SUPPRESSION OF LOW-K TURBULENCE BY ALFVÉN EIGENMODES IN THE DIII-D TOKAMAK

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Strong interactions between gradient-driven long-wavelength ($k_\perp\rho_i<1$) turbulence and energetic particle-driven Alfvén eigenmodes (AEs) via nonlinearly driven poloidal flows have been demonstrated to improve confinement in DIII-D plasmas. As fusion research advances into the eve of burning plasmas, the traditional division of fusion plasma studies into distinct areas such as thermal particles, energetic particles, and their associated confinement, is becoming increasingly inadequate. In future fusion reactors, drift waves driven by thermal particles, which govern the thermal confinement, will coexist with AEs driven by fusion-born energetic particles. Proof-of-principle experiments in DIII-D tokamak demonstrate the existence of nonlinear cross-scale interactions between low-k turbulence, including ion temperature gradient modes (ITG) and trapped electron modes (TEM), and AEs mediated by shear flow. Specifically, ITG/TEM turbulence can be robustly mitigated or even fully suppressed in the presence of AE activity, leading to sustained improvements in thermal plasma confinement over multiple confinement times. These findings present new challenges for accurately predicting the plasma performance of future devices, but also offer exciting opportunities to optimize plasma performance in burning plasma regimes.

In a series of dedicated DIII-D experiments, low-k turbulence ($k_\perp\rho_i<1$), which is predicted to be TEM by TGYRO codes, is robustly mitigated through the excitation of a single toroidicity-induced AE (TAE) near the plasma edge. One example is shown in Fig. 1. Specifically, TEM and TAE are unambiguously identified by analyzing the phase shift of density fluctuations, measured by a pair of poloidally separated beam emission spectroscopy (BES) channels, which are 1.5cm apart poloidally at the same radial location. TEM exhibits a linear increase in the phase shift with the increase of the frequency, due to the broad-k spectra characteristic under a constant E×B flow. On the other hand, TAE is identified by a phase shift close to zero, as its poloidal wavelength is much larger than that of TEM. As seen from Fig. 1(b), the TEM amplitude is significantly reduced by about 50% when the TAE appears. Conversely, TEM amplitudes recover, when the TAE amplitude decreases.

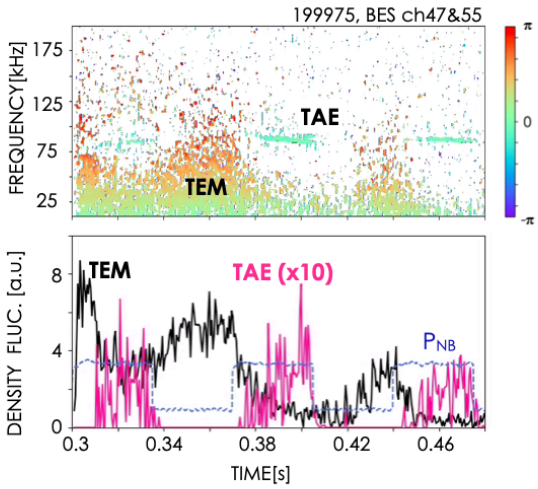

Fig. 1 (a) Time evolution of phase shift in density fluctuations between two BES channels that are separated poloidally by 1.5cm at radial location R=2.22m is shown for shot 199975 with a modulated beam of 81keV. TAE and TEM are labeled. (b) Time evolution of TEM (black curve) and TAE (red curve) amplitudes.

Complete suppression of long-wavelength turbulence ITG is also observed, when multiple TAEs, sharing two identical toroidal mode numbers of $n=3$ and $n=4$, are excited, as seen from Fig. 2(a). Importantly, this is accompanied by a noticeable improvement in plasma confinement, with a ~30% increase in both electron and ion temperatures at constant heating power, as seen from Fig. 2(b). This improvement of plasma confinement persists for several energy confinement times. The TGYRO code, which does not take account the effect of TAEs, predicts that the linear growth rate of ITGs should remain nearly unchanged during the suppression phase, highlighting the critical roles of TAEs.

To understand the underlying physics behind the observed turbulence mitigation and suppression, turbulent eddies are visualized using a two-dimensional 8×8 BES array. We compare the shape of turbulent eddies under similar heating power, with and without the presence of TAEs. This comparison is made possible by using multiple low voltage 50 keV beams to match the heating power of high voltage 81 keV beams. It is known that the low voltage beams are much less efficient at driving TAEs through resonant conditions compared to high voltage beams. The results show that: (1) In the case with low-voltage neutral beams and without TAE (Fig. 3A), the eddy size is the largest, covering a broad radial extent. (2) In the case with the high-voltage beam and TAEs (Fig. 3B), the turbulent eddies become tilted and exhibit the smallest radial scale. This is similar to the observed turbulent eddies under strong shear flow, as reported in [1]. Velocimetry measurements from BES also reveal a formation of a strong, narrow, poloidal flow shear layer, which reaches up to 160kHz and exceeds the local ITG decorrelation rates. In a plasma condition at a lower magnetic field, Doppler backscattering diagnostics find an increase in axisymmetric E×B shear flow, correlated to the turbulence reduction during each burst of AEs. It should be noted that, in the cases analyzed, the dilution of fast ions of the thermal plasma changes by only a few percent, suggesting a minimal impact on TEM/ITG growth rates.

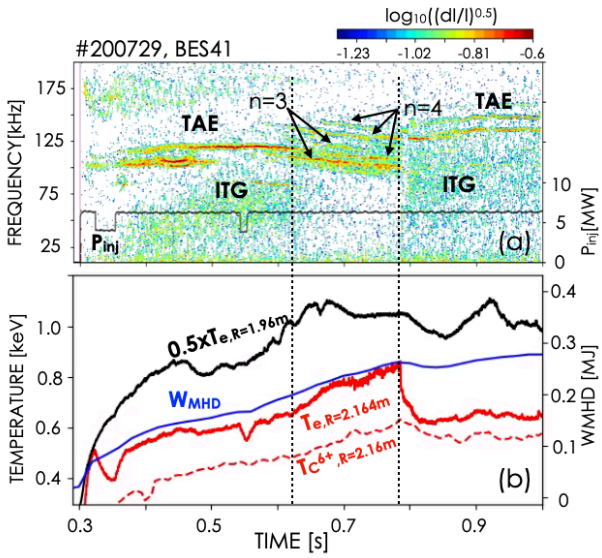

Fig. 2 Time evolution of ITG and TAE amplitudes measured by BES, along with neutral beam heating power in (a); electron and ion temperature along with the stored energy in (b).

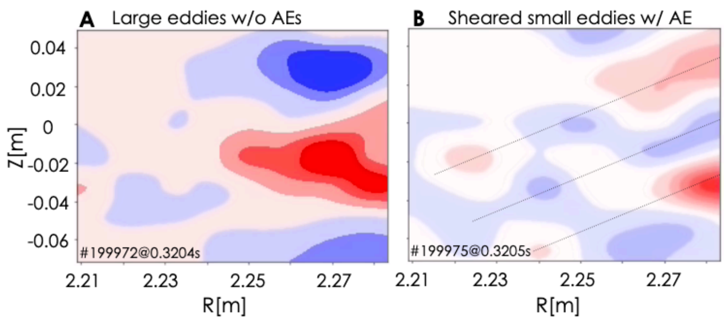

Fig. 3 Turbulent eddy images, obtained by BES system, in low voltage neutral beam of 3MW without TAE (A) and in high voltage beam of 3.3MW with TAE (B).

The observed shear flow may arise from two sources: (1) polarization induced by resonant EP nonlinearity [2]. A rapid change of the plasma potential and rotation is also observed, when energetic particle driven resistive interchange modes are excited [3]. The transient formation of radial current is associated with non-ambipolar transport of energetic particles induced by resonant interactions [4]; (2) the spontaneous excitation of modulation instabilities, when the amplitudes of the TAEs exceed a certain threshold. This process is related to the Reynolds and Maxwell stress, originating from the contribution of the thermal plasma [5]. Moreover, evidence of increased Reynolds stress force, related to the formation of shear flow layer, has also been obtained in experiments.

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