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Behaviors of Unstable Low Frequency Waves by Pump hf Waves in an Inhomogeneous Plasma in the Presence of Beam Ion

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Abstract

In an ion beam-inhomogeneous plasma system, multiple ion cyclotron harmonic (ICH) waves up to $n\omega_{ci}$, (ω_{ci} is the ion cyclotron frequency, n is the integer) have been unstable [1], where n is determined by the inhomogeneity of the plasma. Further, it is observed that low frequency waves with frequencies in the neighborhood of the lower hybrid frequency are unstable

By the external application of high frequency (*hf*) field, the suppressions of unstable waves are observed. The suppression is due to the ponderomotive force of the pump *hf* field and fields of both sideband waves. This suppression occurs, as the frequency of pump *hf* field is only lower than the frequency of the Trivelpiece-Gould (T-G) mode. These behaviors and results agree qualitatively with numerical analyses by the theory.

Keywords:

ion cyclotron harmonic modes, lower hybrid waves, inhomogeneity, high frequency modes, ponderomotive force

1. Introduction

In the vicinity of polar cusp region of the magnetosphere, the broadband electrostatic emission at the ICH has been observed [2,3], but the mechanism on generation of this emission remains uncertain. When the electron drift frequency ω^* exceeds harmonics of the ion cyclotron frequency $n\omega_{ci}$, ICH waves may be excited by coupling between electron drift waves [4] generated by the inhomogeneity and the ion Bernstein waves [5]. We have observed the excitation of ICH waves, when the ion beam is injected parallel to the magnetic field in a cylindrical plasma [1,5]. Further, unstable low frequency waves near the lower hybrid frequency are observed. These low frequency waves are identified as lower hybrid waves.

By the external application of *hf* field, the suppression of unstable ICH waves has been observed [6]. The all or partial suppression of low frequency unstable waves are observed by the external application of *hf* field in the neighborhood of frequency of T-G modes. The suppression occurs, only when the frequency of *hf* field is lower than the frequency of the T-G mode. This behavior agree qualitatively with the numerical analysis due to the theory.

2. Experimental Procedures

Experiments are performed in the linear vacuum chamber of 10 cm in diameter and 90 cm long [1]. The ion beam source generated by an argon gas discharge

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(via a cold cathode) is set at the end of the chamber in the uniform magnetic field $\boldsymbol{B}_0$ (B_0 = 100–700 G). Ion beam with diameter = 9 mm is extracted by applying the dc potential (V_a = 100–500 V) between the anode electrode of the ion beam source and the mesh accelerating electrode (diameter of mesh = 10 mm). An ion beam is continuously injected into the plasma produced by a dc argon gas discharge (via a hot cathode) at the opposite side of the ion beam source. The external *hf* field is applied to one of accelerating electrodes of the ion beam. The region in a beam-plasma system is maintained at pressure $p \simeq 1$ mTorr. The plasma density and electron temperature are measured by axially and radially movable Langmuir probes, and the wave intensity received with axially and radially movable antennas is detected by the spectrum analyzer

3. Experimental Results and Comparisons with Theory

In an ion beam-plasma system, spontaneously excited waves appear at the frequency $\omega \geq n\omega_{ci}$ and at the frequency in the neighborhood of the lower hybrid frequency. The frequency spectra of unstable waves with frequency near $n\omega_{ci}$ are shown in Fig. 1(a), where $\omega_{ci}/2\pi$ = 10.4 kHz. At least, waves with frequencies up to 6th harmonics of ω_{ci} are unstable. These waves have been identified as ICH waves in previous papers [1,5]. Then the number of modes of unstable ICH waves is determined by the inhomogeneity of plasma, that is, $n\omega_{ci} < \omega^*$ (ω^* is the electron drift frequency). Spectra of the another unstable waves with frequency near the lower hybrid frequency are shown by the dotted curve in Fig. 2. This unstable wave was not observed previously [1,5]. These unstable waves are confined within the plasma column, and axial and radial interferometer wave patterns can not be obtained. It is considered that waves are standing waves. The wave number $k_\parallel$ parallel to $\boldsymbol{B}_0$ of this wave is estimated to 0.046 cm^{-1}. The velocity of an ion beam v_b is also 2.5×10^6 cm/s (energy 140 eV). Then observed frequency of unstable wave (frequency $\simeq$ 0.58 MHz) satisfies $\omega \simeq k_\parallel v_b$. Therefore, this unstable wave is excited by the coupling with the slow space charge wave of an ion beam. On the other hand, The wave number $k_\perp$ perpendicular to $\boldsymbol{B}_0$ is estimated from the radial profile of waves amplitude which corresponds to the profile of 1st Bessel function. Then $k_\perp \simeq 1.52$ cm^{-1}. These wave numbers and observed frequency satisfy the dispersion relation of the lower hybrid wave $\omega^2 = (\omega_{pi}^2/(1 + \omega_{pe}^2/\omega_{ce}^2))\ (1 + (m_i/m_e)\ (k_\parallel^2/k_\perp^2))$, where ω_{pi} and ω_{pe} are plasma frequencies of the ion and the electron, respectively, ω_{ce} is the electron cyclotron frequency, m_i and m_e are ion and electron masses. Therefore, these unstable waves are identified as lower hybrid waves.

The *hf* field with the frequency ω_0 near the frequency of the T-G modes ($\omega \simeq \omega_{pe}\ (k_\parallel/k)$) is externally applied. Then frequency spectra of unstable waves are shown in Fig. 1(b) and by the solid curve in Fig. 2 for the pump *hf* field with the frequency 60.16 MHz. Here the frequency ω_T of the T-G mode is estimated to 60.5 MHz, if $(k_{\parallel 0}/k_0)^2 \simeq 0.003$ is assumed.

It is seen in Fig. 1(b) that the 1st, 2nd and 3rd ICH waves are at least suppressed by the pump of *hf* field,

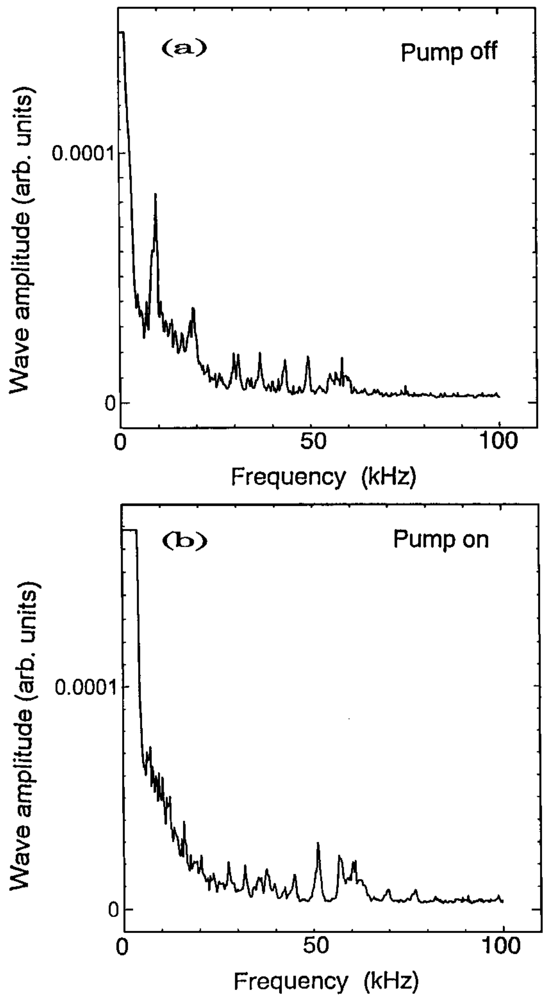

Fig. 1 (a) Frequency spectra of spontaneously excited ICH waves, where plasma density $n_p = 2.4 \times 10^{10}$ cm^{-3}, $T_e \simeq 4$ eV, beam density ratio $n_b/n_p \simeq 0.01$, beam energy V_b = 140 eV. (b) Frequency spectra of unstable ICH waves for pump *hf* field with 60.16 MHz.

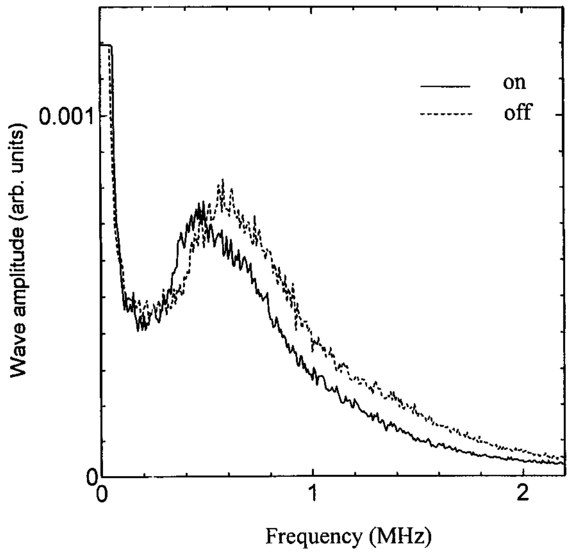

Fig. 2 Frequency spectra of unstable lower hybrid waves for no *hf* field (dotted curve) and pump *hf* field (solid curve) with 60.16 MHz.

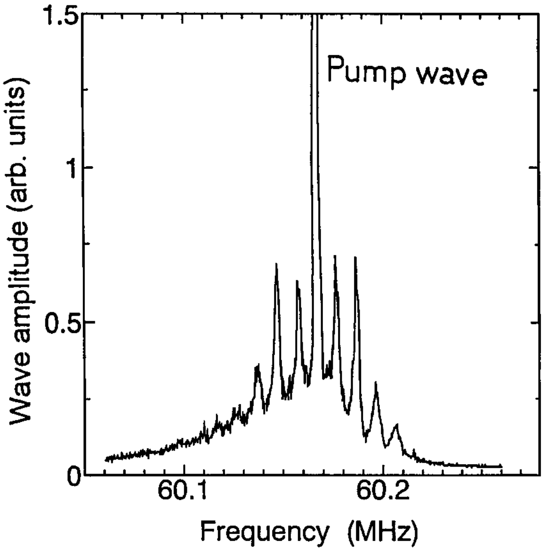

Fig. 3 Lower and upper sideband frequency spectra around the frequency spectrum of pump *rf* field with 60.16 MHz.

although higher ICH modes do not disappear. Further, as shown in Fig. 2, the amplitude of unstable lower hybrid waves is also reduced. Figure 3 shows frequency spectra of lower and upper sideband waves around the frequency ω_0 of pump *hf* field. Then amplitudes of lower and upper sideband waves (frequency ω_1 and ω_2) have nearly equal magnitude, and the relation $\omega_{1,2} = \omega_0 \pm \omega$ satisfies. These sideband fields interact with the pump *hf* field and a ponderomotive force acting on the low frequency unstable waves is generated. It is considered that this ponderomotive force suppresses unstable waves [7]. Figure 4 shows the amplitude of unstable lower hybrid waves as a function of the frequency of the pump *hf* field. In the frequency region of applied *hf* field whose frequency is lower than the frequency ($\omega_T/2\pi$ = 60.5 MHz) of the T-G mode, unstable waves are suppressed. On the other hand, when the frequency of applied *hf* field is higher than ω_T, unstable waves enhance.

We attempt the numerical analysis of unstable waves in the presence of the applied *hf* field. The analysis is performed by taking the boundary condition perpendicular to the magnetic field as the cylindrical ion beam and plasma column i.e., the nonlocal theory. The treatment is similar to that in ref. [7], and the ponderomotive force due to the pump *hf* field and fields of both sideband waves is taken in nonlinear terms. The obtained nonlinear dispersion relation is given by

$$\varepsilon + \frac{\mu_1}{\dfrac{\omega_T k_{1\parallel} r_0}{\omega_0 - \omega} - \lambda_{n_1,\ell_1}} + \frac{\mu_2}{\dfrac{\omega_T k_{1\parallel} r_0}{\omega_0 + \omega} - \lambda_{n_2,\ell_2}} = 0, \quad (1)$$

$$\mu_{1,2} = \frac{\omega_{pi}^4}{\omega_{ci}^2 \omega_0^2} \Gamma_n^2 \Gamma_{n_1,n_2}^2 \ell_{1,2}^2 \left| \int_0^{r_0} \left(1 - \frac{r^2}{r_0^2}\right) \frac{r}{r_0} \right.$$

$$\left. \times J_\ell (k_{\perp n} r) \frac{\partial \Phi_0}{\partial r} e^{-\frac{\xi_{1,2}^2}{2}} \xi_{1,2}^{\ell_{1,2}} L_{n_{1,2}}^{\ell_{1,2}}(\xi_{1,2}^2) dr \right|^2,$$

$$\omega_T^2 = \omega_{pe}^2 \frac{k_{0\parallel}^2}{k_0^2}, \quad \Phi_0 = \frac{(e/m_e)\,\phi_0}{c_s^2},$$

$$\xi_{1,2}^2 = \frac{\omega_T k_{1,2\parallel} r_0}{\omega_{1,2}} \frac{r^2}{r_0^2}, \quad \lambda_{n_{1,2},\ell_{1,2}} = 2(2n_{1,2} + \ell_{1,2} + 1).$$

where ε is the local linear dielectric function of an inhomogeneous ion beam-plasma system [1,5], (ω, k), (ω_0, k_0), (ω_1, k_1) and (ω_2, k_2) are the unstable, pump *hf*, lower and upper sideband modes, ϕ_0 is the wave potential of *hf* field, c_s is ion acoustic velocity, Γ_n and $\Gamma_{n_{1,2}}$ are the normalized factor. With respect to the wave potential for the finite mode of each wave, $n_{1,2}$ and $\ell_{1,2}$ are radial and azimuthal mode numbers of each mode, r_0 is the plasma radius, J_ℓ is ℓth Bessel function, L_n^ℓ is nth and ℓ-order generalized Laguerre polynomials, and other notations are standard. We have calculated the growth rates of unstable lower hybrid waves for the pump *hf* field from eq.(1). The growth rates of unstable waves as a function of the frequency of the pump *hf* field are shown in Fig. 5 for various applied normalized potential of of the *hf* field. It is seen in Fig. 5 that growth rates of unstable waves are reduced, when the frequency ω_0 of pump waves is less than the frequency ω_T of the T-G

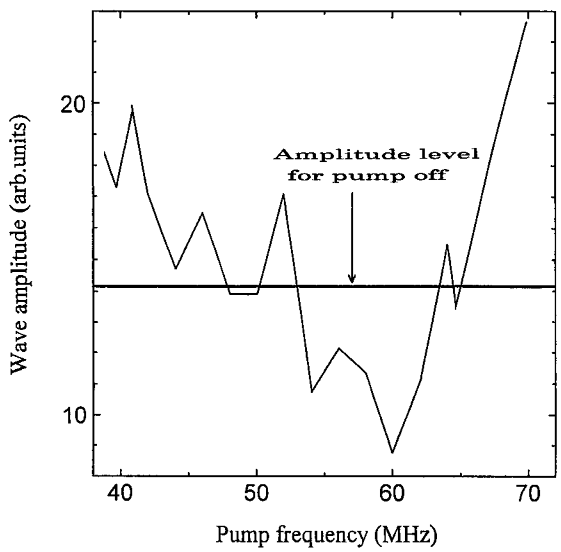

Fig. 4 Wave amplitude of unstable lower hybrid waves (frequency $\simeq$ 0.58 MHz) versus frequencies of pump *hf* field.

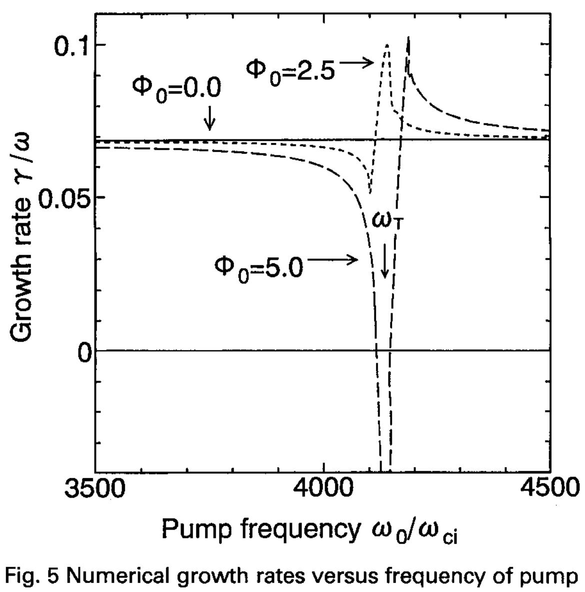

Fig. 5 Numerical growth rates versus frequency of pump *hf* field for various normalized pump field intensities, where plasma density n_p = 2.0 × 10^{10} cm^{-3}, $T_e \simeq$ 4 eV, beam density ratio n_b/n_p = 0.01, beam energy V_b = 140 eV.

mode, the growth rate of waves is decreases with increasing of the pump wave intensity, and then waves damps for Φ_0 = 5.0. Also, when ω_0 is higher than ω_T, growth rates of unstable waves increase. Therefore although there is somewhat a discrepancy (at least $\simeq$ 83 %) between the calculation and the experiment, the numerical behaviors agree qualitatively with the experimental ones for the dependence of the growth rate of unstable waves on the pump *hf* field.

4. Conclusions

In an ion beam-inhomogeneous plasma system, when the drift frequency ω^* exceeds the harmonics of $n\omega_{ci}$, multiple ICH waves are excited by the plasma inhomogeneity and by an ion beam injection. Further, the lower hybrid wave is unstable. The excitation of unstable lower hybrid wave occurs by the coupling with the slow space charge wave of an ion beam. By the external application of *hf* field near the frequency of the T-G mode, the suppression of these unstable waves are observed. When the frequency of pump *hf* field is lower (higher) than the frequency of the T-G mode, unstable waves suppress (enhance). These behaviors of unstable waves agree qualitatively with that of the nonlocal theory taken into account of the ponderomotive force due to a combination of the applied *hf* field and fields of both sideband waves.

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