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], J. B. Lestz[1], E. D. Fredrickson[1], K. Tritz[3]
1) Princeton Plasma Physics Laboratory, Princeton NJ, USA
2) University of California, Los Angeles, California, USA
3) Johns Hopkins University, Baltimore MD, 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 Alfvén eigenmodes (CAEs) and global Alfvén eigenmodes (GAEs), driven unstable through the Doppler shifted cyclotron resonance with the super Alfvénic NBI ions [1,2]. High-frequency AEs 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 ITER plasma due to anisotropies in alpha particle distribution. Observations link these modes to flattening of electron temperature profiles and anomalously low central temperature at high beam power in the NSTX [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 nonlinear MHD-kinetic simulations of NBI-driven CAEs [6], which demonstrate that CAEs can convert to kinetic Alfvén wave (KAW) at the Alfvén resonance location, and channel significant fraction of the beam energy to the resonant location at the edge of the beam density profile, modifying the energy deposition profile.

The hybrid code HYM [7] has been used to investigate properties of beam ion driven CAE in NSTX. 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. 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 beam velocity 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 [8,9]. Numerical simulations for this case show that most unstable modes for n=5-7 are counter-rotating GAEs, which have shear Alfvén wave polarization in the core. Most unstable modes for n=4 and n=8, 9 are co-rotating CAEs, driven unstable by the resonant interaction with the beam ions. Figure 1 shows poloidal contour plots of the perturbed magnetic field for the n=4 (ω=0.34ω_{ci}) CAE. 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 structure shows that its polarization is consistent with that of the kinetic Alfvén wave (KAW). The radial wavelength of the KAW is comparable to the beam ion Larmor radius, $k_\perp \rho_{beam}$ ~ 1. The KAW is propagating in the direction of the beam ion velocity (co-rotating CAE), and $k_\perp$ is directed towards the high-

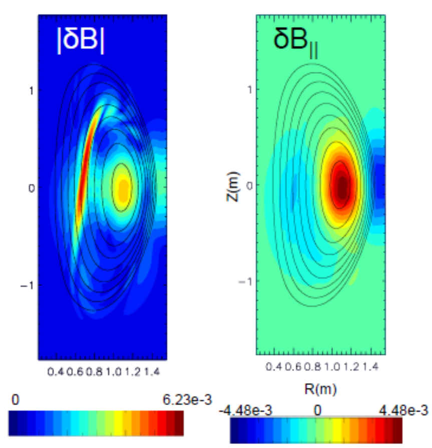

Figure 1. *Contour plots of magnetic field perturbation for n=4 co-rotating CAE mode.*

density side. This results in a structure which is tilted relative to the magnetic flux surfaces (Fig.1), and is not up-down symmetric. The location of the shear Alfvén 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-evanescent [2,9], 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.

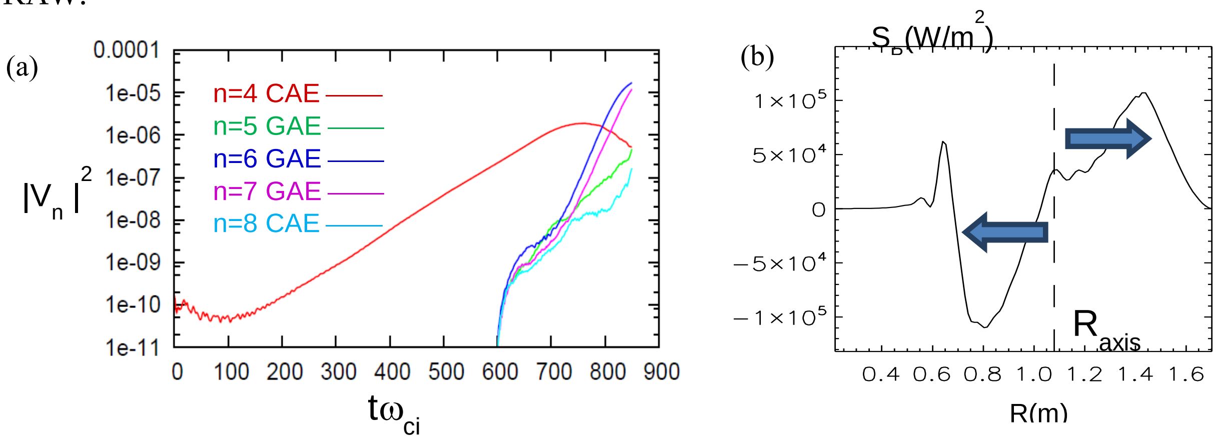

Figure 2. (a) *Time evolution of amplitudes of different toroidal harmonics from nonlinear simulations for NSTX shot 141398; (b) Radial component of Poynting vector* ***S***=<***E***x***B***> *at the midplane at t=750.*

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]). Fully nonlinear simulations including 32 toroidal harmonics show saturation of the n=4 CAE mode (Fig. 2a) by particle trapping. Initial conditions for nonlinear run were obtained by running the n=4 linearized simulations to obtain a converged linear mode structure of the CAE. Nonlinear run also shows growth of n=5,6,7 GAEs and n=8 CAE modes. Saturation amplitude of the n=4 CAE, $\delta B_{||}/B_0 = 6.6\times10^{-3}$, is comparable to values obtained by analysing experimental data from the same NSTX shot. Thus, measured plasma displacement $|\xi| = 0.1\text{-}0.4$ mm [8] corresponds to $\delta B/B_0 = (0.9\text{-}3.4)\times10^{-3}$. Figure 2b shows radial component of the Poynting vector at the midplane. The calculated change of the energy flux across the resonant layer at R~0.7m is 1.5×10^5 W/m^2, which corresponds to power absorption at the high-field-side resonance of P= (0.3-0.5) MW. Therefore, the nonlinear simulations show that a significant fraction of NBI energy can be channelled to the location of the resonant mode conversion at the edge of the beam density profile. 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).

[1] E. D. Fredrickson, *et al.*, Phys. Rev. Lett. **87**, 145001 (2001).
[2] N. N. Gorelenkov , E. Fredrickson, E. Belova, *et al.*, Nucl. Fusion **43**, 228, (2003).
[3] D. Stutman, *et al*., Phys. Rev. Lett. **102**, 115002 (2009).
[4] N.N. Gorelenkov, D. Stutman, K. Tritz et al., Nucl. Fusion **50** 084012 (2010).
[5] Ya. I. Kolesnichenko, Yu. V. Yakovenko, and V. V. Lutsenko, Phys. Rev. Lett., **104**, 075001 (2010).
[6] E. V. Belova, N. N. Gorelenkov, N. A. Crocker, et al., Phys. Rev. Lett., **115**, 015001 (2015).
[7] E. V. Belova, et al., Phys. Plasmas **7**, 4996 (2000); **10**, 3240 (2003).
[8] N. A. Crocker, *et al.*, Nucl. Fusion **53**, 043017, (2013).
[9] E. D. Fredrickson, N. N. Gorelenkov, M. Podesta, *et al*., Phys. Plasmas, **20**, 042112 (2013).

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