Hybrid-kinetic simulation of resonant interaction between energetic-ions and tearing modes in a tokamak plasma

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The effect of energetic-ions on magnetohydrodynamic (MHD) instabilities is pivotal in the basic physics that will be vital in burning plasma experiments. Recently, it has been found in the HL-2A tokamak that an m/n=2/1 unstable tearing mode (TM) interacts with energetic-ions, resulting in amplitude-bursting and frequency-chirping fishbone-like activities, and it is numerically identified that co-passing energetic-ions play a dominant role in the wave-particle resonances. Motivated by fully and deeply understanding such a resonant interaction between energetic-ions and TM, a more detailed study of global nonlinear hybrid kinetic-MHD simulations with M3D-K code is performed in the present work. The kinetic effect of co-passing energetic-ions from non-adiabatic response is interestingly found to be strongly destabilizing. For passing energetic-ions, the m/n=2/1 TM is found to be most unstable in the case of \(q_0 = 1.5\), where \(q_0\) is the central safety factor. Effects of energetic-ion beta \(\beta_h\) and pinch angle \(\Lambda_0\) determining different energetic-ion fraction on the resonance features, such as growth rate, frequency chirping and mode structure, are discussed in detail. The relevant simulation results are consistent with the observations on HL-2A. Furthermore, the effects of both counter-passing and trapped energetic-ions on the TM have also been explored, but the corresponding resonance phase space is found to be very narrow in the \(P_\phi - E\) plane. In addition, the redistribution and loss induced by the resonant interaction between TM and energetic-ions are analyzed in multiple-mode simulations, Significant redistribution and loss are clearly observed, and the scaling of energetic-ion loss fraction with the fluctuation amplitude is found to be \(I_{\text{loss}} \propto \sqrt{A_{\text{max}}}\), indicating that the loss is convective. These discoveries are conductive to understanding the mechanisms of TM-induced energetic-ion loss through the resonant interaction.

References
[1] X L Zhu et al 2020 Nucl. Fusion 60 046023

Figures

Fig 1. The perturbed distribution function (\(\delta f\)) around the magnetic moment \(\mu = 0.555\) in the phase space of \(P_\phi - E\).

Fig 2. Time evolution of energetic-ion distribution function in \((P_\phi, E)\) space around the magnetic moment \(\mu = 0.247\) at \(t = 0(a), t = 500\tau_A(b), t = 800\tau_A(c), t = 1200\tau_A(d)\).