J. Plasma Fusion Res. SERIES, Vol. 2 (1999) 165–168

Interaction of Unstable Ion Cyclotron Harmonic Waves and Lower Hybrid Waves in an Ion Beam-Plasma System

UTSUNOMIYA Shohei, SUGAWA Masao, SHARMA Suresh C.,
MAEHARA Tsumehiro and SUGAYA Reiji
Department of Physics, Faculty of Science, Ehime University,
Matsuyama 790-8577, Japan

(Received: 8 December 1998 / Accepted: 24 August 1999)

Abstract

In an ion beam-inhomogeneous plasma system, when the drift frequency ω^* exceeds the harmonics of the ion cyclotron frequency $n\omega_{ci}$, ion cyclotron harmonic waves with frequencies up to $n\omega_{ci}$ are observed experimentally. By the application of externally launched *rf* field near the lower hybrid frequency, the suppression of these unstable waves has been observed. Suppression is based on the ponderomotive force due to a combination of the pump *rf* field and fields of both sideband waves. When the frequency of pump *rf* field is higher than the lower hybrid frequency, the enhancement of unstable waves has been observed. These results agree qualitatively with analyses from the nonlocal theory taken into account of the ponderomotive force via applied fields.

Keywords:

ion cyclotron modes, inhomogeneity, parametric instability, ponderomotive force

1. Introduction

The instability at the multiple ion cyclotron harmonics in the magnetized ion beam-plasma system is of interest, in part, in order to obtain its possible emission mechanism. In the vicinity of polar cusp region of the magnetosphere, the broadband electrostatic emission at the ion cyclotron harmonics has been observed [1,2] but, the mechanism on generation of these emission remains uncertain. When the electron drift frequency ω^* exceeds harmonics of the ion cyclotron frequency $n\omega_{ci}$, ion cyclotron harmonic (ICH) waves may be excited by coupling between electron drift waves [3] generated by the inhomogeneity and the ion Bernstein waves [4]. We have observed the strong excitation of ICH waves, when the ion beam is injected parallel to the magnetic field in a cylindrical plasma [5]. By the application of externally launched *rf* field near the lower hybrid frequency, the suppression of these unstable ICH waves has been observed. Also, the suppression of naturally excited drift waves in this system has been previously observed [3]. When the frequency of applied *rf* field is higher than the lower hybrid frequency, the enhancement of unstable ICH waves has been observed.

2. Experimental Procedures

Experiments are performed in the linear vacuum chamber of 10 cm in diameter and 90 cm long [5]. The ion beam source generated by an argon gas discharge (via a cold cathode) is set at the end of the chamber in the uniform magnetic field $\boldsymbol{B}_0$ (B_0 = 100–700G). Ion beam with diameter = 9mm is extracted by applying the dc potential (V_a = 100–500V) between the anode electrode of the ion beam source and the mesh accelerating electrode (diameter of mesh = 10mm). An

---

Corresponding author's e-mail: sugawa@phys.sci.ehime-u.ac.jp 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 externally *rf* field is applied to one of accelerating electrodes of the ion beam. The region in a beam-plasma system is maintained at pressure $p \simeq$ 1mTorr. 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 $\omega \geq n\omega_{ci}$ (n is an integer, ω_{ci} is the ion cyclotron frequency). The typical frequency spectra of unstable waves are shown in Fig. 1, where $\omega_{ci}/2\pi$ = 12.4kHz. The magnitude ω^*/ω_{ci} indicates the inhomogeneity of the plasma density. This plasma inhomogeneity is estimated to $\omega^*/\omega_{ci} \simeq 4.8$ from the observed density gradient, if the azimuthal mode number of the drift mode ℓ is taken up to $\ell = 2$. Then waves with frequencies up to 4th harmonics of the ion cyclotron wave may be unstable [4,5]. In Fig. 1, the mode denoted by 0 is the fundamental wave, and modes denoted by 1, 2, 3 are waves with frequencies $\simeq n\omega_{ci}$ (n = 2, 3, 4). Also, the wave number $k_{\|}$ parallel to $\boldsymbol{B}_0$ is estimated to 0.046cm^{-1} (for mode 1) and 0.092cm^{-1} (for modes 2, 3), and the velocity of an ion beam v_b is v_b = 3.8 × 10^{6}cm/s (energy 300 eV). Then modes 1–3 can satisfy approximately the relation $\omega = k_{\|}v_b$ for mode 1 or $\omega = k_{\|}v_b - n\omega_{ci}$ for mode 2 (n = 2) and mode 3 (n = 1). Therefore unstable modes of 1–3 are 2rd–4th ICH waves excited by the plasma inhomogeneity and the ion beam injection [5], but the mode 0 may be the fundamental ICH wave excited by only the plasma inhomogeneity.

The *rf* field with the frequency ω_0 near the lower hybrid frequency is externally launched. Then typical frequency spectra of unstable waves (frequency ω) are shown in Fig. 2 for the pump of *rf* field with the frequency 60.16MHz. Here the lower hybrid frequency ω_L is estimated to 60.5MHz, if $(k_{\|0}/k_0)^2 \simeq 0.003$ is assumed. It is seen that the fundamental, 3rd and 4th ICH waves (modes 0, 2 and 3) are reduced by the pump of *rf* field, and the 2nd ICH wave (mode of 1) almost disappears. Fig. 3 shows frequency spectra of lower and upper sideband waves around the frequency of *rf* field. Then amplitudes of lower and upper sideband waves (frequency ω_1 and ω_2) have nearly equal magnitude, and the relation $\omega_{1,2} = \omega_0 \pm \omega$ is satisfied (e.g. for mode 0 with frequency 0.013MHz, both sideband waves have $\omega_{1,2}$ = 60.156 ± 0.013MHz). It is seen that amplitudes of both sideband waves corresponding to mode 1 are excited most strongly. It is considered that the

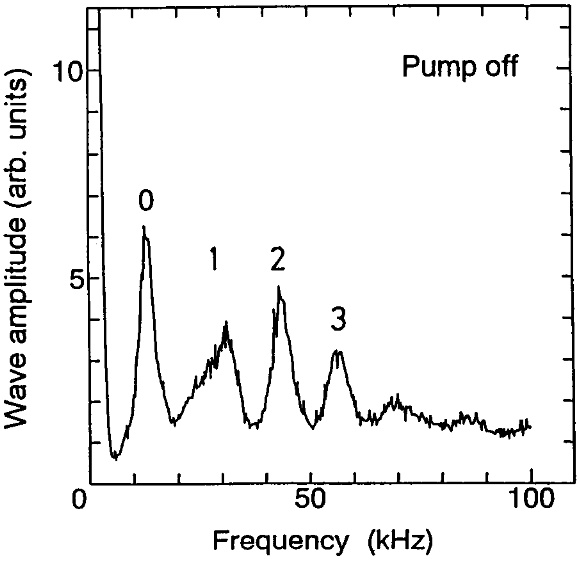

Fig. 1 Frequency spectra of unstable waves for no *rf* field, where plasma density n_p = 2.4 × 10^{10}cm^{-3}, $T_e \simeq$ 5eV, beam density ratio $n_b/n_p \simeq 0.01$, beam energy V_b = 300eV.

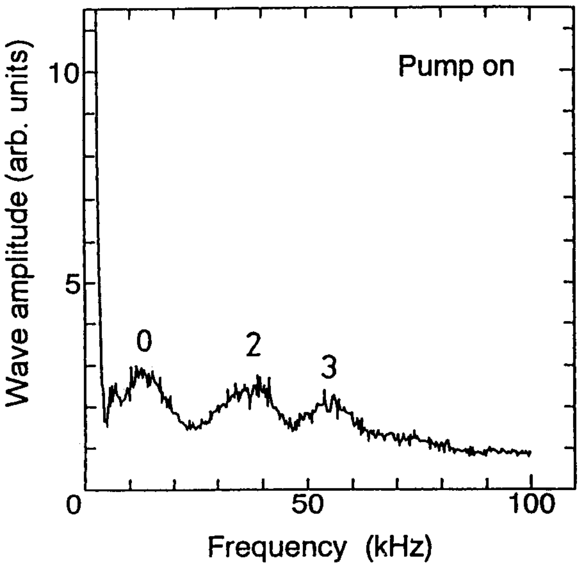

Fig. 2 Frequency spectra of unstable waves for pump *rf* field with frequency 60.16MHz.

suppression of unstable ICH waves is occurred by the pump *rf* field and fields of both sideband waves.

On the other hand, when the frequency of applied *rf* field is higher than the lower hybrid frequency ω_L, the enhancement of unstable ICH waves is observed. Radial profiles of the wave amplitude of the unstable 2nd ICH mode (mode denoted by 1 in Fig. 1) are shown in Fig. 4 for no pump and the pump of *rf* field, respectively, where the pump frequency ω_0 is 64MHz. It is seen that the wave amplitude increases with the pump of *rf* field, and the increment of the wave amplitude is dominant in the region of the maximum plasma inhomogeneity. Radial profiles of another modes are similar to that of mode 1, but the increment of the wave amplitude is somewhat small, although data are not shown. In this case, the amplitude of lower sideband waves (frequency ω_1) is much larger than that of upper sideband waves (frequency ω_2), although data are not shown in here.

We attempt the numerical analysis of unstable ICH waves in the presence of the applied *rf* field. The analysis are performed by taking in the boundary condition perpendicular to the magnetic field in the cylindrical ion beam and plasma column i.e., the nonlocal theory. The treatment is similar to that in ref. [3], and the ponderomotive force due to the pump *rf* field and fields of both sideband waves is taken in nonlinear terms. The obtained nonlinear dispersion relation is given by

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

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

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

$$\omega_L^2 = \frac{\omega_{pi}^2}{1 + \omega_{pe}^2/\omega_{ce}^2} (1 + \frac{M_i k_{0\parallel}^2}{m_e k_0^2})^2, \ \Phi_0 = \frac{(e/m_e)\phi_0}{c_s^2},$$

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

where ε is the local linear dielectric function of an inhomogeneous ion beam-plasma system [4], (ω, k), (ω_0, k_0), (ω_1, k_1) and (ω_2, k_2) are the unstable, pump *rf*, lower and upper sideband modes, ϕ_0 is the wave potential of *rf* field, c_s is ion acoustic sound velocity, Γ_n and $\Gamma_{n1,2}$ are the nomalized 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 frequency and growth rate of unstable ICH waves for the pump *rf* field from eq.(1). The growth rates of three ICH waves as a function of the normalized frequency of the

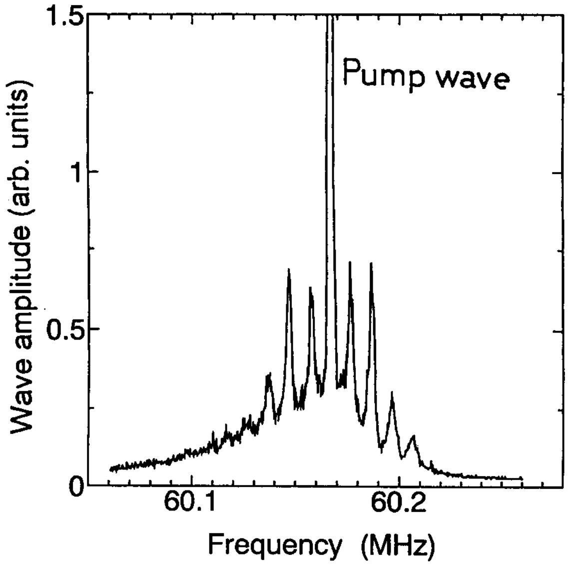

Fig. 3 Lower and upper sideband frequency spectra around the frequency spectrum of pump *rf* field with frequency 60.16MHz.

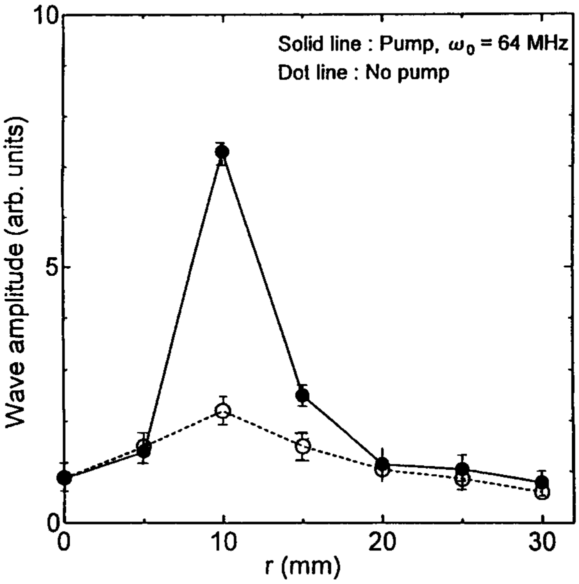

Fig. 4 Radial profile of fundamental ICH wave for pump *rf* field with frequency 64MHz.

pump *rf* field are shown in Fig. 5, where curves denoted by 0, 1, 2 are growth rates of the fundamental, 2nd and 3rd ICH modes, respectively. It is seen in Fig. 5 that growth rates of three unstable ICH waves are strongly reduced, when the frequency of pump waves ω_0 is less than the frequency of lower hybrid waves ω_L. And when ω_0 is higher than ω_L, growth rates of three ICH waves increase. But, the plasma density n_p used in calculation is somewhat smaller ($\simeq$ 83%) than that in experiment, and the azimuthal mode number of each mode is calculated only for ℓ or $\ell_{1,2} = 1$. Then numerical lower hybrid frequency is lower (at least $\simeq$ 83%) than that of the experiment. Therefore although there is such a discrepancy between the calculation and the experiment, numerical results agree qualitatively with the experimental results for the dependence of the growth rate of ICH waves on the pump *rf* field.

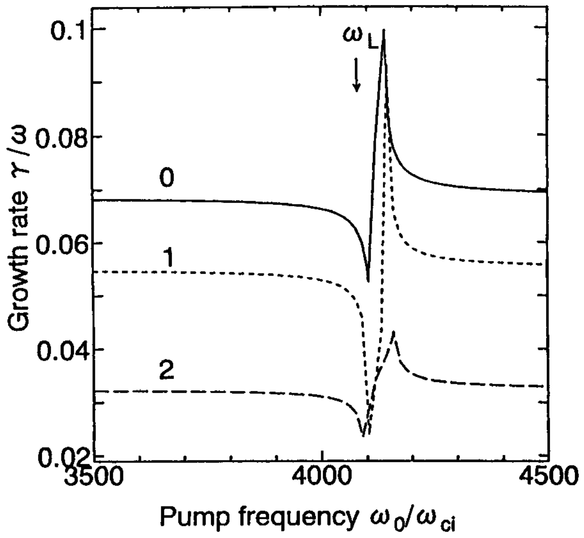

Fig. 5 Numerical growth rate of fundamental (0), 2nd (1) and 3rd (2) ICH waves versus frequency of pump *rf* field, where plasma density $n_p = 2.0 \times 10^{10}\text{cm}^{-3}$, $T_e \simeq 5\text{eV}$, beam density ratio $n_b/n_p = 0.01$, beam energy $V_b = 300\text{eV}$.

4. Conclusions

In an ion beam-inhomogeneous plasma system, the drift frequency ω^* exceeds the harmonics of the ion cyclotron frequency $n\omega_{ci}$, ICH waves are excited by the plasma inhomogeneity, and ICH waves are enhanced by an ion beam injection. By the application of externally launched *rf* field near the lower hybrid frequency, the suppression of these unstable waves has been observed. This suppression is based on the ponderomotive force due to a combination of the applied *rf* field and fields of the lower and upper sideband wave. When the frequency of pump *rf* field is higher than the lower hybrid frequency, the enhancement of unstable waves has been observed. This behavior of unstable ICH waves agree qualitatively with that of the nonlocal theory taken into account of the ponderomotive force due to a combination of the applied *rf* field and fields of both sideband waves.

References

[1] M. Ashour-Abdalla and R.M. Thorne, Geophys. Res. Lett. **4**, 45 (1977).

[2] R.F. Benson, J. Geophys. Res. **90**, 2753 (1985).

[3] G. Praburam, H. Honda and M. Sugawa, J. Phys. Soc. Jpn. **62**, 4262 (1993).

[4] A.B. Mikhailovskii, *Theory of Plasma Instabilities Vol. 2 Instabilities of an Inhomogeneous Plasma* (Consultants Bureau, New York-London, 1974) Part 1.

[5] M. Sugawa, S. Iwamoto, T. Kondo, S. Utsunomiya, T. Maehara and R. Sugaya, *Proceedings of the 1996 International Conference on Plasma Physics*, Nagoya (The Japan Society of Plasma Science and Nuclear Fusion Research, 1996) Vol. 1, p. 82.