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Coupling between Electrostatic Ion Cyclotron Waves and Ion Acoustic Waves

T. Ohnuma,* S. Miyake,† T. Watanabe, T. Watari, and T. Sato
Institute of Plasma Physics, Nagoya University, Nagoya, Japan
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We have observed the linear coupling between an electrostatic ion cyclotron wave and an ion acoustic wave near the second-harmonic ion cyclotron frequency for propagation of an electrostatic ion wave along a magnetic field, where the wave number perpendicular to the magnetic field $k_\perp$ exists.

Recently, the propagation of electrostatic ion waves in a magnetic field has been investigated by many authors.[1-5] For propagation oblique to the magnetic field, Hirose, Alexeff, and Jones investigated in detail the behavior of the wave near the ion cyclotron frequency.[1] Properties of perpendicular propagation were also shown by Ohnuma *et al.*[2,4] and Ault and Ikezi[3] who detected the collisional effect at the ion cyclotron frequency[2] and the collisionless one at its harmonics.[3,4] The dispersive character of the ion mode propagating almost parallel to the magnetic field near the fundamental ion cyclotron frequency has been reported by some authors.[5] Levin and Oleson show this character by coil excitation,[5] in contrast to other reports (mesh excitation). In this Letter, the propagation parallel to the magnetic field is investigated in detail especially near the ion cyclotron frequency and its harmonics.

The simplified experimental setup is shown at the top of Fig. 1. The experiments are performed with a *QP* machine[6] on an argon plasma produced by a PIG plasma source. The plasma dimension is about 4 cm in diameter and 10 m in length with a density of 1.0×10^{10} cm^{-3} and an electron temperature of 4.5 eV. The wave was excited by a mesh (6 cm in diameter) aligned perpendicular to the magnetic field, and was detected by another one (2 cm in diameter) movable along the plasma column. Wave patterns of parallel propagation were displayed on an X-Y recorder by using an interferometer technique.

Typical experimental wave patterns are shown at the bottom of Fig. 1. They show that two kinds

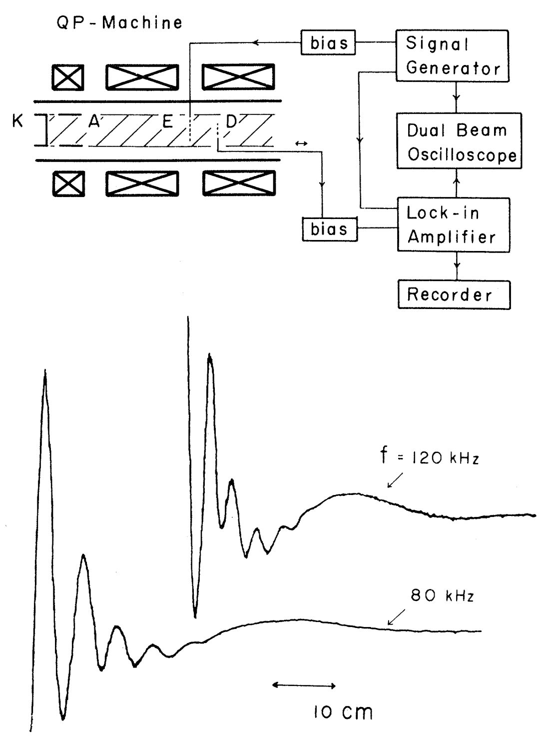

FIG. 1. Block diagram of the experimental setup, and the typical wave patterns obtained by a lockin amplifier.

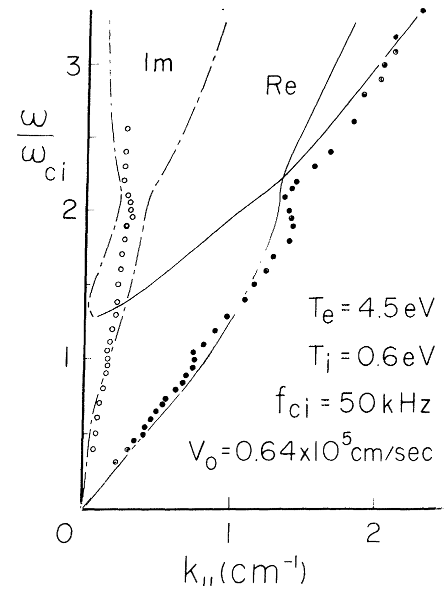

FIG. 2. Normalized frequency ω/ω_{ci} versus the real and imaginary part of the wave number $k_{\parallel}$ parallel to the magnetic field. The experimental results are plotted as solid and open circles. The plasma density is $N_0 = 1.0\times10^{10}$ cm^{-3}, and the wave number perpendicular to the magnetic field is $k_{\perp} = 0.8$ cm^{-1}. The theoretical curves are obtained from the dispersion relation of electrostatic modes in a magnetic field.

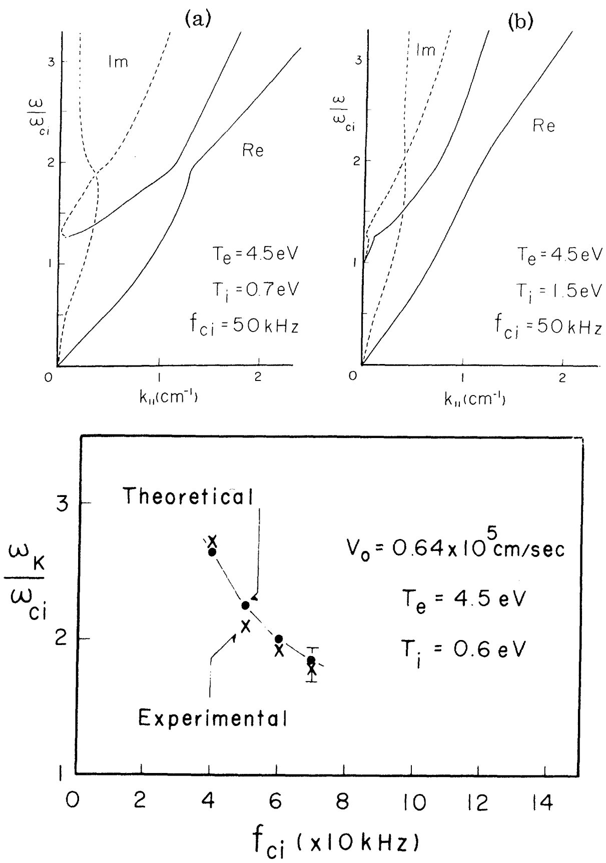

FIG. 3. Top, dispersion curves of electrostatic waves in a magnetic field. In (a) and (b), the ion temperature is changed with $f_{ci} = 50$ kHz and the plasma flow $V_0 = 0$. Bottom, the frequency ω_K (experimental and theoretical), at which an ion acoustic mode couples strongly with an electrostatic ion cyclotron mode, versus the ion cyclotron frequency. The plasma density is $N_0 = 1.0\times10^{10}$ cm^{-3}.

of waves coexist; the mode of shorter wavelength is treated in this Letter. Figure 2 shows the experimentally obtained dispersion curve and the factor of the wave damping for a magnetic field strength of $f_{ci} = 50$ kHz (f_{ci} is the cyclotron frequency). The theoretical curves, which are also drawn in the figure, are discussed later. The perpendicular wave number $k_{\perp}$ is nearly 0.8 cm^{-1}, even if the wave frequency is changed. This was determined by the fact that the wave is equiphase in the radial direction of the plasma column. The dispersive character of the dispersion curve in the vicinity of the second-harmonic ion cyclotron frequency is clearly observed in the figure. The observed imaginary part of the wave number $k_{\parallel}$ is shown to be larger at that frequency by a factor of 10–30% in comparison with those of nearby frequencies. The weak dispersive character at the fundamental ion cyclotron frequency in Fig. 2 becomes too weak in other magnetic fields to deduce some properties experimentally. As shown in Fig. 3, the frequency ω_K at which the dispersive character of the dispersion relation appears increases with a decrease in the strength of the magnetic field (i.e., the ion cyclotron frequency).

In order to explain the experimental results, we have computed the dispersion relation of electrostatic waves in a magnetic field given by Lominadze and Stepanov[7] and Stix[8]:

$$1 + \sum_{j=e,i} \sum_{n=-\infty}^{\infty} \frac{k_{Dj}^2}{k^2} e^{-\lambda} I_n(\lambda)[1 + \alpha_0 Z(\alpha_n)] = 0, \quad (1)$$

where

$$k_{Dj}^2 \equiv \frac{\omega_{pj}^2}{\kappa T_j/m_j}, \quad \lambda \equiv \frac{k_{\perp}^2/\omega_{cj}^2}{\kappa T_j/m_j},$$

$$\alpha_{nj} \equiv \frac{\omega - k_{\parallel} V_0 + n\omega_{cj}}{k_{\parallel}(2\kappa T_j/m_j)^{1/2}},$$

with ω_{pj}, ω_{cj}, T_j, m_j, $Z(\alpha)$, and $I_n(\lambda)$ the ion plasma frequency, the ion cyclotron frequency, the temperature, the mass of the jth component, the plasma dispersion function,[9] and the modified Bessel function, respectively.

Numerical calculations were performed near the experimental conditions with a computer (HITAC-8500) at our Institute. When the effects of the plasma flow are neglected, the typical dispersion curves obtained by the theory are shown with the ion temperature as a parameter for $f_{ci} = 50$ kHz. The coupling of two modes is shown between the ion acoustic mode and the electrostatic ion cyclotron mode. The coupling occurs near the second-harmonic ion cyclotron frequency and appears strongly with low ion temperature (i.e., T_e/T_i is large). The theoretical dispersion relation is also shown with solid and dot-dashed lines in Fig. 2 for the experimental conditions. The experimental data are almost in accordance with the theoretical curves. When the strength of the magnetic field is changed, the frequency at the coupling of the two modes changes as shown in Fig. 3. The theoretical results are clearly in accord with the experimental ones. That is, the observed wave in Fig. 2 is thought to be the ion acoustic mode for $\omega \lesssim 2\omega_{ci}$ and the electrostatic ion cyclotron mode for $\omega \gtrsim 2\omega_{ci}$. In the transition region from one mode to another, stronger dispersive effects are shown in both the theoretical and experimental results. For the frequency range of $2\omega_{ci} \gtrsim \omega \gtrsim \omega_{ci}$, it may be due to the method of wave excitation that the observed wave is an ion acoustic mode in spite of the existence of the electrostatic ion cyclotron mode with less damping than that of the ion acoustic mode.

We now discuss the mode of the larger wavelength in Fig. 1. The phase velocity is about 8 times the phase velocity of the mode investigated in this report, and is independent of the wave frequency and the exciting voltage. That is, the mode is not thought to be a pseudowave[10] with regard to the value of the phase velocity, the dispersion relation, and the behavior with the exciting frequency. Further consideration of these points is now in progress. Furthermore, the mode is observed for both the frequency ranges larger and smaller than the ion cyclotron frequency. That is, the mode is not thought to be the electrostatic ion cyclotron wave. The electrostatic property in this Letter is also ascertained by the fact that the value of $n^2/|K_{ij}| \approx 10^6$ (Ref. 8, p. 224) under our experimental conditions is much larger than 1. We must next consider the boundary effect, which is included in the perpendicular wave number $k_\perp$ in this Letter. The frequency at which two modes couple is found to become high with an increase in the perpendicular wave number, i.e., the observed coupling between the ion acoustic mode and the ion cyclotron mode is affected by the boundary.

From the investigation discussed above, the stronger dispersive effect we have detected near the second-harmonic ion cyclotron frequency can be concluded to be due to the coupling between the ion acoustic mode and the electrostatic ion cyclotron mode.

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*Permanent address: Department of Electrical Engineering, Tohoku University, Sendai, Japan.

†Permanent address: Welding Research Institute of Osaka University, Osaka, Japan.

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