Characterization of Zonal Flows and Their Dynamics in the DIII-D Tokamak, Laboratory Plasmas, and Simulation

by
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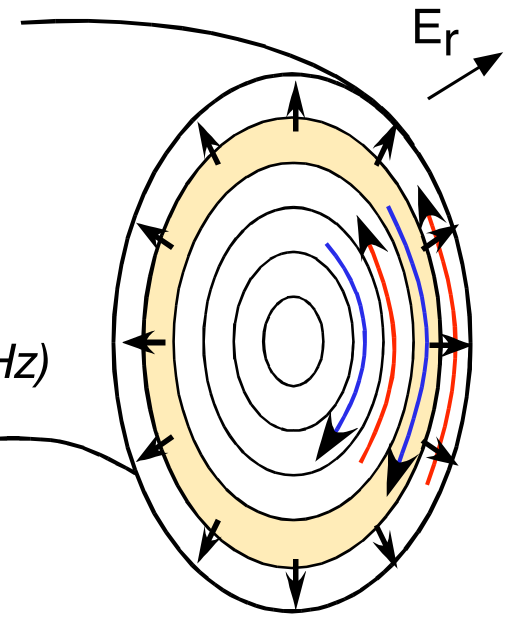
Overview and Motivation

- **Zonal flows are a central element of drift-wave turbulence from theory and simulation**
  - *Zero-mean-frequency zonal flow (ZMF-ZF) detected in the core of a high-temperature tokamak plasma for the first time*
  - *Method: Spatio-temporal analysis of multipoint, high-sensitivity Beam Emission Spectroscopy density fluctuation measurements*
  - *Transition from zero-mean-frequency zonal flow in core to Geodesic Acoustic Mode (GAM)-dominated spectrum near plasma edge*
- **Geodesic Acoustic Mode scales strongly with safety factor, q_{95}**
  - *Consistent with theory and simulation*
- **GAM is shown to interact nonlinearly with ambient turbulence:**
  - *Mediates a forward cascade of energy to higher frequency*
- **Turbulence-driven zonal flow observed in Controlled-Shear Decorrelation Experiment (CSDX), permitting detailed examination of nonlinear turbulence/zonal flow dynamics and comparison to simulation**

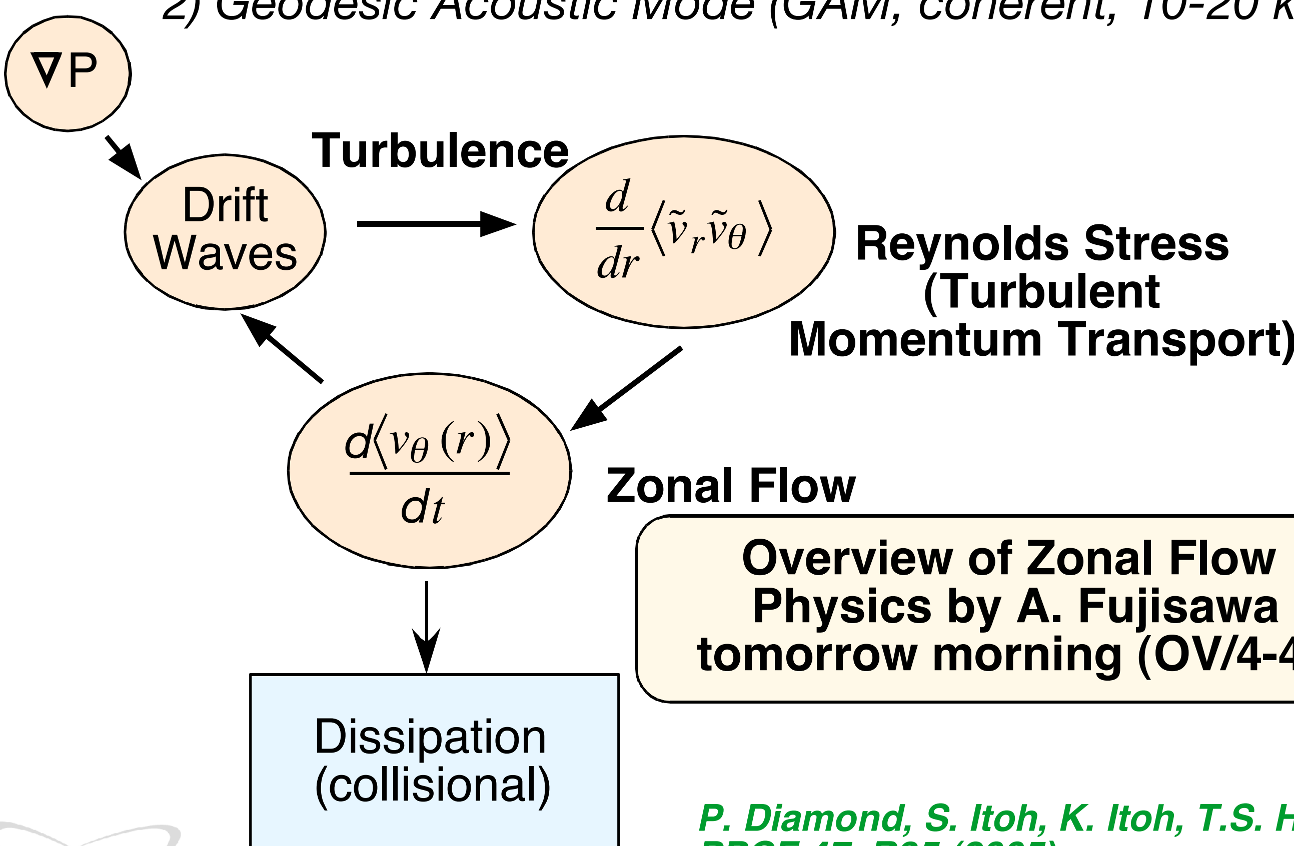
Zonal Flows Thought Crucial to Mediating Fully Saturated Turbulence in Plasmas

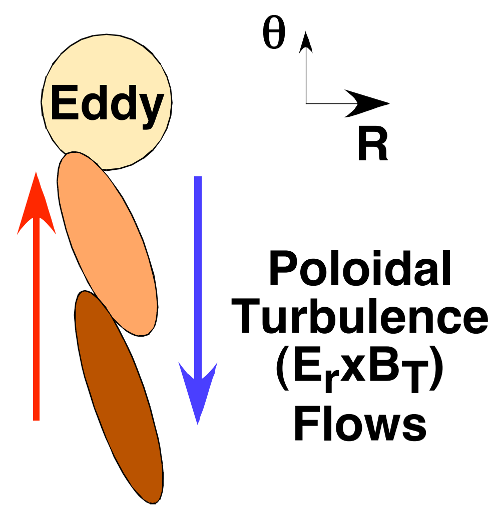


- **Regulate turbulence via fluctuating $E_r x B_T$ (v_θ) flows**
  - *Self-generated by turbulence via Reynolds stress*
  - *Observed in turbulence simulations*
- **Radially-localized, n=0, m=0, electrostatic potential**

  1) Zero-Mean-Frequency zonal flow(ZMF-ZF, $\Delta f \sim \nu_{ii}$ < 10 kHz)

  2) Geodesic Acoustic Mode (GAM, coherent, 10-20 kHz)





Overview of Zonal Flow Physics by A. Fujisawa tomorrow morning (OV/4-4)

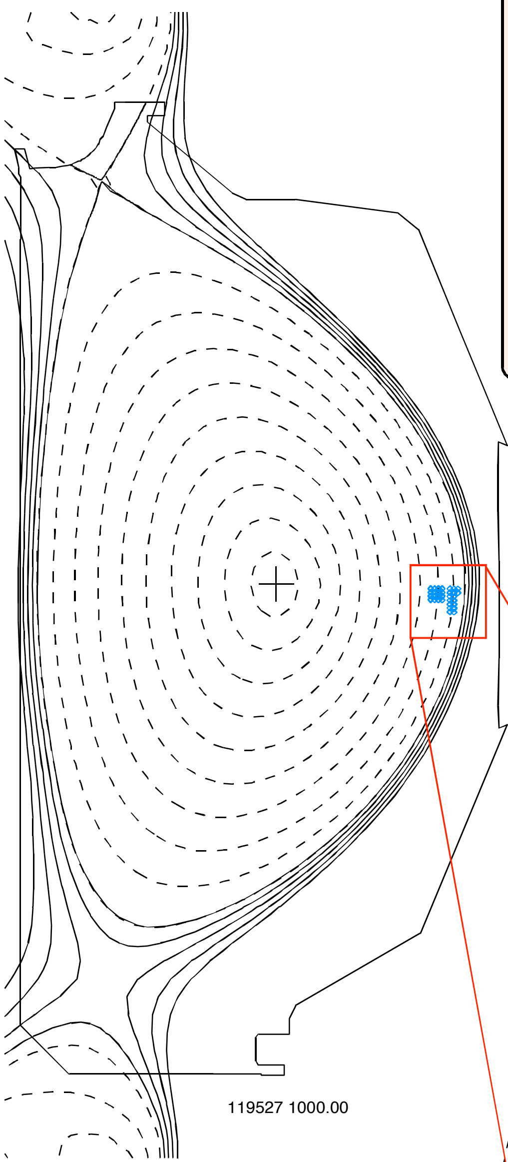
P. Diamond, S. Itoh, K. Itoh, T.S. Hahm, PPCF 47, R35 (2005).

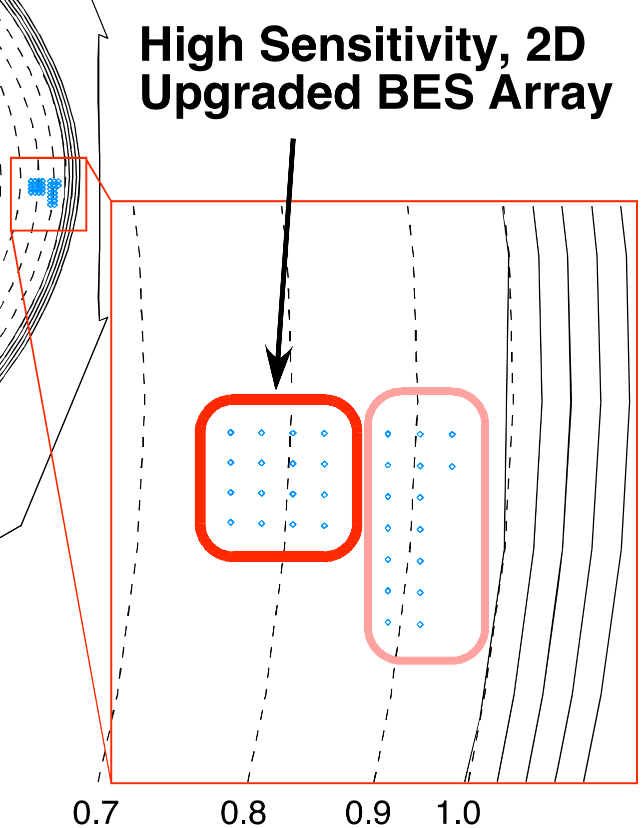
Beam Emission Spectroscopy Configured to Provide Zonal Flow Measurements via Turbulence Velocity Inference

- BES measures localized, long-wavelength ($k_\perp \rho_I < 1$) density fluctuations
- Radially scannable: $0.2 < r/a < 1.0$
- 2D (R,Z) 4x4 grid (now 5x6)

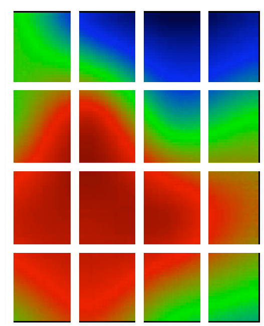
Measurement of ZF has been a challenge:

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



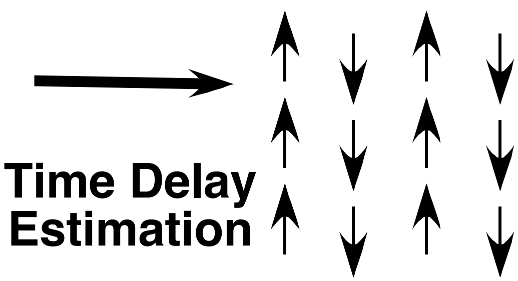


$\tilde{n}(r,z,t)$



Time Delay Estimation

$\tilde{v}_\theta(r,z,t)$



1) Time-resolved cross-correlation
2) Wavelets
3) Dynamic Programming

$$\tilde{v}_\theta(t) = E_r x B_T + \eta v_{dia}$$

Zonal Flow

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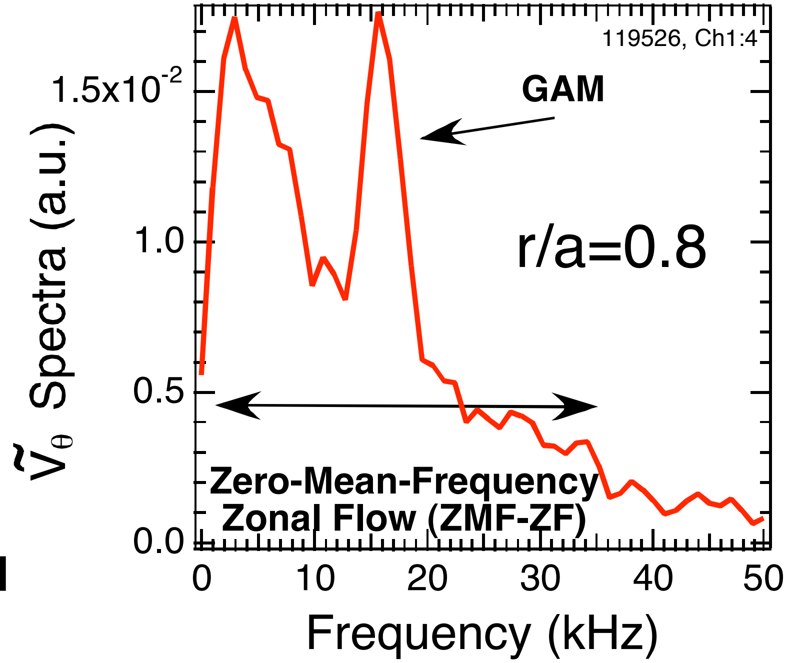
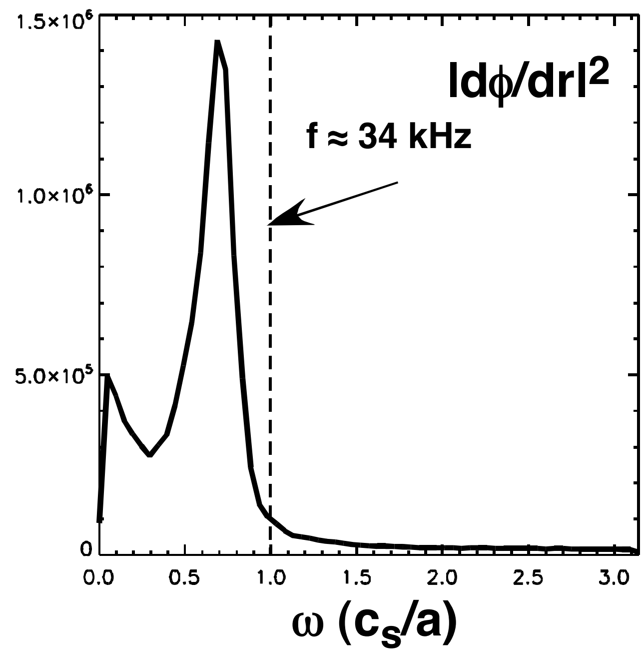
ZMF-Zonal Flow Signatures Observed in V_θ : First Detection in the Core of a High-Temperature Tokamak Plasma

- **Spectrum shows broad, low-frequency structure:**
  - *Peaks near zero frequency*
  - *Width, $\Delta f \sim 20$ kHz*
  - *Similar to theoretical predictions of zonal flow structures*
- **GAM also clearly observed near f = 15 kHz**
  - *Observed previously on DIII-D and other experiments (JFT-2M, ASDEX, HL-2A, JIPP-TIIU, CHS)*
- **GYRO simulation of zonal flow spectrum exhibits qualitative similarity to measured spectrum**



Poloidal velocity spectrum measured with BES



GYRO
(q=3,
flux tube,
kinetic
electrons)

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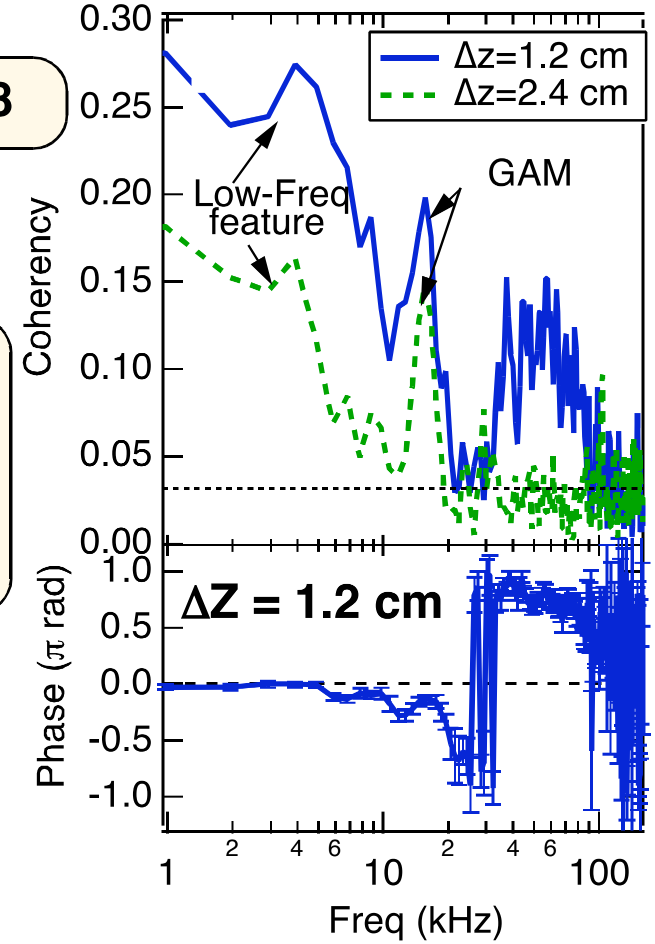
ZMF-Zonal Flow Exhibits Zero Poloidal and Radial Phase Shift, Consistent with Expectations

- **Spectra indicate broad, low-frequency structure with zero measurable phase poloidal shift:**
  - *Consistent with low-m (m=0?)*
- **Zero radial phase shift suggests random (turbulent) flow structure**
  - *Contrasts with GAM which has well-defined k_r, finite radial phase shift*

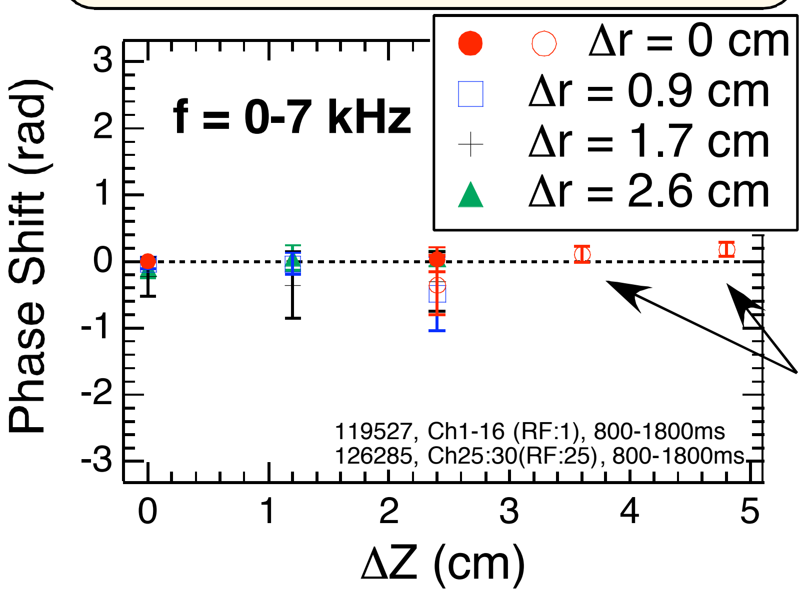
r/a=0.8

$\tilde{v}_\theta$ Spectra



Gupta et al., Phys. Rev. Lett. 97, 125002 (2006)

Phase Shift Measurements in R, Z Plane



Measurements with recently expanded 2D array

T.S. Hahm et al., PPCF 42, A205 (2000).

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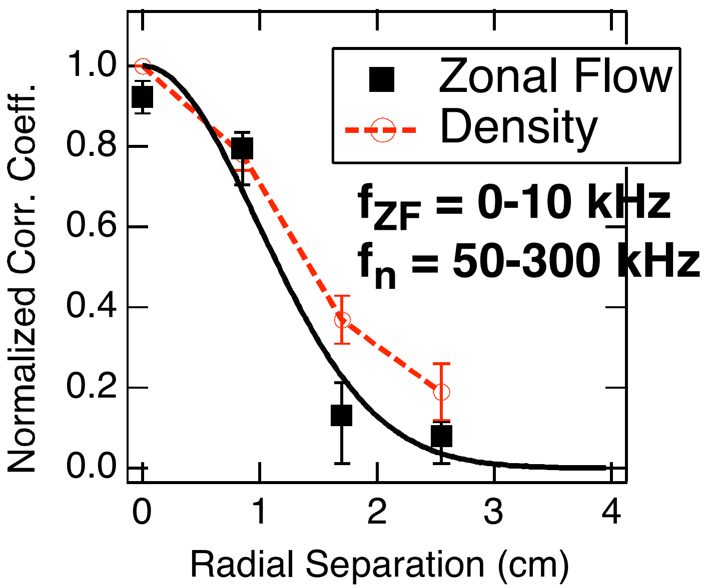
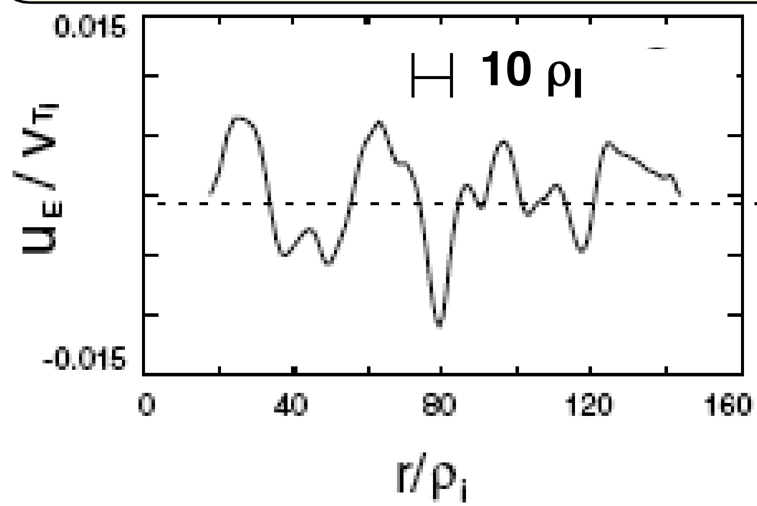
Zonal Flow Has Radial Correlation Length Similar to That of Density Turbulence

Radial Correlation function of ZMF-zonal flow and density fluctuations (BES)



- **Radial correlation length is of order 10 ρ_i, similar to radial correlation length of ambient density fluctuations**
- **Gyrokinetic simulation indicates similar structure scale size, ~10 ρ_i**
- **Consistent with zonal flow regulating radial scale size of ambient turbulence**

Simulation of Zonal Flow Structure



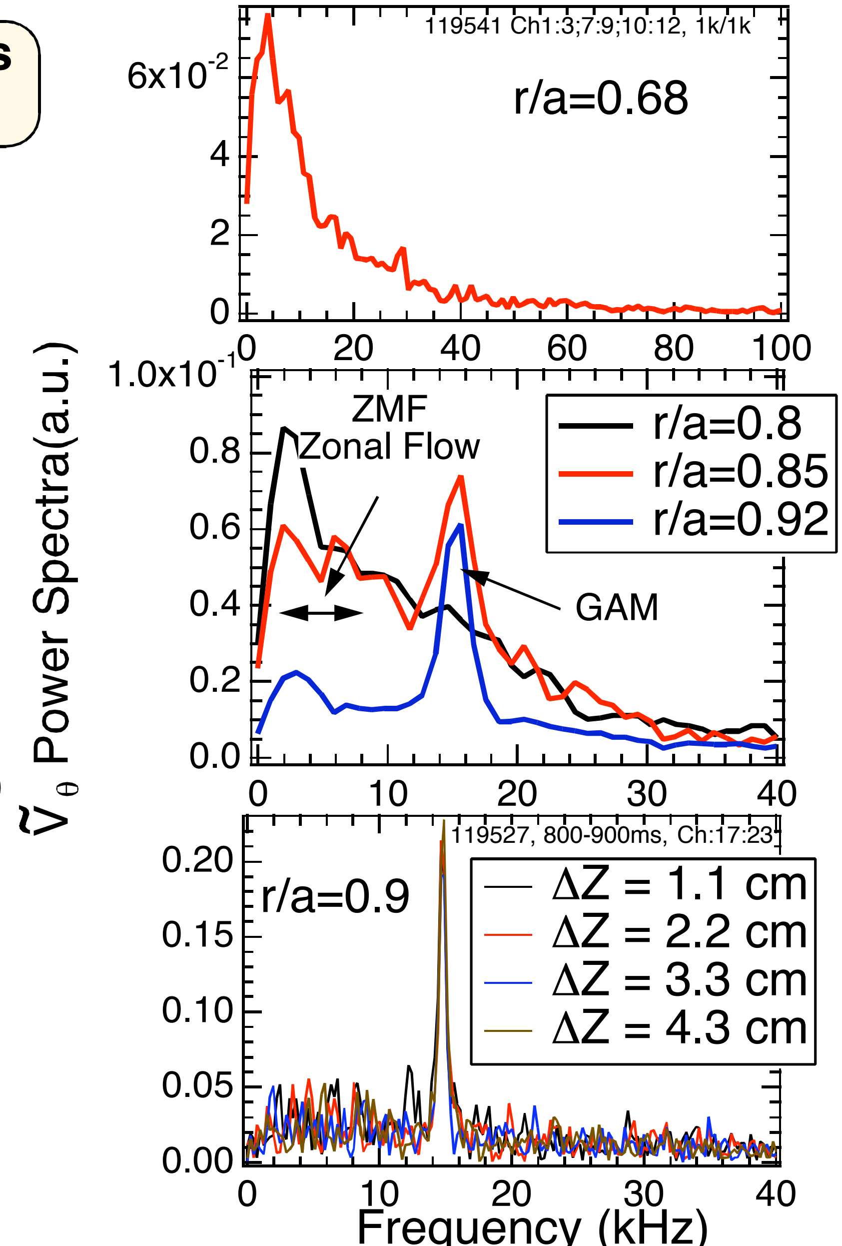
T.S. Hahm et al., PPCF 42, A205 (2000)

Transition from ZMF-Zonal Flow-Dominated Core Region to GAM-dominated Edge region

Measured v_θ Spectrum vs. Radius in L-mode Discharges

- **Velocity spectra exhibit broad ZMF-ZF spectrum for r/a < ~0.8**
- **Broad ZMF-ZF spectrum and GAM superimposed near r/a=0.85**
- **Geodesic Acoustic Mode dominates spectrum for r/a > 0.9**
- **Theory and simulation predict ZMF-ZF to dominate at lower q (core) while GAM dominates at higher q (edge)**
- **High coherence, f/Δf > 20, indicates GAM lifetime (τ_{GAM} > 1 ms), two orders of magnitude longer than turbulence decorrelation time:**

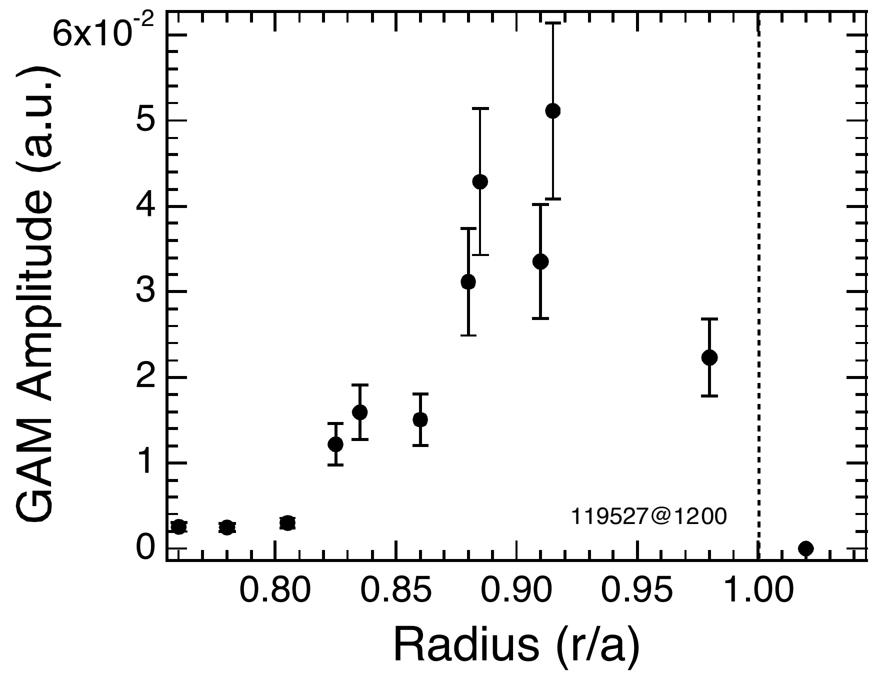
$$\tau_{GAM} >> \tau_{Turbulence} (\sim 10\ \mu s)$$



RADIAL STRUCTURE OF GAM PEAKS NEAR OUTER REGION OF PLASMA

- **GAM velocity oscillation amplitude peaks near r/a ~ 0.9-0.95**
  - *Decays near separatrix: GAM oscillation cannot be sustained on open field lines*
  - *Radial wavenumber $k_r \sim 1\ cm^{-1}$*
  - *Decays inboard, though still detectable to r/a ~ 0.75*
- **Conversely, zero-mean-frequency zonal flows are not observed near outer plasma region (r/a > ~0.9) yet increase towards core**

GAM Amplitude vs. Minor Radius



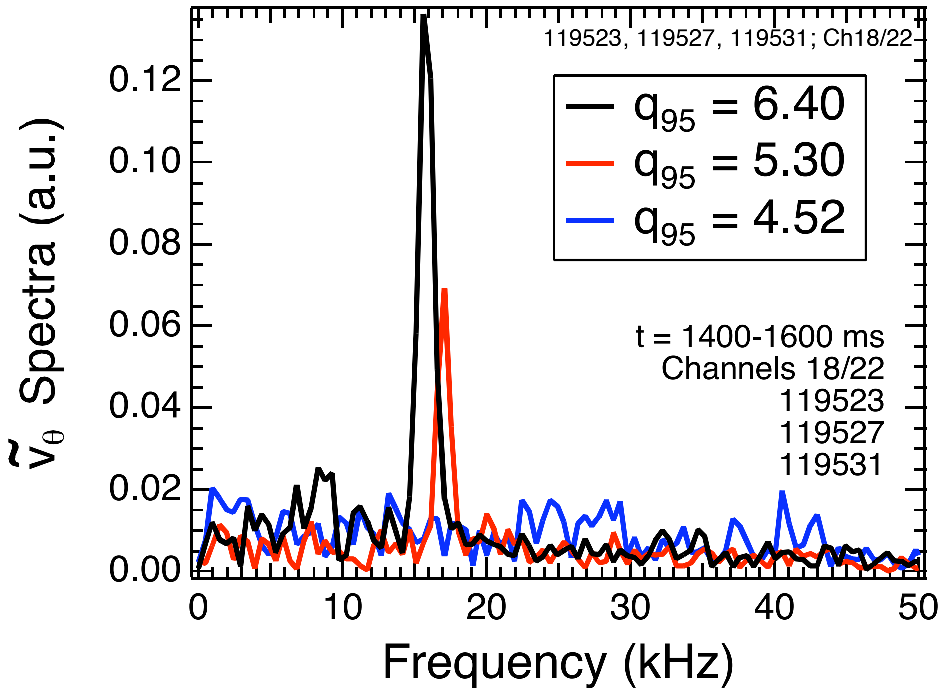
McKee et al., PPCF (2006).

Similarity to HIBP measurements on JFT-2M (Ido et al., PPCF 2006)

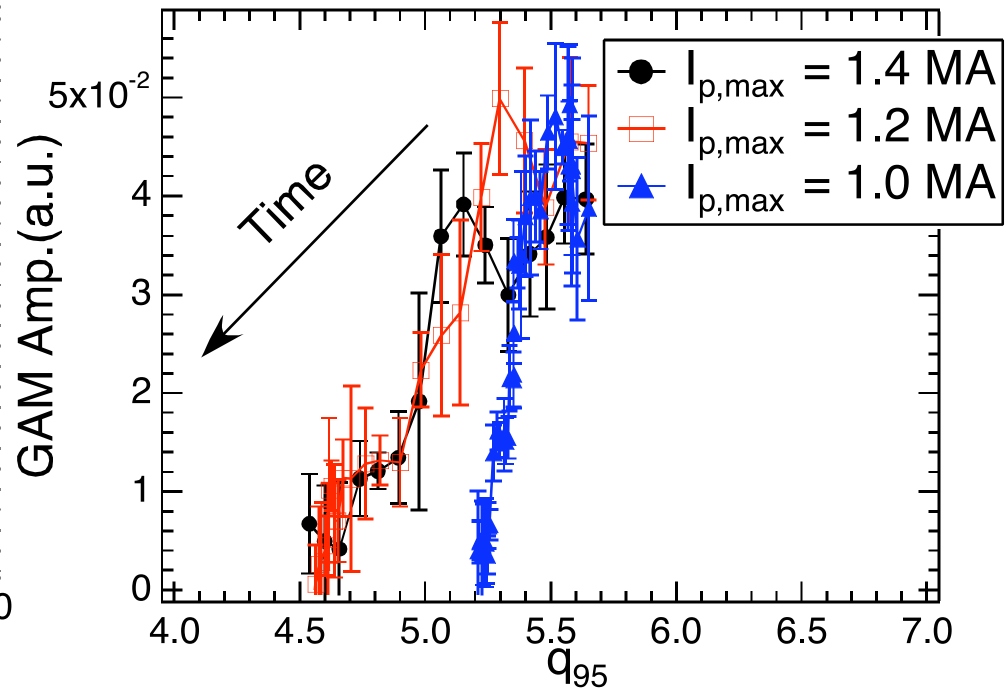
GAM Amplitude Increases Strongly with q_{95}

- q_{95} varied systematically via I_p scan in a set of discharges as other parameters held fixed

$\tilde{v}_\theta$ Spectra vs. q_{95}



GAM Amplitude vs. q_{95} & time



- GAM exhibits largest amplitude near $q_{95} = 6.4$, not observed for $q_{95} < 4.5$
- Consistent with ion Landau damping and GYRO simulations (Kinsey et al.)

$$\nu_{GAM} \approx \omega_{GAM} \exp(-q^2)$$

- Increased coupling to sound waves may also play a role

Hinton, Rosenbluth, Plasma Phys. Control. Fusion 41, A653 (1999)

Nonlinear Transfer of Energy Can be Measured Experimentally

- **Consider a simple model of density evolution**

$$\frac{\partial \tilde{n}}{\partial t} \approx -V_x \frac{dn_0}{dx} - V_x \frac{\partial \tilde{n}}{\partial x} - V_y \frac{\partial \tilde{n}}{\partial y} + D\nabla_\perp^2 \tilde{n}$$

$$x \rightarrow r$$

$$y \rightarrow r\theta$$

Holland et al., submitted to PRL

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$$\rightarrow \frac{1}{2}\frac{\partial \left\langle |\tilde{n}|^2 \right\rangle}{\partial t} = -\left\langle \Gamma_x \right\rangle \frac{dn_0}{dx} - \mathrm{Re}\left\langle \tilde{n}^* V_x \frac{\partial \tilde{n}}{\partial x} \right\rangle - \mathrm{Re}\left\langle \tilde{n}^* V_y \frac{\partial \tilde{n}}{\partial y} \right\rangle + D\left\langle |\nabla_\perp \tilde{n}|^2 \right\rangle$$

$$= -\left\langle \Gamma_x(f) \right\rangle \frac{dn_0}{dx} + \sum_{f'} T_n^X(f,f') + \sum_{f'} T_n^Y(f,f') + D\left\langle |\nabla_\perp \tilde{n}(f)|^2 \right\rangle$$

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Holland et al., submitted to PRL

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Coupling of flux to background density gradient (source)

Collisional dissipation of fluctuation energy (sink)

Nonlinear "three-wave" interactions which exchange energy between different space/timescales

$$T_n^X(f,f') = -\mathrm{Re}\left\langle \tilde{n}^*(f) V_x(f-f') \frac{\partial \tilde{n}}{\partial x}(f') \right\rangle$$

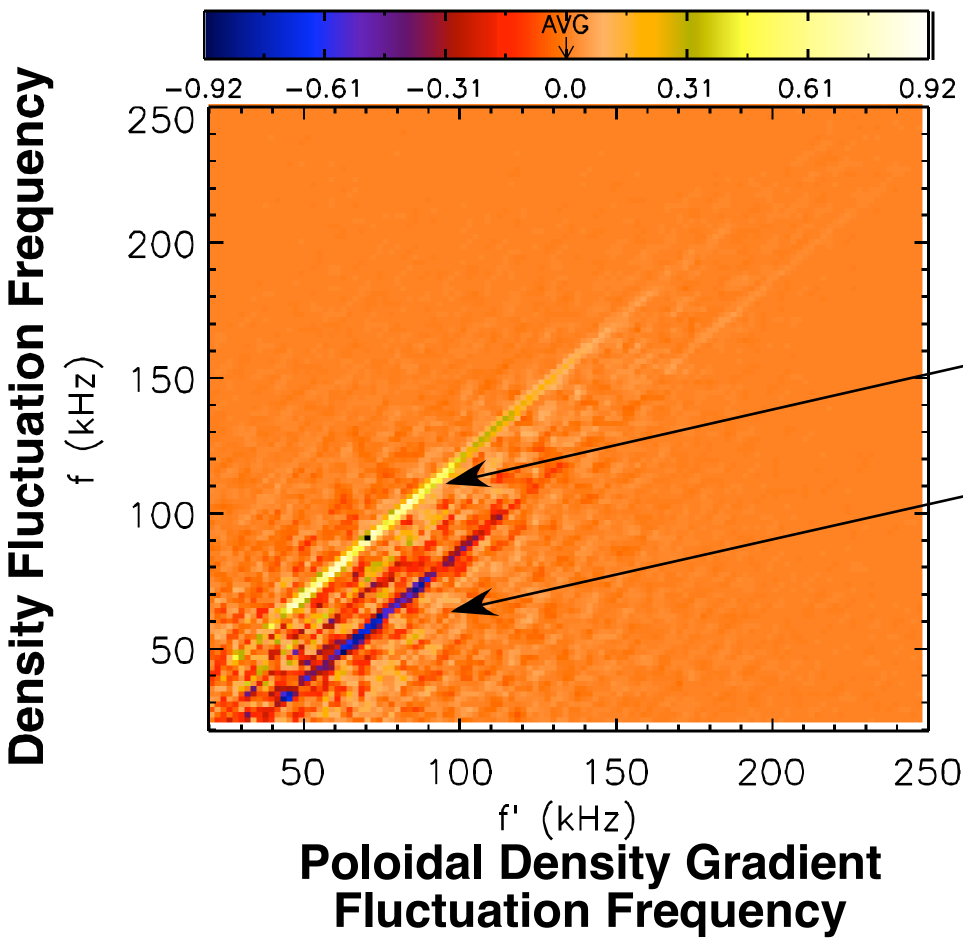
$$T_n^Y(f,f') = -\mathrm{Re}\left\langle \tilde{n}^*(f) V_y(f-f') \frac{\partial \tilde{n}}{\partial y}(f') \right\rangle$$

Holland et al., submitted to PRL

GAM Interacts Nonlinearly with Ambient Turbulence: Drives Forward Cascade of Energy to High Frequency

$$T_n^Y(f',f) = -\mathrm{Re}\left\langle n^*(f)V_y(f-f')\frac{\partial n}{\partial y}(f')\right\rangle$$

Bispectrum measures 3-wave interaction

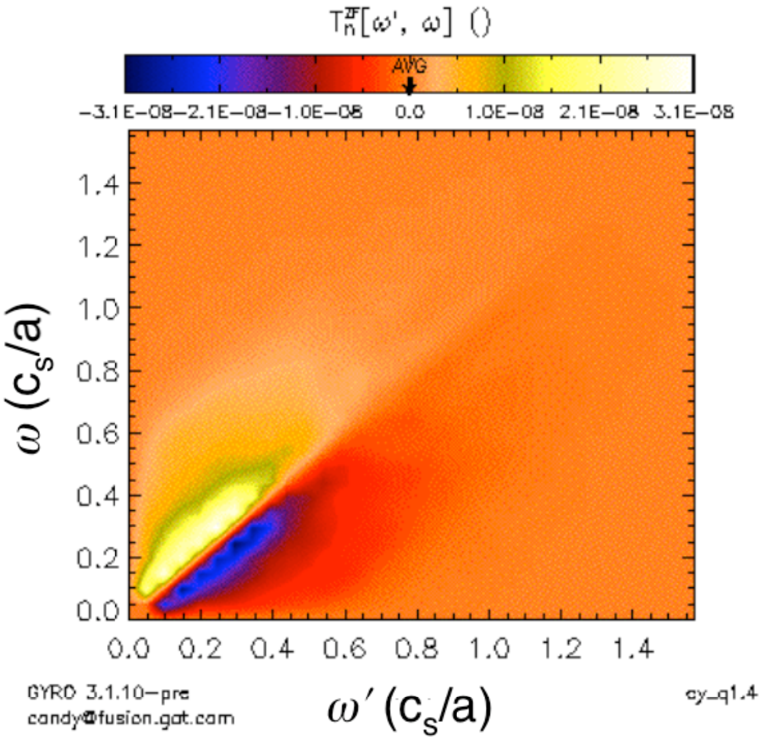


- All quantities are experimentally measured with BES
- Strong interaction at |f - f'| = f_{GAM}
- Density fluctuations at f gain energy from poloidal density gradient fluctuations at f' = f - f_{GAM} , and lose energy to those at f' = f + f_{GAM}
- Energy moves between n, dn/dy to higher f in steps of f_{GAM}
- Convection of density fluctuations by the GAM leads to a cascade of energy to higher f
- GAM plays an active role in mediating turbulence spectrum

Holland et al., (2006)

Similar Forward Cascade of Energy Driven by ZMF-Zonal Flow in Simulation Data from GYRO

$$T_n^Y(\omega',\omega) = -\mathrm{Re}\left\langle \tilde{n}^*(\omega) V_y^{ZF}(\omega-\omega') \frac{\partial \tilde{n}}{\partial y}(\omega') \right\rangle$$

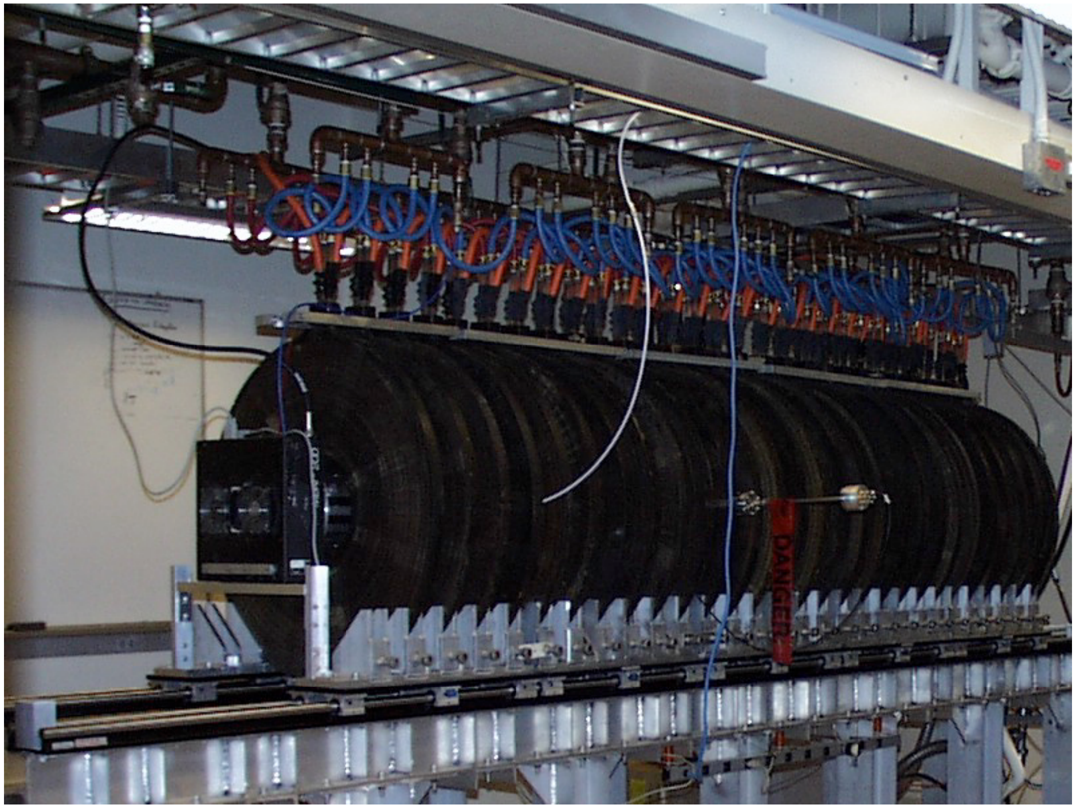


- **Data from long-time GYRO simulation to achieve convergence in frequency space (CYCLONE base case)**
  - *density fluctuation data from outboard midplane utilized*
- **Same physical process occurring in simulation data as in measurements**
- **Key difference is that energy transfer now occurs over a broad frequency range**
- **GYRO "data" allows for calculation in wavenumber space, which connects more directly to theory, as well as frequency space:**

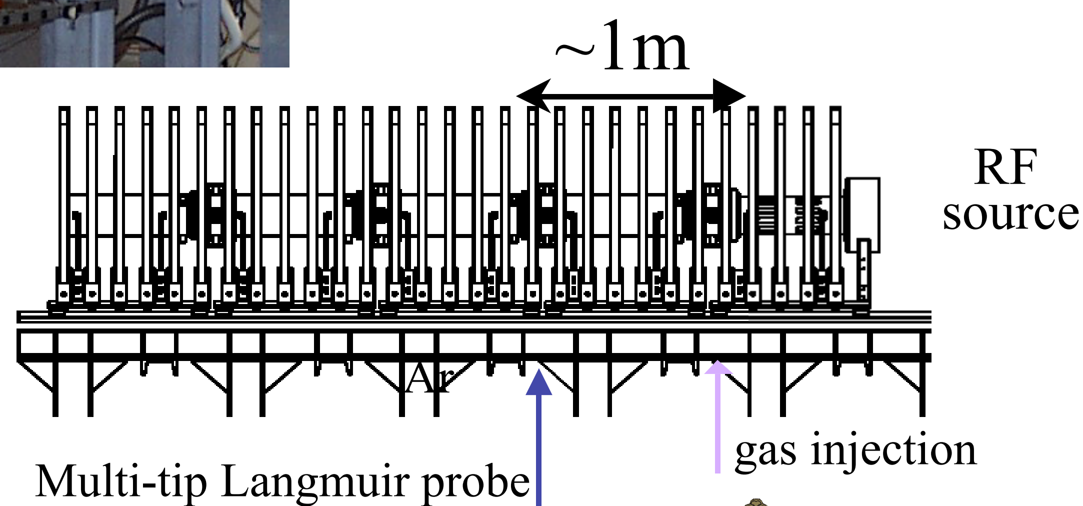
  similar result that at fixed k_θ, energy cascade to higher k_r observed

Holland et al., (2006)

The Controlled Shear De-Correlation EXperiment (CSDX) Validates Fundamental Turbulence-Zonal Flow Physics



- $T_e \approx$ 3 eV
- $T_i \approx$ 0.7 eV
- $n_e \approx$ 1-10 1012 cm-3
- Source: 1.5 kW,
  13.56 MHz Helicon
- $B_T \leq$ 1000 G



- **Linear plasma column**
- **Well-understood collisional drift wave turbulence**

Tynan et al., PPCF (2006).

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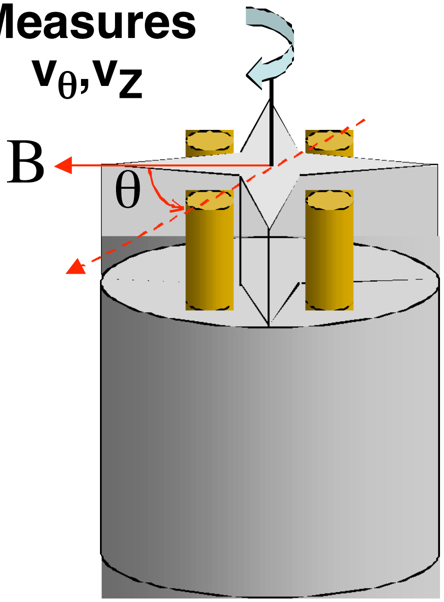
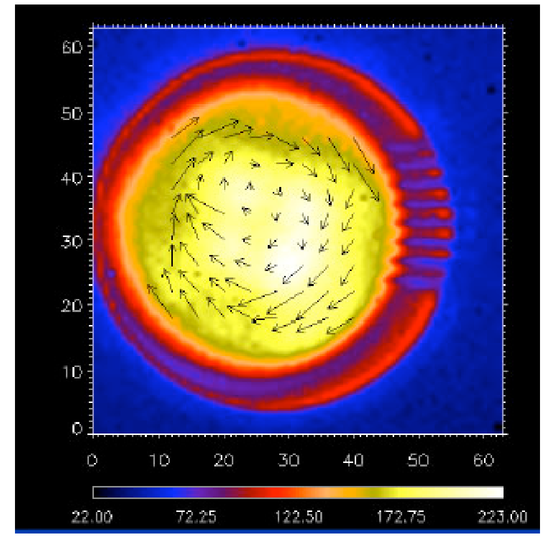
Array of Diagnostics Provide Detailed Turbulence Measurements

Mach Probe Measures v_θ, v_Z

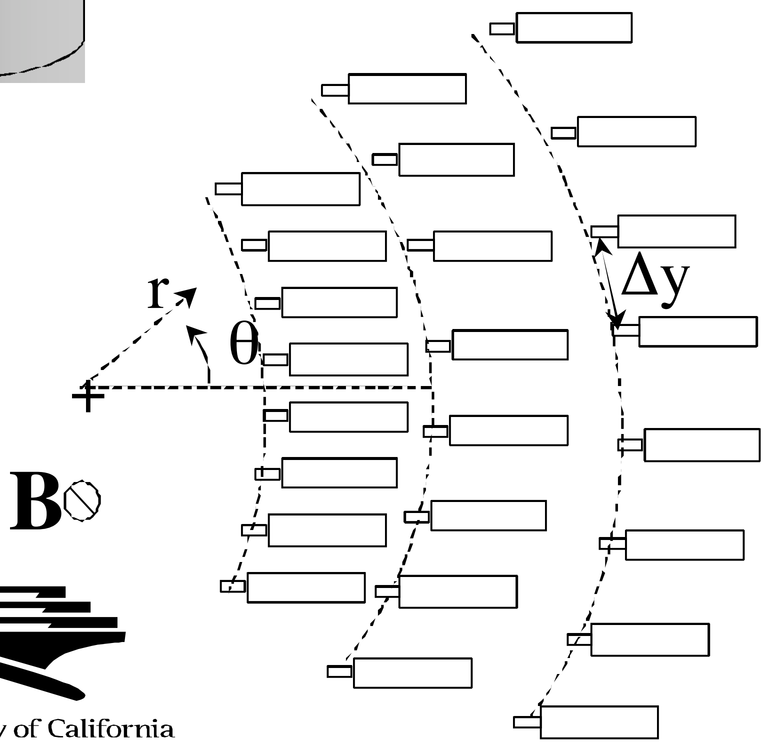


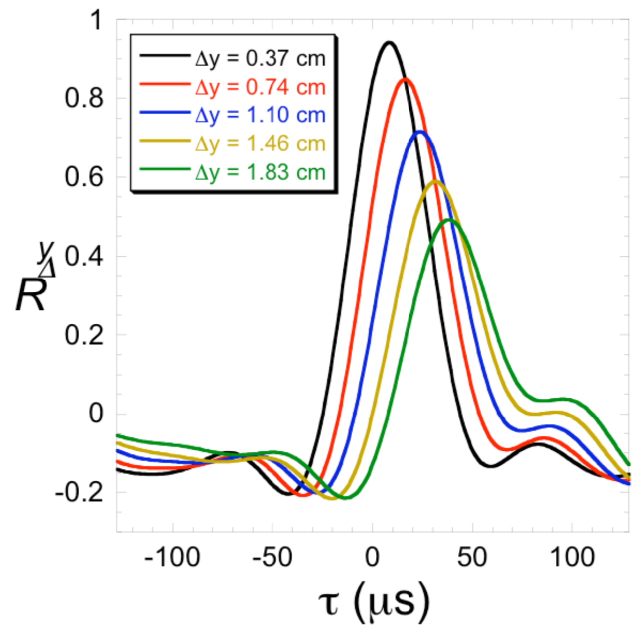
Rotate about probe axis to find $M_{||}$, M_{perp}

Fast Camera Examines Flows via Time Delay Estimation



Radial/Poloidal Probe Array for $\tilde{n}$, $\tilde{\phi}$





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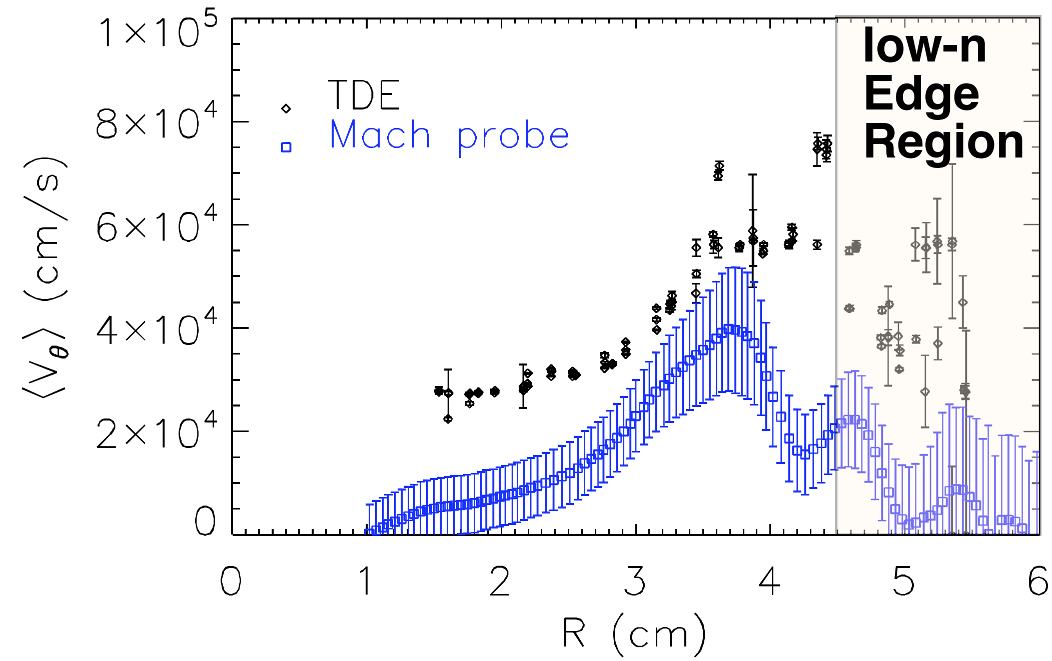
Reasonable Agreement Between Measurements, Simulation and Turbulent Momentum Balance

Comparison of V_θ from Mach Probe and TDE



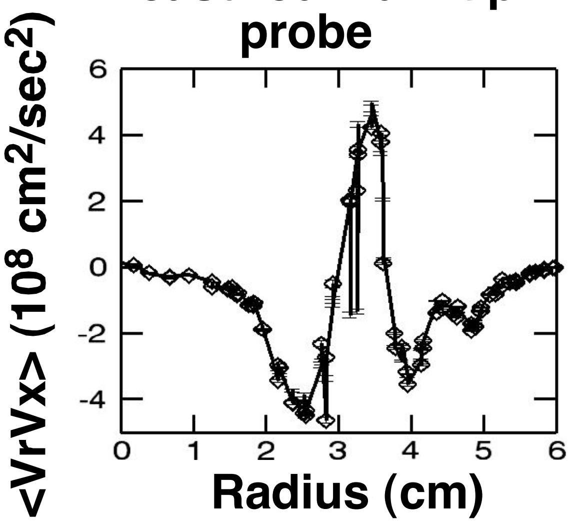
Holland et al., PRL (2006)

Reasonable Agreement Between Measurements, Simulation and Turbulent Momentum Balance

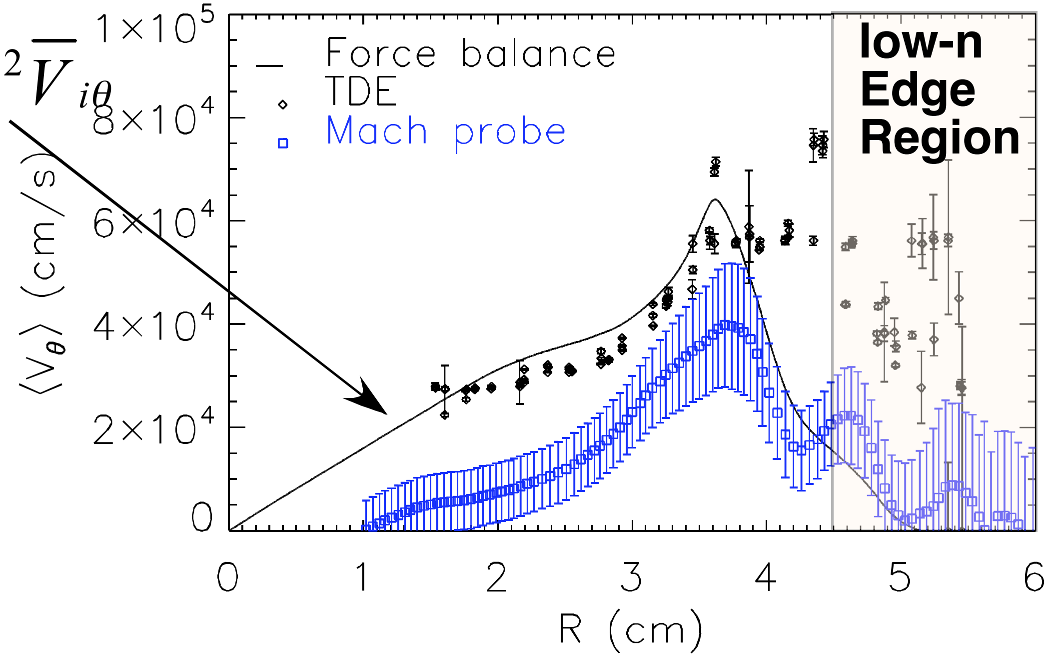
Azimuthal component of the ion momentum balance equation:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\langle\tilde{v}_r\tilde{v}_\theta\rangle\right) = -\nu_{io}\overline{V}_{i\theta} + \mu_{ii}\nabla^2\overline{V}_{i\theta}$$

- **Reynolds Stress measured via 4-tip probe**
- **ion-neutral dissipation**
- **ion-ion collisional viscosity**



Comparison of V_θ from measurement and force balance



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Reynolds Stress measured via 4-tip probe

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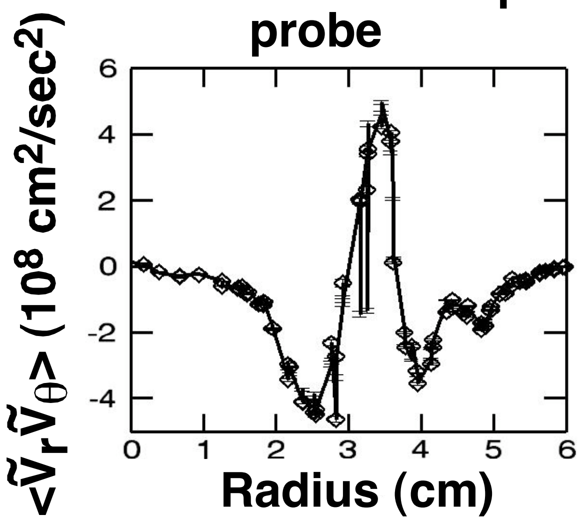
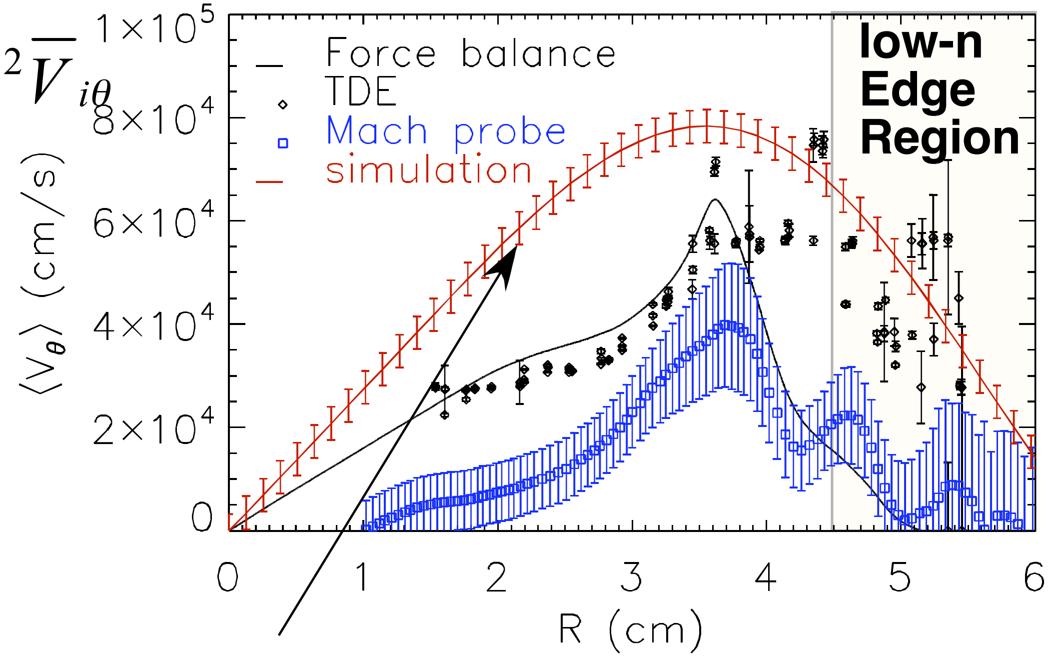


Comparison of V_θ from measurement and simulation



- **Hasegawa-Wakatani (2D) two-fluid model in cylindrical geometry shows formation of a zonal flow sustained against damping**
- **Reynolds Stress-driven azimuthal zonal flow is sustained against damping**
- **Turbulent particle flux quenched near radial location of maximum shear**

Holland et al., PRL (2006)

SUMMARY AND CONCLUSIONS

- **Zero-Mean-Frequency zonal flows have been detected for the first time in the core regions of a high-temperature tokamak plasma**
  - *Measured via application of TDE to multipoint high-sensitivity BES*
  - *Exhibit radial correlation length comparable to that of density turbulence*
  - *Zero poloidal and radial phase shift across finite spatial domain (m~0)*
- **Geodesic Acoustic Mode exhibits following characteristics:**
  - *Peaks near r/a=0.9-0.95*
  - *Exhibits a strongly increasing amplitude with safety factor, q_{95}*
    - *consistent with ion Landau damping and GYRO simulations*
- **GAM drives nonlinear transfer of energy from low to high frequencies**
  - *Similar features observed with ZMF-ZF in GYRO simulations*
- **CSDX experiment, with excellent diagnostic access, has demonstrated:**
  - *Existence of azimuthal zonal flow sustained against damping and driven nonlinearly by a turbulent Reynolds stress*
  - *Mach probe, TDE measurements on probes & camera show good agreement*
  - *Good agreement with Hasegawa-Wakatani simulation*

Demonstration in large experiment and laboratory device of essential element of drift-wave/zonal-flow dynamics

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