Measurements of the Spatial Structure of Geodesic Acoustic Modes in DIII-D

Presented by

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In collaboration with
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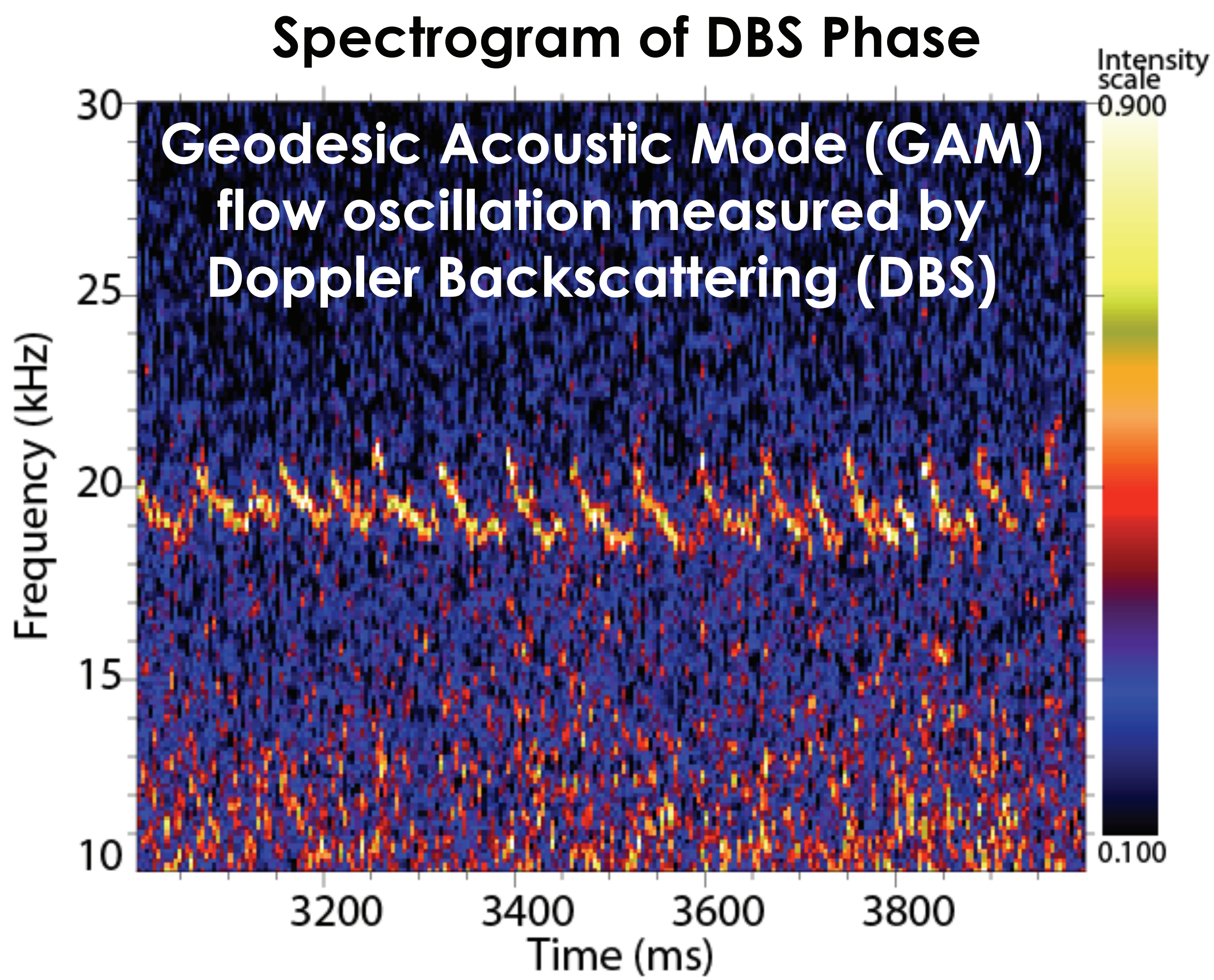

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

US DEPARTMENT OF ENERGY Fusion Energy Sciences Fellowship and Postdoctoral Programs

UCLA

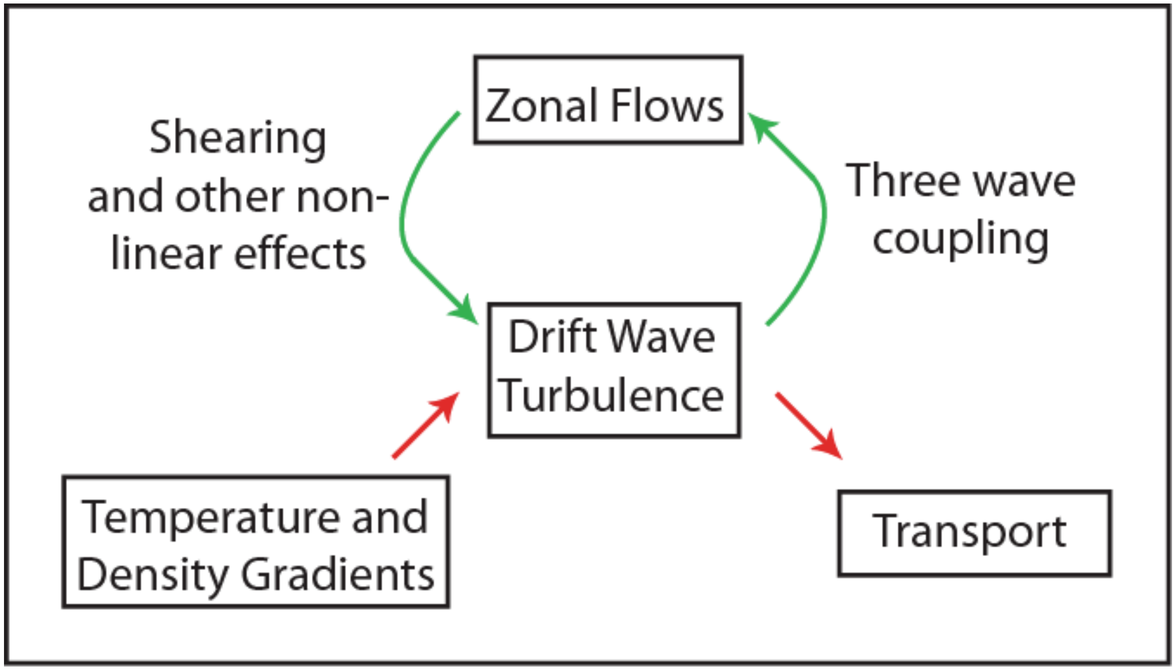
Long-Range Toroidal Correlations Associated with the GAM have been Measured in DIII-D

- **Unique data set from two multichannel DBS systems separated toroidally by 180°, simultaneously measuring GAM flow oscillations in the core of an L-mode plasma**
  - The channels probe 7 radial locations spanning ~2 cm

- **Experimental measurements show long-range (~7 m) toroidal correlations in the flow with high coherency**
  - Demonstrates the coherent toroidal nature of the GAM

- **Outward radial propagation of the GAM observed and wavelength measured**

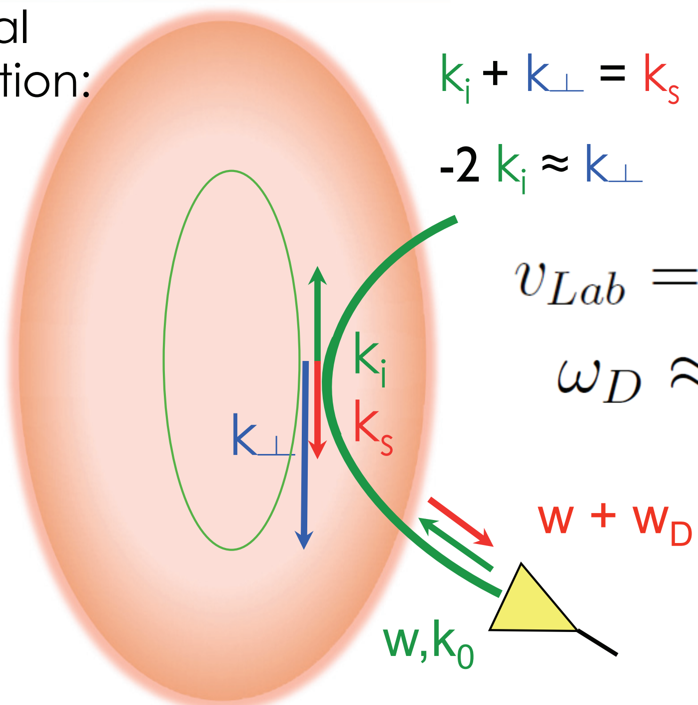
GAMs can Play an Important Role in Establishing the Saturated Level of Turbulence in Fusion Plasmas



- **Zonal flows play an important role in establishing the saturated turbulence level**
- **GAMs are a high frequency type of zonal flow characterized by:**
  - m=0, n=0, finite k_r oscillating v_{ExB} flow with $\omega_{GAM} \approx \sqrt{2}\frac{c_s}{R}$
  - m=1, n=0 density perturbation, zero on midplane; can be driven at rational surfaces
    - See e.g. Theory: Winsor Phys. Flu. 1968, Gao POP 2008, Zonca EPL 2008, Hager POP 2009; Experiment: McKee POP 2003, Conway PPCF 2005, Ido PPCF 2006, Lan PPCF 2006, Melnikov PPCF 2006, Yan NF 2007, Cheng NF 2009, Silva PPCF 2009, and others

Principles of Doppler Backscattering

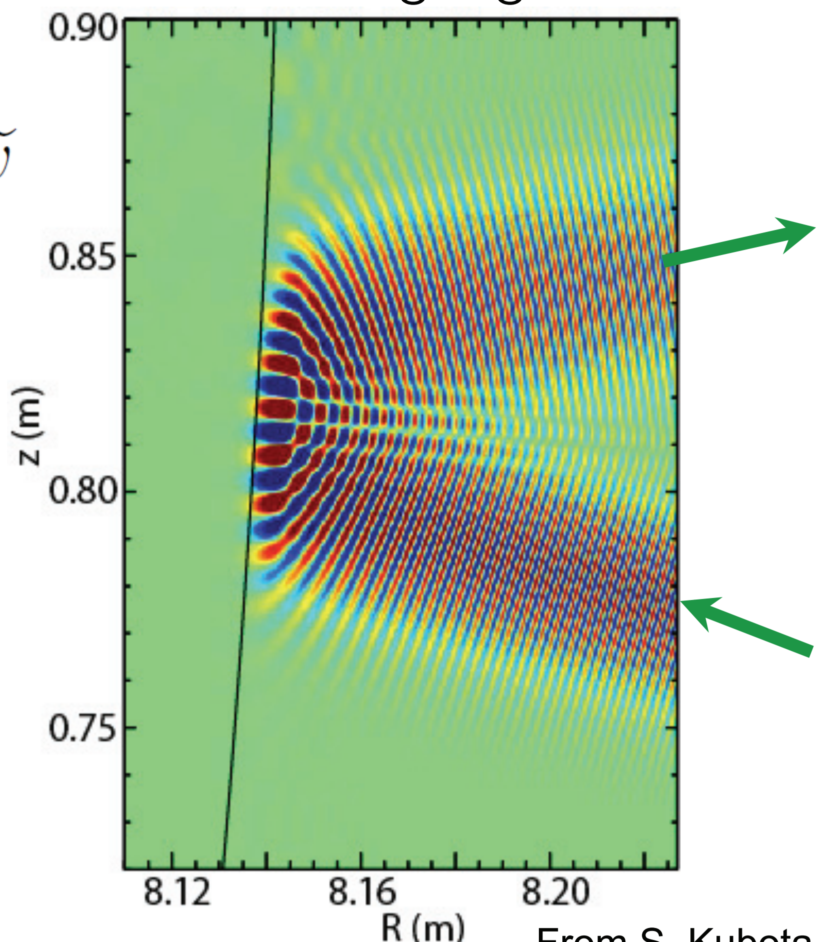
Poloidal Cross-section:



$$v_{Lab} = v_{E\times B} + \widetilde{v}$$

$$\omega_D \approx k_\perp v_{Lab}$$

Fullwave calculation focusing on scattering region:



From S. Kubota

- **DBS measures the *radially localized* propagation velocity and fluctuation level of intermediate-k turbulent structures**
  - Wavenumber range: $k_\perp \rho_i \sim 1\text{-}4$, $k_\perp \sim 2\text{-}15\ \text{cm}^{-1}$
  - Radial spatial resolution: Dr < 5 mm
  - Wavenumber resolution: $\Delta k_\perp / k_\perp \leq 0.4$

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For more on DBS see e.g. Holzhauer PPCF 1998, Hirsch PPCF 2001, Gusakov PPCF 2004; for DBS systems at DIII-D see Schmitz RSI 2008 and Hillesheim RSI 2009

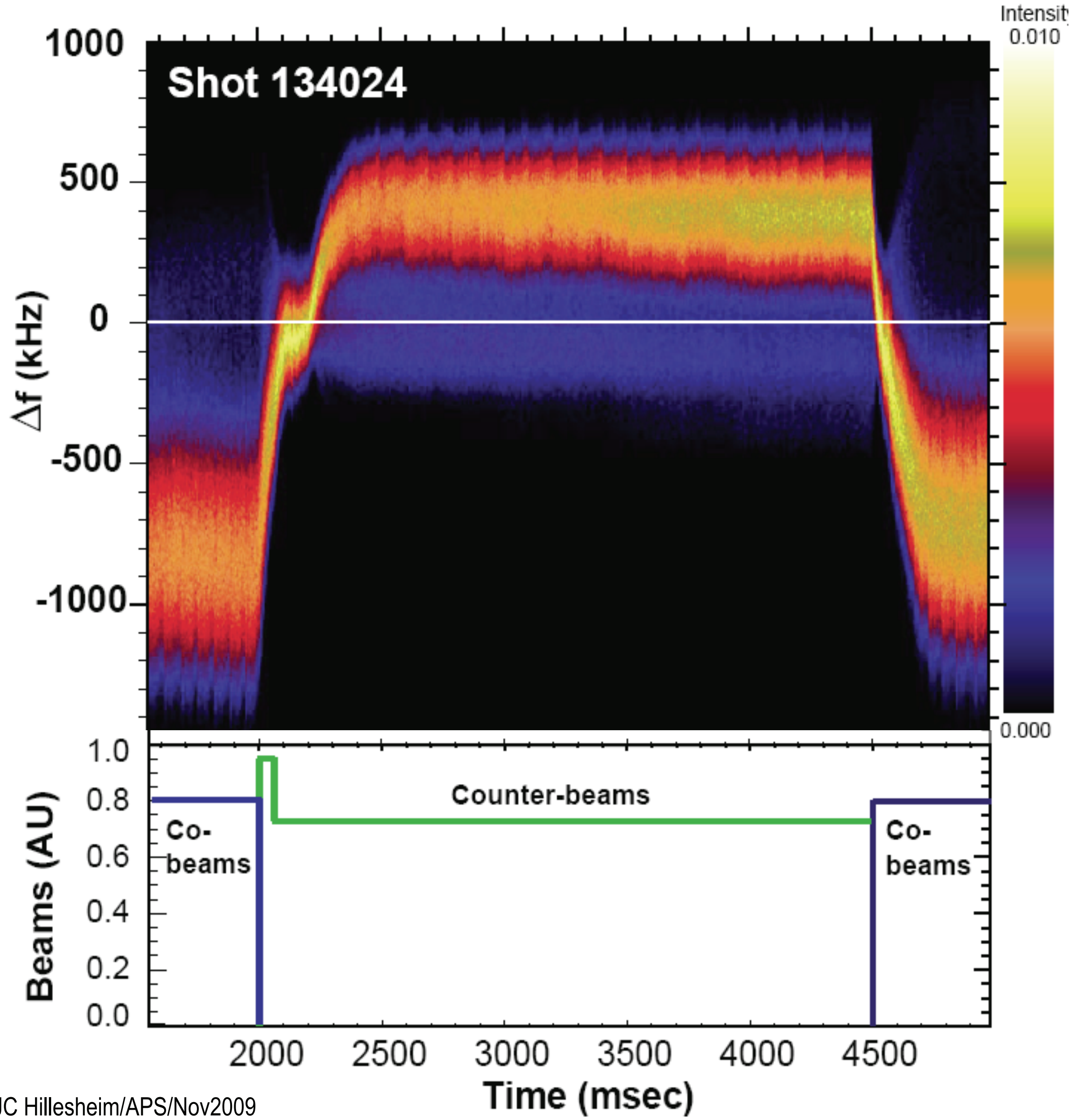
Doppler Backscattering can Measure the Propagation Velocity of Turbulence in the Laboratory Frame

- Propagation velocity of turbulent structures results in Doppler shift in lab frame:

$$v_{Lab} = v_{E\times B} + \widetilde{v}$$

$$\omega_D \approx k_\perp v_{Lab}$$

- Example of Doppler shift changing due to change in neutral beam injection



JC Hillesheim/APS/Nov2009

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Direct Analysis of DBS Phase for High Time Resolution Measurements of Flow Fluctuations

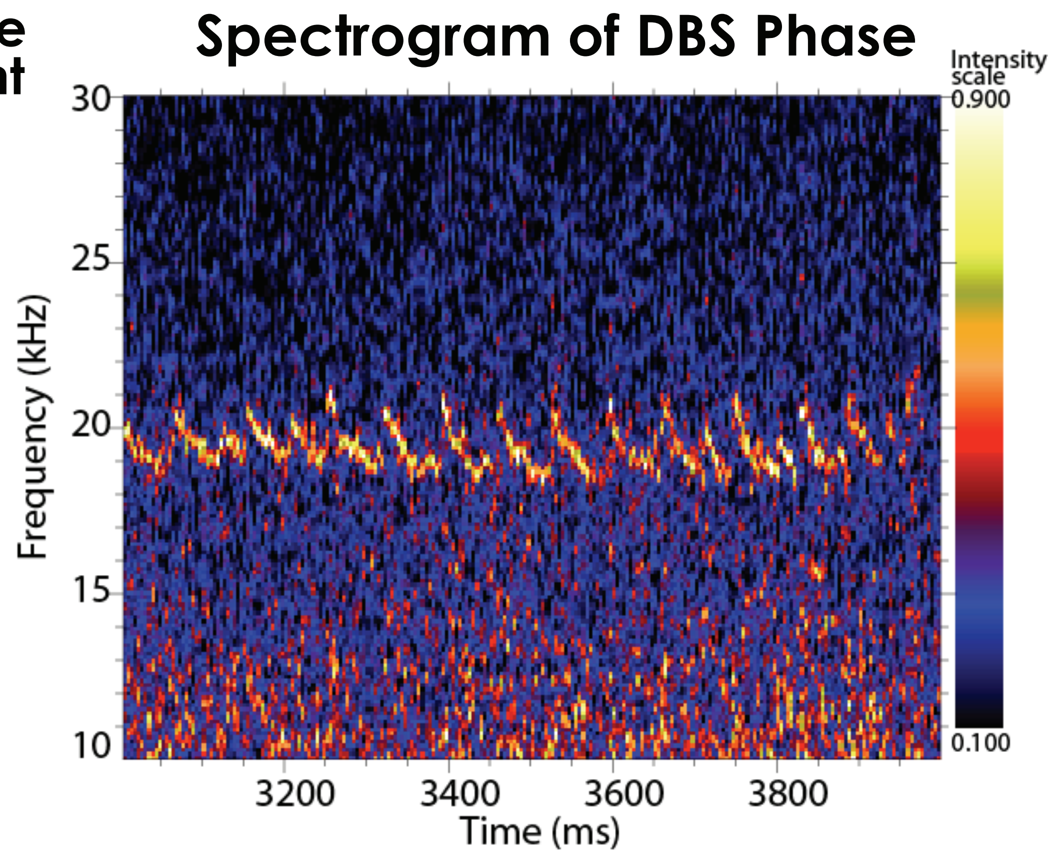
- **The phase (referenced to a signal at the launch frequency) of the backscattered electric field can be analyzed directly to study coherent flow oscillations such as GAMs**
  - To see this, assume the lab frame velocity is due only to the GAM:

$$v_{Lab} = v_{GAM} \cos\left(\omega_{GAM} t\right)$$

$$\omega_D = k_\perp v_{GAM} \cos\left(\omega_{GAM} t\right)$$

$$\varphi_{GAM}(t) = \frac{k_\perp v_{GAM}}{\omega_{GAM}} \sin\left(\omega_{GAM} t\right)$$

  - The Fourier transform of the phase will then be sharply peaked at the GAM frequency



Two toroidally Separated DBS Systems Used to Measure GAM Structure in an L-mode Plasma

- **Plasma conditions:**
  - Beam heated L-mode, B_T=2.2 T
  - At $\rho \approx 0.8$: T_e~600 eV, T_i~800 eV
- **DBS setup:**
- **Two multichannel DBS systems**
  - Separated by 180° toroidally, ~10° poloidally
  - 7 radially separated channels covering ~2 cm
    - 5 channels at one location, 2 at second location
- **Both aligned to measure:**
  - Near the midplane, where the GAM density perturbation is at a minimum
  - Intermediate-k density fluctuations ($k_\perp \approx 4$ cm^{-1}, $k_\perp \rho_i \sim 1$)
  - $\rho \approx 0.8$, Near q=2 surface, R ≈ 2.2 m

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Expected GAM Frequency Scaling Observed

- **GAM identified using DBS phase analysis**
- **Expected GAM frequency scaling:**

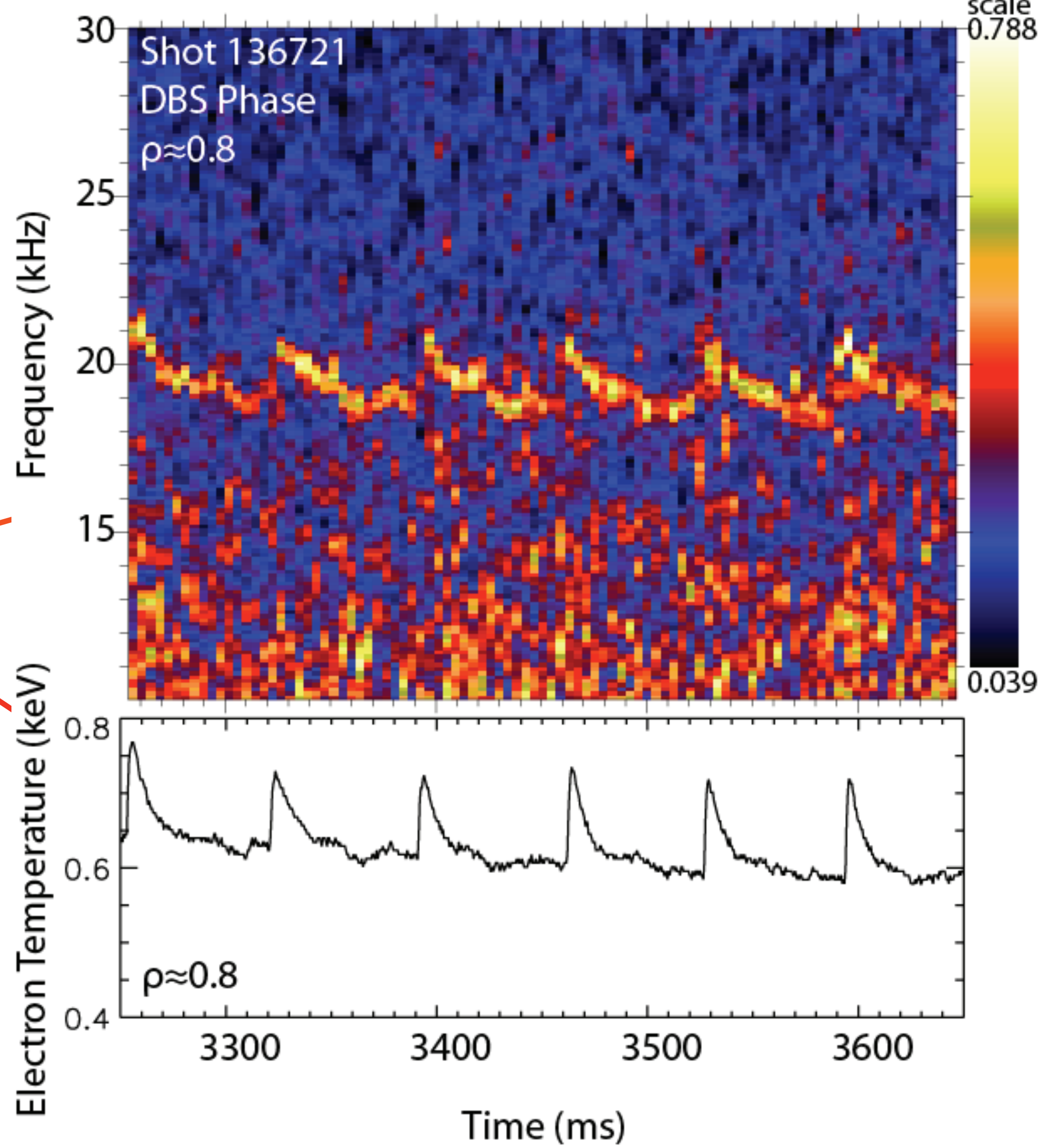
$$\omega_{GAM} \approx \sqrt{2}\frac{c_s}{R}$$

- **Coherent flow frequency varies with temperature pulse from sawteeth at $\rho \approx 0.8$**

$$f \,\tilde{\propto}\, \sqrt{T_e}$$

- **Measurement location for this work near q=2**
- **Nothing significant on magnetic coils or interferometer chords at these frequencies**

Spectrogram of DBS Phase



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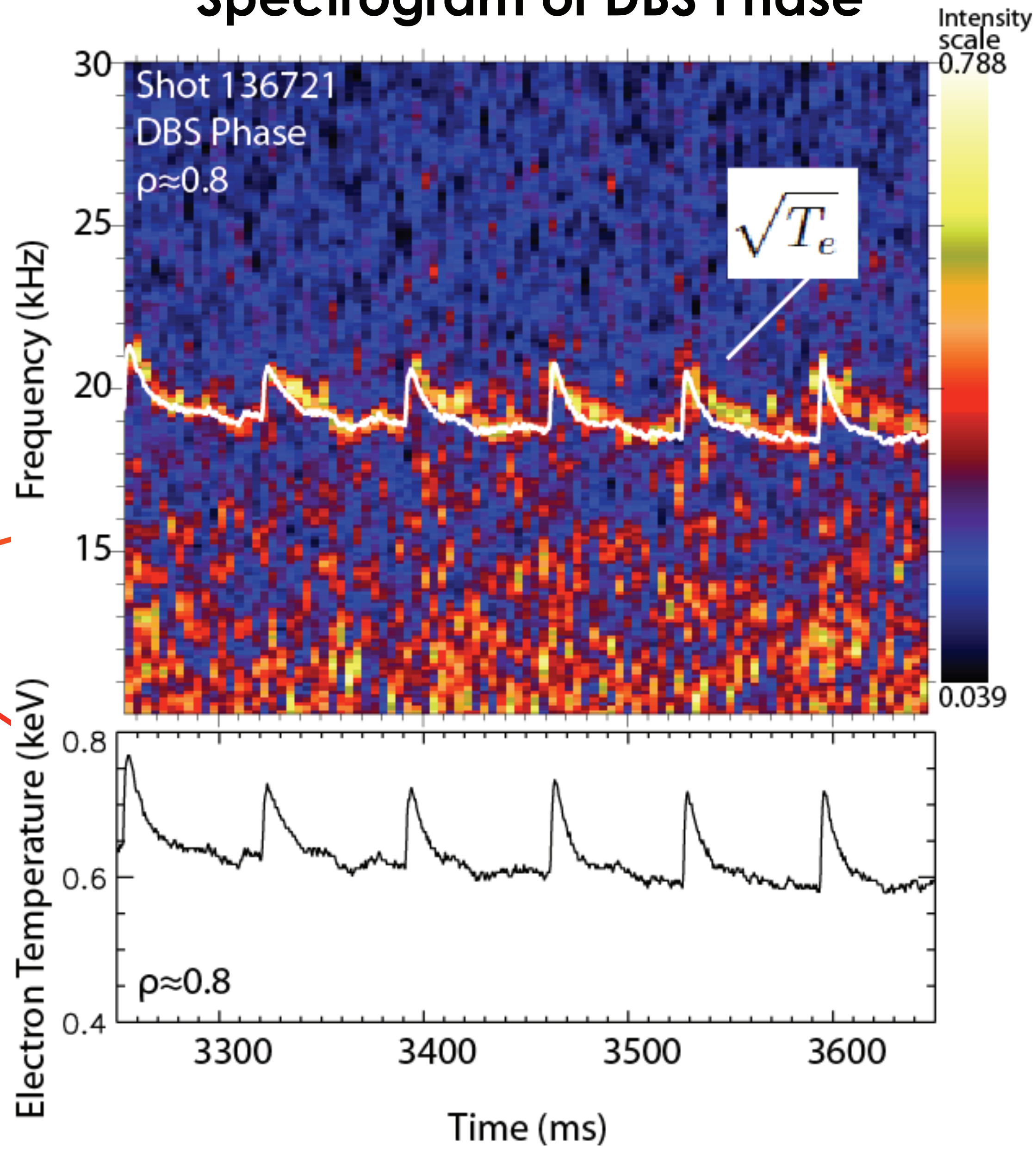

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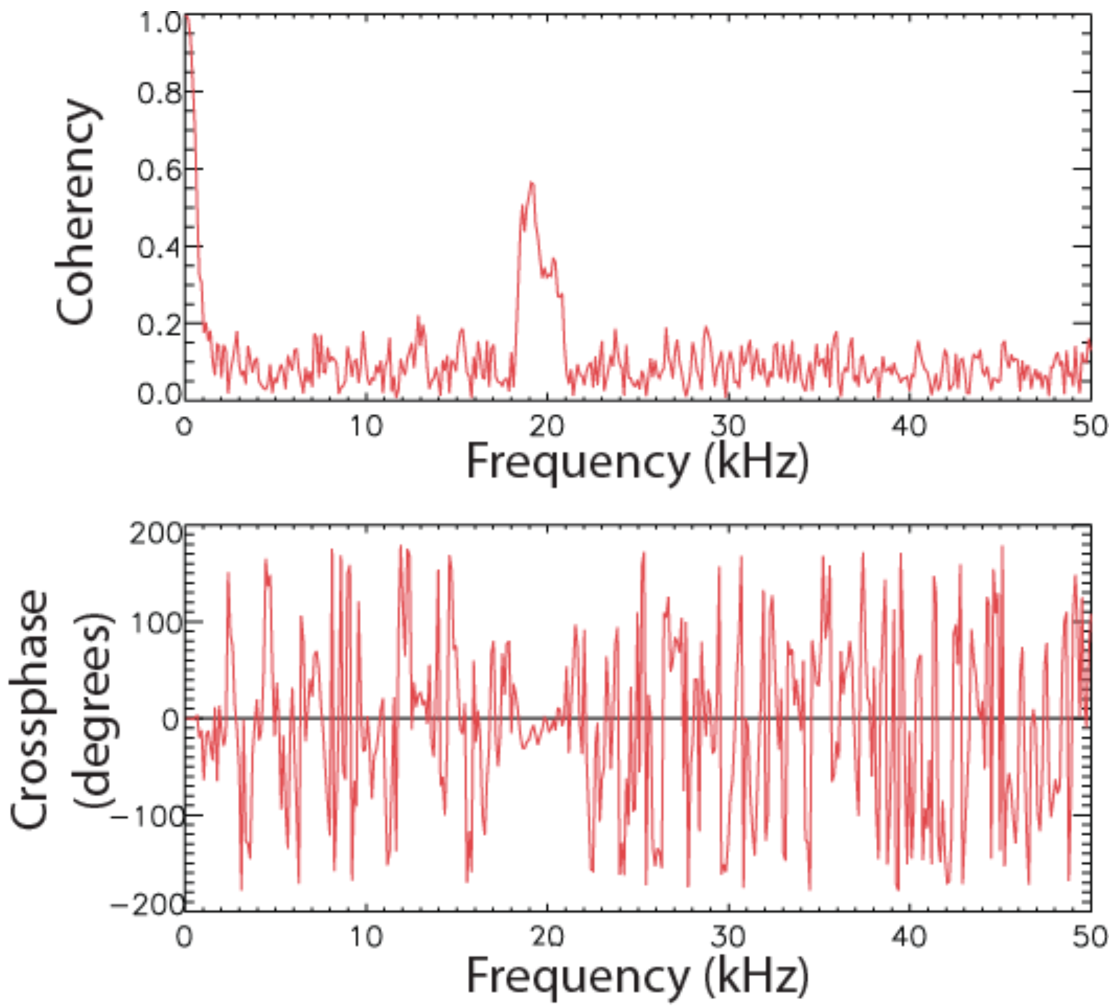
Long-Range Toroidal Correlation of GAM Flow Oscillations Observed

- GAM flow oscillation correlates 180° toroidally around the tokamak
  - Also separated by ~10° poloidally and nearly aligned radially (separation ~1 mm)
  - Observed toroidal phase angle small
- Width of peak is due to temperature perturbations from sawteeth
- Coherency ≥ 0.5 between any pair of channels
  - GAM radial correlation length greater than 2 cm

Correlation between the phase of two DBS channels separated by 180° toroidally:



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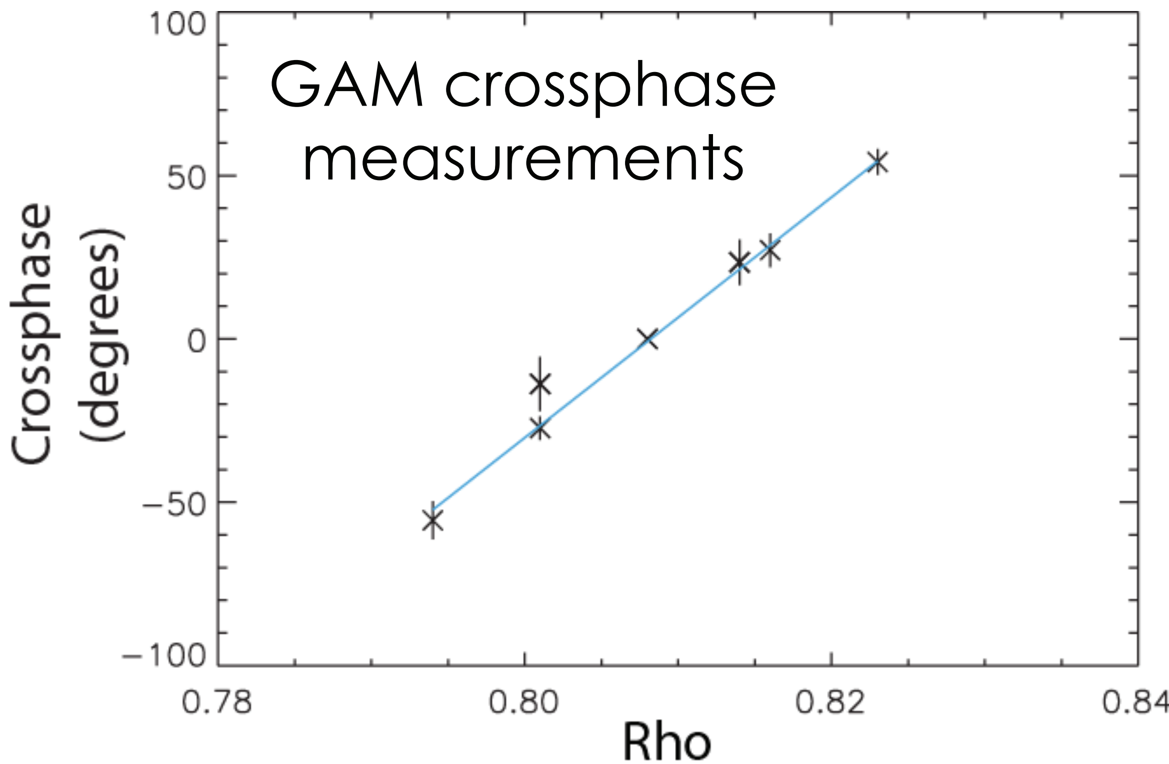
GAM Outward Radial Propagation Measured Using all 7 DBS Channels



$$\langle \theta_{xy}(\omega_{GAM}) \rangle_t = \mathbf{k} \cdot \mathbf{x} \approx k_r r$$

$$k_r = \frac{\Delta \theta_{xy}}{\Delta r} \Rightarrow \lambda_{GAM} \approx 2.7\ cm$$

- **Measured flow crossphase between channels indicates outward radial propagation and a radial wavelength of about 2.7 cm**
  - Propagation direction consistent with theory and previous experiments
  - Measured wavelength consistent with expected characteristic length scale L_{GAM} ~1.2 cm, consistent with other experiments
    - See e.g. Gao POP 2008, Zonca EPL 2008, Hager POP 2009, Melnikov PPCF 2006, Silva PPCF 2009, Ido PPCF 2006, Yan NF 2007

Summary of Results

- **Long-range (~7 m) flow correlations associated with the Geodesic Acoustic Mode measured between two locations separated by 180° toroidally and ~10° poloidally in the core of an L-mode plasma**
  - Demonstrates the coherent toroidal nature of the GAM in fusion plasmas

- **Measurements consistent with theoretically expected GAM attributes:**
  - Axisymmetric m=0 and n=0 flow structure
  - Finite k_r radial flow structure with outward propagation
  - Magnitude of measured radial wavelength