Characteristics of Zonal Flows and their Dynamics in the DIII-D Tokamak, Laboratory Plasmas, and Simulation*

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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 DIII-D tokamak core. These flows have long been predicted theoretically to be the crucial turbulence saturation mechanism 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 $\Delta f \approx 10 \text{ kHz}$. These flows 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 low-frequency zonal flow becomes dominant deeper in the plasma core. GAM amplitude is shown to be a strong function of the safety factor, $q_{95}$, consistent with theoretical predictions based on ion Landau damping. Experiments in a laboratory plasma device show the presence of an azimuthally sheared flow consistent with a turbulent momentum balance that includes the measured turbulent Reynolds stress and flow damping. Zonal flow is shown to quench the turbulent particle flux. A nonlinear transfer of turbulent energy to higher frequency is measured in the tokamak fluctuation data and suggests that the GAM plays a role in saturating the turbulence in the near edge transition region. Application of an 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 $f_0 \pm f_{\text{GAM}}$, leading to a net transfer of energy from low to high frequencies. These experimental observations of zonal flows from confinement and laboratory devices and comparison with turbulence simulation validate the fundamental nonlinear dynamics of turbulence in plasmas and aid in the development of a fully predictive transport capability in future burning plasma experiments.

*Work supported by US DOE under DE-FG03-96ER54373, DE-FG02-04ER54758, DE-FG03-95ER54309, DE-FG02-92ER54141.