Particle-in-cell simulations of parametric instability driven by the lower hybrid pump wave in the EAST tokamak

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The lower hybrid (LH) wave is widely adopted to auxiliary drive the toroidal current in tokamaks. However, the parametric instability (PI) comes to be an obstacle for extending such technique to higher plasma density or higher power injection.[1] To understand the physics of PI, plenty of works on have been done via the parametric dispersion relation [2]. For the tokamak plasma, the two primary channels are the decay into a LH sideband and an ion sound quasi-mode (ISQM) or an ion cyclotron quasi-mode (ICQM). The frequency of ISQM is $\omega_r \simeq k_{\parallel} c_s$, while for ICQM it is $\omega_r \simeq \omega_{ci} + k_{\parallel} c_s$. ($k_{\parallel}$ is the longitudinal wave number and c_s is the ion sound speed, ω_{ci} is the ion cyclotron frequency.) By numerically solving the dispersion relation, the change of density was found able to determine which decay channel dominates. Over the past decades, methods to study PI is limited to the aspect of growth rate and amplification factors under a weak turbulence assumption. To fill the gap, first-principle simulations are performed in this paper to examine and extend the present understanding of PI.

In our analytical work, an explicit expression of the PI growth rate is derived by solving the dispersion relation. By analyzing the contribution of ion susceptibility, the plasma pressure is found as a key parameter determining the decay channels, updating the previous opinion where only density is the involved parameter. In the low-pressure regime, ISQM is the dominant decay channel. As the pressure increases, ISQM destabilizes and the ICQM-type PI takes in charge and its harmonics emerge in succession. In the high-pressure limit, where the finite Larmor effects of ion is weak, the quasi-mode transits from multiple harmonics of ICQM to a single quasi-mode Landau damped by the free-streaming ions. Further derivation under each pressure regime gives dependence of growth rates on plasma parameters in detail, which are supported by growth rates calculated by numerically solving the dispersion relation.

For our first-principle simulations, particle-in-cell method with full-kinetic ions and electrons is used. The processes of ICQM and ISQM-type PI decay are reproduced in homogeneous plasmas with EAST-like parameters [1]. For parameters near the separatrix, two new spectra at frequencies near $\omega_0 - \omega_{ci}$ and $\omega_0 - 2\omega_{ci}$ emerge as pump power increases to the nonlinear stage, which are identified as LH sidebands of ICQM-type PI and its secondary harmonic, respectively. Ion cyclotron heating probably due to the secondary harmonic of ICQM is also observed in the case. For parameters near the LH antenna mouth, new spectra near $\omega_0 - k_{\parallel} c_s$ are found in the nonlinear stage, which is actually the LH sidebands of the ISQM-type PI. Comparison between the two cases show the domination of ISQM-type PI in the low-density plasma and ICQM-type PI in the high-density plasma of relatively high pressure, following the analytical prediction from the dispersion relation. For both the decay channels, their LH sidebands are excited with wide spectra with respect to the parallel refractive index N_z, where the N_z of the strongest ICQM-type sideband is larger than the ISQM-type. Such a wide spectrum (For a fixed temperature at 25eV, the maximum $N_{\parallel}$ can extend up to 30.) is found able to interact with the bulk electrons and cause significant heating as the trapping widths in velocity space of the high-$N_{\parallel}$ modes overlap together. The maximum accelerated electron velocity depends on the lowest $N_{\parallel}$ of the sidebands that involved in the overlapping.

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