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Linear Excitation and Nonlinear Saturation of Low Frequency Alfven Eigenmodes in DIII-D

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Energetic particle (EP) interactions with thermal plasmas can lead to the excitations of various Alfven eigenmodes (AE) ranging from low frequency beta-induced Alfven eigenmode (BAE), to high frequency reversed shear Alfven eigenmodes (RSAE) and toroidal Alfven eigenmodes (TAE). Furthermore, EP could influence thermal plasma dynamics including the microturbulence responsible for turbulent transport of thermal plasmas and macroscopic magnetohydrodynamic (MHD) modes, potentially leading to disastrous disruptions.

Therefore, integrated simulation of multiple kinetic-MHD processes by treating both EP and thermal plasmas on the same footing need to be verified and validated. We have developed first-principles capability for global integrated simulation of nonlinear interactions of multiple kinetic-MHD processes by treating both EP and thermal plasmas on the same footing. Verification and validation for GTC (1) gyrokinetic simulations of RSAE/TAE in a DIII-D plasma have been carried out using most of active EP codes in the world fusion program (five gyrokinetic turbulence codes, two hybrid MHD-gyrokinetic turbulence codes, and an eigenvalue code) (2). GTC has further been validated in the simulations of various AEs in DIII-D, JET, HL-2A, and KSTAR tokamaks (3-6) and LHD stellarator (7). EP effects on neoclassical tearing mode (NTM) in the DIII-D tokamak have also been studied in GTC simulations (8). In this paper, we report linear excitation and nonlinear saturation of BAE and lower frequency modes, EP interactions with the NTM (8), as well as nonlinear interactions of RSAE/TAE with microturbulence in the DIII-D experiments.

Linear excitation of BAE and lower frequency modes in DIII-D —Linear GTC simulations of n=3 perturbation in DIII-D #178631 have found strongly unstable BAEs with growth rate comparable to real frequency, for both classical and relaxed fast ion profiles. Fig.1 shows the frequency and radial profiles of BAE and lower frequency modes, together with ideal MHD continua from ALCON, which confirms that the frequencies, lying in experimentally observed range, place in beta-induced gap.

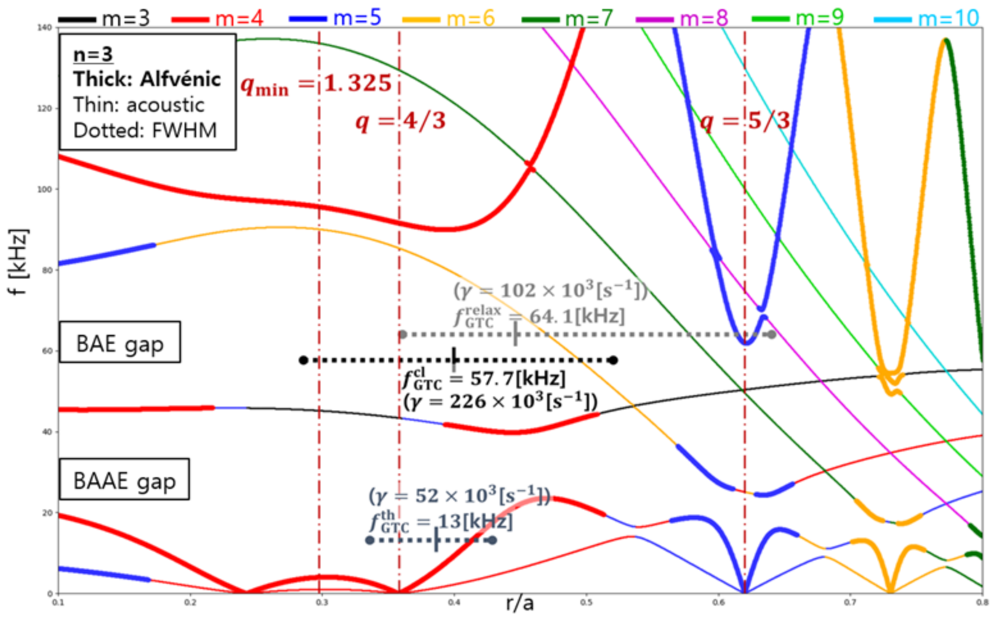

Figure 1: Frequency and radial width of BAE and lower frequency modes from GTC simulations are plotted with ALCON MHD continua.

Role of zonal fields in BAE saturation and EP transport —Fig. 2 is a result of nonlinear BAE simulations with and without zonal fields, clearly showing that zonal fields prevent robust nonlinear evolution of BAE and suppress it by strong regulation within a few linear oscillation periods. BAE amplitude is strongly suppressed by zonal flow shearing. Note that the BAE also undergoes strong phase shift which directly affect radial EP fluxes so that they can even flip signs from outward to inward. Consequently, outward fast ion transport due to BAE is significantly reduced by both zonal flow shear-induced suppression and phase shift. Furthermore, we have observed nonlinear evolution of the zonal flow structure evolving from strong single transport barrier to multiple barriers after initial suppression of BAE.

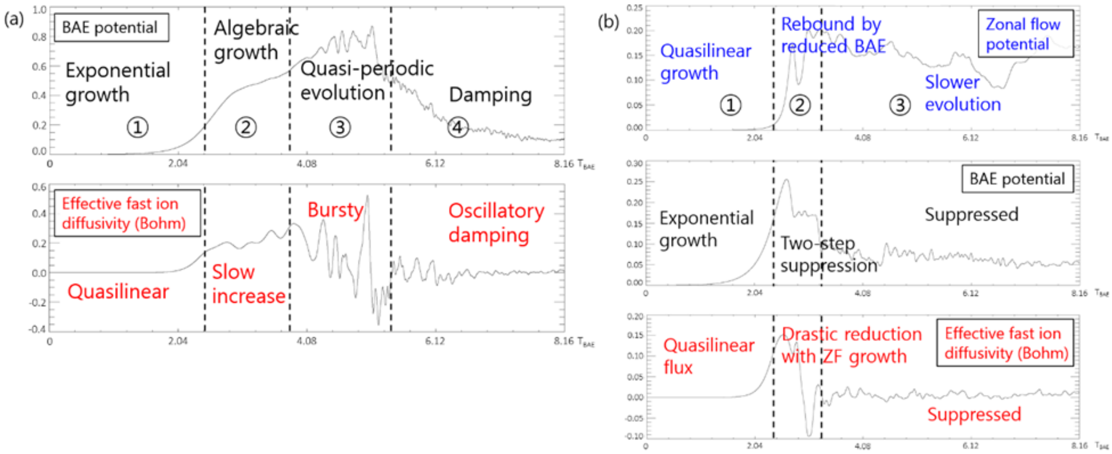

Figure 2: Nonlinear time evolution of BAE potential and fast ion flux (a) without and (b) with zonal fields.

EP couplings with thermal plasmas —Furthermore, we have performed self-consistent linear and nonlinear GK simulation of EP-driven AEs for the same discharge using GTC to identify their nonlinear behaviors. Linear simulations with broad range of toroidal mode number n have found that high-n ion temperature gradient (ITG) mode dominates in outer edge, with co-existing low-n RSAE in core and weakly unstable intermediate-n TAE in outer edge. Fig. 3 shows that this aspect changes dramatically in nonlinear regime, as zonal fields strongly regulate RSAE and ITG turbulence. Also, it has been found that the ITG turbulence spreads inward after local saturation. As a result, we have identified a mechanism approaching to nonlinear co-existence of RSAE, TAE and ITG turbulence in DIII-D plasmas.

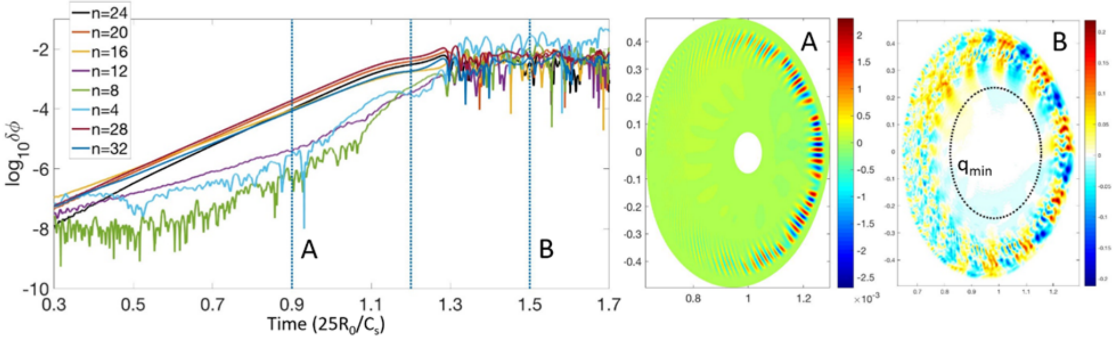

Figure 3: ITG growth rate γ as a function of ExB shearing rate ω_s, where γ_0 is the growth rate when $\omega_s = 0$.

EP interactions with NTM islands —GTC simulations find that EP radial profile is partially flattened within the NTM magnetic island regions and that there are stochastic regions in the particle phase space. Radial particle flux is induced mainly around the magnetic island regions and decreases with time to almost zero when the initial EP distribution achieves a new steady-state in the absence of EP sources. Stochastic regions of magnetic field lines induced by the superposition of multiple islands have weak effects on the particle flux when the width of stochastic regions is smaller than the EP drift orbit width. The perturbed parallel EP current induced by the magnetic islands has weak stabilizing effects on the linear growth rate of the NTM instability in this DIII-D experiment (8).

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