Frequency-Resolved Nonlinear Turbulent Energy Transfer into Zonal Flows in Strongly Heated *L*-Mode Plasmas in the HL-2A Tokamak

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The absolute rate of nonlinear energy transfer among broadband turbulence, low-frequency zonal flows (ZFs) and geodesic acoustic modes (GAMs) was measured for the first time in fusion-grade plasmas using two independent methods across a range of heating powers. The results show that turbulent kinetic energy from intermediate frequencies (20–80 kHz) was transferred into ZFs and GAMs, as well as into fluctuations at higher frequencies ($>$ 80 kHz). As the heating power was increased, the energy transfer from turbulence into GAMs and the GAM amplitudes increased, peaked and then decreased, while the energy transfer into the ZFs and the ZFs themselves increased monotonically with heating power. Thus there exists a competition between ZFs and GAMs for the transfer of turbulent energy, and the transfer into ZFs becomes dominant as the heating power is increased. The poloidal-radial Reynolds stress and the mean radial electric field profiles were also measured at different heating powers and found to be consistent with the energy transfer measurement. The results suggest that ZFs play an important role in the low-to-high (*L*-*H*) plasma confinement transition.

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