SIMULATIONS OF TAES IN NSTX-U

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The enhanced particle transport by low frequency Alfvén eigenmodes (AEs), in particular the toroidal Alfvén eigenmodes (TAEs), is one of the main mechanisms affecting the energetic ion confinement in both the currently operating experiments and in the next-step fusion devices, including ITER. Self-consistent simulations of beam-driven AEs in the TAE frequency range have been performed for National Spherical Torus experiment (NSTX-U) using full-orbit kinetic beam ion option of the HYM code [1]. Alfvén eigenmodes driven by super-Alfvénic fast ions were routinely observed in neutral beam heated plasmas on the NSTX and NSTX-U in a wide range of frequencies, from $f \sim 10$ kHz to $f \sim f_{ci}$. These modes, especially in the lower frequency range, can significantly impact fast ion transport, causing fast ion redistribution and losses [2]. Self-consistent linear and nonlinear simulations of AEs have been carried out using experimental plasma parameters and profiles for the NSTX-U discharge #204707, where the AEs were observed for toroidal mode numbers n=1-7, with normalized frequencies $f \sim 0.02\text{-}0.03 f_{ci}$ and the estimated growth times ~ 40μsec, $\gamma \sim 0.03\text{-}0.05\omega$, where f_{ci}=4.15MHz. Higher frequency modes (in the GAEs/CAEs range) with $f \geq 0.3 f_{ci}$ were also observed in this discharge but with larger toroidal mode numbers $n \geq 6$. Experimental spectrogram from this shot in the lower frequencies range is shown in Fig.1a, where a significant down chirping of AEs and possibly coupling or converting to lower frequency (fishbone) modes can be observed, particularly for the n=3 mode (green).

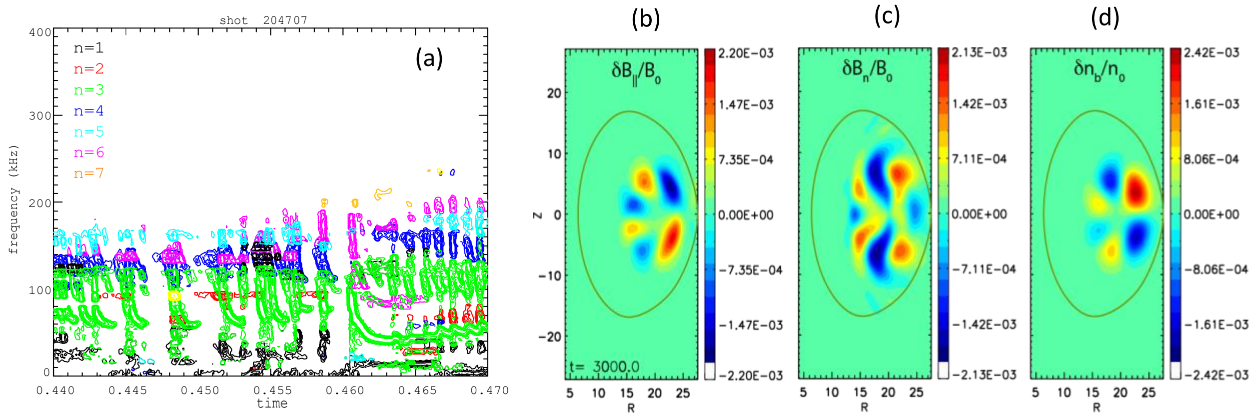

FIG.1. (a) Spectrogram of magnetic fluctuations for NSTX-U discharge #204707; different colors correspond to different toroidal mode numbers; (b-d) Poloidal contour plots of magnetic field and beam ion density perturbation from nonlinear simulations for n=3 mode. Length is normalized to ion skin depth d_i=5.62cm. Beam parameters: v_0/v_A = 2.0 and n_b/n_0= 0.24 and λ_0 = 0.65.

In this particular NSTX-U discharge the beam ion density and beta were relatively large: n_b/n_0=0.24 and β_{beam}=0.135, resulting in the strong instability drive. In comparison, the thermal plasma beta was β_{pl}=0.08, making the net beta for this case > 0.21. Numerical simulations for low toroidal mode numbers show instabilities with normalized mode frequencies and growth rates: $\omega=0.03\omega_{ci}$, $\gamma=0.0024\omega_{ci}$ and $\omega=0.04\omega_{ci}$, $\gamma=0.0033\omega_{ci}$ for the n=3 and n=4 modes respectively (higher frequency modes (GAE/CAEs) are also unstable for the n=4 with $\omega \sim 0.5\omega_{ci}$). Linear mode structure of the n=3 AE can be seen in Fig.1(b-d), where $\delta B_{\parallel}$, one of the $\boldsymbol{\delta B_\perp}$ components and δn_b are shown (δB_n= $\boldsymbol{\delta B} \cdot \nabla\psi/|\nabla\psi|$). For n=3 mode, the dominant poloidal mode numbers were m=3 and m=4, with larger amplitude for the m=3 component.

Nonlinear evolution of the mode amplitude is shown in Fig.2a,b, showing saturation of the instability at relatively large amplitude $\delta B/B_0 \sim 4\ 10^{-3}$, and the frequency change in the nonlinear phase of the simulation. The time evolution of the frequency spectrum from the n=3 simulations (Fig.2c) shows the nonlinear frequency chirping, and the appearance of the lower frequency mode with $\omega \sim 0.01\omega_{ci}$ later in the simulation.

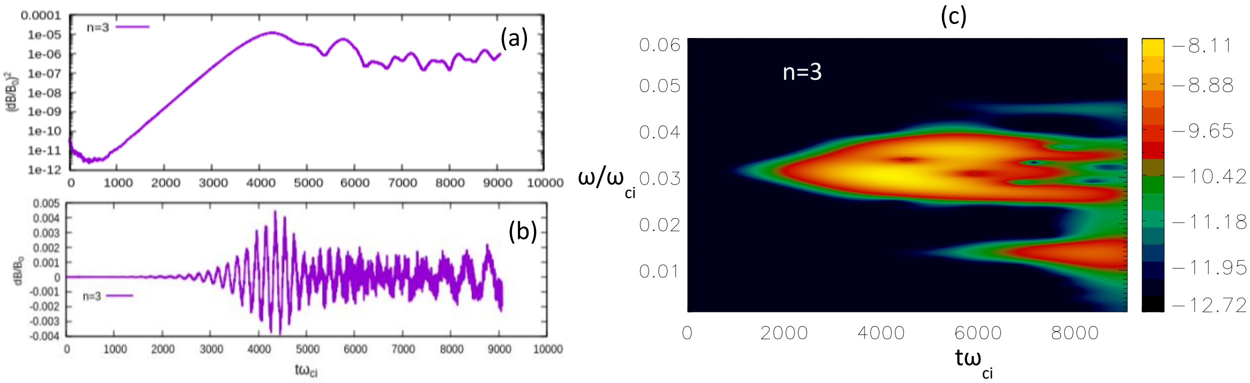

FIG.2. (a) Log plot of perturbed magnetic field energy vs time; (b) time evolution of $\delta B_\perp/B_0$; (c) corresponding time evolution of frequency spectrum from nonlinear simulations for n=3.

Comparison of the normal plasma velocity perturbation with the experimentally obtained displacement profile shows a good agreement in mode location and structure, with the linear mode amplitude peaked at R≈1.32m. However, the striking feature of the simulations is a very large compressional component of $\boldsymbol{\delta}\mathbf{B}$, comparable in amplitude to perpendicular component (Fig.1b,c). The compressional perturbation is localized away from the plasma edge, close to the peak of the beam ion density gradient, reducing sharply near the edge and making the mode polarization at the edge the shear Alfvén-like. The experimental measurements of the mode polarization using the Mirnov coil array located about 0.2m away from plasma edge and slightly off the midplane also show a mostly shear Alfvén polarization for these modes.

Several possible mechanisms, including the finite plasma pressure gradients, the geodesic curvature and toroidicity-induced coupling between shear Alfvén waves and acoustic modes could force the shear Alfvén perturbations to couple strongly to compressional perturbations [3,4]. Additional simulations have been performed to find the relation of the mode polarization and plasma or beam beta. New self-consistent equilibria were calculated by reducing either the thermal plasma pressure by half (from β_{pl} = 0.08 to 0.04, while keeping the beam density the same), or reducing the beam density by 1/2, so the beam beta became about 0.07, and keeping the thermal pressure the same). In both cases the *n*=3 mode was unstable with frequency close to the TAE frequency, $\omega = 0.5\omega_A$, but the amplitude of the compressional magnetic field component was noticeably reduced compared to the original case. This indicates a strong effect of plasma beta on mode polarization, when even a relatively small reduction of total beta makes the polarization more sheared. Simulations using the M3D-C1-K code [5] for the NSTX case (studied previously in [6] using M3D-K code) also show that AEs in the TAE frequency gap have a very large compressional magnetic field perturbation.

Large $\delta B_\parallel$ can significantly modify the wave-particle interactions, have a strong effect on EP redistribution and losses, and, possibly, alter the nonlinear dynamics of unstable modes. The effects of significant compressional magnetic field perturbation and dependence on plasma β need to be further investigated. Additional simulations will be performed to study the kinetic effects of thermal ions on the unstable modes with large compressional component, and to more closely benchmark the NSTX and NSTX-U simulations by the M3D-C1 and HYM codes.

References

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