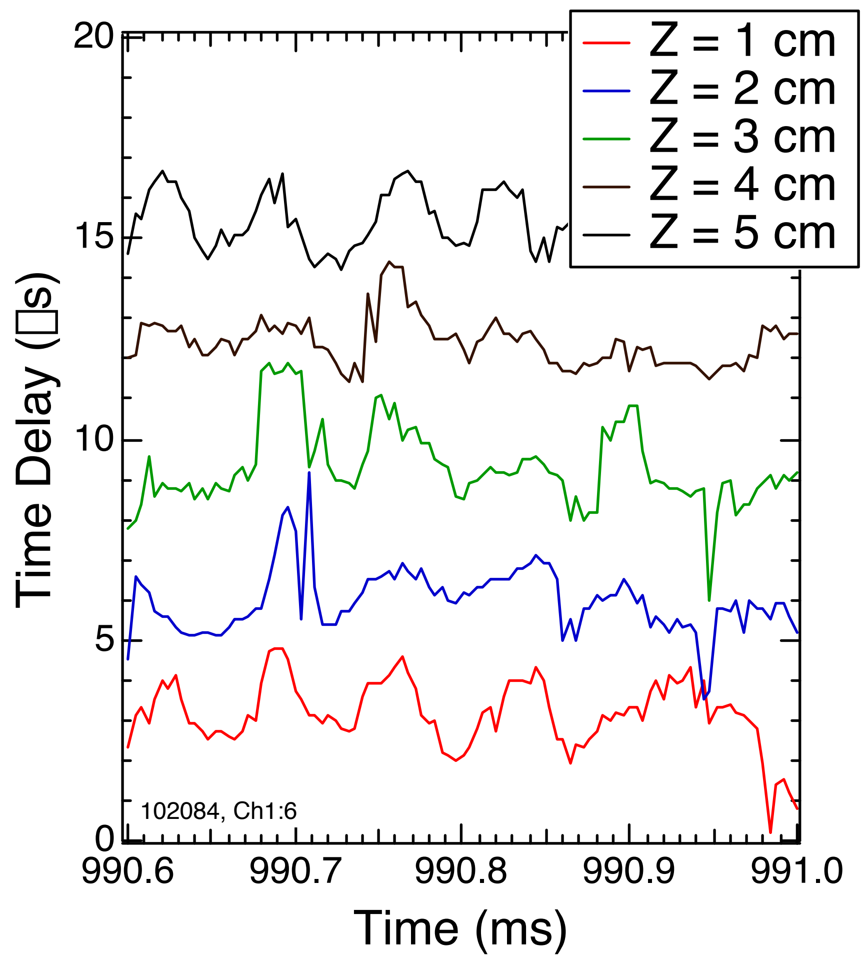


Coherent Velocity Oscillation Observed in TDE Analysis Measurements

- Oscillation in phase
- Amplitude significant fraction of equilibrium
- Similar flow observed in decorrelated turbulence

$$v_\theta(t) = \frac{\Delta Z}{\tau(t)} \approx \frac{\Delta Z}{t_o}\left(1 - \frac{\partial \tau(t)}{t_o}\right)$$

Channel-to-channel time-delay measurements



(Channels offset vertically for clarity)

Poloidal Velocity Spectra Exhibit Coherent Oscillation with Long Poloidal Correlation Length

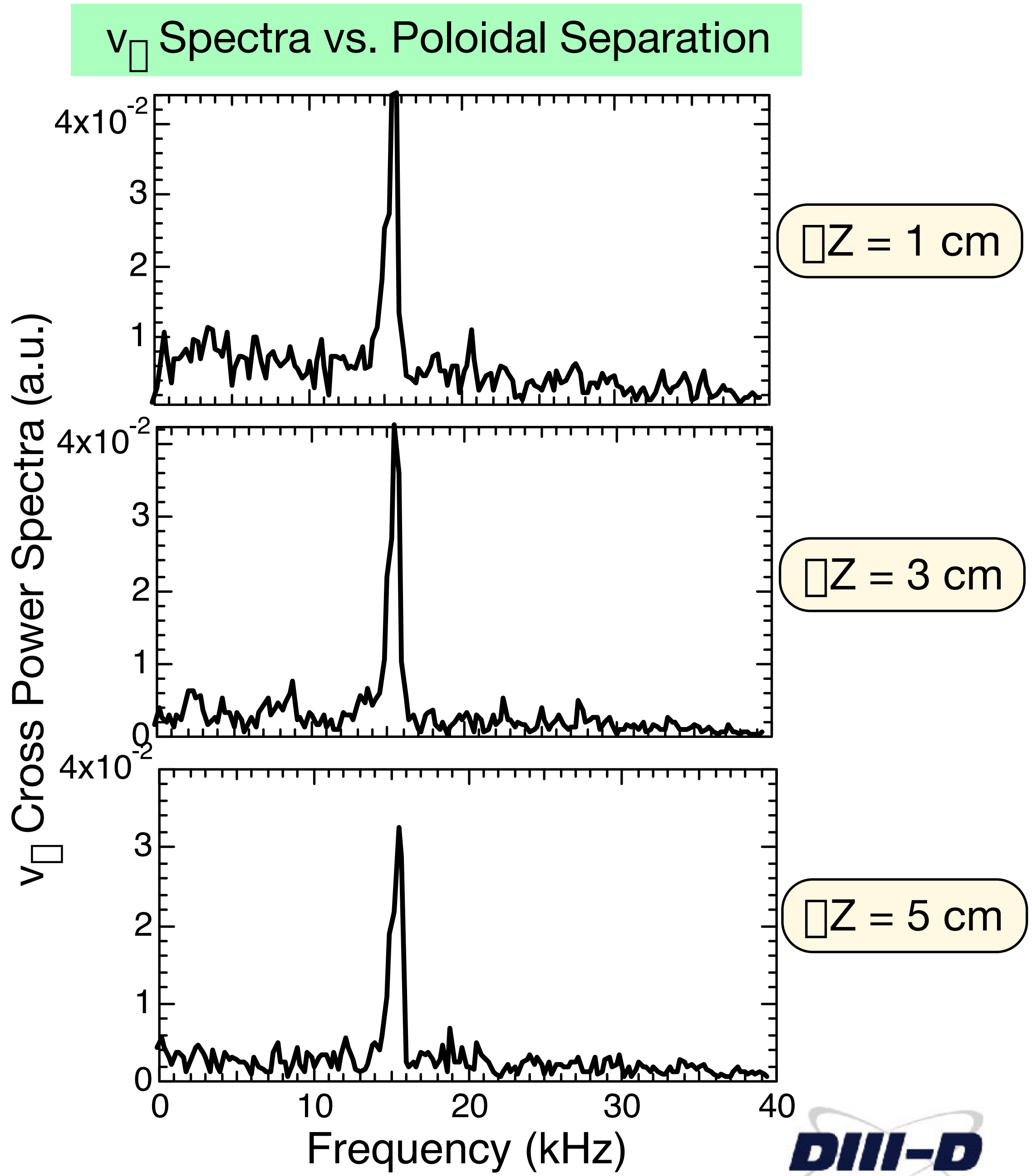
- Highly coherent frequency -> long-lived structure

$$\tau_{flow} >> \tau_{turbulence}$$

- High spatial correlation over > 5 cm

$$L_{c,\theta}|_{flow} >> L_{c,\theta}|_{\tilde{n}}$$

- f ≈ $c_s/2\pi R$ (12 kHz)
- Consistent with expected features of a: **Geodesic Acoustic Mode**



Geodesic Acoustic Modes: A Brief Overview

- Electrostatic acoustic oscillation in toroidal plasmas
- Radially localized zonal flow (m=0, n=0)
- Nonuniform poloidal **E**x**B**/B^2 flow causes pressure asymmetries on a flux surface
- Coupled to an m=1/n=0 pressure perturbation: $\tilde{p}=p_o \sin(\square)$

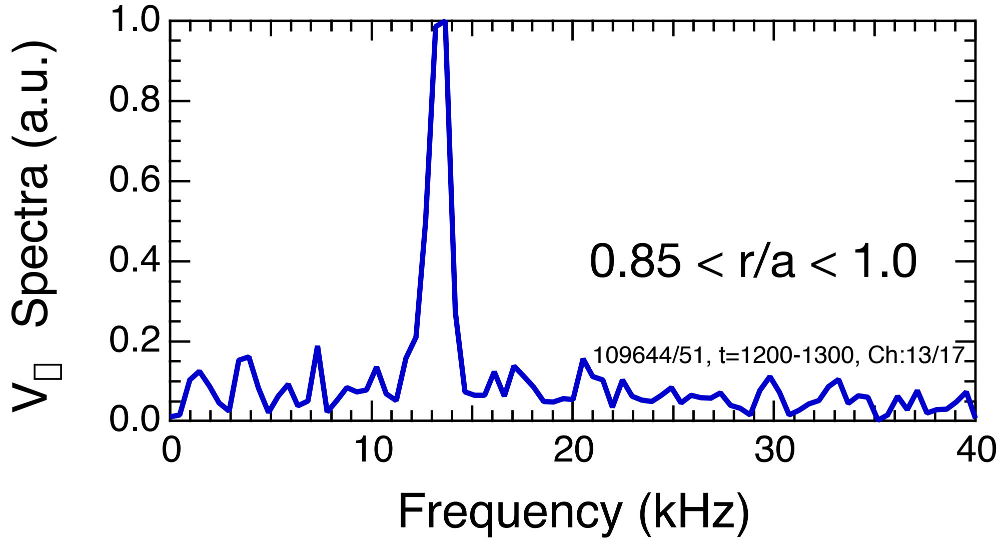
==> restoring force on the flux surface, arising from radial component of the diamagnetic current, leads to the coherent oscillation

- Frequency: $\square \approx c_s / R$ (correction terms of order unity)
- Driven by turbulence via Reynold's stress

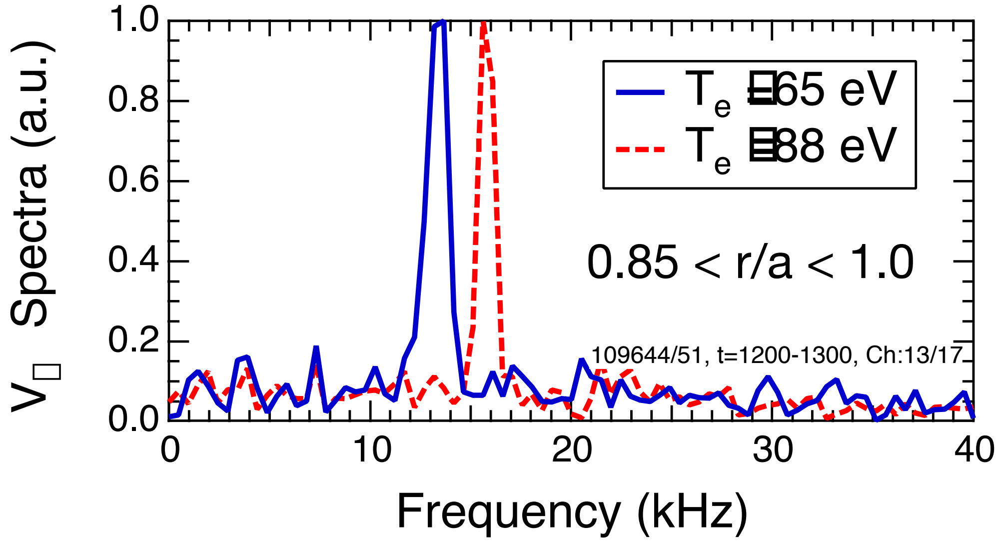
<u>**References**</u>

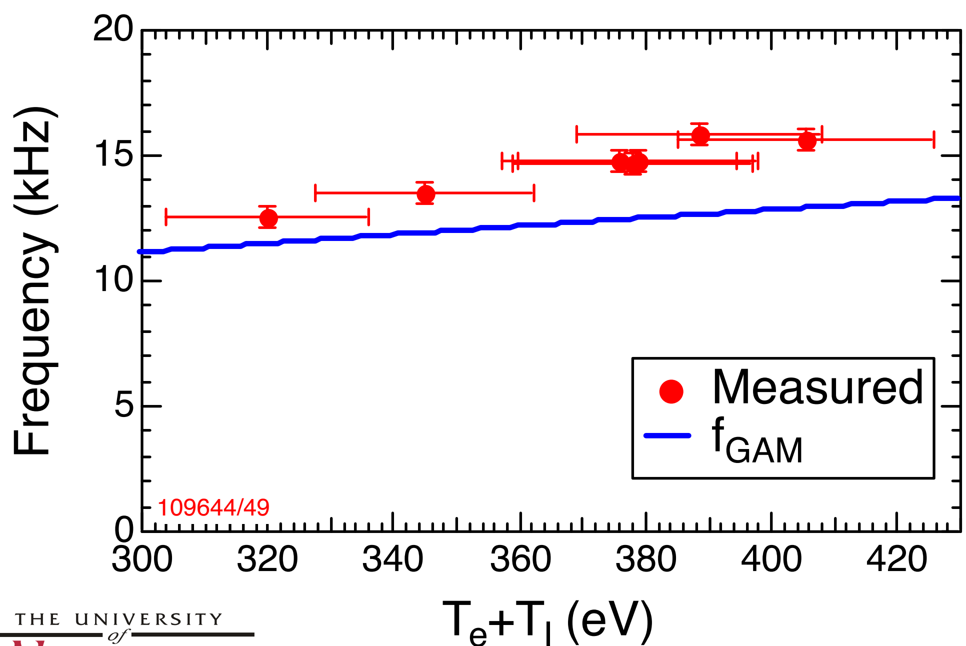
Winsor, Johnson, Dawson, Phys. Fluids 11, 2448 (1968).
Hallatschek, Biskamp, Phys. Rev. Lett. 86, 1223 (2001).
Ramish, Stroth, Niedner, Scott, New J. Physics 5, 12.1 (2003).

Frequency of Coherent V FEATURE Scales with Local Temperature



Frequency of Coherent V□ Feature Scales with Local Temperature





- Mode frequency increases with temperature:
  - suggests oscillation is a Geodesic Acoustic Mode:

    $f_{GAM} = c_S/2$□$R=12$ kHz

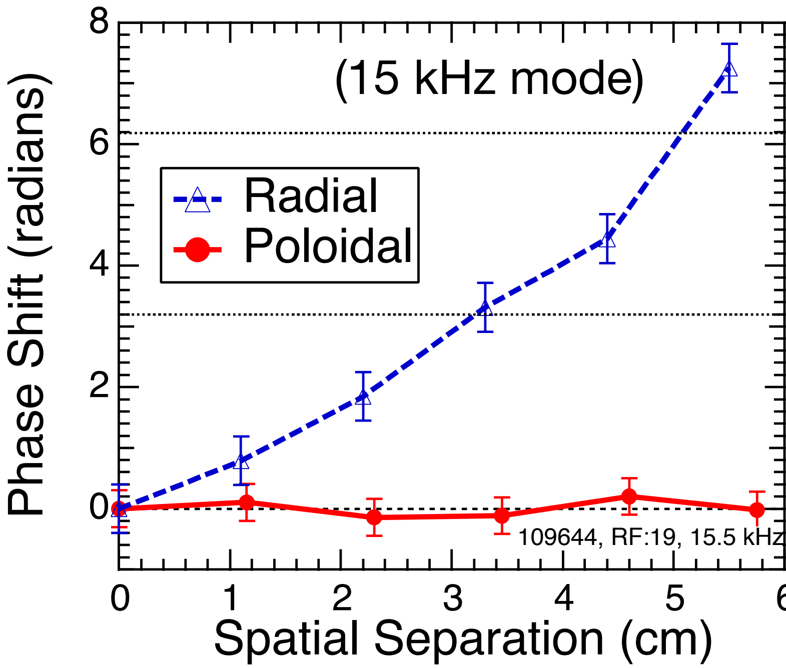
    $$c_s = \sqrt{(T_e + T_I)/M_I}$$

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

- Average frequency of mode scales with local T_e+T_I
  - Correction factors of order unity

Spatial and Phase Relationship of Coherent v_θ Feature Indicates Poloidally-Uniform, Radially-Sheared Flow

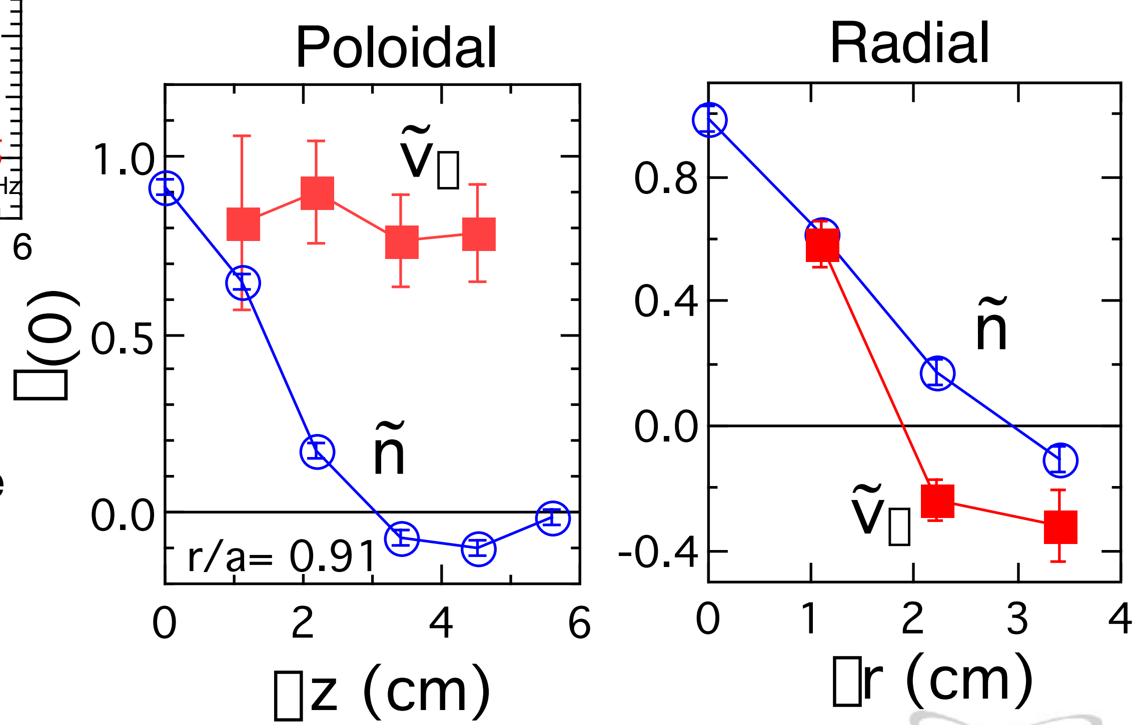
Radial and poloidal phase shift of v_θ measurements



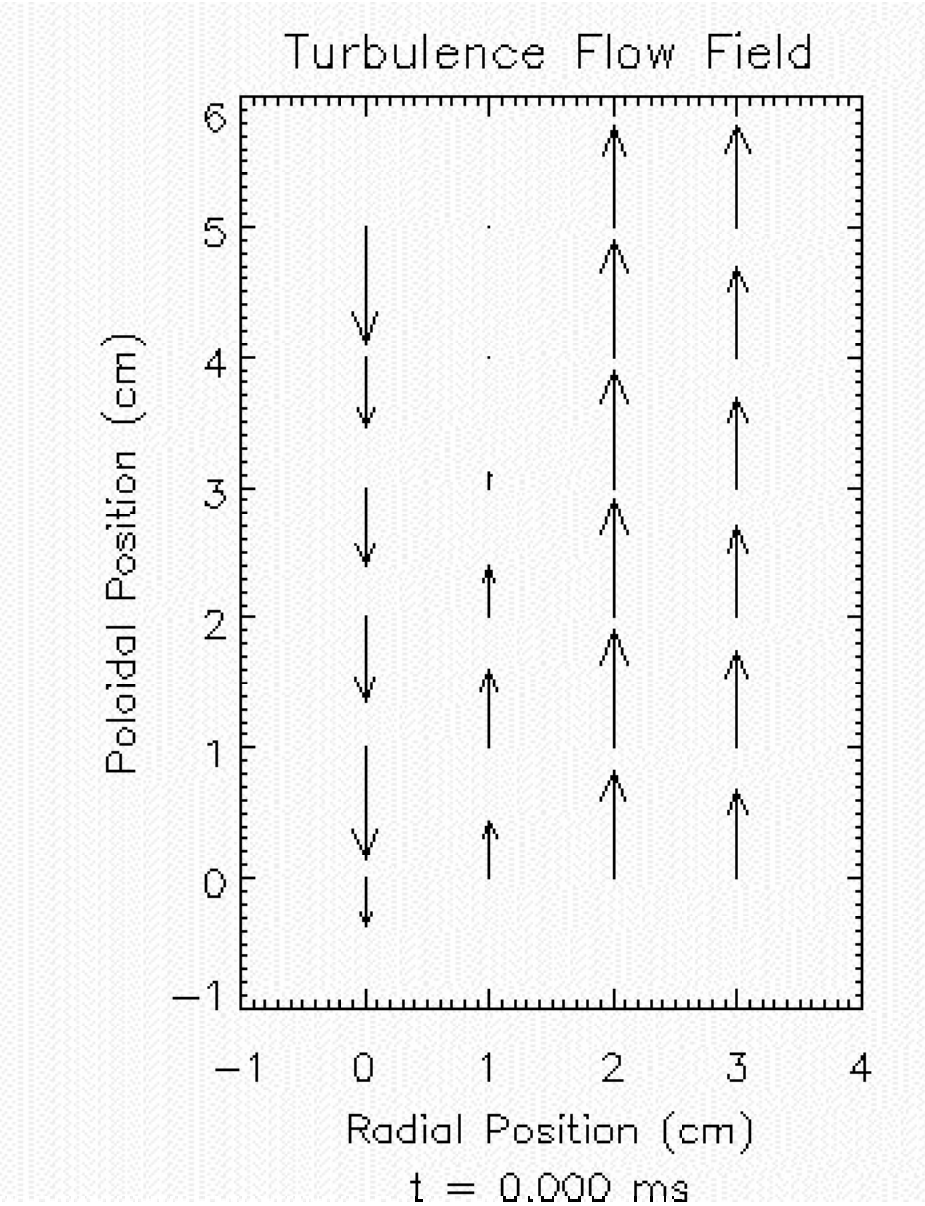
- Poloidally extended structure (low-m)
- Radially narrow (~Δr_n)

- Poloidally, little or no measurable phase shift, (|m| < 2, possibly m=0)
- Radially, 180° shift in ~3 cm

Spatial Correlation Functions



TIME-RESOLVED TURBULENCE FLOW FIELD EXHIBITS ZONAL FLOW CHARACTERISTICS



- Movie derived from ensemble-averaged, time-lag cross-correlations
- Exhibits expected spatial and temporal phase relationship of zonal flow oscillation
- Radial shear apparent over observed region
  - Poloidally, nearly uniform flow
- Peak velocity amplitude ~0.5 km/s

Effective Shearing Rate of v_θ Oscillation Can Affect Turbulence

- Approximate RMS magnitude of oscillation: $\tilde{v}_\theta \approx 500 m/s$

- Estimate shearing rate: $\omega_s \approx \frac{d\tilde{v}_\theta}{dr} \approx \frac{2(500 m/s)}{0.03 m} = 0.3 \times 10^5 s^{-1}$

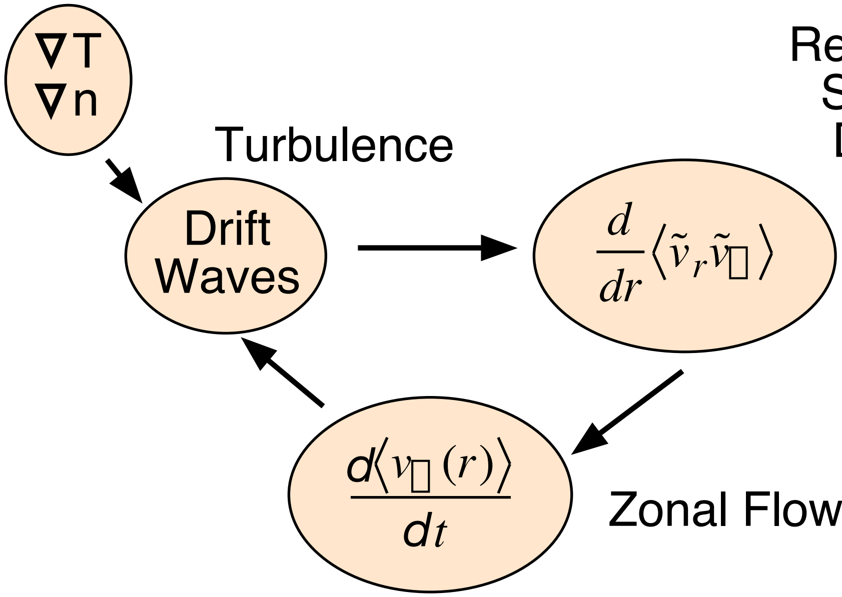
- Measured turbulence decorrelation rate: $\omega_T \sim 1/\tau_c \sim 1 \times 10^5 s^{-1}$

- Comparison: $\omega_s < \omega_T$, but values are comparable

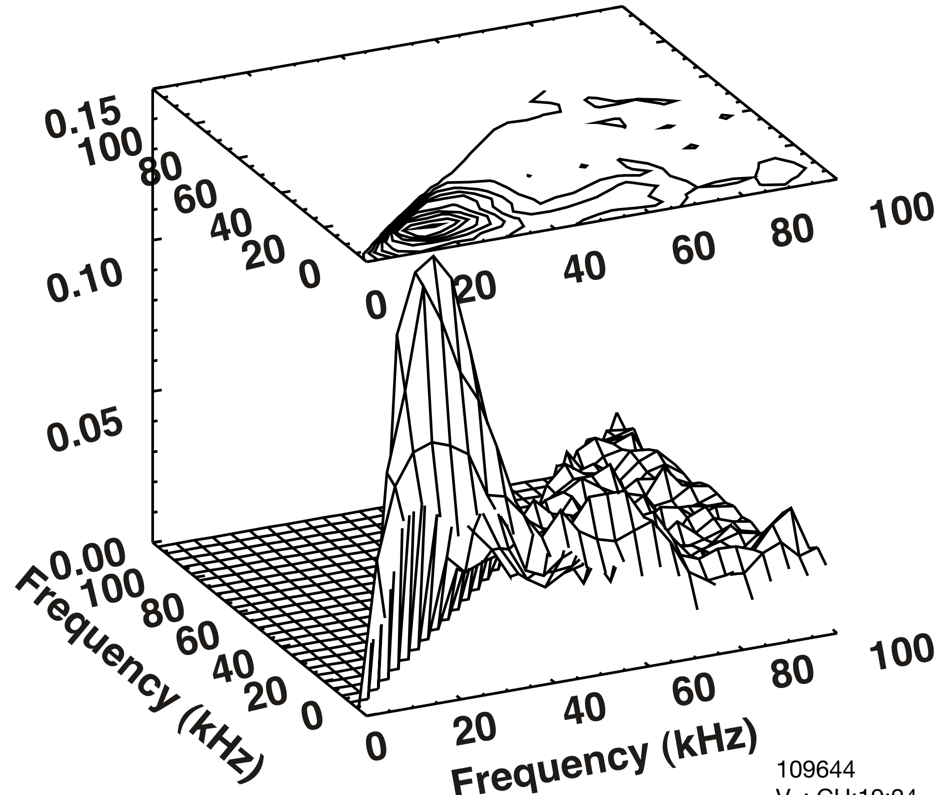
Oscillation can affect turbulence and reduce amplitude

Measurable Bicoherence Suggests Reynolds Stress Drive

- Reynolds stress gradient can drive zonal flow:



Bicoherence: $\hat{b}^2 = \frac{\left|\langle n_{f_1} n_{f_2} v_\theta^* \rangle\right|}{\left[\langle n_{f_1} n_{f_2} \rangle \sqrt{\langle v_\theta v_\theta^* \rangle}\right]}$



109644
V_θ: CH:19:24
n: CH:22:28

- Represented as 3-way interaction
- Finite phase coupling of density fluctuations to v_θ oscillation
- Suggests Reynolds stress contribution

Diamond, Phys. Rev. Lett. (2000).
Tynan, Phys. Plasmas (2001).
Moyer, Phys. Rev. Lett. (2001).
Shats, Phys. Rev. Lett. (2002).
Holland, Proc. 19th IAEA (2002).

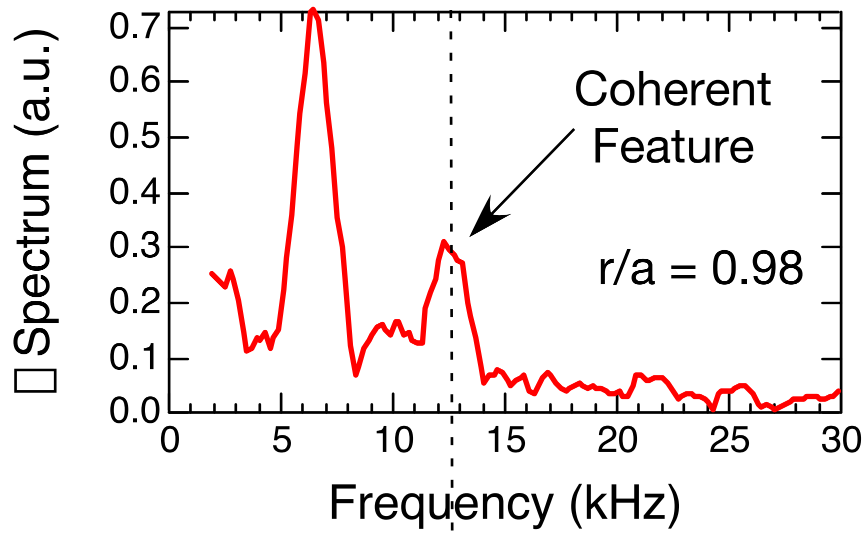
POTENTIAL FLUCTUATION MEASUREMENTS FROM LANGMUIR PROBE EXHIBIT ~13 KHZ FEATURE

- Semi-coherent *potential* fluctuation near separatrix (r/a~0.98) with Langmuir Probe

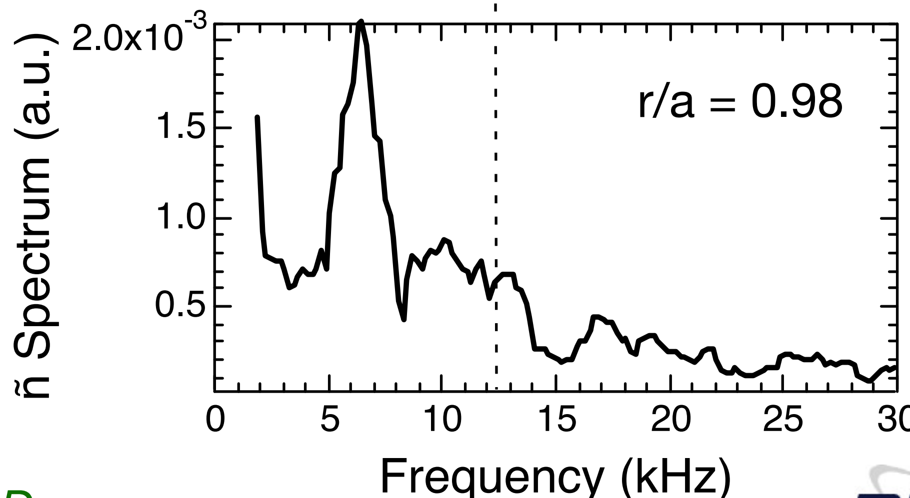
- I_{SAT} spectrum (ñ) does not exhibit similar 13 kHz feature
  - 13 kHz feature likely a low m structure

- Consistent with expectation that flow oscillation seen with BES is electrostatic ($E_r x B_T$)

Potential Fluctuation Power Spectrum



I_{SAT} Fluctuation Power Spectrum



University of California San Diego

D. Rudakov, R. Moyer, UCSD

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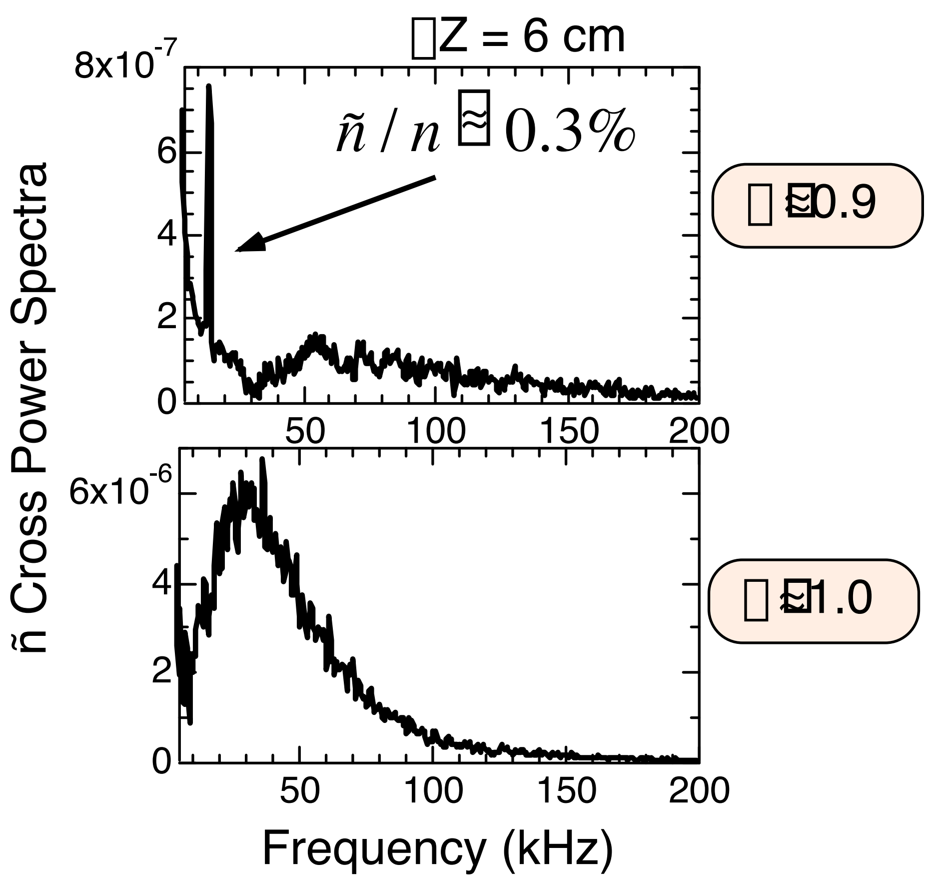
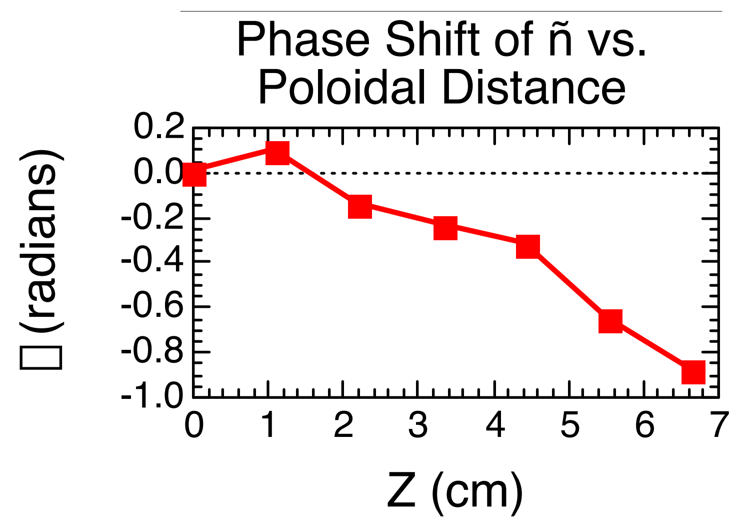
Small but Finite Density Fluctuation Associated with GAM Oscillation: Not Predicted Theoretically

Density Fluctuation



- GAMs couple to m=1/n=0 p̃
- Density fluctuation observed at v_θ oscillation frequency
- Not observable near separatrix
- ñ phase shift: m ~ 10
- Propagates in **electron** diamagnetic direction



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GAM NOT OBSERVED IN ALL DISCHARGES: NOT APPARENT IN LOW q_{95} DISCHARGES

- Higher-q plasma exhibits strong GAM oscillation, lower-q exhibits no hint of GAM oscillation

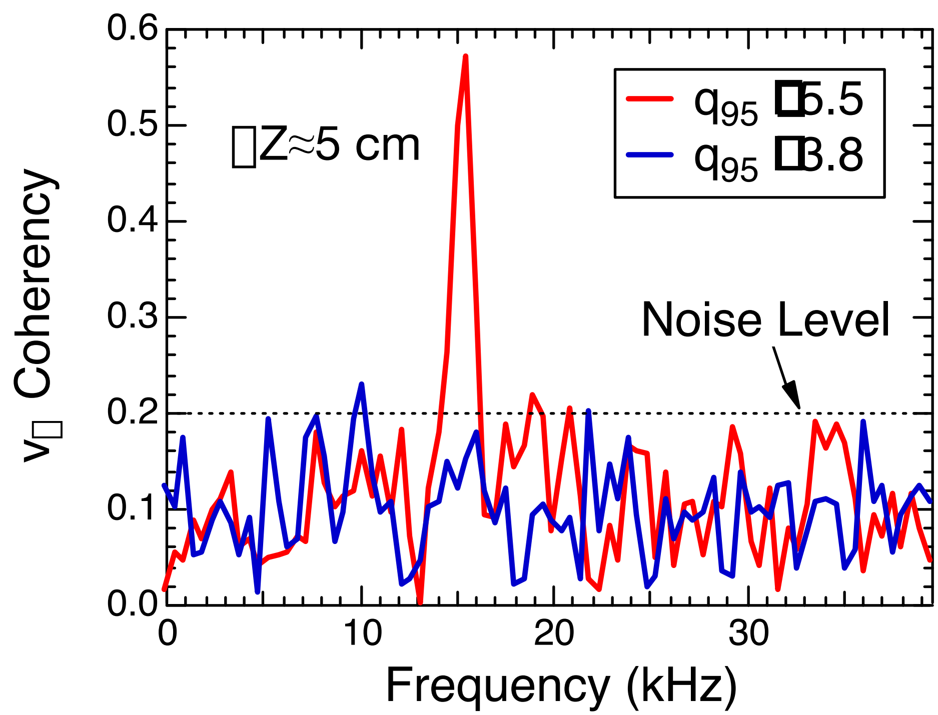
- Qualitatively consistent with theoretical damping rate:

  $$\gamma_{damp} = \omega_{GAM} \exp(-q^2)$$

  [Hinton, Rosenbluth, PPCF, 1999]

- Requires further systematic experimental study for validation

Coherency of poloidally-separated $v_\theta(t)$ measurements



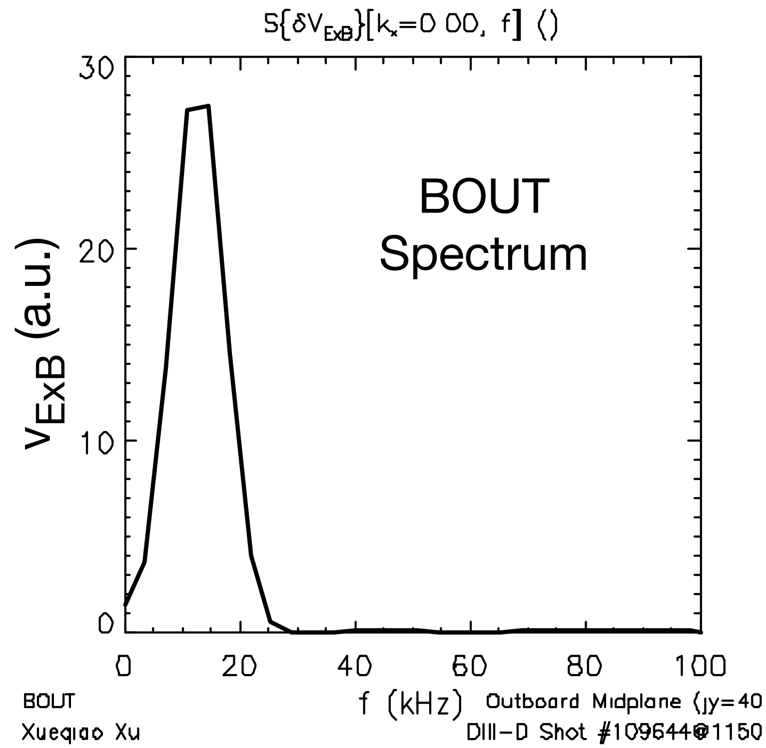
Suggests that GAM amplitude reduced at lower q_{95}

BOUT SIMULATION EXHIBITS GEODESIC ACOUSTIC MODE AT SIMILAR FREQUENCY TO MEASURED V□ OSCILLATION

- BOUT models boundary-plasma turbulence with modified 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)



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

- BOUT models boundary-plasma turbulence with modified Braginskii equations in realistic geometry
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- Coherent GAM observed in simulation as m=0, localized potential fluctuation

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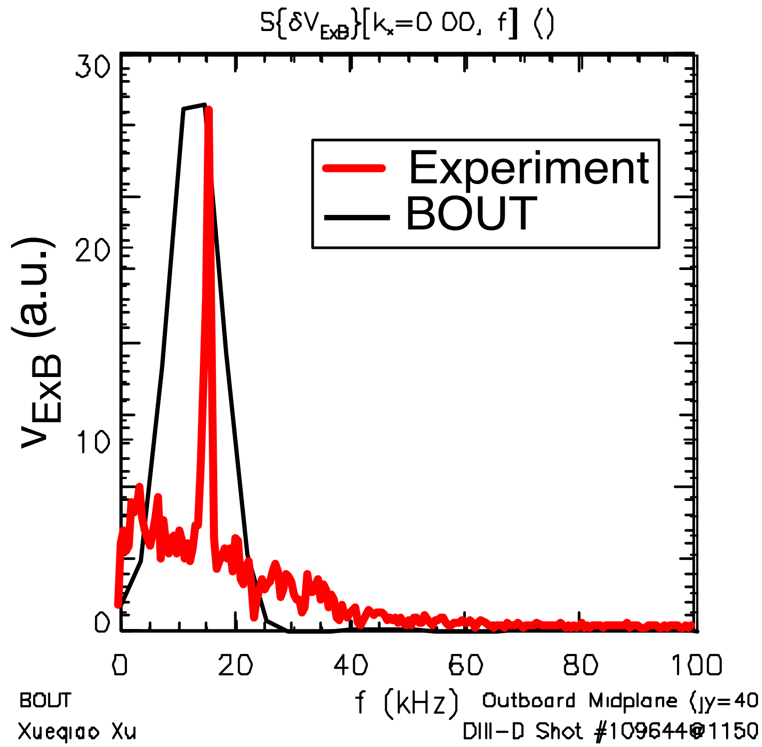
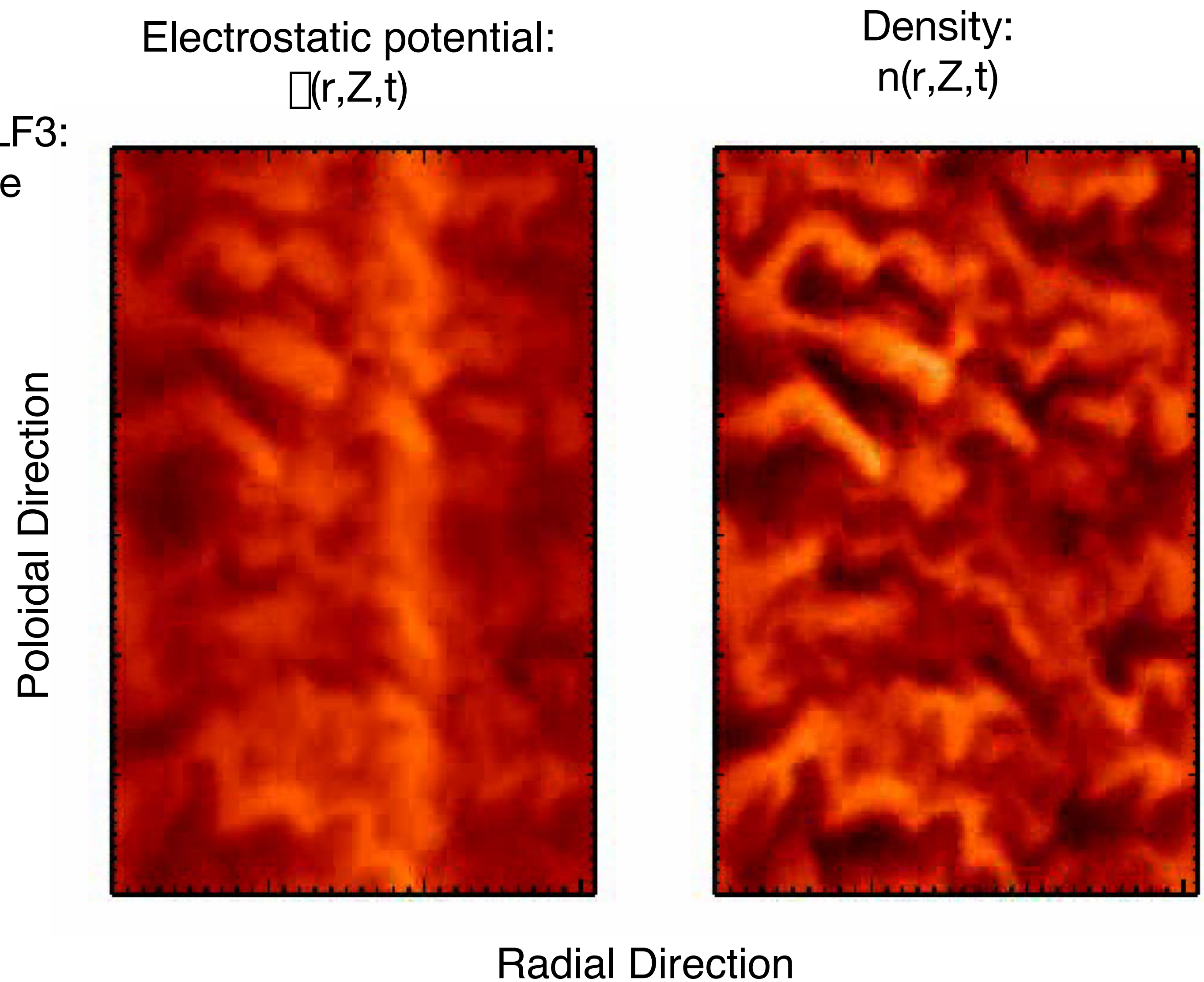


DALF3 Turbulence Simulation Illustrates Density Turbulence Oscillation with GAM

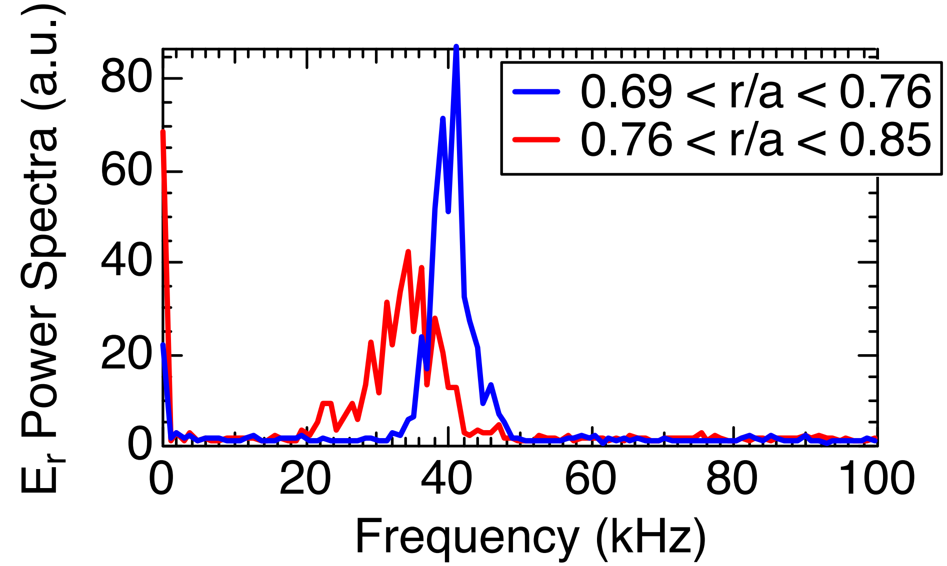
- Drift Alfvén code, DALF3: nonlinear, 3D flux-tube fluid simulation of boundary turbulence
- GAMs observed, interact strongly with turbulence
- Density turbulence observed to oscillate with GAM



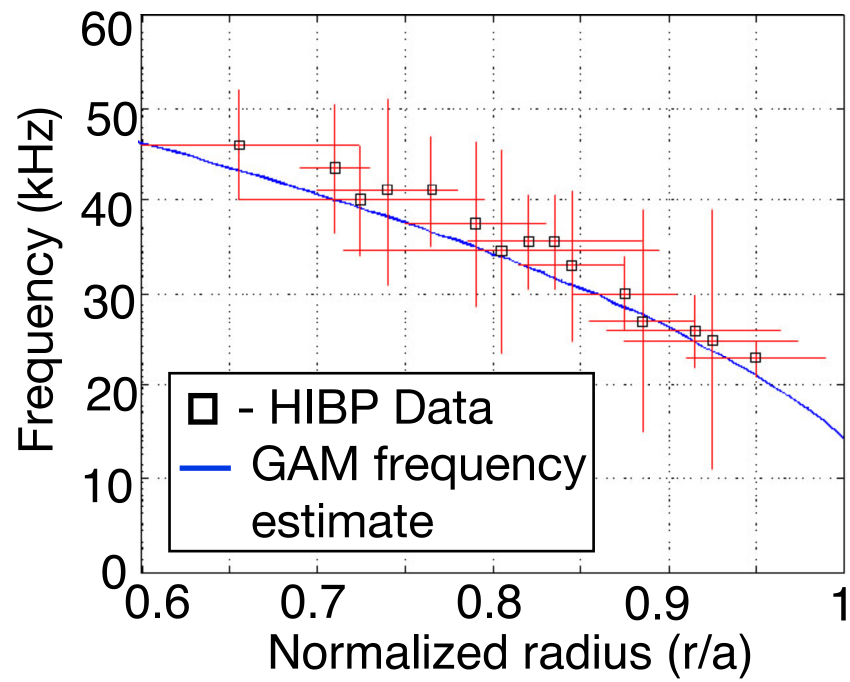
Courtesy: M. Ramisch, U. Stroth, *University of Kiel*
B. Scott, *Max Planck Institut für Plasmaphysik*

Potential Oscillation Observed in TEXT Tokamak with HIBP: Also Exhibits "GAM" Temperature Scaling Properties

- Heavy Ion Beam Probes measures □ and ñ fluctuations
- Radially-localized electrostatic mode
  - Little associated density fluctuation
- m=0 mode
  - Poloidally-separated multi-point measurements
- Frequency scales as Geodesic Acoustic Mode



□ mode vs. GAM frequency



Reference

P.M. Schoch, K.A. Connor, D.R. Demers, X. Zhang, Rev. Sci. Instrum. **74**, 1846 (2003).

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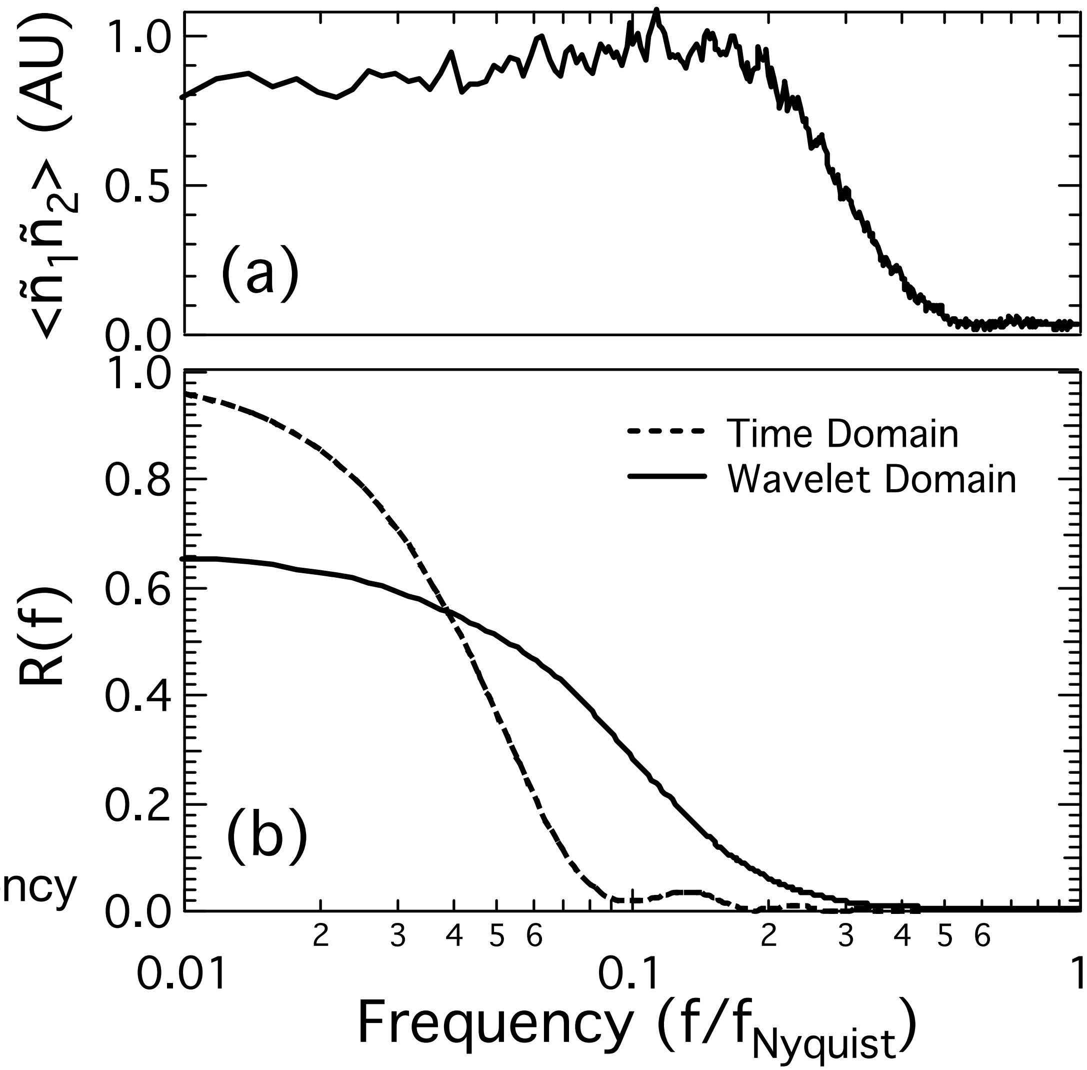
Summary and Conclusions

- 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 (~15 kHz); frequency scales with* $T_e + T_I$
  - *No measurable poloidal phase shift:* $|m| < 2$
  - *180° radial shift over 3 cm*
  - $\square_s \sim 1/\square_c$ *: may modulate turbulence amplitude*
  - *Possible safety factor dependence: GAMs weaken at lower q?*
  - *Similar zonal flow (GAM) characteristics observed HIBP data from TEXT*
- BOUT simulations:
  - *Predicts geodesic acoustic mode at similar frequency to measurement*

Zonal flows (GAMs) observed in DIII-D, exhibit features consistent with simulations, and are a component of fully saturated turbulence state

TRANSFER FUNCTIONS FOR TIME-DELAY-ESTIMATION DERIVED VIA SIMULATION

- Relates measured (output) time delay to actual (input) time delay
- Strongly dependent on:
  - velocity magnitude
  - density spectrum
  - signal-to-noise ratio
- Iterative analysis procedure required quantify results
- Time-domain more sensitive at low frequencies, wavelet method exhibits higher frequency response



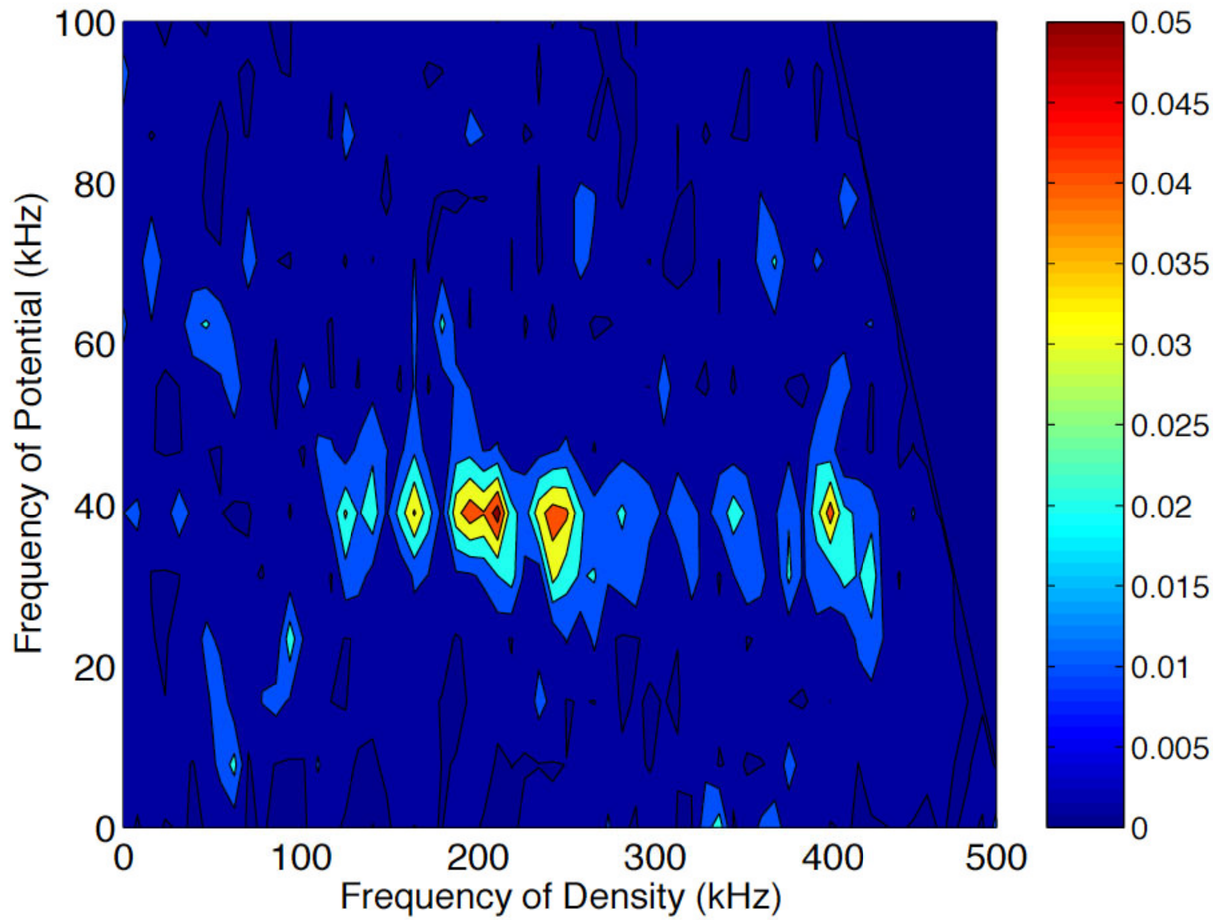
M. Jakubowski, Ph.D., Thesis U. Wisconsin (2003)

HIBP Data from TEXT: Finite Bicoherence Observed Between Density and Potential Near GAM Frequency

- Finite bicoherence between □ at “GAM” frequency and broad band n fluctuations

- Suggests nonlinear coupling of ñ fluctuations to GAM oscillation

Bicoherence between density and potential fluctuations



$$b^2(f_1, f_2) = \left\langle \frac{\left| N_e(f_1)\,\Box\,(f_2) N_e^*(f_1 + f_2) \right|^2}{\left| N_e(f_1) \right|^2 \left|\,\Box\,(f_2)\right|^2 \left| N_e(f_1 + f_2) \right|^2} \right\rangle$$

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ZONAL FLOW BEHAVIOR INFERRED FROM EXPERIMENTAL OBSERVATIONS

- Measurements of radially propagating density fluctuations with $k_{\square} \sim 0$ obtained with Phase Contrast Imaging at DIII-D
  - S. Coda S, M. Porkolab, K. H. Burrell, Phys. Rev. Lett. **86**, 4835 (2001).

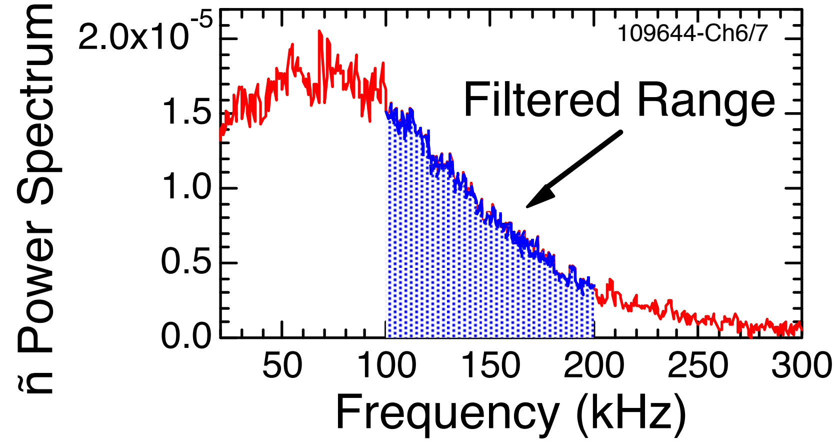
- Increased Reynolds Stress gradient prior to poloidal accelerations and improved confinement regime from edge probe measurements
  - Y. Xu *et al.*, Phys. Rev. Lett. **84**, 3867 (2000)

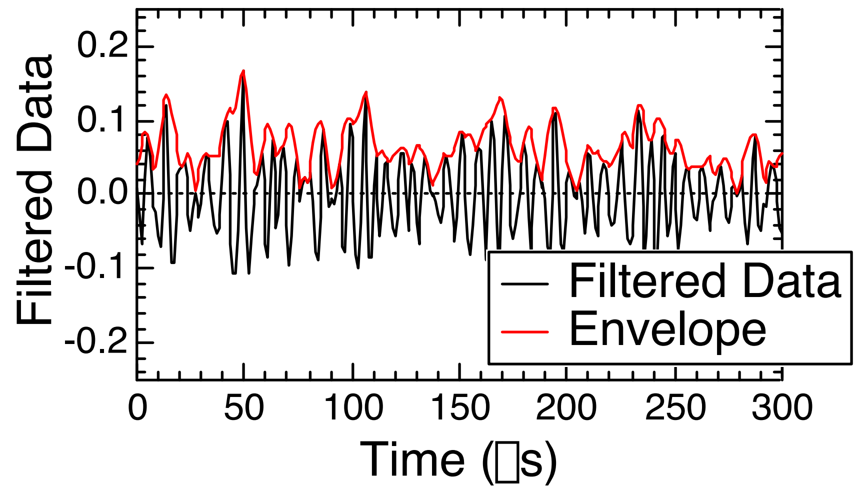
- Increased Bicoherence prior to LH Transition suggestive of Reynolds Stress, a zonal flow driving mechanism, from edge probe measurements:
  - P. Diamond *et al.*, Phys. Rev. Lett. **84**, 4842 (2000)
  - R. Moyer *et al.*, Phys. Rev. Lett. **87**, 135001-1 (2001)
  - G. Tynan *et al.*, Phys. Plasmas **8**, 2691 (2001)
  - C. Holland, IAEA 2002

- Poloidally symmetric (m=0) flows/potential fluctuation nonlinearly coupled to fluctuations in H-1 Heliac from probe measurements
  - M. Shats *et al.*, Phys. Rev. Lett. **88**, 045001-1 (2002)

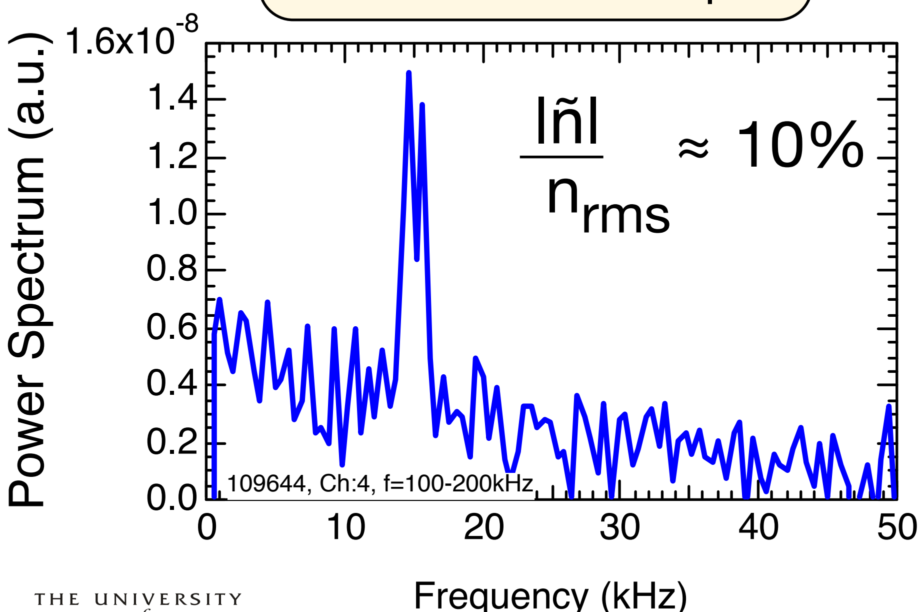
V□ OSCILLATION MODULATES TURBULENCE AMPLITUDE

- Density fluctuations frequency—filtered: 100 < f < 200 kHz (f >> v□)
- Amplitude envelope evaluated; power spectrum determined
- Lower frequency fluctuations show modest but less effect from v□ oscillation





Power Spectrum of Fluctuation Envelope



- Suggests energy exchange between waves/fluctuations and GAM flow

(Diamond et al., Nuclear Fusion 2002)