Coupling of Neutral-beam-driven Compressional Alfvén Eigenmodes to Kinetic Alfvén Waves in NSTX and energy channelling

E. V. Belova[1], N. N. Gorelenkov[1], N. A. Crocker[2], E. D. Fredrickson[1], K. Tritz[1]
1) Princeton Plasma Physics Laboratory, Princeton NJ, USA
2) University of California, Los Angeles, California 90095, USA
E-mail: ebelova@pppl.gov

Experimental observations from National Spherical Torus Experiment (NSTX) suggest that many modes in a sub-cyclotron frequency range are excited during neutral beam injection (NBI). These modes were identified as compressional Alfven eigenmodes (CAEs) and global Alfven eigenmodes (GAEs), driven unstable through the Doppler shifted cyclotron resonance with the super Alfvenic NBI ions [1,2]. Observations also link these modes to flattening of electron temperature profiles and anomalously low central temperature at high beam power [3]. Several mechanisms have been suggested to explain the observed temperature profiles by a strong anomalous electron transport [4]. Other estimates [5] suggest that the energy channeling from core-localized GAEs to continuum damping closer to the edge can be responsible for the observed flattening of the T_e profiles. This paper reports first MHD-kinetic simulations of NBI-driven CAEs in NSTX, which demonstrate that CAEs can mode convert to kinetic Alfven wave (KAW) at the Alfven resonance location, and discusses possible effects of CAE/KAW coupling on the electron temperature profiles in the NSTX.

The hybrid code HYM [6] has been used to investigate properties of beam ion driven CAE in NSTX. The HYM code is a 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. The excitation of CAEs has been studied for the H-mode plasma of NSTX shot 141398, where plasma was heated by 6 MW of 90keV Deuterium beams with n_b=3.5×10^{18} m^{-3}, n_e= 6.7×10^{19} m^{-3}, B_t= 0.325 T, I_p= 0.8 MA, and v_0= 4.9V_A. In this shot, significant GAE/CAE activity has been observed, and detailed measurements of GAE and CAE amplitudes and mode structures were obtained [7]. Linearized simulations for this case show that most unstable modes for n=5-7 are counter-rotating GAEs. The most unstable modes for n=4 and n=8, 9 are co-rotating CAEs. The calculated range of the unstable toroidal mode numbers, frequencies, and mode polarizations appear to be reasonably close to experimental observations [7,8].

In NSTX, the CAEs are driven unstable by the resonant interaction with the beam ions. Numerical analysis of the wave-particle interaction for the n=8 CAE simulation shows two groups of resonant particles, one group which satisfies the regular resonance condition: $\omega - k_{||}v_{||} = 0$, and a group of higher energy particles which satisfy the Doppler-shifted cyclotron resonant condition: $|\omega| + \omega_{ci} - k_{||}v_{||} = 0$. In was found that the main contribution to the instability drive comes from the first group, and the contribution from the cyclotron resonances is negligible. Figure 1 (a) shows poloidal contour plots of the perturbed magnetic field for the n=8 (ω=0.48ω_{ci}) CAE. Here R is major radius, normalized to the ion skin depth λ_i=3.93cm, the magnetic axis is at R=27.5 and the plasma edge is at R~37.5. It can be seen that the CAE is localized in the core, near the magnetic axis, and $\delta B_{||}$ is significantly larger than $\delta B_\perp$ everywhere, except in the radially localized region on the high-field-side where the resonant condition ω_A(Z,R)= ω is satisfied. Analysis of magnetic and velocity perturbations of the resonant mode shows that its polarization is consistent with that of the kinetic Alfven wave (KAW). The radial wavelength of the KAW is comparable to the beam ion Larmor radius, $k_\perp \rho_{beam} \sim 1$. The KAW is propagating in the direction of the beam ion velocity (co-rotating CAE), and $k_\perp$ is directed towards the high-density side. This results in a mode structure which is tilted relative to the magnetic flux surfaces (Fig.1), and is not up-down symmetric. The condition $k_\perp \rho_b \sim 1$ implies that the ion and electron motions are decoupled, leading to generation of finite parallel electric field perturbations, which is typical for KAW (Fig. 1b). The location of the shear Alfven resonance always coincides with the edge of an effective potential for CAE: $V_{eff} = -\omega^2/V_A^2 + k_{||}^2$, within which the CAE is non-evanescant [2,8], leading to a strong coupling between compressional mode and KAW. Simulations for both low-n and high-n co-rotating CAEs show resonant coupling to the KAW.

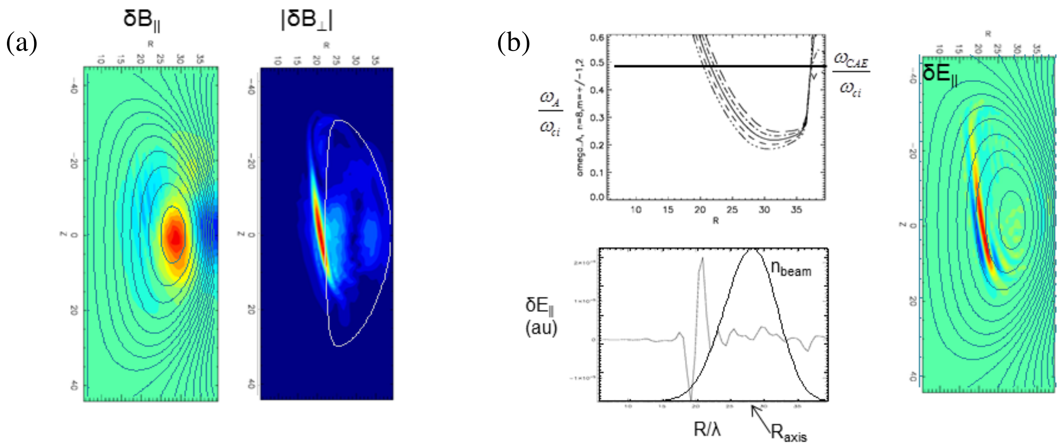

Figure 1. *(a) Contour plots of magnetic field perturbation for n=8 co-rotating CAE mode; solid contour line on* $|\delta B_\perp|$ *plot corresponds to the resonant condition* $\omega_A(Z,R) = \omega$; *(b) Radial profiles of Alfven continuum,* $\delta E_{||}$ *and beam ion density, and contour plot of* $\delta E_{||}$ *for the n=8 CAE/KAW mode.*

Numerical simulations demonstrate that a resonant mode conversion of CAE to kinetic Alfven wave will occur for any unstable CAE in NSTX, independent of toroidal mode number or mode frequency. The strong CAE/KAW coupling supports an alternative mechanism for T_e flattening, in which beam-driven CAE dissipates its energy at the resonance location with KAW, therefore significantly modifying the energy deposition profile (similar to a mechanism suggested qualitatively in [5]). Self-consistent calculations of energy flux from CAE to KAW will require nonlinear simulations, and will be performed in the future. Fraction of NBI power transferred to CAE can be estimated as $P = 2\gamma \int (\delta B)^2/4\pi \, d^3x$, where $\delta B/B_0 = (0.9\text{-}3.4)\times 10^{-3}$ has been found using HYM-calculated linear mode structure for the n=4 CAE with $\omega = 0.35\omega_{ci}$, and measured displacement $|\xi| = 0.1\text{-}0.4$ mm [7]. For $\gamma/\omega_{ci} = 0.005\text{-}0.01$, it gives P=(0.013-0.4)MW, therefore, a significant fraction of NBI energy can be transferred to several unstable CAEs of relatively large amplitudes. In this case, the energy flux from the CAE to the KAW and dissipation at the resonance location can have a direct effect on the temperature profile (changes in core T_e up to several hundred eV). In addition, radially overlapping KAWs can strongly enhance plasma transport due to finite $\delta E_{||}$. Our simulations show that the radial width of KAWs is comparable to the beam ion Larmor radius, which is relatively large for 90keV beams in NSTX. In cases when several CAEs are observed, the KAWs will likely overlap radially, and can have a direct effect on both the electron transport and the beam ion re-distribution.

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