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

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Zonal flows, including the zero-mean-frequency, spectrally broad flows and the higher frequency, oscillatory geodesic acoustic mode (GAM), have been characterized in the core of the DIII-D tokamak. The nonlinear transfer of turbulent energy to higher frequency by the GAM is measured and suggests that the GAM is playing a role in saturating the turbulence in the near edge region. These zonal flows [1] 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 both experiment and simulation that the shear flows 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-scaled turbulence.

The zero-mean-frequency zonal flow [2], is identified here for the first time in the core of a fusion-grade tokamak plasma using multipoint, two dimensional measurements of the density turbulence and its resulting velocity-field. These measurements are obtained with a recently implemented high sensitivity 2D beam emission spectroscopy (BES) density fluctuation diagnostic system on DIII-D. The flows are manifest in the inferred velocity field of the turbulence and are observed in the core region from $0.6 < r/a < 1.0$. 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, as shown in Fig. 1. They exhibit a long poloidal wavelength, consistent with the expected m=0 poloidal structure, and a short radial correlation length of a few cm. This radial correlation length (about 10 ρ_i), is comparable to that of the higher frequency turbulence.

The poloidal velocity spectrum is dominated near the edge of the plasma ($0.9 < r/a < 0.95$) by the GAM [3], while the zero-mean-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}, in a manner that is consistent with ion Landau damping on the resonant ion population [4], with the damping rate given approximately as $\nu_{GAM} = \omega_{GAM} \exp(-q^2)$. The GAM amplitude is undetectable for $q_{95} < 4.5$ and increase strongly up to $q_{95} > 6$. This q-dependence is also qualitatively consistent with results from the GYRO simulation code [5].

Experiments in a laboratory plasma device, with a radial and poloidal array of probes and well-understood pressure-driven drift wave turbulence, show the presence of an azimuthally sheared flow that is consistent with a turbulent momentum balance that includes the mea-

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sured turbulent Reynolds stress and flow damping (Fig. 2). Furthermore, numerical simulations using a two-fluid drift-turbulence model [6] shows the formation of a zonal flow sustained against damping that is in quantitative agreement with the experimental observations. The zonal flow is also shown to quench the turbulent particle flux.

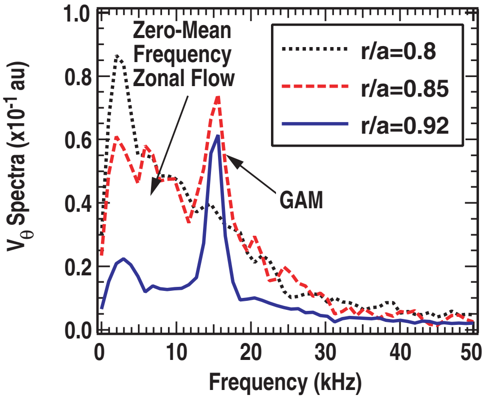

Fig. 1. Poloidal velocity spectra of turbulence from BES showing zonal flows as a broad structure (0-30 kHz), peaking at low frequency, and a coherent GAM (~15 kHz) at 3 radii.

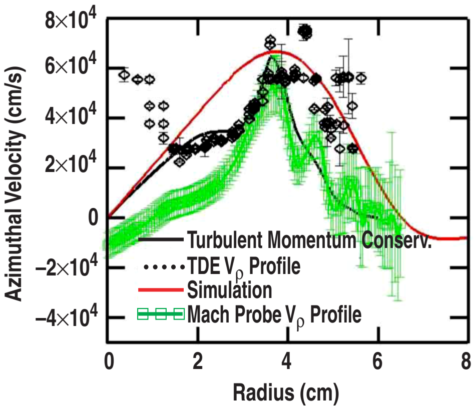

Fig. 2. Measured zonal flow velocity profile (diamonds and squares), Reynolds-stress driven flow profile (solid black line), and simulation (red line) in the Controlled Shear Decorrelation eXperiment.

In addition to the spatio-temporal characterization of the zonal flows in both confinement and laboratory experiments, their nonlinear interaction with the turbulence has been directly measured in a high-temperature plasma for the first time. Broadband density fluctuations associated with ambient plasma turbulence are shown to be nonlinearly upscattered in frequency by the GAM. The application of a novel algorithm that calculates energy transfer between density fluctuations demonstrates a GAM-mediated transfer of energy from poloidal density gradient fluctuations with frequency $f_o - f_{\mathrm{GAM}}$ to density fluctuations at frequency f_o (Fig. 3, yellow curve) over a wide frequency range with a corresponding transfer of energy from density fluctuations with frequency f_o to gradient fluctuations with frequency $f_o + f_{\mathrm{GAM}}$ likewise observed (Fig. 3, blue curve), indicating 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 with the GYRO code.

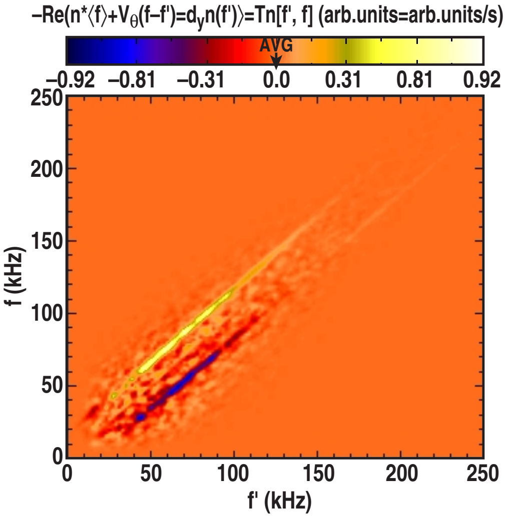

Fig. 3. Nonlinear transfer of energy between fluctuations (measured with BES) at frequency f and poloidal density gradient fluctuations at frequency f'.

These experimental observations of zonal flows from confinement and laboratory devices, and comparison to turbulence simulation are validating the fundamental nonlinear dynamics of drift wave/zonal flow turbulence in fusion plasmas and thereby aiding the development of predictive capability for transport in future burning plasma experiments.

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