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Simulation study of energetic-particle driven off-axis fishbone instabilities in tokamak plasmas

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Kinetic-magnetohydrodynamic hybrid simulations were performed to investigate the linear growth and the nonlinear evolution of off-axis fishbone mode (OFM) destabilized by trapped energetic ions in tokamak plasmas. The spatial profile of OFM is mainly composed of $m/n = 2/1$ mode inside the $q = 2$ magnetic flux surface while the $m/n = 3/1$ mode is predominant outside the $q = 2$ surface, where m and n are the poloidal and toroidal mode numbers, respectively, and q is the safety factor. The spatial profile of the OFM is a strongly shearing shape on the poloidal plane, suggesting the nonperturbative effect of the interaction with energetic ions. The frequency of the OFM in the linear growth phase is in good agreement with the precession drift frequency of trapped energetic ions, and the frequency chirps down in the nonlinear phase. Two types of resonance conditions between trapped energetic ions and OFM are found. For the first type of resonance, the precession drift frequency matches the OFM frequency, while for the second type, the sum of the precession drift frequency and the bounce frequency matches the OFM frequency. The first type of resonance is the primary resonance for the destabilization of OFM. The resonance frequency, which is defined based on precession drift frequency and bounce frequency for each resonant particle, is analyzed to understand the frequency chirping. The resonance frequency of the particles that transfer energy to the OFM chirps down, resulting in the chirping down of the OFM frequency. A detailed analysis of the energetic ion distribution function in phase space shows that the gradient of the distribution function along the $E' = const.$ line drives or stabilizes the instability, where E' is a combination of energy and toroidal canonical momentum and conserved during the wave-particle interaction. The distribution function is flattened along the $E' = const.$ line in the nonlinear phase leading to the saturation of the instability. The waveform distortion as a unique characteristic of OFM is observed in the simulations and attributed to the higher-n harmonics which are generated through MHD nonlinearity. The physical mechanism for the waveform distortion will be discussed.

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