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

G.R. McKee 1), R.J. Fonck 1), C. Holland 2), G.R.Tynan 2), K.H. Burrell 3), J. Candy 3), P.H. Diamond 2), K. Hallatschek 4), D.K. Gupta 1), F.L. Hinton 3), J.E. Kinsey 5), D.J. Schlossberg 1), M.W. Shafer 1), R.E. Waltz 3), and J. Yu 2)

1) University of Wisconsin-Madison, Madison, Wisconsin 53706, USA
2) University of California-San Diego, La Jolla, California 92093, USA
3) General Atomics, San Diego, California 92186-5608, USA
4) Max Planck Institut für Plasmaphysiks, Garching, Germany
5) Lehigh University, Bethlehem, Pennsylvania, USA

e-mail contact of main author: mckee@fusion.gat.com

Abstract. Zonal flows are observed and have been characterized in the core and edge of the DIII-D tokamak. These include the zero-mean-frequency, spectrally broad residual flows and the generally higher frequency, oscillatory geodesic acoustic mode (GAM). These zonal flows have long been predicted theoretically to be the crucial mechanism by which turbulence saturates in magnetically confined plasmas. The zero-mean-frequency zonal flow has been identified for the first time in the core of a tokamak plasma using multipoint, 2-D measurements of the density turbulence and its resulting velocity-field. These zonal flows are observed as a low frequency, spectrally broad feature in the derived poloidal turbulence velocity spectrum, peaking near zero frequency and exhibiting a width of $\Delta f \approx 10$ kHz. They exhibit a long poloidal wavelength and a short radial correlation length of a few cm. This velocity spectrum is dominated near the edge of the plasma ($0.9 < r/a < 0.95$) by the GAM, while the lower-frequency zonal flow becomes dominant deeper in the plasma core. The GAM amplitude is shown to be a strong function of the safety factor, q_{95}, consistent with theoretical predictions based on ion Landau damping. Application of a novel algorithm that calculates energy transfer between density fluctuations of different frequencies demonstrates a GAM-mediated transfer of energy between density fluctuations with frequency f_0 to poloidal density gradient fluctuations with frequency $f_0 \pm f_{GAM}$, leading to a net transfer of energy from low to high frequencies, suggesting that the GAM is playing a role in saturating the turbulence in the edge region. In related work, experiments in the CSDX laboratory plasma device show the presence of an azimuthally sheared flow that is consistent with a turbulent momentum balance that includes the measured turbulent Reynolds stress and flow damping. This zonal flow is also shown to quench the turbulent particle flux.

1. Introduction

The nonlinear dynamics of turbulence in a magnetically confined plasma plays a central role in the turbulence saturation process and ultimately in the radial transport of particles, energy and momentum. This turbulence, driven by temperature and density gradients, determines plasma particle and energy confinement and thus plasma performance. To more fully understand this critical saturation process, a detailed experimental study of the plasma fluctuations, self-driven zonal flows, and the effects of the zonal flows on the turbulent spectrum in the DIII-D tokamak have been performed. In addition, related experiments have been conducted in the Controlled Shear Decorrelation Experiment (CSDX) laboratory experiment, where more detailed characterization of the fluctuations and flows can be conducted.

Zonal flows [1] have been characterized in the core of the DIII-D tokamak. These include the zero-mean-frequency (ZMF), spectrally broad residual flows [2], and the higher frequency, oscillatory geodesic acoustic mode (GAM) [3,4]. The nonlinear transfer of turbulent energy to higher frequency by the GAM is measured and suggests that the GAM is playing an important role in saturating the turbulence in the near edge region. These zonal flows have long been predicted theoretically to be the crucial turbulence saturation mechanism in magnetically confined plasmas. This process of turbulence self-regulation through nonlinear generation of zonal flows is well established theoretically and has been observed in nonlinear simulations of plasma turbulence, but the dynamics have yet to be verified experimentally. The turbulence saturation process acts via nonlinear energy transfer from the turbulence to the linearly damped zonal flow. Experimental understanding of this mechanism is critical to verifying the physics of nonlinear turbulence simulations and establishing a predictive capability for turbulent driven transport in future burning plasma experiments. Here we show evidence from experiment and simulation that these shear flows exist in high-temperature tokamak plasma and laboratory devices, are generated nonlinearly by the turbulence, that these flows affect the transport fluxes and nonlinearly regulate the turbulence spatial scales, and thus play a critical role in determining transport rates from ion-scale turbulence.

2. Measurement of Zonal Flow Structures via Spatio-Temporal Fluctuation Analysis

These experiments are conducted in L-mode discharges in the DIII-D tokamak, with I_p = 0.6-1.4 MA, $B_T = 2.0$ T, $P_{inj} =$ 5 MW, in an upper-single-null divertor configuration. Turbulence and turbulence flows are characterized by measuring long-wavelength ($k_\perp \rho_i < 1$) density fluctuations with the multipoint, two-dimensional beam emission spectroscopy (BES) density fluctuation diagnostic system on DIII-D [5,6]. BES measures localized density fluctuations by observing collisionally-induced D_α (n = 3-2, λ_o = 656.1 nm) fluorescence of the heating neutral beams ($E_b \sim 75$ keV, $P \sim 2.5$ MW). Spatial resolution is approximately 1 cm in the radial-poloidal plane and is sampled at 1 MHz. Multiple channels are deployed to obtain 2D measurements. The diagnostic has been significantly upgraded recently to provide dramatically enhanced sensitivity to small-scale ($\tilde{n}/n < 1\%$) density fluctuations arising from turbulence and other instabilities in the core of tokamak plasmas. The diagnostic was deployed as shown in Fig. 1 for this experiment. A 4x4 array of channels covered an approximately 3.6 (radially) x 5.0 (poloidally) cm rectangular region at the outboard midplane of the plasma, as indicated, and was radially scanned on a shot-to-shot basis in the range $0.6 < r/a < 1.0$.

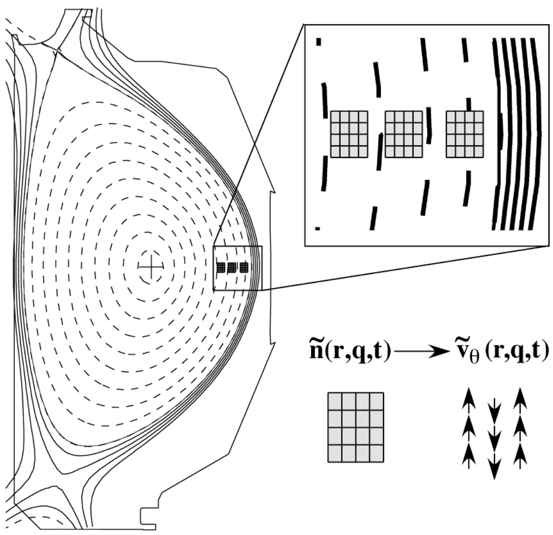

FIG. 1. Experimental configuration of BES channels for this experiment-4x4 grid, measuring a 3.6 (radial) x 5.0 (poloidal) cm region at the outboard midplane and radially scanned, as shown in inset. Flow measurements are derived via TDE analysis of 2D measurements, illustrated in lower inset.

A central aspect of this study was the measurement of time-dependent poloidal flows. Zonal flows (including GAMs) are radially localized electrostatic potentials, which thus have a finite radial electric field and associated ExB poloidal flow. The shear in this flow is thought to regulate turbulence via radially-sheared flow, or equivalently, transfer of energy from turbulence to the flows. Such flows should be manifest as fluctuations in the poloidal flow velocity of the turbulent eddies, which also exhibit a quasi-equilibrium poloidal flow associated with the background radial electric field. Signatures of zonal flows can thus in principle be identified experimentally by measuring the time-dependent poloidal flows and their spectra. This is accomplished by applying time-delay-estimation (TDE) techniques to poloidally-separated density fluctuation measurements [7,8]. To successfully perform such measurements, the channels must be well within a correlation length of the turbulence, and the channel-to-channel eddy transit time must be less than a decorrelation time of the turbulence, which is the case here. A time-dependent poloidal velocity of the turbulence is derived from the 2D measurements via these techniques, as illustrated schematically in Fig. 1 (bottom right). The predicted time-scale for zonal flow lifetime is the ion-ion collision times, typically up to several kHz for these discharges.

The general characteristics of the long-wavelength density turbulence in these discharges are demonstrated in Fig. 2. Here, measurements are obtained near $r/a = 0.6$, and the broadband fluctuation spectra is observed over ~50-450 kHz at an approximate normalized fluctuation level of $\tilde{n}/n < 1\%$ (a neutral beam oscillation below 80 kHz makes the data difficult to interpret in this frequency range at low fluctuation amplitudes). Data are ensemble-averaged over 0.5 s. The cross-phase between two poloidally separated channels ($\Delta Z = 1.2$ cm) in Fig. 2(b) shows a linearly increasing phase shift, indicating a uniform poloidal advection of fluctuations across the observed wavenumber spectrum ($k_\perp < 3\ \mathrm{cm}^{-1}$), as would be expected with a dominant background $E_r x B_T$ flow. Time lag cross correlations [Fig. 2(c)] between poloidally separated channels exhibit a 13 km/s poloidal advection, or a 0.9 μs channel-to-channel transit time, well-below the 10 μs decorrelation times, and a poloidal correlation length of 3.5 cm, several times the 1.2 cm channel spacing, readily satisfying the requirements to apply the TDE method to determine high-frequency turbulence velocity fluctuations. In addition, new techniques based on dynamic programming algorithms [9] are being developed and give similar results to those presented.

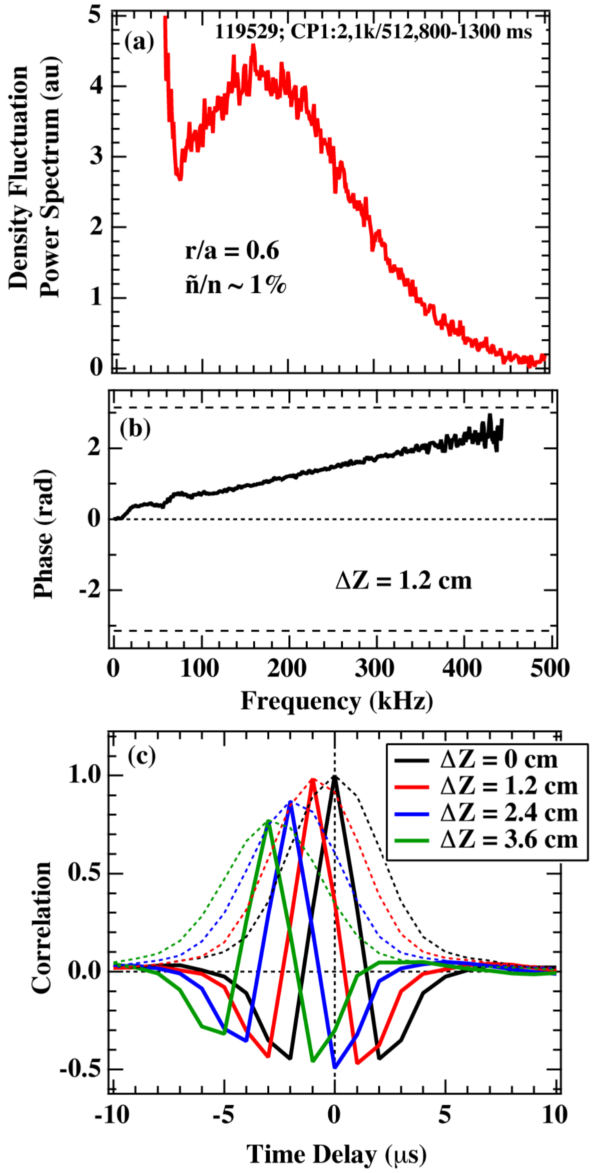

FIG. 2. (a) ñ spectrum near $r/a = 0.6$, (b) phase shift vs freq. for poloidally-separated channels, (c) time-lag cross-correlations showing poloidal propagation, finite decorrelation time and length (solid lines: correlations; dashed lines: envelope).

3. Zero-Mean-Frequency Zonal Flow

The ZMF zonal flow has been identified for the first time in the core of a fusion-grade tokamak plasma [10]. These flows are observed as a low frequency, spectrally broad feature of the derived poloidal turbulence velocity spectrum, peaking near zero frequency and extending up to 20-30 kHz. An example of the derived velocity spectrum from near

$r/a = 0.68$ is shown in Fig. 3(a). This spectrum shows a wide feature peaking near zero frequency, and extending out to about 20 kHz. Cross phase measurements of this signal from 0-7 kHz from a similar discharge are shown in Fig. 3(b). Radially and poloidally separated measurements show essentially zero phase shift. The zero poloidal phase shift is consistent with the expected $m = 0$ structure, though this measurement array extends over too small a poloidal region to be able to discern an accurate m-number.

The calculated velocity spectra of the $n = 0$ (zonal) radial electric field from GYRO simulations [11] is shown in Fig. 4. These spectra are obtained from a long-time electrostatic flux-tube computation at $q = 3$ and $q = 1.4$ using kinetic electrons. This spectrum exhibits qualitative similarity to the observed one, showing a peaking near zero frequency with a broad spectral width. Here, the GAM as well as higher k_r features are observed for the $q = 3$ case (black curve) between $0.5 < \omega < 1.0\ c_s/\mathbf{a}$. $\omega = 1.0\ c_s/\mathbf{a}$ (indicated by a dashed line in Fig. 4) is equivalent to approximately 34 kHz in Fig. 3, evaluating parameters locally.

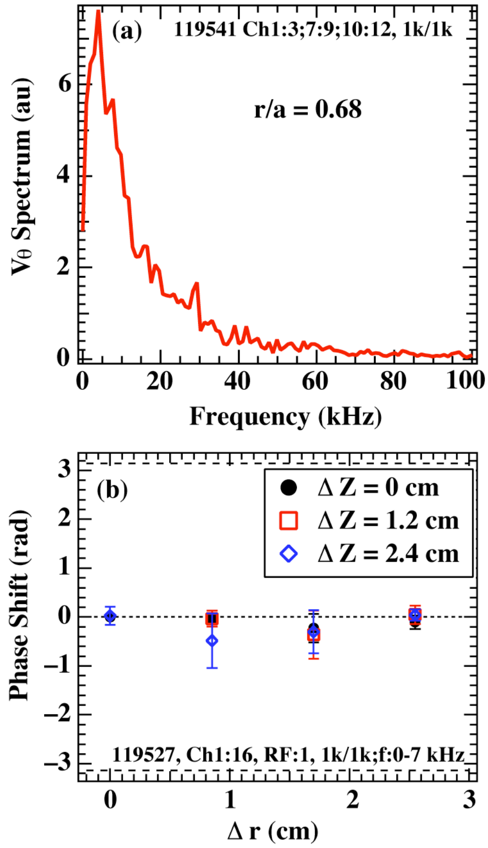

FIG. 3. (a) Derived spectrum of poloidal velocity fluctuations at $r/a = 0.68$ in a 0.6 MA discharge, (b) measured phase shift over 0-7 kHz across the 2D radial-poloidal array showing essentially zero phase difference.

Additional derived velocity spectra and their radial dependence from a 1.0 MA discharge are shown in Fig. 5(a,b). These spectra show the cross power of the velocity fluctuations at increasing radial separation for the four available channels in the measurement array. The signal shows monotonically decaying radial cross power, indicating a radial correlation length of the zonal flow structure of a couple cm. The spectra in Fig. 5(a) are from $r/a = 0.65$, while those in Fig. 5(b) are near $r/a = 0.88$. Both spectra exhibit the broad zonal flow structure peaking near zero-frequency, while the spectra at larger radius exhibits an additional coherent oscillation near 15 kHz, which has been previously identified as the GAM. Figure 6 shows the radial correlation of the zonal flow structure from a different discharge with I_p = 0.6 MA, demonstrating a 1-2 cm radial correlation length, consistent with what was observed in Fig. 5. This radial correlation length (about 10 ρ_i), is com-

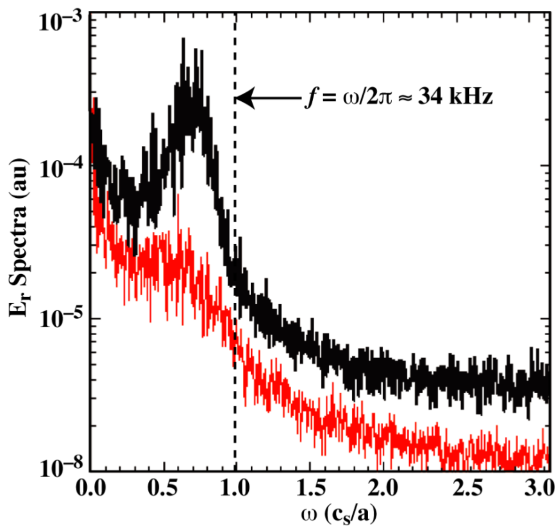

FIG. 4. $n = 0$ radial electric field spectra from GYRO flux-tube electro-static simulations with kinetic electrons at $q = 3$ (black) and $q = 1.4$ (red). $\omega = 1$ (dashed line) ≈34 kHz equivalent from Fig. 3(a).

parable to that of the higher frequency ($70 < f < 500$ kHz) density turbulence.

4. Structure and Safety Factor Dependence of the Geodesic Acoustic Mode

The poloidal velocity spectra vary significantly with radius and are shown in Fig. 7 for several radii from a 0.8 MA discharge. The poloidal velocity spectrum is dominated near the edge of the plasma ($0.9 < r/a < 0.95$) by the GAM [7], while the ZMF zonal flow becomes dominant deeper in the plasma core. At the inner radii ($r/a = 0.8$), only the broad ZMF zonal flow structure is observed, while at $r/a = 0.85$, a superposition of both the ZMF flow and the GAM at 15 kHz is seen. Further out radially at $r/a = 0.92$, the GAM dominates the velocity spectrum.

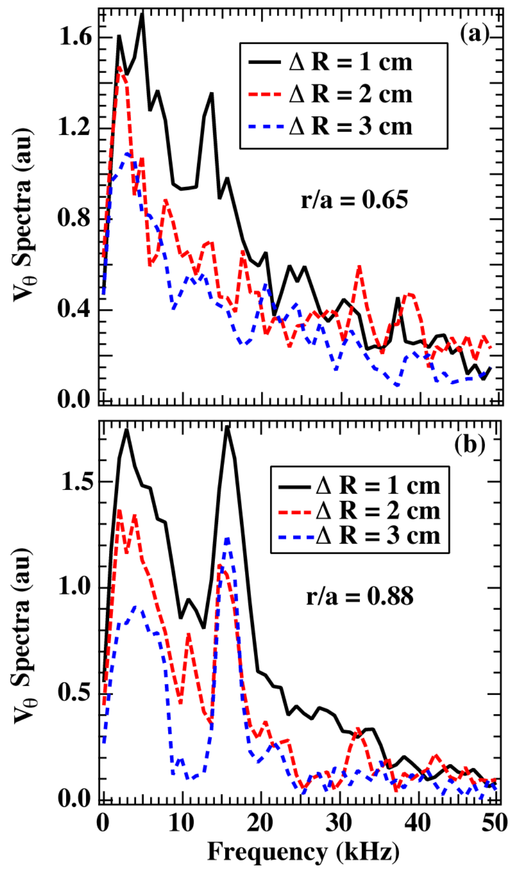

FIG. 5. Cross power spectra of velocity fluctuations at increasing radial separation in a 1.0 MA discharge at (a) $r/a = 0.65$, and (b) $r/a = 0.88$.

The radial structure of the GAM has been determined with a radial scan of the detector array and isolation of the GAM component [12]. The amplitude profile is shown in Fig. 8 along with the safety factor profile for this discharge. The GAM is observed to peak near $r/a = 0.9$, though it can be detected from $0.75 < r/a < 0.98$. This measurement is very similar to an observation obtained with the heavy ion beam probe on JFT-2M [13]. Outside of the separatrix, the GAM is virtually undetectable. As an acoustic oscillation driven by pressure asymmetries resulting from nonuniform $E_r x B_T$ flows, it is only expected to be observed on the closed flux surfaces. The GAM has a finite radial wavenumber of approximately 1 cm^{-1} [8] and can thus only be excited up to within a finite distance to the separatrix.

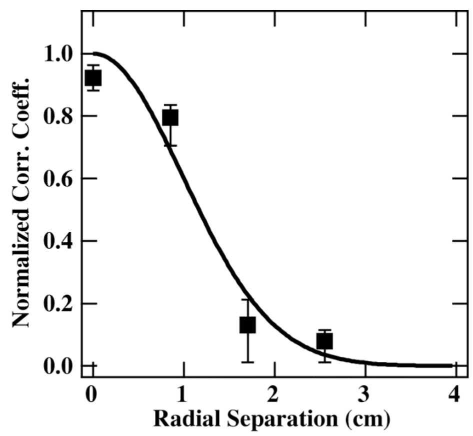

FIG. 6. Radial correlation function for 0-7 kHz zonal flow structure in a 0.6 MA discharge near $r/a = 0.8$.

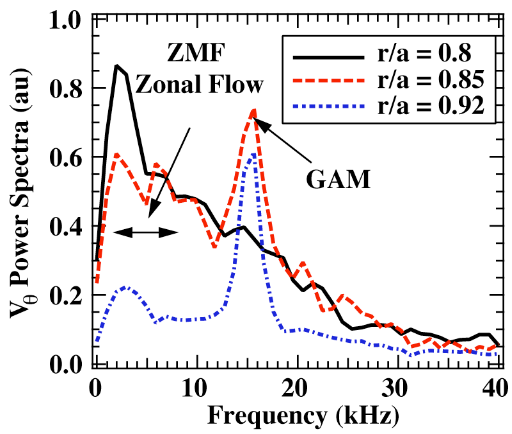

FIG. 7. Velocity fluctuation profile at three radii showing a transition from ZMF-dominated spectrum to a GAM-dominated spectrum.

The GAM amplitude is shown to be a strong function of the safety factor, q_{95}, in a manner that is consistent with ion Landau damping on the resonant ion population [14]. Figure 9(a) shows the derived velocity spectrum, with the dominant GAM structure near $r/a = 0.9$ from three plasmas with varying q_{95}, and otherwise similar parameters. The GAM amplitude is relatively large at $q_{95} = 6.4$, smaller at $q_{95} = 5.3$, and has virtually disappeared by $q_{95} = 4.5$. A similar example is shown in Fig. 9(b) where the relative GAM amplitude is shown vs q_{95}. Unlike the data from Fig. 9(a), which was obtained from three similar discharges at the same time and location, this data is from a single discharge with maximum current of 1.4 MA. During the current ramp phase, the GAM evolves rapidly with the amplitude obtained at different times and plotted against the corresponding q_{95} values. This strong dependence of the GAM amplitude on q_{95} is qualitatively consistent with theoretical considerations. The GAM damping rate is given approximately as $\nu_{GAM} = \omega_{GAM} \exp(-q^2)$ by considering the fraction of the ion population with a bounce frequency resonant with the GAM, which suggests an increasing amplitude at higher q_{95}. This q-dependence is also qualitatively consistent with results from the GYRO simulation code [15].

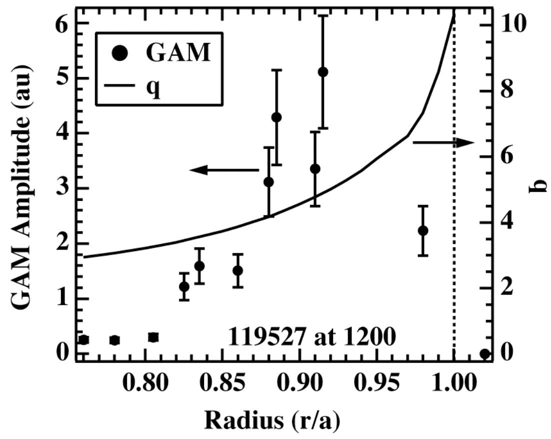

FIG. 8. Radial profile of GAM amplitude and associated q profile from a 1.0 MA plasma.

5. GAM-Driven Nonlinear Energy Transfer

In addition to the spatio-temporal characterization of the zonal flows, their nonlinear interaction with the turbulence has been directly measured in a high-temperature fusion-grade plasma for the first time [16]. Broadband density fluctuations associated with ambient plasma turbulence, measured with BES at DIII-D, are shown to be nonlinearly upscattered in frequency by the GAM. The application of a novel algorithm that calculates energy transfer between density fluctuations, the poloidal density gradient fluctuations, and the TDE-measured poloidal velocity demonstrates a GAM-mediated transfer of energy from poloidal density gradient fluctuations with frequency $f_0 - f_{GAM}$ to density fluctuations at frequency f_0. This is illustrated in Fig. 10, where the yellow region (offset diagonal) shows positive energy gain by the fluctuations from the gradient fluctuations over a broad frequency range from 40 to 150 kHz. The blue region (offset-diagonal) likewise shows a corresponding transfer of energy from

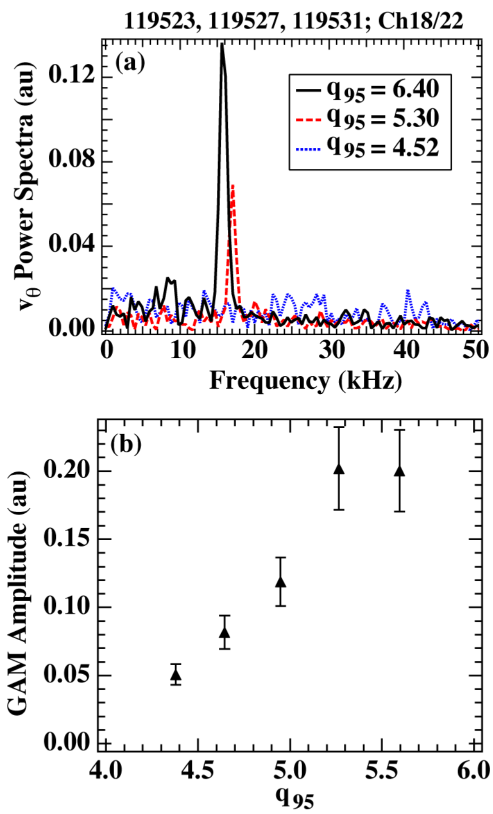

FIG. 9. (a) velocity spectra for three values of q_{95} at the same time and radial locations, (b) GAM amplitude vs q_{95} at several times during a single discharge during the current ramp (evolving q_{95}).

density fluctuations with frequency f_0 to gradient fluctuations with frequency $f_0 + f_{GAM}$. These nonlinear measurements indicate that the GAM shearing drives a "forward cascade" of internal energy from low to high frequencies. A qualitatively similar observation of zonal flow-mediated energy transfer is measured with density fluctuation data obtained from GYRO simulations. A modulation of the ambient density fluctuations at the GAM frequency is also observed and has a well-defined phase relationship with the GAM itself.

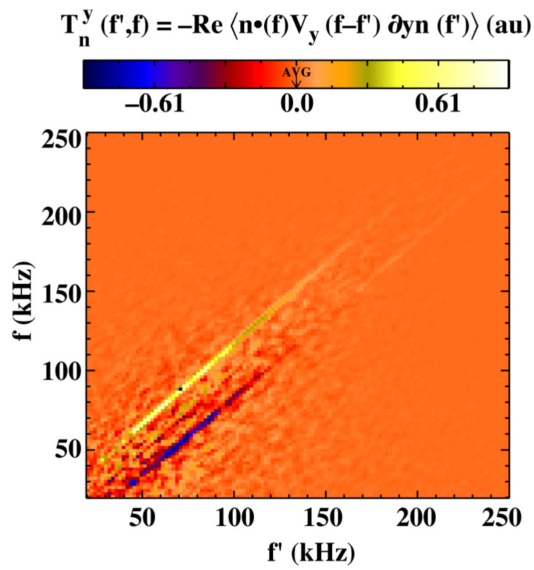

FIG. 10. Calculation of energy transfer between plasma density fluctuation, density gradient fluctuations, and poloidal velocity fluctuations; the yellow (blue) lines indicate positive (negative) energy exchange between the corresponding fluctuation frequencies.

6. Zonal Flow Measurements in the Controlled Shear Decorrelation Experiment (CSDX)

These results from BES measurements on DIII-D clearly show the existence and characteristics of the ZMF and GAM zonal flow branches, and the results in Fig. 10 show how GAMs nonlinearly regulate the temporal (and thus spatial) scales of the higher frequency turbulent fluctuations; however, they do not show that the shear flows are sustained by the turbulence. Recent experiments in the CSDX laboratory plasma device bridges this gap by providing comprehensive measurements of plasma profiles, turbulence characteristics and turbulence-driven, radially sheared flows. These results are thereby helping to validate the theoretical picture of the drift wave-zonal flow system in magnetized plasmas [17]. CSDX has a 3 m Ar plasma column with a 5 cm radius, $B_Z < 0.1$ T, and a radial and poloidal array of probes used to measure electrostatic fluctuations. The plasma source is a 1.5 kW, 13.56 MHz helicon antenna that produces plasmas with density up to $n_o >$ several 10^{12} cm^{-3}, $T_e \leq 3$ eV, and line-averaged neutral and ion temperatures of 0.5 and 0.7 eV, respectively. An azimuthally sheared flow is observed via both Mach probes and TDE applied to azimuthally displaced measurements. Both are found to be in quantitative agreement, demonstrating measurement consistency as well as helping to experimentally validate the TDE approach to flow measurement. The azimuthal component of the ion momentum balance equation:

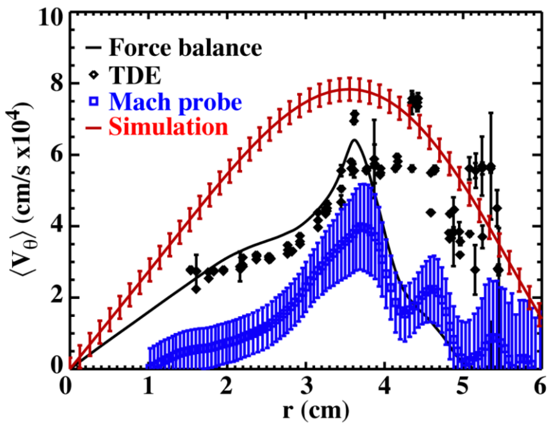

FIG. 11. Measurements of azimuthal (zonal) flow in the CSDX laboratory plasma via Mach probes and TDE method, flow calculation from azimuthal force balance with flow damping, and comparison to simulation.

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left\langle \tilde{V}_r \tilde{V}_\theta \right\rangle\right) = -\nu_{i-n}\left\langle V_\theta \right\rangle + \mu_{ii}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\left\langle V_\theta\right\rangle}{\partial r}\right) - \frac{\left\langle V_\theta\right\rangle}{r^2}\right] ,$$

is used to evaluate the time-averaged poloidal fluid velocity using measurements of the electrostatic Reynolds stress (turbulent transport of momentum), measured with a 4-tip Langmuir probe, as well as ion-neutral dissipation and ion-ion collisional viscosity, which are inferred from measurements [18]. The calculated flow is compared with zonal flow measurements, and simulation in Fig. 11 showing good agreement near mid-radius. The numerical simulation, using a two-fluid drift-turbulence model [19], shows the formation of a zonal flow sustained against damping that is in quantitative agreement with the experimental observations. Finally, the turbulent particle and momentum fluxes are quenched near the peak of the zonal flow (r = 3.6 cm), demonstrating the existence of a transport barrier.

7. Conclusion

A comprehensive exploration of zonal flow phenomenon in both a fusion-grade magnetically confined plasma as well as a laboratory scale device suggests a common underlying phenomenology inherent to two-dimensional magnetized plasma fluid systems. The detection and characterization of zero-mean-frequency zonal flows along with measurements of the radial structure and q_{95} scaling properties of the Geodesic Acoustic Mode as well as its mediation of a forward energy cascade have been performed via application of newly implemented diagnostic capability and application of novel analysis techniques. These experimental observations from confinement and laboratory devices and comparison with turbulence simulation are validating the fundamental nonlinear dynamics of drift wave-zonal flow turbulence in fusion plasmas and thereby aiding the development of a fully predictive capability for transport in future burning plasma experiments.

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References

[1] DIAMOND, P.H., *et al.,* Plasma Phys. Control. Fusion **47** (2005) R35.
[2] ROSENBLUTH, M.N., and HINTON, F.L., Phys. Rev. Lett. **80** (1998) 000724.
[3] WINSOR, N., *et al.,* Phys. Fluids. **11** (1968) 2448.
[4] HALLATSCHEK, K., and BISKAMP, D., Phys. Rev. Lett. **86** (2001) 1223.
[5] GUPTA, D.K., *et al*., Rev. Sci. Instrum. **75** (2004) 3493.
[6] McKEE, G.R., *et al*., Rev. Sci. Instrum. **77**, 10F104 (2006).
[7] JAKUBOWSKI, M., *et al.,* Phys. Rev. Lett **89** (2002) 265003.
[8] McKEE, G.R., *et al.,* Phys. Plasmas **10** (2003) 1712.
[9] SCHLOSSBERG, D.J., *et al*., "Velocity fluctuation analysis via dynamic programming," accepted Rev. Sci. Instrum. (2006).
[10] GUPTA, D.K., *et al*., Phys. Rev. Lett. **97**, 125002 (2006).
[11] CANDY, J., and WALTZ, R.E., J. Comp. Phys. **186** (2003) 545.
[12] McKEE, G.R., *et al.,* Plasma Phys. Control. Fusion **48** (2006) S123.
[13] IDO, T., *et al*., Plasma Phys. Control. Fusion **48** (2006) S41.
[14] HINTON, F.L., and ROSENBLUTH, M.N., Plasma Phys. Control. Fusion **41** (1999) A653.
[15] KINSEY, J.E., *et al.,* "Phys. Plasmas **13** (2006) 022305.
[16] HOLLAND, C., *et al*., "Measurement of Nonlinear Interactions Between Geodesic Acoustic Modes and Edge Turbulence in DIII-D," submitted to Phys. Rev. Lett. (2006).
[17] TYNAN, G.T., *et al.,* Plasma Phys. Control. Fusion **48** (2006) S51.
[18] HOLLAND, C., *et al*., Phys. Rev. Lett. **96** (2006) 195002.
[19] WAKATANI, M., and HASEGAWA, A., Phys. Fluids **27** (1984) 611.