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Theory for control of sub-cyclotron Alfvén instabilities and implications for anomalous electron energy transport in tokamaks

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High frequency ($\omega < \omega_{ci}$) compressional (CAE) and global (GAE) Alfvén eigenmodes are routinely driven unstable by super-Alfvénic neutral beam ions in spherical tokamaks such as NSTX(-U) and MAST(-U). These instabilities have also been observed in the conventional tokamaks DIII-D and AUG, where the beam ions are typically sub-Alfvénic. In NSTX, the presence of strong CAE/GAE activity was experimentally linked to the anomalous flattening of electron temperature profiles at high beam power, potentially limiting fusion performance. Specifically, CAEs and GAEs can effectively channel energy away from the core [2,3], resulting in presently unpredictable modifications to the core plasma heating. In addition, early NSTX-U operations serendipitously discovered the robust stabilization of counter-propagating GAEs with relatively small amounts of off-axis beam injection [4]. A detailed understanding of the preferential conditions for CAE/GAE excitation and stabilization, therefore, is vital to predicting and controlling their effects on thermal plasma confinement.
A comprehensive set of 3D hybrid kinetic-MHD simulations, using the HYM code, has been performed for a wide range of beam parameters, providing a wealth of information on CAE and GAE destabilization in realistic spherical tokamak configurations. This study is unique in that it uses a full orbit kinetic description of the energetic beam ions, necessary to capture the Doppler-shifted cyclotron resonances which mediate the instability. Furthermore, new instability conditions have been derived for CAEs and GAEs using perturbative linear theory in order to complement and interpret the simulation results. The simulations demonstrate that the excitation of CAEs vs GAEs has a complex dependence on the fast ion injection velocity and geometry. It is found that the analytic instability conditions accurately describe key properties of the unstable modes in the simulations, offer a straightforward and generalizable explanation of the GAE stabilization observed in NSTX-U, and resolve puzzling observations from past DIII-D experiments. A cross validation between the theoretical stability bounds, simulation results, and a large database of experimental measurements in NSTX shows favorable agreement for both the unstable CAE and GAE spectra's dependence on fast ion parameters. Based on these insights, new mechanisms for the stabilization of CAEs and GAEs are identified in order to aid the investigation of their role in anomalous electron energy transport in future NSTX-U experiments. The combined numerical and analytical approach developed in this work lays the foundation for a powerful predictive capability for effective control of sub-cyclotron Alfvén instabilities and the energy transport which they induce.

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