Non-monochromatic RF power injection to control lower hybrid parametric instabilities in tokamak plasmas

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Abstract

Within the development of a full-spectrum kinetic parametric instability modelling of lower hybrid (LH) waves in the outer layers of a tokamak plasma, we present here, in the homogenous plasma limit, a new parametric dispersion relation (PDR) where the driver-pump is considered non-monochromatic. Numerical solutions of the new PDR shows that it is possible to control parametric instabilities with a different $n_{//}$ peaking of pump spectral components, suggesting a new design of lower hybrid current drive (LHCD) experiments in high density plasmas relevant to ITER.

Introduction

In present day LHCD experiments, parametric instabilities (PIs) must be controlled for the accessibility of the driver-pump to the inner plasma layers of a tokamak [1]. The theory of the parametric interaction of a monochromatic LH driver-pump with a magnetized plasma [2] has been successfully applied for a better understanding of LH experiments [1,3]. The study of parametric phenomena in magnetized plasmas produced by the action of a non-monochromatic driver-pump has been also undertaken [4]. These theoretical studies have shown that in this latter case a variety of PIs exists, compared to the simpler monochromatic pump case, and that, when the angular frequency bandwidth of the driver-pump is much larger than the PI resonance width, the threshold of instabilities is significantly increased. However, concerning PIs of LH waves, the adoption of the dipole approximation for the driver-pump prevented a deeper understanding of the influence of the LH wavenumber spectrum on PIs. Also, a systematic experimental investigation of a non-monochromatic pump in the LH range of frequencies has been performed [5]. A variety of finite bandwidth pumps, produced by amplitude modulation (AM) and frequency modulation (FM) of the driver-pump, and a multi-pump spectrum has been investigated on a linear plasma configuration. However, if we look at the technical feasibility of these experimental results, no real practical solutions could be found since stabilization effects on

PIs can be achieved only if the angular frequency bandwidth of the modulated driver-pump or the angular frequency separation between spectral components of a multiple driver-pump is larger than the resonance width of PIs. Unfortunately, these solutions are seriously limited by the frequency bandwidth of available power sources, with the multi-pump solution also limited by the high costs due to the necessary utilization of a power plant with many power amplifiers. As a breakthrough of this work, we discover a new driver-pump scheme exploitable within the frequency bandwidth of microwave power sources, suggesting a new design for LHCD experiments.

PDR with a non-monochromatic pump

In this work we derive a new nonlinear PDR for a non-monochromatic pump. This equation is based on a full-spectrum nonlinear kinetic model of LH wave propagation, useful to analyse the instabilities emerging in the outer plasma layers of a tokamak [6,7]. In order to obtain a kinetic description of the nonlinear mode coupling of the HF lower hybrid waves with the LF plasma fluctuations, the general Maxwell-Vlasov system of equations is solved by means of a perturbative method up to the third order [7]. The Vlasov equation is reduced to a 1D kinetic equation in velocity space to take into account only the dominant particle dynamics parallel to the confinement magnetic field [6,7,8]. We assume that the velocity distribution function for both ion and electron populations is isotropic in the perpendicular direction. Thus, the analysis is limited to fluctuations at frequencies much smaller than the ion cyclotron frequency ($\omega_{LF} \ll \omega_{ci}$) and characteristic lengths in directions perpendicular to the static magnetic field much larger than the ion Larmor radius ($k_\perp \rho_i \ll 1$). We use a slab geometry with the static magnetic field $\boldsymbol{B}_o = B_o \hat{\boldsymbol{z}}$ and with the inward radial direction oriented as $\hat{\boldsymbol{x}}$. We consider steady-state solutions for an homogenous plasma. These assumptions allow us to solve the Maxwell-Vlasov system of equations by means of a spectral method as shown in [6]. We consider a non-monochromatic pump as a result of a sinusoidal AM which assures a finite pump spectrum useful for analytical derivations. This pump spectral representation is quite general and is equivalent to a multiple driver-pump for some values of the modulation index m: i.e. when m = 2 it reduces to a multi-pump with three equal components and when m >> 1 it approximates well a double driver-pump. Of course, when m = 0 we have the standard case with a monochromatic pump. In order to derive the new PDR we consider three simultaneous parametric decays of three drivers resulting from the AM of the pump. Similarly to the monochromatic pump case [1,2,3], we consider here a four wave interaction between: 1) the central driver-pump wave

$\tilde{E}_{z0}\, e^{-j(\omega_0 t-\boldsymbol{k}_0\cdot \boldsymbol{r})}$, a lower sideband $\tilde{E}_{z1}\, e^{-j(\omega_1 t-\boldsymbol{k}_1\cdot \boldsymbol{r})}$, an upper sideband $\tilde{E}_{z2}\, e^{-j(\omega_2 t-\boldsymbol{k}_2\cdot \boldsymbol{r})}$ and a low frequency quasi-mode $\tilde{E}_z\, e^{-j(\omega t-\boldsymbol{k}\cdot \boldsymbol{r})}$, with selection rules $\omega = \omega_{1,2} \pm \omega_0$, $\boldsymbol{k} = \boldsymbol{k}_{1,2} \pm \boldsymbol{k}_0$; 2) the lower AM sideband wave $\tilde{E}_{zL1}\, e^{-j(\omega_{L1} t-\boldsymbol{k}_{L1}\cdot \boldsymbol{r})}$, a lower sideband $\tilde{E}_{z3}\, e^{-j(\omega_3 t-\boldsymbol{k}_3\cdot \boldsymbol{r})}$, an upper sideband $\tilde{E}_{z4}\, e^{-j(\omega_4 t-\boldsymbol{k}_4\cdot \boldsymbol{r})}$ and a low frequency quasi-mode $\tilde{E}_z\, e^{-j(\omega t-\boldsymbol{k}\cdot \boldsymbol{r})}$ with selection rules $\omega = \omega_{3,4} \pm \omega_{L1}$, $\boldsymbol{k} = \boldsymbol{k}_{3,4} \pm \boldsymbol{k}_{L1}$; 3) the upper AM sideband wave $\tilde{E}_{zL2}\, e^{-j(\omega_{L2} t-\boldsymbol{k}_{L2}\cdot \boldsymbol{r})}$, a lower sideband $\tilde{E}_{z5}\, e^{-j(\omega_5 t-\boldsymbol{k}_5\cdot \boldsymbol{r})}$, an upper sideband $\tilde{E}_{z6}\, e^{-j(\omega_6 t-\boldsymbol{k}_6\cdot \boldsymbol{r})}$ and a low frequency quasi-mode $\tilde{E}_z\, e^{-j(\omega t-\boldsymbol{k}\cdot \boldsymbol{r})}$, with selection rules $\omega = \omega_{5,6} \pm \omega_{L2}$, $\boldsymbol{k} = \boldsymbol{k}_{5,6} \pm \boldsymbol{k}_{L2}$. Here we define $\omega_{L1,2} = \omega_0 \mp \omega_M$ as the angular frequencies of the lower (index 1) and upper (index 2) AM sideband and ω_M is the angular modulation frequency. Taking into account this discrete representation for the electric field, we can write the following expression for the PDR with an amplitude modulated pump:

$$\varepsilon = \left(1+\sum_i \chi_i\right)\left(\frac{e^2\left|\tilde{E}_{z0}\right|^2}{m_e T_e k_z v_e^2}\right)\left[H_1 + \frac{m^2}{4}(H_2+H_3)\right]$$

where $m \equiv \left|\tilde{E}_{zL1,2}/\tilde{E}_{z0}\right|$ is the modulation index, ε is the low frequency dielectric function, χ_i is the ion susceptibility, $H_1 \equiv \tilde{G}_1^{HF} A + \tilde{G}_2^{HF} B$, $H_2 \equiv \tilde{G}_3^{HF} A' + \tilde{G}_4^{HF} B'$, $H_3 \equiv \tilde{G}_5^{HF} A'' + \tilde{G}_6^{HF} B''$, $\tilde{G}_h^{HF} \equiv k_{zh}^2\, \omega_{p,e}^2 \,/\, k_h^2\, \omega_h^2\, \varepsilon_h$, ε_h is the high frequency dielectric function (h=1,2,3,4,5,6) and other symbols are defined as in [6,7].

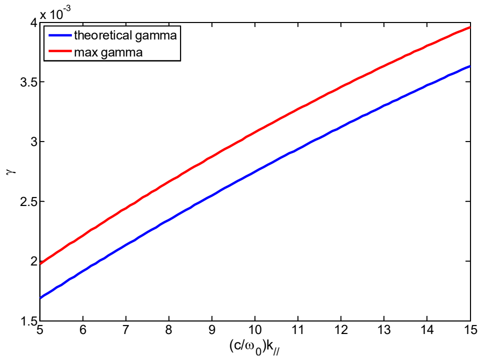

Fig. 1

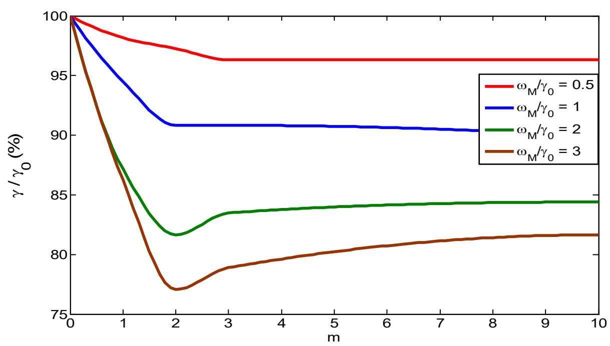

Fig. 2

Numerical results

First, we validate the new PDR in the monochromatic driver-pump case (m=0) comparing its numerical solutions against approximate analytical solutions [8]. As shown in Fig. 1, for the SOL plasma of FTU [9] (n_e = 2 10^{12} cm^{-3}, T_e = 10 eV, f_0 = 8 GHz, $n_{//0}$ = 2, B_0 = 4.5 T, P_{den}= 3 kW/cm^2), we obtain a good agreement in terms of PIs growth rate, overcoming the numerical problems previously found in [7]. After, in the non-monochromatic pump case, we compute the maximum growth rate for the SOL plasma of FTU and EAST [10,11] (n_e = 10^{12} cm^{-3}, T_e

= 12 eV, f_0 = 2.45 GHz, $n_{//0}$ = 2.1, B_0 = 1.8 T, P_{den} = 1.45 kW/cm^2) at constant total power when varying the modulation index m and the angular modulation frequency ω_M (for $(c/\omega_0)k_{//}$ = 15), as shown in Fig. 2 and Fig. 3 respectively, obtaining also a good agreement with previous experimental observations of LH experiments [5], i.e. the growth rate reduction vanishes when ω_M approaches the PIs resonance width γ_0 (i.e. the growth rate without amplitude modulation). Finally, we set the modulation frequency well below the PIs resonance width (f_M = 10 kHz << $\gamma_0/2\pi \approx$ 5-15 MHz) and we select a different $n_{//}$ peaking of the AM sidebands respect to the central driver-pump peaked at $n_{//0}$ (with a relative variation $|\Delta n_{//0}|/n_{//0} \approx 10\%$). We compute the maximum growth rate for the SOL plasma of FTU and EAST at constant total power when varying the modulation index m (for $(c/\omega_0)k_{//}$ = 10), as shown in Fig. 4, obtaining an important reduction of the growth rate (about 32% at m = 2 for both tokamaks), for the first time within the frequency bandwidth of a typical microwave power source. This important result suggests a new design for LHCD experiments and it will be analysed more in depth in a dedicated paper.

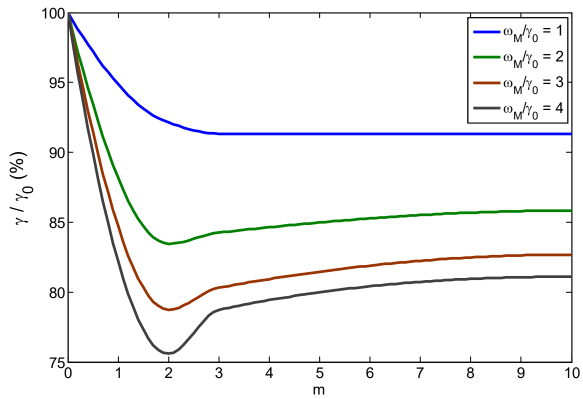

Fig. 3

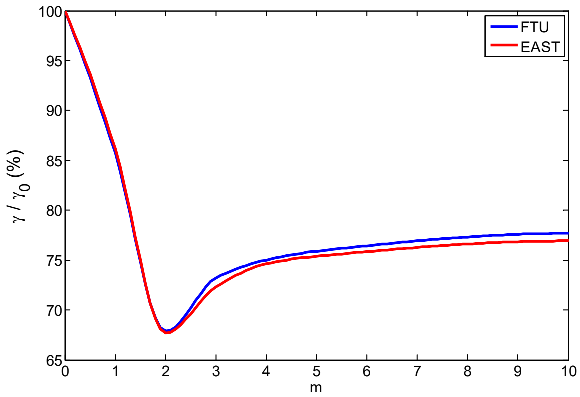

Fig. 4

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