Influence of collisions on parametric instabilities produced by lower hybrid wave power

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The active control of the plasma current density profile is mandatory to achieve sufficient stability and energy confinement of the plasma in fusion reactors based on the tokamak concept. The lower hybrid current drive (LHCD) effect [1] has been proved as a flexible and efficient tool to achieve such goal and extend the duration of the inductive plasma current, which is intinsically transient. A proper design of the LHCD systems in fusion reactors requires to control the parametric instabilities (PI), which can occur in the plasma region located near the LHCD antenna mouth. The typical signature of PI, as detected by radiofrequency (rf) probes and frequency spectra analyzers, consists in a large broadening (up to about 40 MHz) at the operating line f_o of the rf power source. PI were responsible for the failure of the early experiments of injection of lower hybrid waves in tokamaks to achieve the efficient ion heating predicted by the theory [2],[3],[4]. In the early LHCD experiments, operating at lower plasma density (up to line-averaged value $n_{e,av} \sim 0.4\ 10^{20}\ m^{-3}$), PI were comparably weak [5] and the rf power penetrated in the plasma core, successfully driving a plasma current [6]. However, PI play an important role also in LHCD scenarios. The observed weak broadening of the frequency spectrum due to PI should be indeed accompanied by a significant broadening of the spectrum in the parallel refractive index $N_\parallel$, as suggested in Ref. [7]. A full wave analysis of the propagation of a LH wave power pulse, performed in the frame of nonlinear fluid theory, predicted a spectral broadening $\Delta N_\parallel / N_\parallel$ of the order of unity for typical LH and plasma parameters [8]. Such spectral broadening has a profound effect on the the LHCD physics, concerning the power absorption and current drive in the plasma core. The latter are indeed based on the LHW interaction at the Landau resonance $v_\parallel = c/N_\parallel$ with a significant fraction of the plasma electrons, as given by the distribution function $f(v_\parallel)$ in the velocity along the static magnetic field. Based on the numerical code LH^{star} it was shown that the spectral broadening is an important contribution to bridge the $N_\parallel$ gap in LHCD [9,10]. The spectral gap problem in LHCD physics consists in explaining the mechanisms that broaden and up-shift the launched power spectrum in $N_{\|}$. A redistribution in the $N_{\|}$ spectrum coupled by LH antennas [11], is necessary for justifying the power absorption and the amount of current driven in the experiments, which should be otherwise negligible. A more remarkable success of the LHCD modeling taking into account the effects of PI is the prediction, confirmed by the experiments, that LHCD approaching reactor-graded high plasma densities can have success provided that a relatively high electron temperature in the outer plasma should be produced [12]. This allows to overcome the density limit observed in LHCD experiments, namely a threshold of the line-averaged density above which the current driven by the rf power injection becomes much lower than expected by the LHCD theory and sharply disappears. Important evidences of LH power penetration in the plasma core were obtained in the FTU tokamak at reactor relevant central plasma density $n_{e,o} \approx 5\ 10^{20}\ m^{-3}$ in low recycling regimes achieved with suitable plasma operations, e.g. performing wall lithization or injecting pellets to increase the core plasma density without perturbing the edge. This allowed to keep the edge electron temperature sufficiently high that the PI induced spectral broadening in the frequency domain was reduced by a factor two with respect to FTU plasma discharges with standard operations, in which, at even lower central plasma density $n_{e,o} \approx 3\ 10^{20}\ m^{-3}$, no LH wave-particle interactions in the plasma core are observed. This result suggests that in fusion reactor scenarios, such as ITER or DEMO, the edge electron temperature is sufficiently high to prevent the onset of PI. In this case, the LHCD power deposition and current drive can be controlled by two parameters of the coupled spectrum vs. the refractive index parallel to the static magnetic field, namely the peak value $N_{//o}$ and the width $\Delta N_{//o}$ of the main lobe [13]. These are determined, following the linear theory, only by the phasing of the waveguide array launcher, which can be varied electronically during the rf pulse. However, a robust and safe design of the LHCD system in fusion reactors requires that the LHCD antennas should be located in the shadow of a port of the vacuum vessel, where the rf power coupling is expected to occur in a cold, private plasma. In such conditions, strong PI are expected to occur [14]. As a main result of the present theoretical analysis, we have found that collisional suppression of PI allows such robust and safe design. Collisions are neglected in the standard modeling of PI in LHCD experiments [14], though they were included in the Miklos Porkolab's pioneering work on PI induced by LHW near the lower hybrid resonance [15] and their effects were confirmed by experiments [16]. A role of collisions on PI induced by LH waves, especially near the antenna mouth, can be expected in LHCD scenarios, observing that in such cold ($T_e \leq 10$ eV) and dense plasma ($n_e \sim 10^{18}\ m^{-3}$) the collision rates of the electrons are of the order of the frequency of the ion-acoustic quasi-modes.

The latter are involved in the main channel of the PI induced by LH power waves in current drive experiments. The present analysis is based on a specific collisional parametric dispersion equation derived to evaluate the growth rates of PI induced by LH wave power in the plasma region in front of the LH antenna mouth for LHCD scenarios. Details of the derivation will be proposed elsewhere, we limit the present discussion to the basic assumptions. Uniform and stationary plasma model is used, with Cartesian axis Z aligned along the static magnetic field $\mathbf{B}_o$. The basic equations are given by the self-consistent system of the Maxwell equations coupled to the kinetic equation for the single particle distribution functions f_α. Following [15], we adopt a particle-conserving BGK collision operator as an approximate model of the collision integral, $(\partial f_\alpha/\partial t)_{coll} \cong -\nu_\alpha[f_\alpha - f_\alpha^o(n_\alpha/n_\alpha^o)]$, where f_α^o is the unperturbed, local equilibrium, ν_α are characteristic relaxation rates involving the plasma particle species α and n_α, n_α^o are their number density corresponding respectively to f_α, f_α^o. We observe that the ion relaxation rates are two order of magnitude lower than the electron collision rates. As a result, we have found that the introduction of the collision operator into the ion kinetic equation has a negligible effect on the solutions of the parametric dispersion relation. The relaxation rates do not include the electron-neutral collisions as we are mainly interested to low recycling regimes and assume that the residual neutrals are ionized by the injected rf power. The plasma electrons are considered as completely magnetized, i.e. their motion can be represented by the 1D motion of their guide center along the direction of the magnetic field. The plasma ions do not contribute to the nonlinear dynamics. They are assumed fixed concerning the high frequency dynamics and completely magnetized concerning the low frequency dynamics. We observe that in the plasma region near LH antennas, with typical kinetic parameters $T_e \le 10$ eV and $n_e \le 5\ 10^{18}$ m^{-3}, the motion parallel to the magnetic field has been indeed recognized as the dominant dynamics concerning the standard collisionless parametric dispersion equation [17,18]. We use the spectral method and the perturbation theory to solve the self-consistent system obtained coupling the kinetic equation to the Maxwell equations. The expansion parameter is $\varepsilon = e|E_{z,o}|/m_e\omega_o \mathrm{v}_{th,e} \ll 1$, where e is the elementary charge, $|E_{z,o}|$ is the maximum amplitude of the z-component of the rf electric field, and $\omega_o = 2\pi f_o$ is the peak angular frequency of the injected rf wave power. We consider four waves interaction, involving the injected LH pump wave (subscript 0) two LH sidebands at lower (subscript 1) and higher (subscript 2) frequency, and a resonant mode or quasi-mode at low frequency (no subscript). The relevant selection rules for such interaction are given in standard notations by $\omega_1 = \omega - \omega_o, \boldsymbol{k}_1 = \boldsymbol{k} - \boldsymbol{k}_o, \omega_2 = \omega + \omega_o, \boldsymbol{k}_2 = \boldsymbol{k} + \boldsymbol{k}_o$. The parametric dispersion relation (PDR) thus obtained can be cast in the form $f_{PD}(\omega, k_\parallel, k_\perp, \delta, \omega_o, k_{\parallel,o}, \varepsilon, \sigma) = 0$ where f_{PD} is the parametric dispersion function, which is defined by $f_{PD} = 1 - (\mu_1/\varepsilon_1^{hf} + \mu_2/\varepsilon_2^{hf})/\varepsilon^{lf}$ where $\varepsilon_{1,2}^{hf}$ and ε^{lf} are, respectively, the linear dispersion functions for the low and high frequency fields and $\mu_{1,2} \propto \varepsilon^2$ are the nonlinear coupling parameters. Here the subsripts ∥ (⊥) indicates components parallel (perpendicular) to $\mathbf{B}_o$, $\delta = \angle(\boldsymbol{k}_\perp, \boldsymbol{k}_{\perp,o})$ and σ indicates the plasma parameters (density, temperatures of the electron and ion species and plasma composition). For fixed values of the subset of parameters $\{k_\parallel, k_\perp, \delta, \omega_o, k_{\parallel,o}, \varepsilon, \sigma\}$, the solution of the PDR thus consists of finding the zeros of the complex function f_{PD} of the complex variable ω. The imaginary part γ of such zeros is identical to the imaginary part of $\omega_{1,2}$ and discriminates stable ($\gamma < 0$) and unstable ($\gamma > 0$) LH modes. The real and imaginary part of the zeros of the collisionless (a) and collisional (b) PDR, corresponding to the maximum values of γ (with respect to $k_\perp$ and δ) are plotted in figure 1 as a function of $N_\parallel = ck_\parallel/\omega_o$ for different LH pump frequencies f_o and power density assumed proportional to f_o. The stabilizing effect of the collisions here shown is confirmed by an extensive analysis of PI in LHCD scenarios.

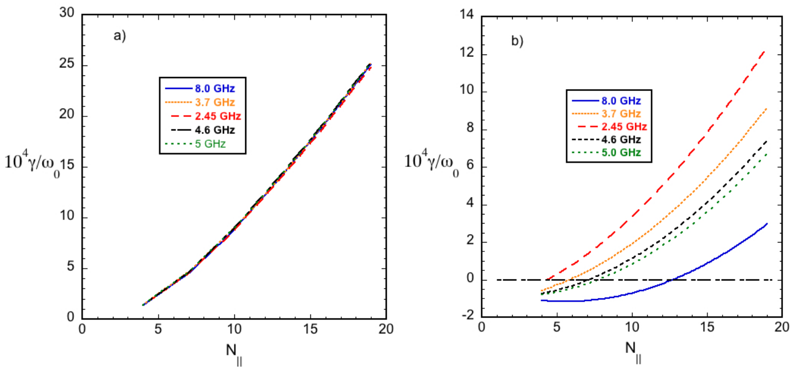

Fig. 1. Growth rates of LH sidebands for different frequencies f_o of the LH pump waves in collisionless (a) and collisional (b) D plasmas, $n_e = 3\, n_{e,cut-off}$, $T_e = T_i = 5$ eV, $N_{\parallel,o} = 1.85$, P(kW/cm^2) = 0.6 f_o (GHz).

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