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

by
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for
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Presented at the
21st IAEA Fusion Conference
Chengdu, China

October 16–21, 2006

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

GRM/IAEA06

THE UNIVERSITY of WISCONSIN
MADISON

OVERVIEW AND MOTIVATION

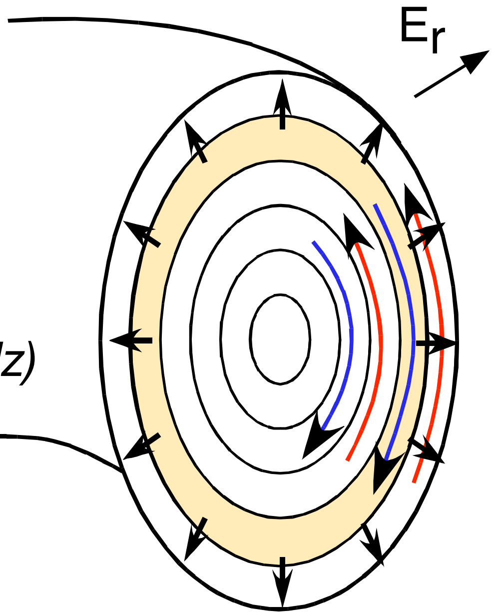
- **Zonal flows are a central element of drift-wave turbulence from theory and simulation**
  - *Zero-mean-frequency zonal flow (ZMF-ZF) detected in the core of a high-temperature tokamak plasma for the first time*
  - *Method: Spatio-temporal analysis of multipoint, high-sensitivity Beam Emission Spectroscopy 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**

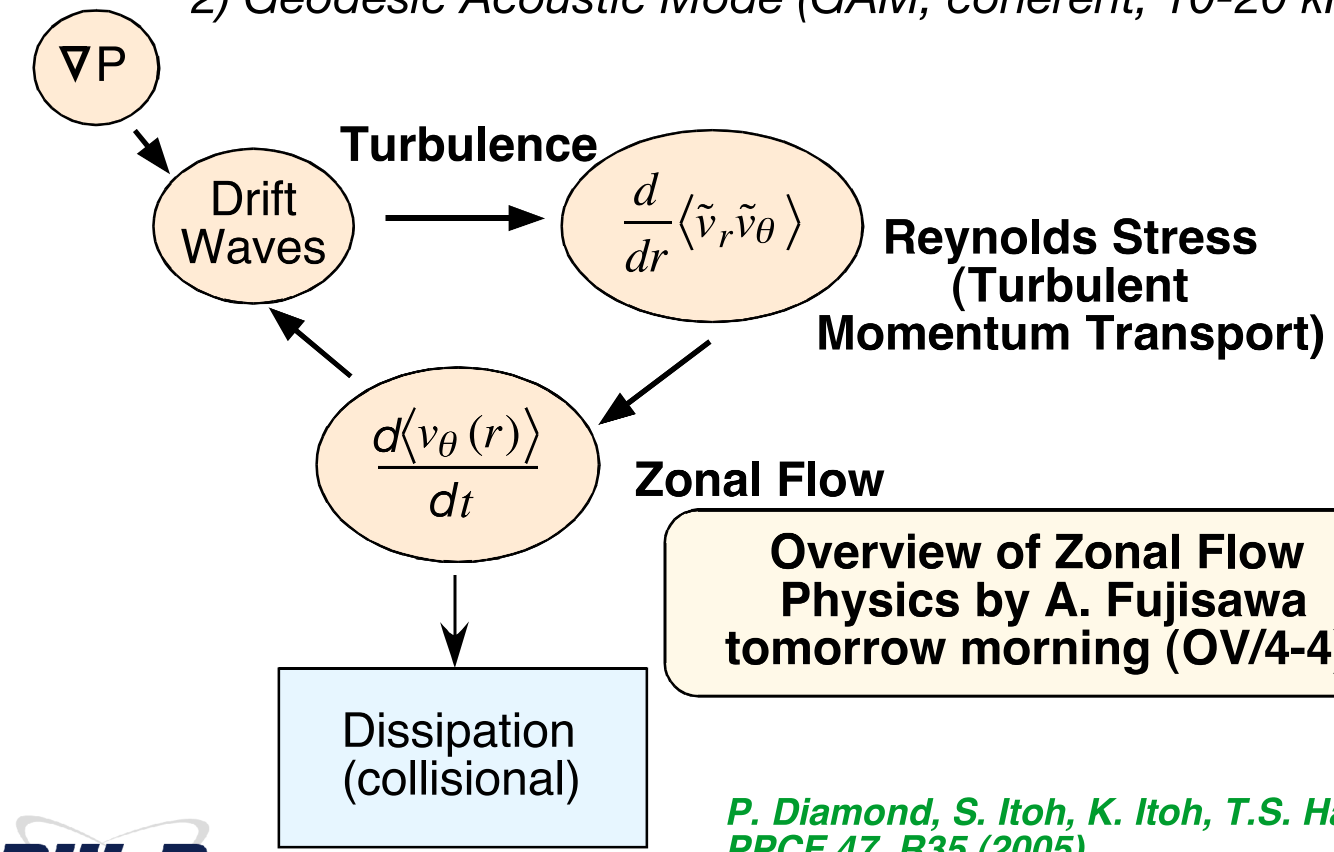
ZONAL FLOWS THOUGHT CRUCIAL TO MEDIATING FULLY SATURATED TURBULENCE IN PLASMAS

- **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**

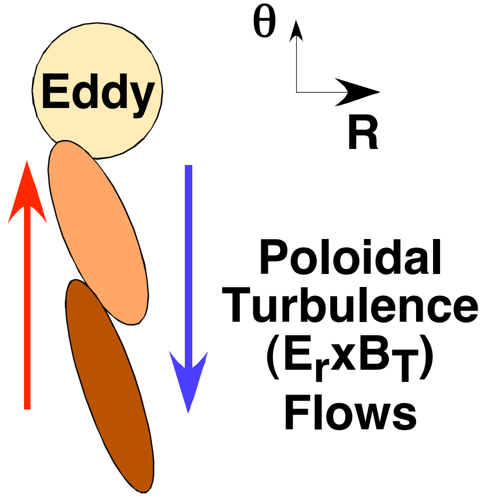
  1) Zero-Mean-Frequency zonal flow(ZMF-ZF, $\Delta f \sim \nu_{ii} < 10$ kHz)

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





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



Poloidal Turbulence ($E_r x B_T$) Flows

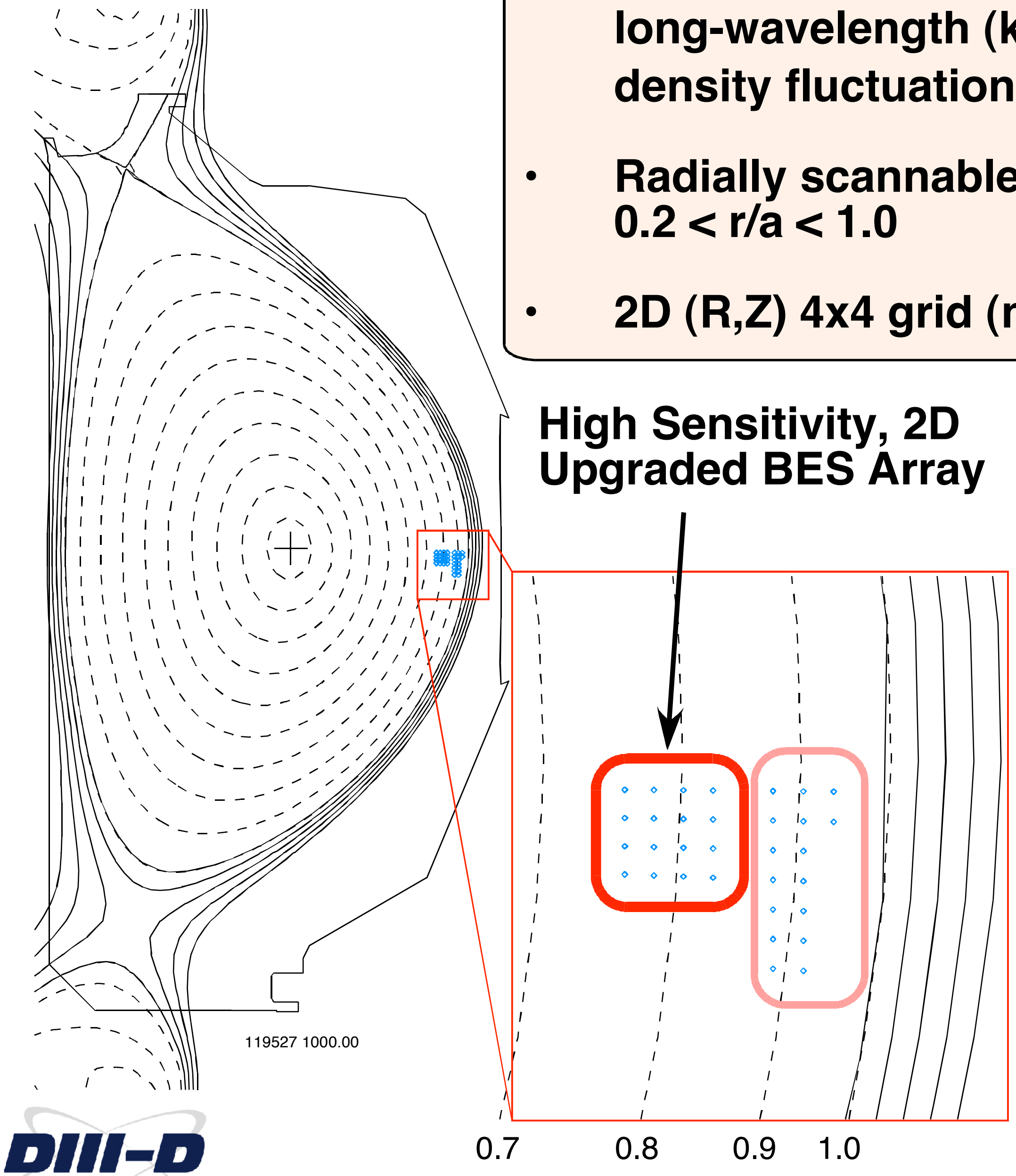
P. Diamond, S. Itoh, K. Itoh, T.S. Hahm, PPCF 47, R35 (2005).

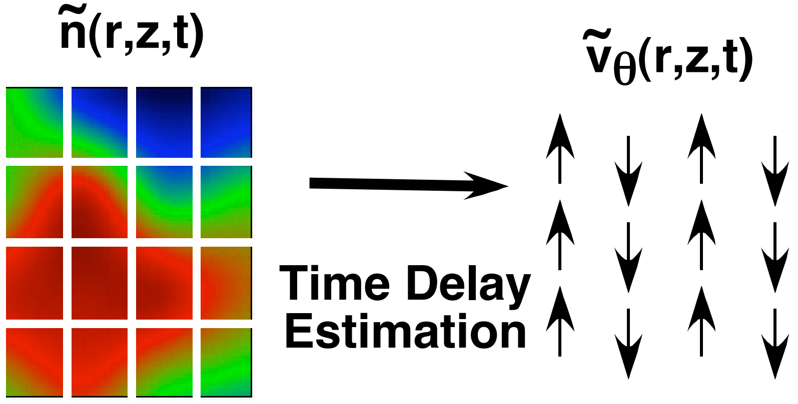
BEAM EMISSION SPECTROSCOPY CONFIGURED TO PROVIDE ZONAL FLOW MEASUREMENTS VIA TURBULENCE VELOCITY INFERENCE

- **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:

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


High Sensitivity, 2D Upgraded BES Array


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

Time Delay Estimation

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

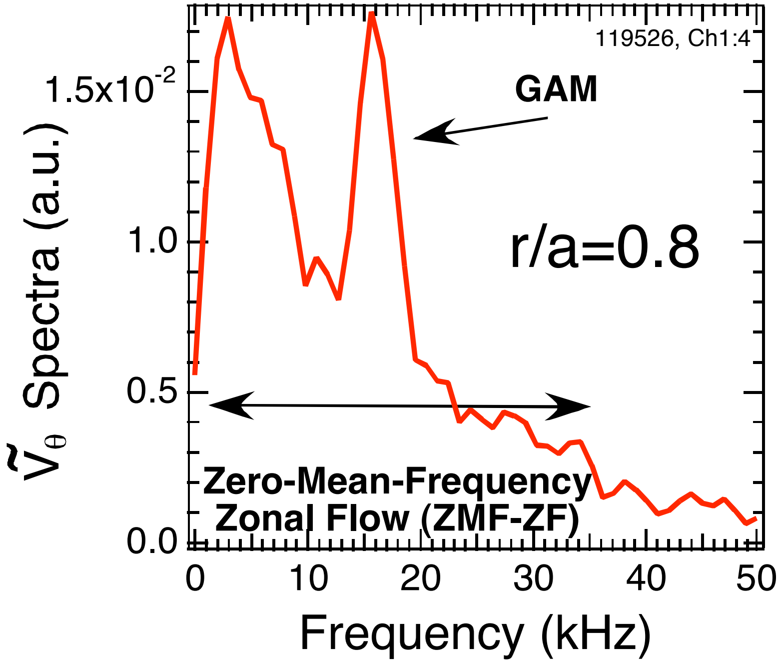
1) Time-resolved cross-correlation
2) Wavelets
3) Dynamic Programming

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

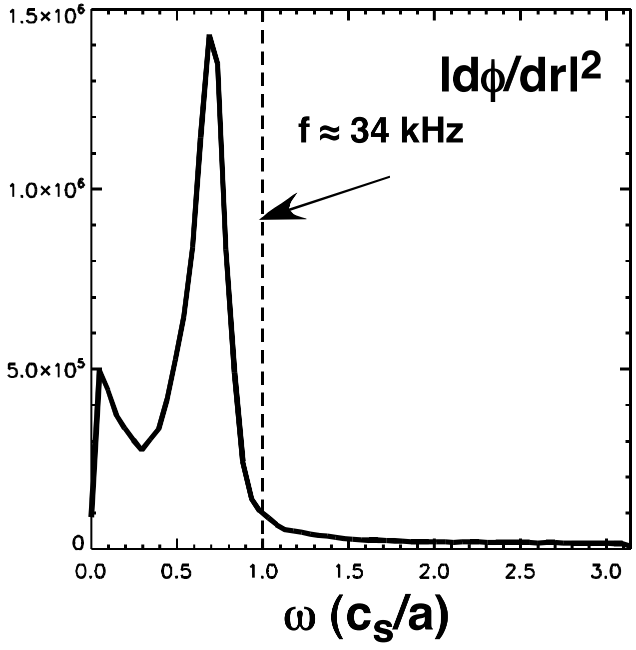
Zonal Flow

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, Δf~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**



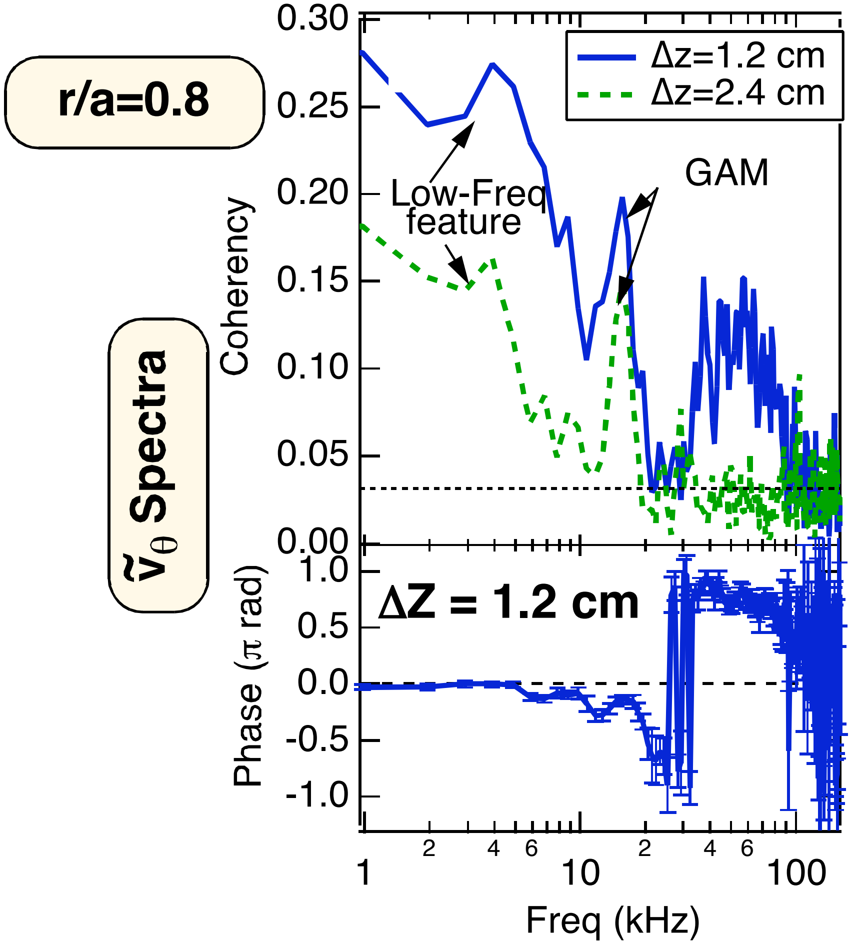
Poloidal velocity spectrum measured with BES



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

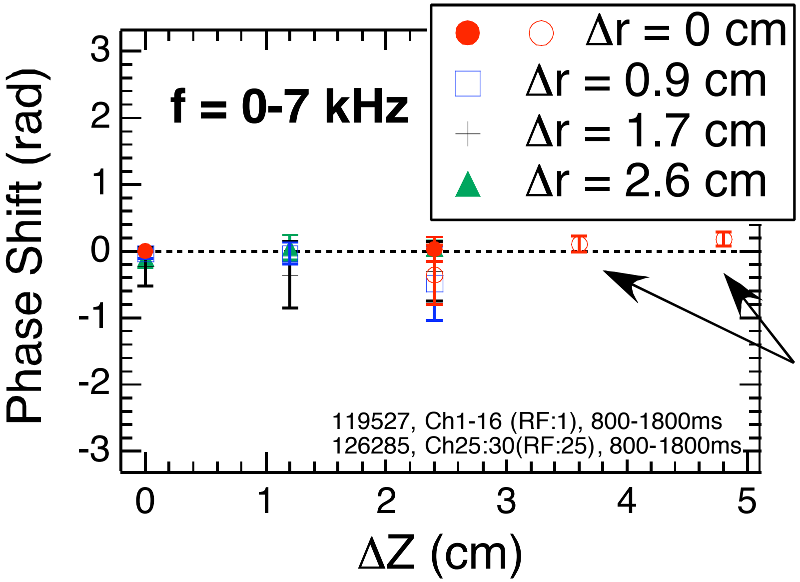
ZMF-Zonal Flow Exhibits Zero Poloidal and Radial Phase Shift, Consistent with Expectations

- **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, radial phase shift*



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

Phase Shift Measurements in R, Z Plane

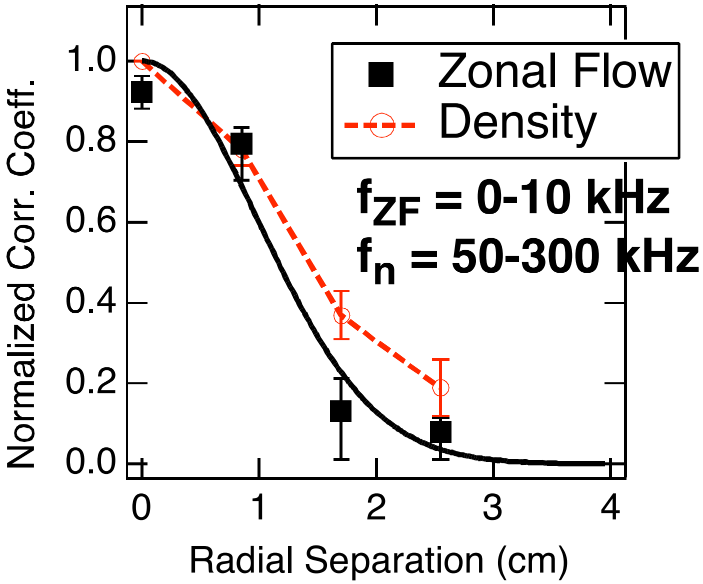


Measurements with recently expanded 2D array

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

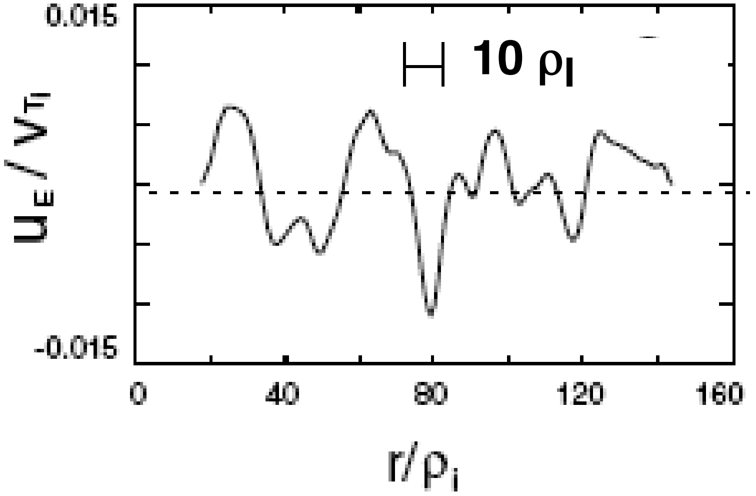
ZONAL FLOW HAS RADIAL CORRELATION LENGTH SIMILAR TO THAT OF DENSITY TURBULENCE

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



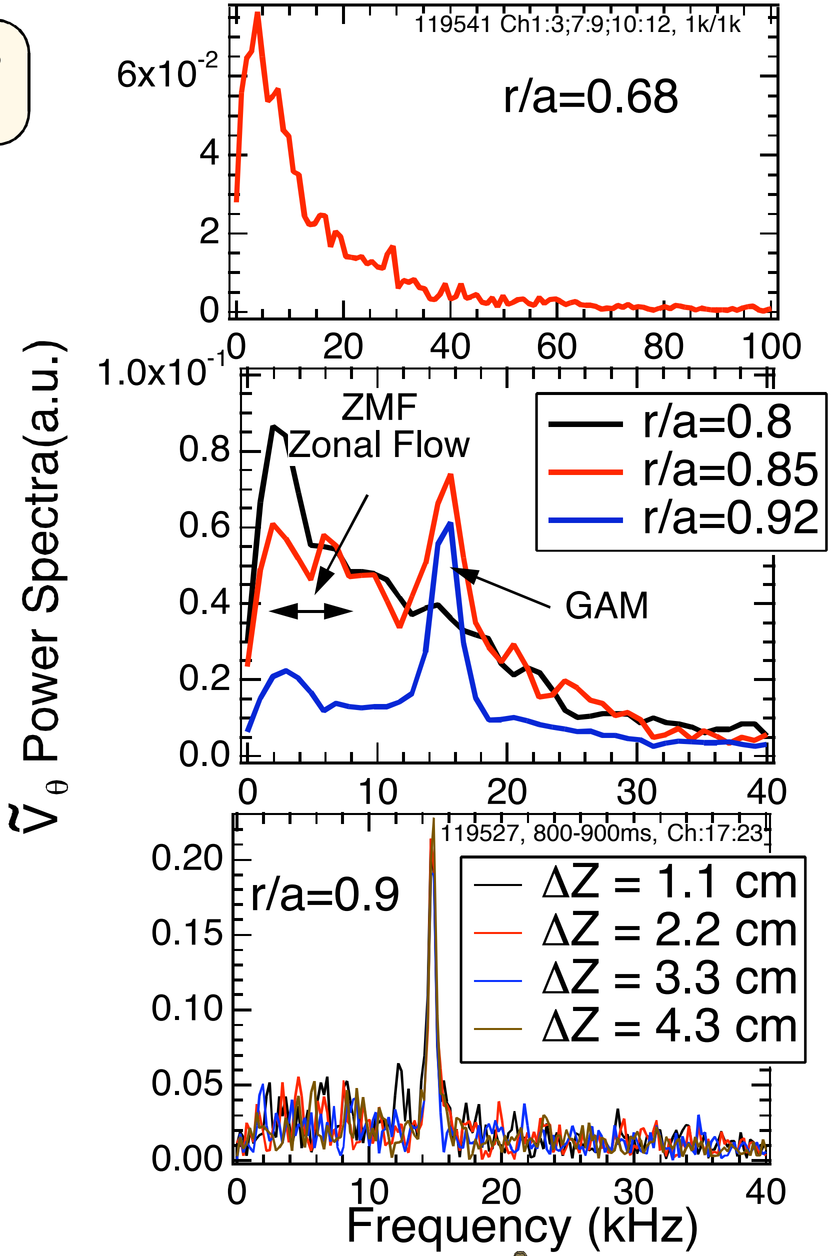
T.S. Hahm et al., PPCF 42, A205 (2000)

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:**

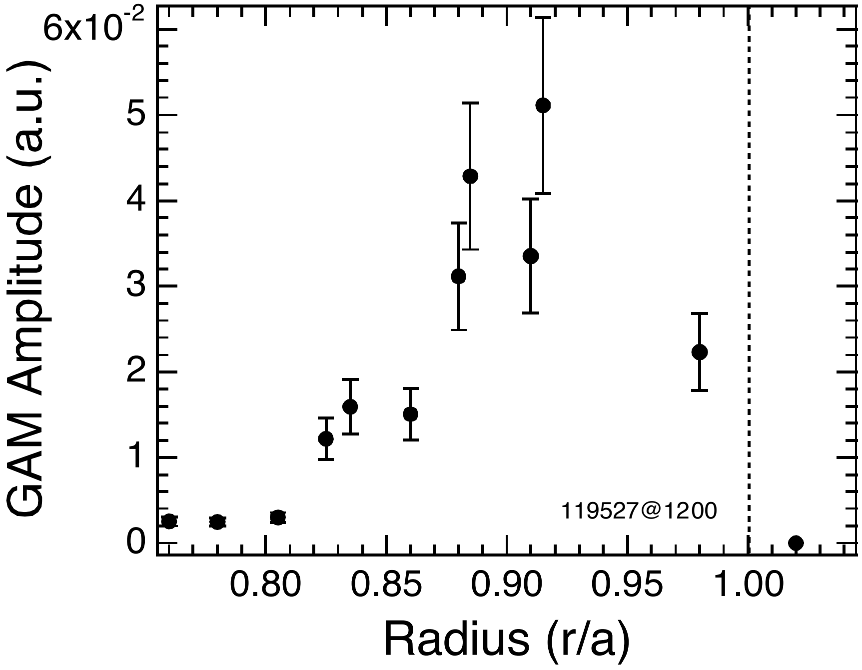
$\tau_{GAM} >> \tau_{Turbulence}$ (~10 μs)



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 $k_r \sim 1\ \mathrm{cm}^{-1}$*
  - *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



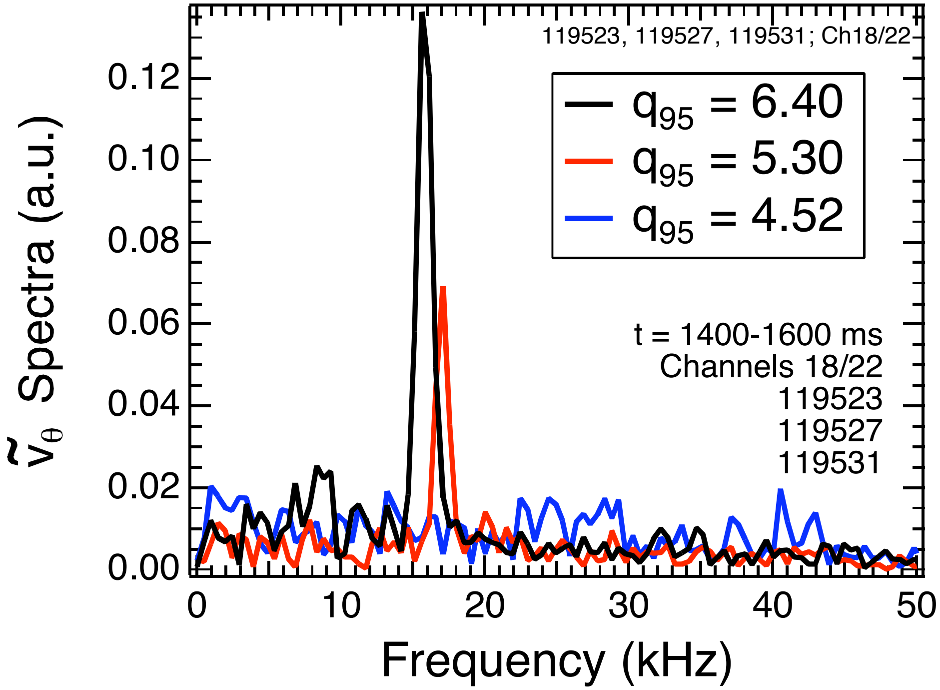
McKee et al., PPCF (2006).

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

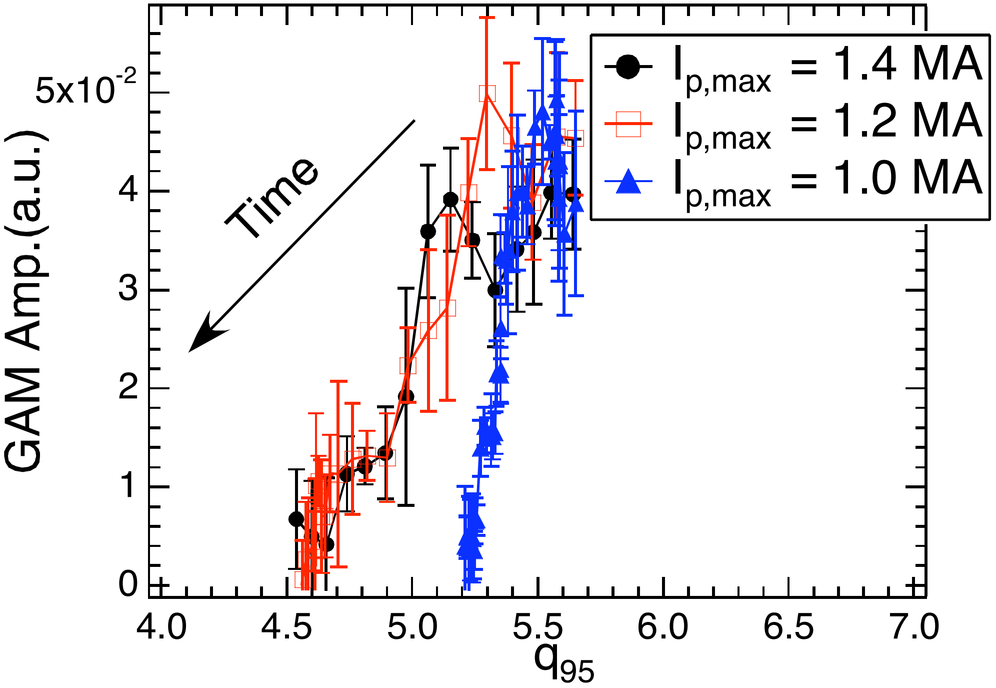
GAM AMPLITUDE INCREASES STRONGLY WITH q_{95}

- **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**

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

$$x \rightarrow r$$
$$y \rightarrow r\theta$$

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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Coupling of flux to background density gradient (source)

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

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

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

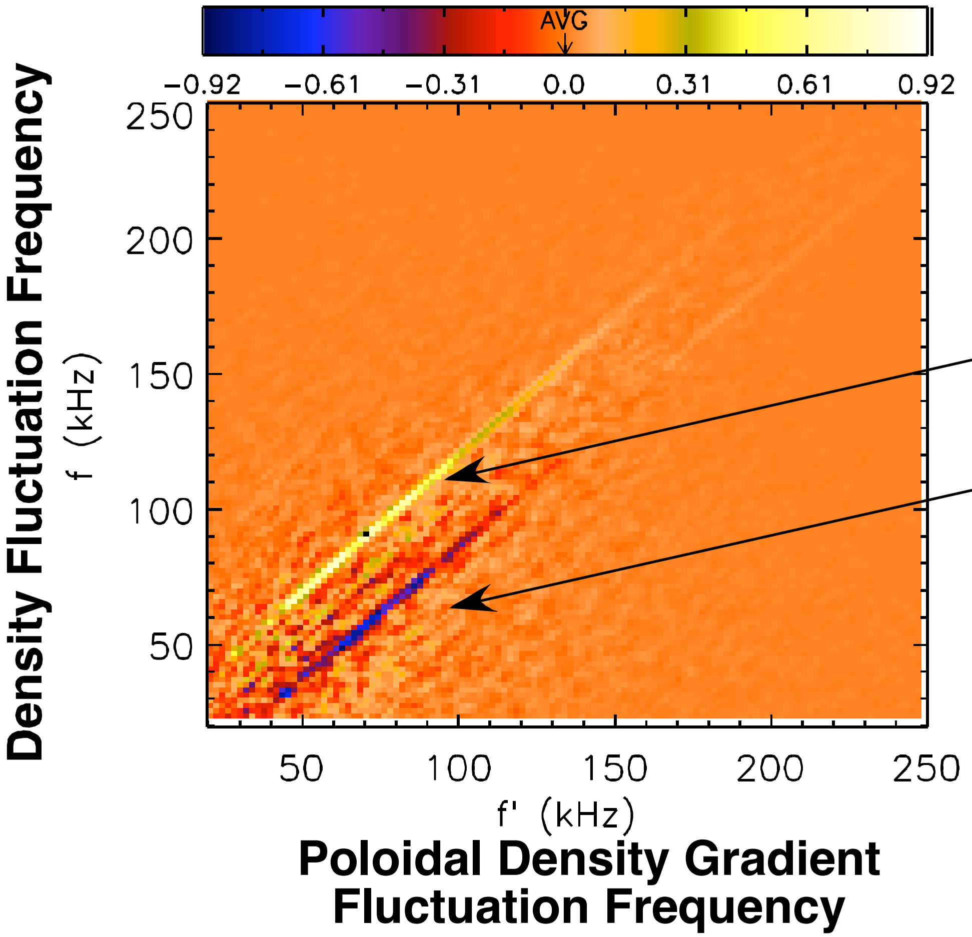
Collisional dissipation of fluctuation energy (sink)

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

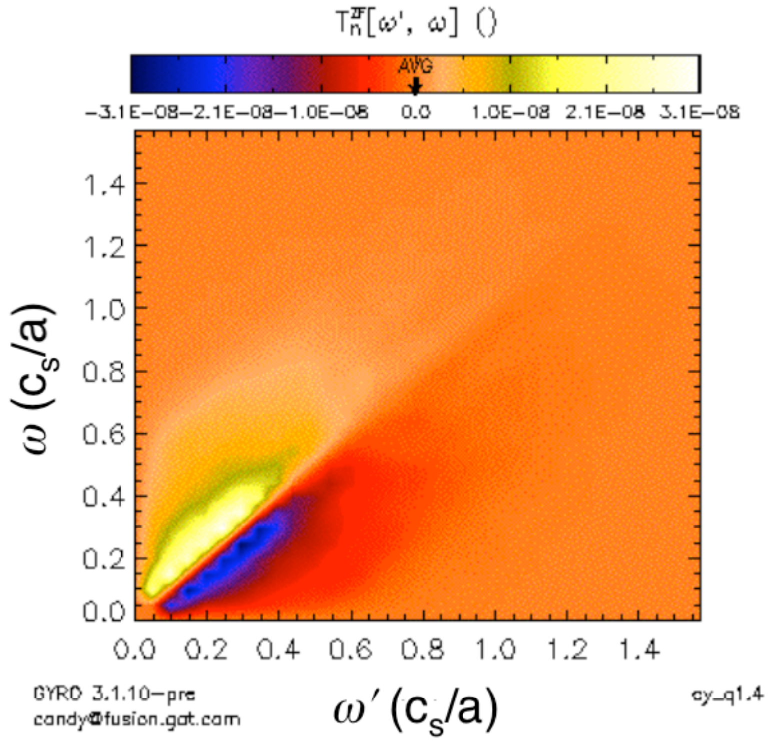


- **All quantities are experimentally measured with BES**
- **Strong interaction at |f - f'| = f_{GAM}**
- **Density fluctuations at f gain energy from poloidal density gradient fluctuations at f' = f - f_{GAM} , and lose energy to those at f' = f + f_{GAM}**
- **Energy moves between n, dn/dy to higher 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

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

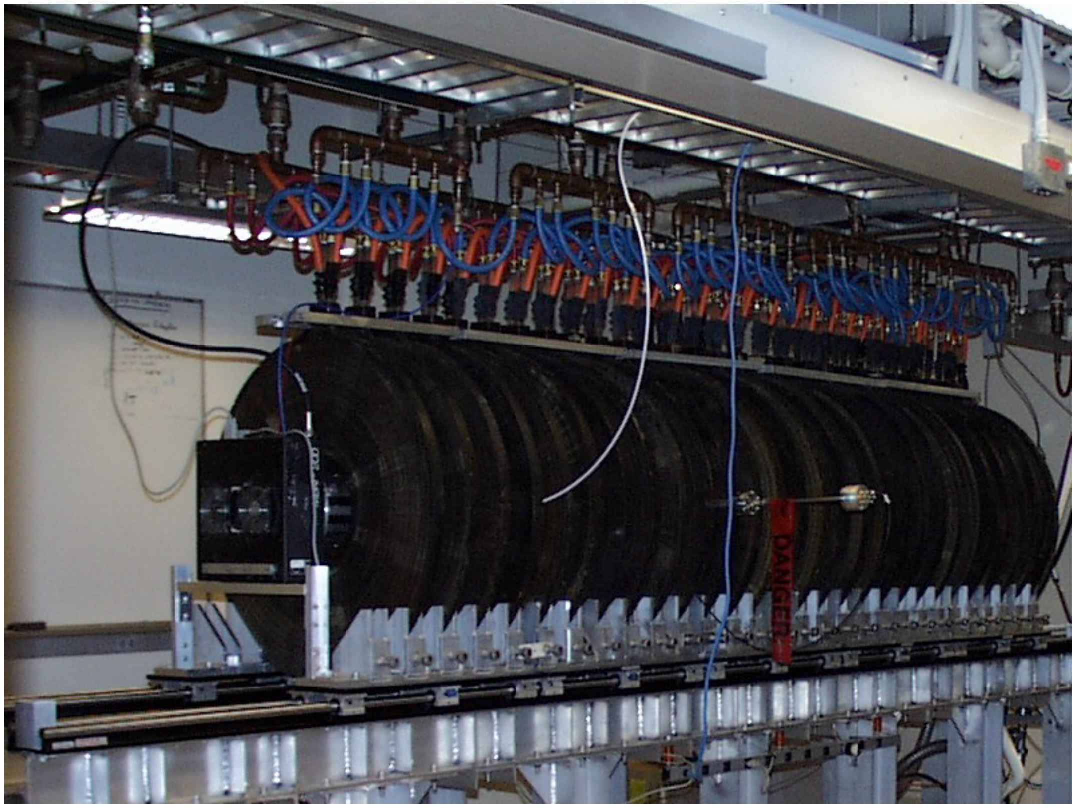


- **Data from long-time GYRO simulation to achieve convergence in frequency space (CYCLONE base case)**
  - *density fluctuation data from outboard midplane utilized*
- **Same physical process occurring in simulation data as in measurements**
- **Key difference is that energy transfer now occurs over 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

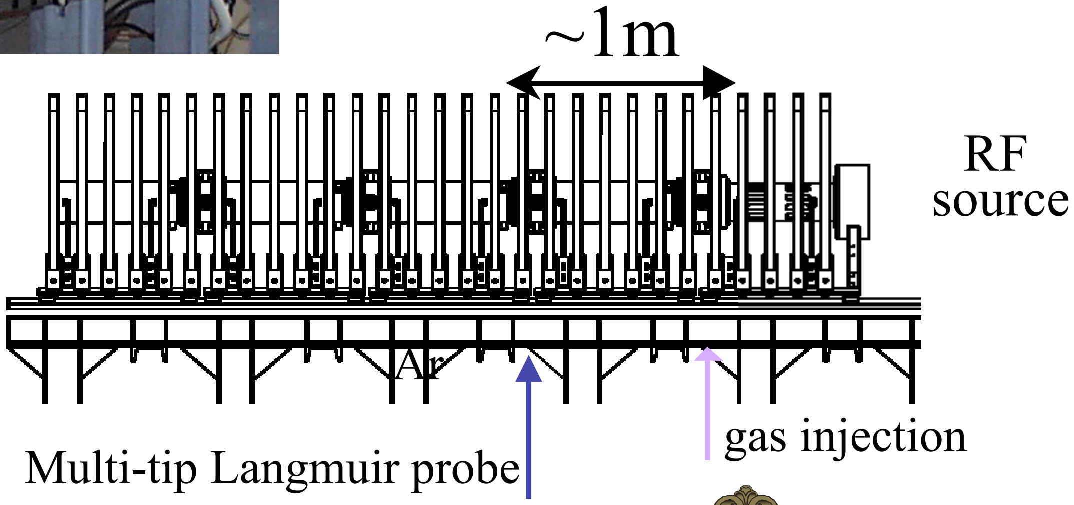
Holland et al., (2006)

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

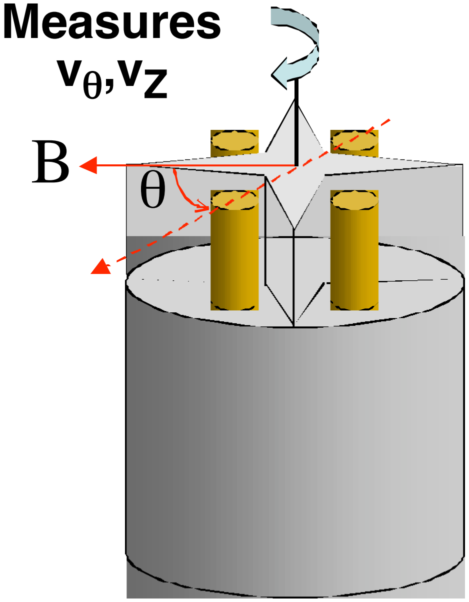
- Linear plasma column
- Well-understood collisional drift wave turbulence



Tynan et al., PPCF (2006).

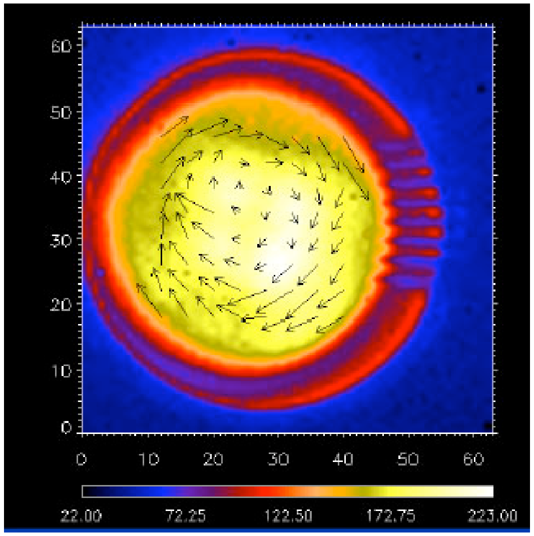
ARRAY OF DIAGNOSTICS PROVIDE DETAILED TURBULENCE MEASUREMENTS

Mach Probe Measures v_θ, v_Z

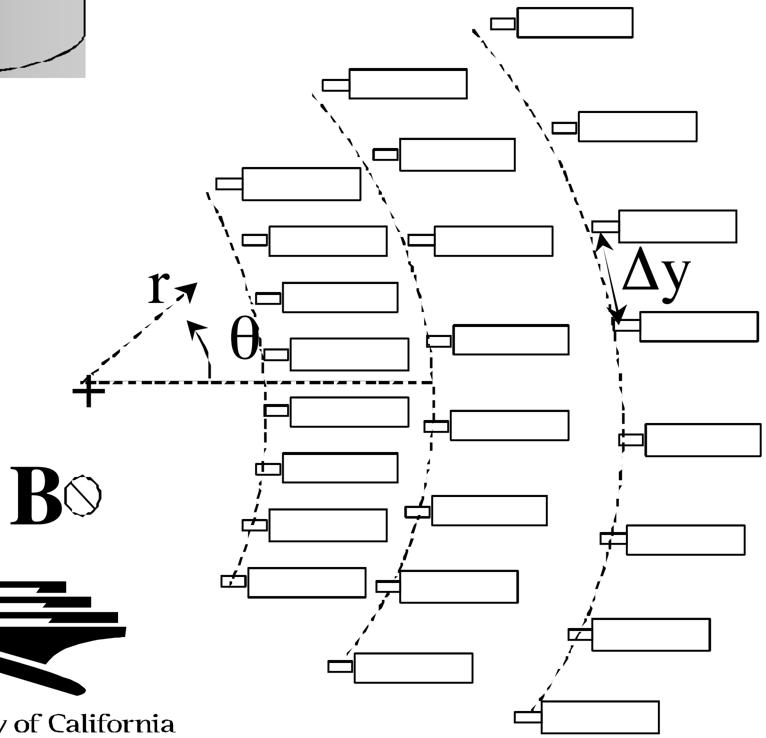


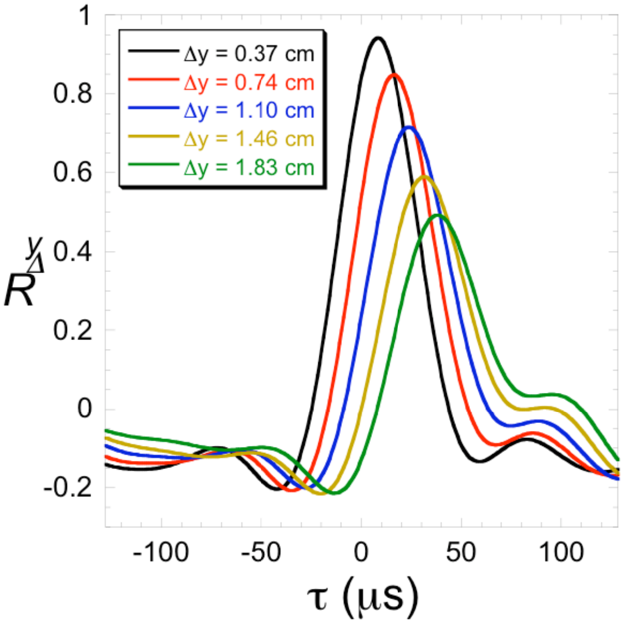
Rotate about probe axis to find $M_{||}$, M_{perp}

Fast Camera Examines Flows via Time Delay Estimation



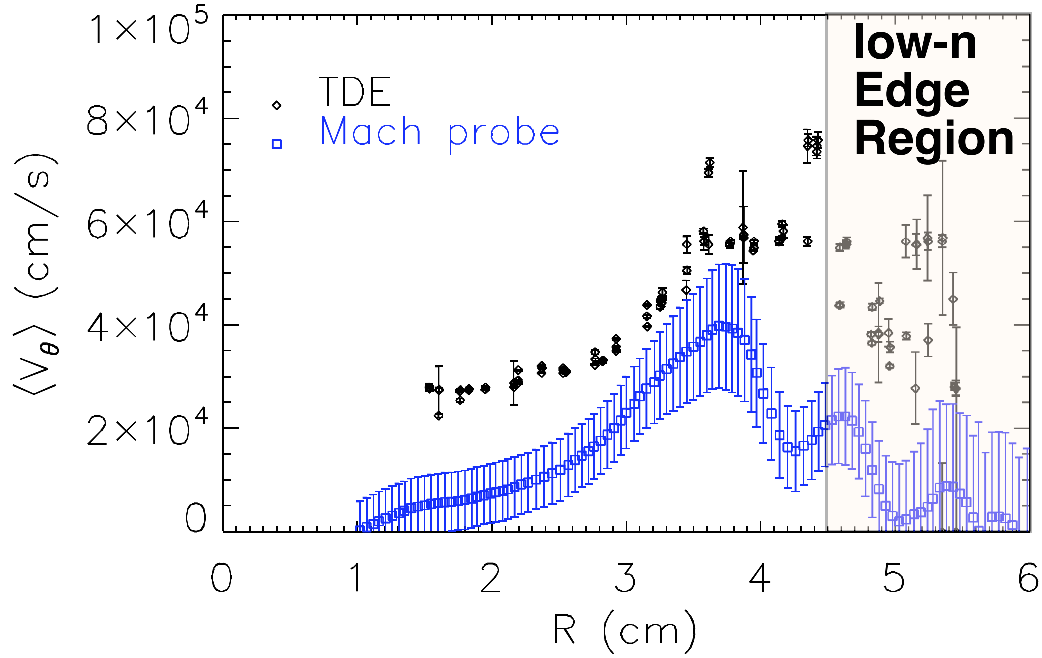
Radial/Poloidal Probe Array for $\tilde{n}$, $\tilde{\phi}$





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

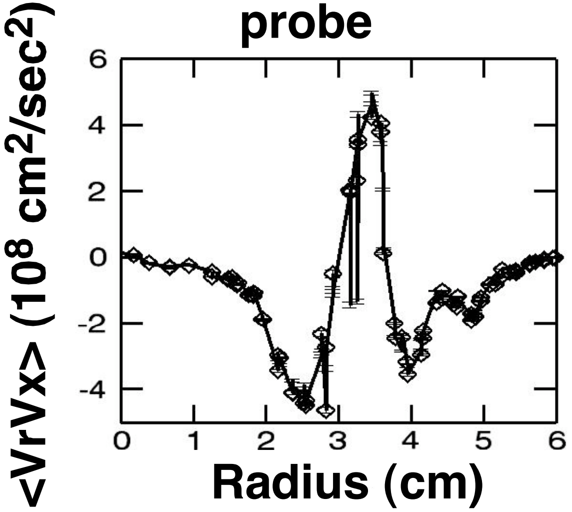
Azimuthal component of the ion momentum balance equation:

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

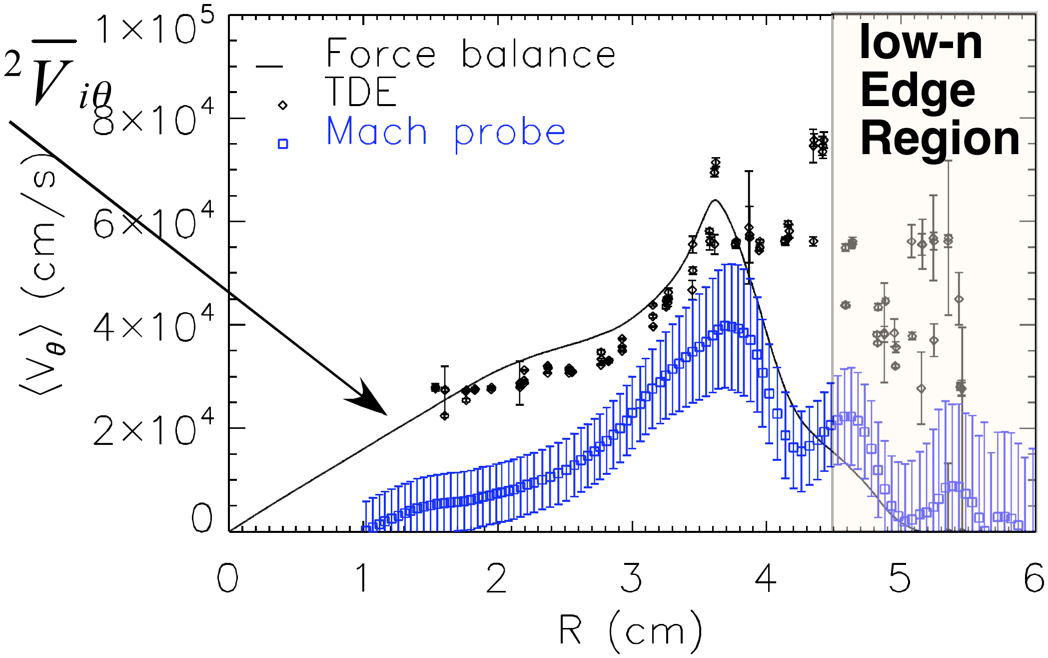
ion-neutral dissipation

ion-ion collisional viscosity

Reynolds Stress measured via 4-tip probe



Comparison of V_θ from measurement and force balance



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collisional viscosity

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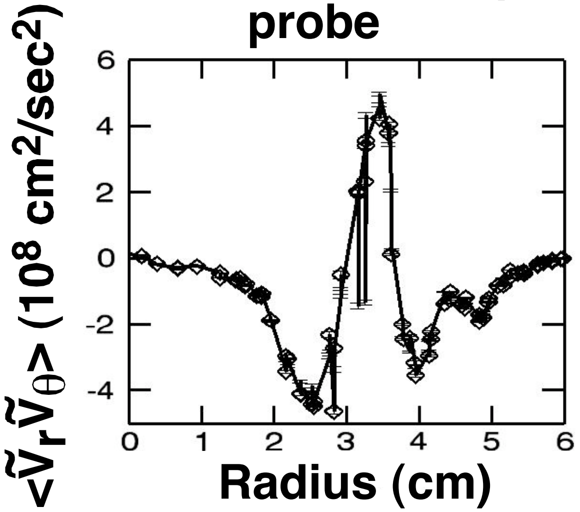
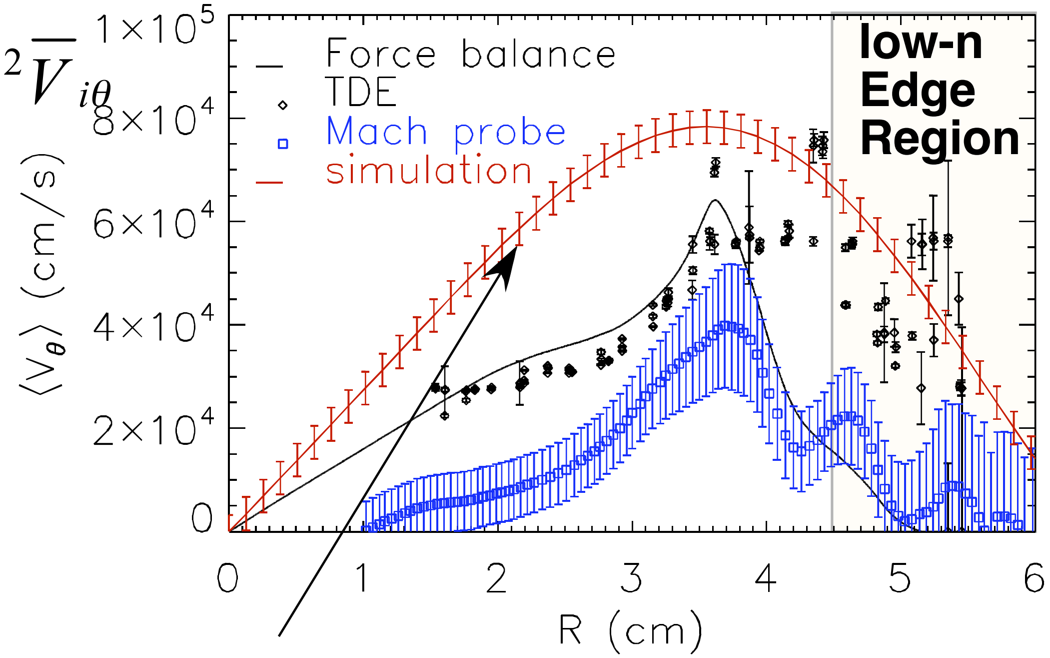
Reynolds Stress measured via 4-tip probe



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

- **ZMF 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