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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 β_h and pinch angle Λ_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 $f_{loss} \propto \sqrt{A_{max}}$, 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

[2] W Chen *et al* 2019 Nucl. Fusion 59 096037

Figures

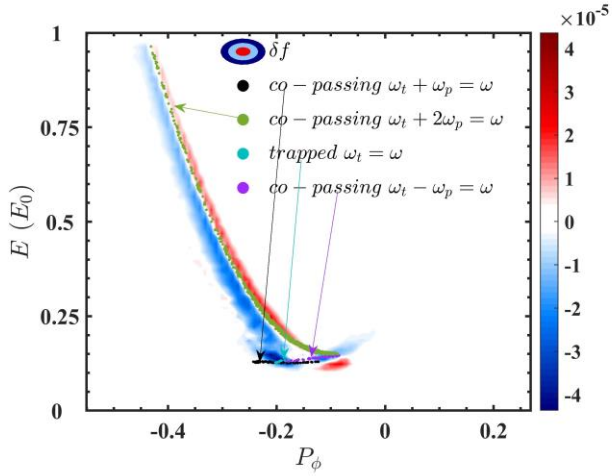

Fig 1. The perturbed distribution function (δf) around the magnetic moment $\mu = 0.555$ in the phase space of $P_\phi - E$.

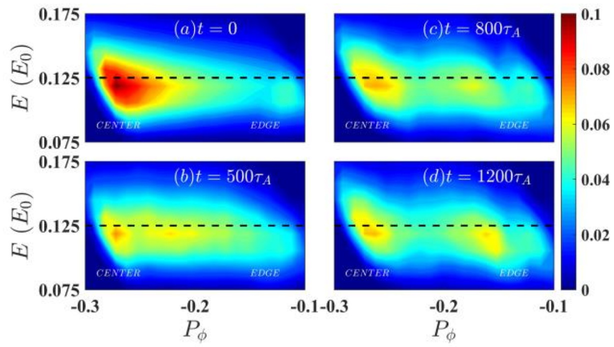

Fig 2. Time evolution of energetic-ion distribution function in (P_ϕ, E) space around the magnetic moment $\mu = 0.247$ at $t = 0(a)$, $t = 500\tau_A(b)$, $t = 800\tau_A(c)$, $t = 1200\tau_A(d)$.