Synopsis CATEGORY TH-W: Magnetic Confinement Theory and Modelling, Energetic Particles

Hybrid Simulations of beam-driven fishbone and TAEs in NSTX

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Energetic particle modes and Alfvénic modes driven by super-Alfvénic beam ions were routinely observed in neutral beam heated plasmas on the National Spherical Torus Experiment (NSTX). These modes can significantly impact beam-ion transport, thus causing beam-ion redistribution and losses. Recent simulation results with the kinetic/MHD hybrid code M3D-K show excitation and nonlinear saturation of n=1 fishbone with strong frequency chirping and beam ion radial profile flattening [1]. The linear simulation results of TAEs show mode radial structure consistent with the reflectometer measurements of electron density fluctuations [2]. In this paper we report on new self-consistent simulations of both fishbone instability and TAEs in NSTX plasmas. Our model is self-consistent with mode structure determined non-perturbatively including effects of energetic particles and plasma toroidal rotation.

A. Fishbone

The stability of the n=1 fishbone is systematically calculated with effects of plasma toroidal rotation for weakly reversed shear q profiles with minimum safety factor above unity. It is found that a new instability region appears for $q_{min} > 1.35$ when plasma toroidal rotation is included. The corresponding fishbone mode structure has strong ballooning feature. In contrast, the fishbone with $q_{min} < 1.35$ has a dominant m/n=1/1 kink structure. Both passing and trapped beam particles contribute to the instability drive. Nonlinear simulation shows strong mode frequency chirping as beam ion distribute is substantially redistributed in radial direction. The mechanism for the strong chirping is investigated systematically by following particles near the resonances. It is found that trapped particles are mainly responsible for the nonlinear frequency chirping although passing particles' instability drive is comparable to that of trapped particles. The initially resonant particles (precessional resonance) mostly stay in resonance as mode frequency chirps down. Furthermore a substantially fraction of non-resonant particles become resonant in the initial phase of chirping and stay in the resonance thereafter. It is also found that the wave particle trapping process is well in the adiabatic regime. In this aspect the nonlinear mechanism of chirping is similar to that of the Berk-Breizman theory of hole/clump dynamics [3]. However we also found that there is no clear hole/clump structure in contrast to the Berk-Breizman theory. Instead, the distribution is flattened radially near the resonance and the flattening region increases in outward direction) as frequency chirps down. This is due to large island width of the phase space resonant structure.

B. TAEs

NSTX experimental results show that multiple low-amplitude beam-driven TAEs with weak frequency chirping can transit to mode avalanche with much larger amplitudes and strong frequency chirping. In order to explore mechanisms of avalanche, nonlinear simulations of multiple beam-driven TAEs and the n=1 fishbone have been carried out for the first time. The simulation results show strong interaction between TAEs and fishbone that either enhances or reduces saturation level of individual modes due to overlap of wave particle resonances in phase space. As beam ion beta increases beyond stability threshold, mode saturation levels are found to increases sharply. When beam ion beta exceeds some critical value, the locally flattening regions of beam ion distribution function merge together resulting in global particle transport and substantial particle loss. Furthermore it is found that the mode saturation levels are very sensitive to q_{min}. When q_{min} drops below a critical value ~1.19, the mode amplitudes increase sharply to large values. This result is similar to the observed transition to TAE avalanche as q_{min} decreases in NSTX.

[1] F. Wang, G.Y. Fu, J. Breslau et al., Phys. Plasmas 20, 102506 (2013)
[2] D. Liu, G.Y. Fu, N. A. Crocker et al, Phys. Plasmas 22, 042509 (2015)
[3] H.L. Berk, B.N. Breizman, J. Candy et al., Phys. Plasmas 6, 3102 (1999)