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Validation of GAE simulation and theory for NSTX(-U) and DIII-D

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New theoretical study of Alfvén eigenmodes (GAEs) in the sub-cyclotron frequency range explains the observed GAE frequency scaling with beam parameters in experiments across devices (1-3). Global Alfvén eigenmodes are frequently excited during neutral beam injection (NBI) in the National Spherical Torus Experiment (NSTX/NSTX-U) (4,5), as well as other beam-heated devices such as MAST and DIII-D (6). These modes are driven unstable through the Doppler shifted cyclotron resonance with the NBI ions, and can be excited in ITER due to super-Alfvénic velocities and strong anisotropy of the beam ions. They can also be excited by alpha particles near the outer edge of the ITER plasma due to anisotropies in the alpha particle distribution. Observations link these modes to flattening of electron temperature profiles and anomalously low central temperature at high beam power in NSTX (7), therefore, the ability to control them will have significant implications for NSTX-U, ITER, and other fusion devices where Alfvénic and super-Alfvénic fast ions might be present.

Numerical simulations using the HYM code have been performed to study the excitation of GAEs in NSTX, NSTX-U and most recently for DIII-D. The HYM code is an initial value 3D nonlinear, global stability code in toroidal geometry, which treats the beam ions using full-orbit, delta-f particle simulations, while the one-fluid resistive MHD model is used to represent the background plasma. Nonlinear HYM simulations show unstable counter-rotating GAEs with toroidal mode numbers, frequencies and saturation amplitudes that match the experimentally observed unstable GAEs in NSTX-U and NSTX (1,2).

New simulations performed for typical DIII-D plasma and beam parameters demonstrate that high-frequency modes with $\omega/\omega_{ci} \sim 0.6$, previously identified as compressional Alfvén eigenmodes (CAEs) (6), have shear Alfven polarization and are in fact the GAEs (Fig.[1]). Simulations show unstable counter-propagating GAEs with $\delta B_{\|} < 0.1\delta B_{\perp}$, high toroidal mode numbers $|n| > 20$, and frequencies close to the observed $\omega/\omega_{ci} \sim 0.6-0.7$ for NBI injection velocity $V_0/V_A = 0.9$. The unstable modes have $k_{\perp}\rho_b \sim 0.5$, and growth rates $\gamma/\omega_{ci} \sim 0.002-0.003$. These simulation results combined with growth rate calculations (Fig.[2]) based on the local dispersion relation (1,3) explain some of the puzzling DIII-D observations. Namely, high-frequency modes (identified as CAEs in Ref.(6)) observed in DIII-D had small values of $k_{\perp}\rho_b$ ($k_{\perp}\rho_b \sim$ 0.8, in some cases <0.5), i.e. smaller than previously predicted (5,8) for the unstable CAEs ($1 < k_{\perp}\rho_b < 2$) or GAEs ($2 < k_{\perp}\rho_b < 4$); the ratio ω/ω_{ci} remained approximately constant when the toroidal field was varied; the most unstable mode frequency scaling with n_e was weaker than the Alfven speed scaling, i.e. weaker than $1/\sqrt{n_e}$; the observed frequency splitting was not consistent with theoretical predictions for CAEs.

Simulation results and growth rate calculations (1,3) show that previously derived and widely cited instability conditions for counter-propagating GAE: $2 < k_{\perp}\rho_b < 4$ and for CAE: $1 < k_{\perp}\rho_b < 2$ (5,8) are valid only for higher frequency modes with $\omega \sim \omega_{ci}$, when the beam injection velocity is very large compared to the resonant velocity $V_0 \gg V_{res}$. The new theory predicts that the GAE linear growth rate is largest for small values of $k_{\perp}$ ($k_{\perp}\rho_b < 1$) (Fig.[2]). For a beam ion distribution function $f(\lambda) \sim exp[-(\lambda-\lambda_0)^2/\Delta\lambda^2]$, a sufficient condition for the instability is: $1 - V_{\|res}^2/V_0^2\ \lambda_0$, where $\lambda = \mu B_0/\varepsilon$ is a pitch related parameter. The most unstable counter-GAEs have frequencies in the range (1):
$(1 + V_0/V_A)^{-1} < \omega/\omega_{ci}\ (1 + V_0/V_A\sqrt{1-\lambda_0})^{-1}$, (1)
where the most unstable frequency roughly corresponds to the upper bound in Eq.(1). For DIII-D parameters ($V_0/V_A \sim 1$, λ_0 ~0.5-0.7), this gives $0.5 < \omega/\omega_{ci}\ 0.65$, consistent with observations and the simulation results. The observed scaling with B_{tor} , λ_0 and weak n_e scaling also agrees with Eq.(1). For example, "left beam sources"in DIII-D, have $\lambda_0 \approx$ 0.5 and excite modes with $\omega/\omega_{ci} \approx$ 0.56, whereas for "right sources" $\lambda_0 \approx$ 0.78 and $\omega/\omega_{ci} \approx$ 0.69 (6). Our theory predicts $\omega/\omega_{ci} \approx$ 0.58 and 0.68 respectively. In addition, it is shown that CAEs have the same instability condition and range of unstable frequencies as the GAEs in the limit $k_{\perp} \ll k_{\|}$, otherwise CAE's growth rates are much smaller than that of GAEs, consistent with simulation results and the NSTX(-U) observations.

Expression (1) correctly predicts the scaling of the most unstable GAE frequencies with NBI parameters for NSTX, NSTX-U and DIII-D. Thus, for λ_0 ~0.6 and large normalized injection velocities in NSTX (V_0/V_A ~3-5), the predicted frequency range ω/ω_{ci} ~0.2-0.3 agrees with observations. Due to stronger toroidal field in NSTX-U, and smaller relative injection velocities (V_0/V_A 2), higher frequency GAEs were observed ω/ω_{ci} ~0.4 (4). For DIII-D conditions with V_0/V_A ~1, a much higher frequencies predicted consistent with the observed ω/ω_{ci} ~0.6 (6).

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