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Hybrid simulation of fishbone instabilities with reversed safety factor profile

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Energetic particle physics is a crucial issue in burning plasmas such as the International Thermonuclear Experimental Reactor (ITER). Instabilities driven by energetic particles, such as fishbones and various Alfvén eigenmodes, can induce the transport and loss of energetic particles, degrade fast particle confinement, and even lead to serious wall damage. A non-monotonic safety factor profile with a reversed magnetic shear configuration has been proposed as an advanced scenario for future ITER operation. For the consideration of the fishbone instability, there are two different conditions: the minimum value of safety factor qmin is less or a little larger than unity. There are few simulations to investigate the fishbone instabilities with reversed safety factor profile. As a result, in this work, linear stability and nonlinear dynamics of the fishbone instabilities with reversed safety factor profile have been investigated by the hybrid code M3D-K[1,2], including both the non-resonant type with qmin larger than unity and the type with dual q = 1 surfaces, which we will infer as non-resonant fishbone (NRF) and dual resonant fishbone (DRF) in the following.

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Based on EAST-like parameters, the linear simulation results of the n = 1 mode with double q = 1 rational surfaces are firstly presented. With fixed total pressure, the linear growth rate and mode frequency as a function of beam ion pressure fraction Phot,0/Ptotal,0 are shown in figure 1, where Phot,0 is the central fast ion pressure, and Ptotal,0 is the central total pressure. At zero beam ion pressure with Phot,0/Ptotal,0 = 0, the ideal internal kink mode is unstable. The corresponding mode structure is shown in figure 1 (a). This mode has an up-down symmetric structure with zero mode frequency, and it exhibits splitting feature due to double q = 1 surfaces. The dominant mode number is n = m = 1, where n is the toroidal mode number and m is the poloidal mode number. When the value of Phot,0/Ptotal,0 is small and increases from 0 to 0.4, the mode is stabilized due to the kinetic effects of beam ions. However, when Phot,0/Ptotal,0 is larger than 0.4, the DRF is excited, which is an energetic particle mode driven by trapped beam ions. Figure 1 (b) shows the mode structure with Phot,0/Ptotal,0 = 0.3. Compared to the ideal internal kink mode, the mode structure shows a twisted feature with finite mode frequency. The mode structure of the DRF with Phot,0/Ptotal,0 = 0.6 is shown in figure 1 (c), and it becomes more twisted with much larger frequency. When qmin increases from below unity to above unity, the fishbone instability transits from the DRF to the NRF, and the mode frequency of the NRF is higher than the DRF as the NRF is resonant with fast ions with larger precessional frequency. The mode structure of the NRF is shown in figure 1 (d).

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Nonlinear simulations show that the saturation of the DRF with Phot,0/Ptotal,0 = 0.6 is due to MHD nonlinearity with a large n = 0 component. Figure 2 shows the reason why the DRF mode cannot saturate just with the nonlinearity of energetic particles. Without MHD nonlinearity, as shown in figure 2 (a), it is found that the distribution of fast ions becomes flattened in the core region during the nonlinear phase. However, near the magnetic axis there still exists the steep radial gradient of the fast ion distribution, which could drive the instability. Correspondingly as shown in figure 2 (c), the inner m/n = 1/1 DRF mode structure shrinks in the central region at t = 700 τA, where τA is the Alfvén time. As a result, the DRF mode still tap the free energy associated with the fast ion radial gradient during the nonlinear phase, and the DRF mode does not saturate without MHD nonlinearity. However, the saturation of the NRF is mainly due to the nonlinearity of fast ions. Figure 3 (a) shows the time evolution of the n = 1 mode amplitude of the NRF. It is observed that the NRF amplitude firstly grows and then saturates from t ≈ 1000 τA. Correspondingly as shown in figure 3 (b), the NRF frequency starts to chirp down at t ≈ 1500 τA from ω ≈ 0.12 ωA to ω ≈ 0.04 ωA, where ωA is the Alfvén frequency. Finally, the redistribution of beam ions due to the DRF and NRF with MHD nonlinearity is discussed, and it is found that the distribution of the fast ions become flattened in the core region. By comparing the fast ion redistribution induced by the DRF, the redistribution level of the fast ions due to the NRF is weaker, and the flattening region of the beam ions is located more centrally in the radial direction, which is consistent with the resonant analysis. Because the equilibrium profiles and parameters are chosen based on EAST-like conditions, the simulation results will provide guidance for and can be verified by future EAST experiments.

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