NONLINEAR SPECTRUM EVOLUTION OF LOWER HYBRID WAVES AND DENSITY LIMIT OF LOWER HYBRID CURRENT DRIVE

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Noninductive current drive is essential for steady-state operation on tokamaks. The density limit, i.e. strong efficiency degradation of lower hybrid current drive (LHCD) at high density, makes the effectiveness of LHCD questionable on ITER and future fusion reactors. It is one of the main reasons that the lower hybrid wave (LHW) system was removed from the second stage upgrade option of heating and current driven (H&CD) system on ITER.[1] This work provides a self-consistent modeling and simulation of LHWs in the SOL plasma by coupling the propagation of waves to the power transfer among waves by parametric instabilities (PIs) in a 3D model. LHW spectrum broadening both in wave frequency and wave number was obtained self-consistently, and, correspondingly, the power flux of the pump was converted to sideband waves. When the density increases exceeding a critical value, stronger PIs transfer most of the pump power flux, resulting in the density limit of LHCD. For the first time, the density limit observed in LHCD experiments on JET[2] , EAST[3], C-Mod [4] and Tore Supra[5] , as well as various efforts to overcome/increase the density limit of LHCD on FTU[6], EAST[7] and C-Mod [8], can be successfully reproduced by the simulation. Based on simulation results and simplified theoretical analysis, a scaling relation of the density limit of LHCD was obtained. According to this scaling, higher LHW frequency, stronger magnetic field and higher periphery plasma temperature makes LHCD remain a promising method of driving plasma current for ITER and future fusion reactors.

Theory: To adapt to the scenarios where non-resonant quasi-mode decays are dominant, the nonlocal theory of PI saturation in an inhomogeneous plasma derived by Rosenbluth [9] should be extended [10-11] beside the local theory of PI excitation should be extended to include necessary nonlinearity and electromagnetic correction. [12] Effect of finite pump width is still dominant in the explicit form but the details of convective amplification should be considered on the wave propagation path. Subsequent analysis shows that both the radial and toroidal direction needs to be considered to derive the appropriate convective amplification of PI, for the daughter LHWs might propagate across the resonant region through both directions.

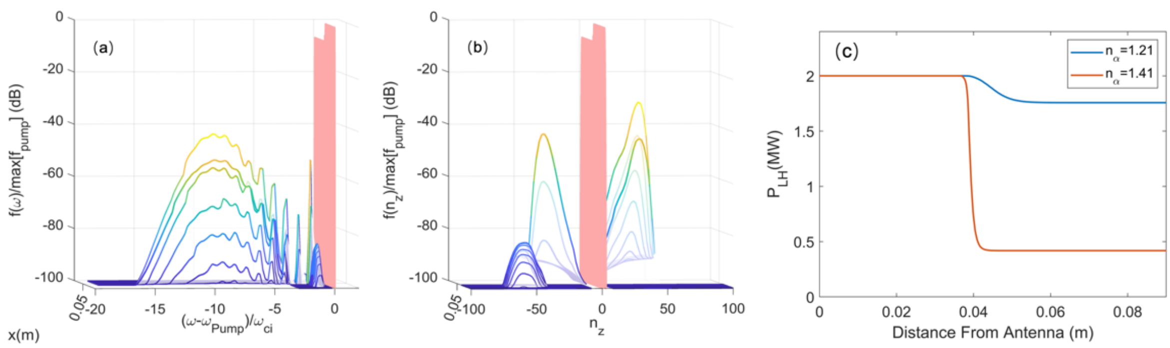

Figure 1. Evolution of LHW frequency spectrum (a) and parallel wavenumber spectrum (b) at $n_\alpha = 1.41$, *where* n_α *is the multiply factor for JET-like reference SOL density profile, and evolution of LHW pump power for* $n_\alpha = 1.21$ *and* 1.41 *(c).*

Simulation: Based on the improved theory, a code involving PIs, named PIPERS, is developed [13] to simulate the self-consistent evolution of the spectrum and power flux of the LH wave in the SOL plasma. The power loss due to PIs is found to be closely related to the density and temperature profile of SOL plasma when the magnetic field and the pump are fixed. A cool and dense SOL plasma (namely, the SOL plasma with gas puffing near the LH antenna to improve the coupling of LHW) leads to considerable PI growth rate and convective loss, which further result in the density limit of LHCD caused by PI. A significant broadening of the LHW spectrum is observed when the SOL profile approaches the density limit, which attributes to the amplification of the channels related to discrete harmonics of the ion-cyclotron quasi-modes (ICQM) with large refraction indices ($n_z > 10$). These LHWs induced by PI deposit their energy instantly in the SOL region, thus causing the anomalous efficiency loss of LHCD. Figure 1 shows the self-consistent evolution of LHW spectrum at critical SOL density profile and corresponding evolution of LHW pump power for different density profiles, which clearly shows the existence of the density limit due to PIs.

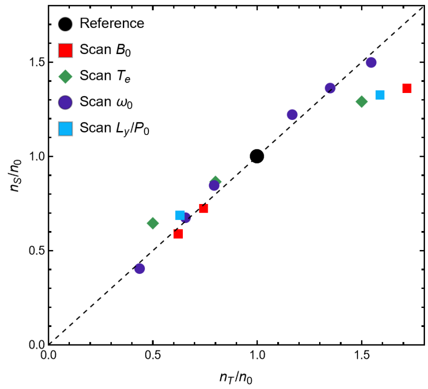

Figure 2. Comparison between density limit n_S *from simulation results and* n_T *from the scaling relation, Eq. (1).*

***Comparison of theoretical, simulation and experimental results*:** Simulation results of the density limit of LHCD roughly follow a scaling relation

$$n_{lim} \propto P_0^{2/3} L_y^{2/3} \omega_0^2 B_0^{2/3} T_e \tag{1}$$

where P_0, L_y, ω_0, B_0 and T_e are the power flux of LHW, the poloidal scale of the antenna, the frequency of LHW, the toroidal magnetic field and the electron temperature in the SOL, respectively, which is shown in figure 2. This relation can be well understood from a simplified theorical model. Both the theoretical model and simulation results can successfully reproduce the experimental findings of density limit of LHCD on JET , EAST and C-Mod, and, moreover, these result can corroborate previous experimental efforts that PIs can be quenched by improving the magnetic field and LHW frequency as well as other methods to optimize the SOL profile such as increasing electron temperature on FTU, EAST and C-Mod.

***Prediction on ITER*:** The scaling provides us an insight on the effectiveness of LHCD for ITER and future tokamak reactors. It is shown that in the parameter regime of ITER, the high LHW frequency, strong magnetic field and higher periphery plasma temperature weaken PIs, and, therefore, the density limit due to nonlinear PIs is far above the expected plasma density in ITER. It indicates that LHCD remains a promising method of driving plasma current for ITER and future fusion reactors.

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