INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

Electromagnetic Cyclotron Harmonic Waves

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RESEARCH REPORT

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Further communication about this report is to be sent to the Research Information Center, Institute of plasma Physics, Nagoya University, Nagoya 464 Japan.

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Abstract

Electromagnetic electron cyclotron harmonic waves just below the electron cyclotron harmonics are investigated numerically and experimentally. Backward waves which are observed to propagate nearly perpendicular to the magnetic field just below the electron cyclotron frequency in a high density magnetoplasma are confirmed to be in accord with the theoretical electromagnetic cyclotron waves.

Much attention has been paid to high density and high temperature plasmas because of an achivement of controlled thermonuclear fusion energy. As for the additional heating, various modes[1] in plasmas have been investigated for the wave heating in detail. Cyclotron waves[2] are also targets for investigations. Especially, plasma modes in the high density and high temperature plasmas must be studied for an actual heating experiments in plasmas. In this report, those typical modes, namely, electromagnetic ordinary and extraordinary modes just below the electron cyclotron harmonics are investigated numerically and experimentally. These modes become important and are observable in a high density and temperature plasma. These modes propagate nealy perpendicular to the magnetic field. The property is a little similar to electrostatic cyclotron harmonic waves, namely, Bernstein waves, which propagate just above the cyclotron harmonics. Instead of the electrostatic mode, which has been studied in detail, the electromagnetic cyclotron harmonic mode is investigated in this report.

Dispersion relations of these electromagnetic modes must be derived from a full electromagnetic kinetic theory. The dielectric tensor for an electron plasma can be obtained from Vlasov and Maxwell equations in the form $D(\omega,\vec{k})\cdot\vec{E}(\omega,\vec{k}) = 0$, where

$$D(\omega,\vec{k}) = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ -D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & -D_{yz} & D_{zz} \end{pmatrix} \qquad (1)$$

$$D_{xx} = 1 - \frac{c^2 k_\parallel^2}{\omega^2} + \frac{\omega_p^2}{\omega^2} \frac{\omega_c^2}{k_\perp^2 v_\perp^2} \sum_{n=-\infty}^{\infty} \Lambda_n n^2 W_n ,$$

$$D_{xy} = i \frac{\omega_p^2}{\omega^2} \sum_{n=-\infty}^{\infty} \Lambda_n' n W_n ,$$

$$D_{xz} = \frac{c^2 k_\parallel k_\perp}{\omega^2} + \frac{\omega_p^2}{\omega^2} \frac{\omega_c^2}{k_\parallel k_\perp v_\perp^2} \sum_{n=-\infty}^{\infty} \frac{\omega - n\omega_c}{\omega_c} \Lambda_n n W_n ,$$

$$D_{yy} = 1 - \frac{c^2 (k_\parallel^2 + k_\perp^2)}{\omega^2} + \frac{\omega_p^2}{\omega^2} \frac{\omega_c^2}{k_\perp^2 v_\perp^2} \sum_{n=-\infty}^{\infty} (n^2 \Lambda_n - 2\lambda^2 \Lambda_n') W_n ,$$

$$D_{yz} = - i \frac{\omega_p^2}{\omega^2} \frac{k_\perp}{k_\parallel} \sum_{n=-\infty}^{\infty} \frac{\omega - n\omega_c}{\omega_c} \Lambda_n' W_n ,$$

$$D_{zz} = 1 - \frac{c^2 k_\perp^2}{\omega^2} + \frac{\omega_p^2}{\omega^2} \frac{\omega_c^2}{k_\parallel^2 v_\perp^2} \left[\frac{\omega^2}{\omega_c^2} + \sum_{n=-\infty}^{\infty} \left(\frac{\omega - n\omega_c}{\omega_c} \right)^2 \Lambda_n W_n \right] ,$$

$$W_n \equiv \frac{\omega - k_\parallel v_0}{|k_\parallel| v_\parallel} Z_n + \frac{1}{2} \left(1 - \frac{T_\perp}{T_\parallel} \right) Z_n' , \quad Z_n \equiv Z \left(\frac{\omega - k_\parallel v_0 - n\omega_c}{|k_\parallel| v_\parallel} \right) ,$$

$$\Lambda_n = I_n(\lambda) e^{-\lambda} , \quad \Lambda_n' = d\Lambda_n / d\lambda , \quad v_\perp^2 = T_\perp / m , \quad v_\parallel^2 = 2T_\parallel / m .$$

The symbols Z_n, I_n, ω_p and ω_c are the plasma dispersion function, the n-th modified Bessel function, the plasma frequency and the cyclotron frequency, respectively. The magnetic field directs to Z-direction and the wave vector is in the X-Z plane. To simplify the model, the isotropic temperature $T_{\parallel}=T_{\perp}$ and no drift velocity $v_0=0$ are assumed in what follows. Even in such a simple plasma, there are many modes which are included in the kinetic dispersion relation $D(\omega,\vec{k})=0$. In order not to confuse those modes, contour maps of $|D(\omega,\vec{k})|$ are used. The typical contour map near the electron cyclotron frequency for a given wave number is shown in Fig.1. The abscissa and the ordinate are the real and imaginary frequency normalized by the electron cyclotron frequency, respectively. In this figure, the wave numbers $k_{\parallel}$ and $k_{\perp}$ are fixed where the suffixes $\perp$ and $\parallel$ stand for the components perpendicular and parallel to the magnetic field. The contour lines express those of $|D(\omega,\vec{k})|$=Const. for various constant values. The plasma parameters of Fig.1 are chosen such as those in the high density and relatively high temperature plasmas near the electron cyclotron frequency. From such a map as Fig.1, the poles of $D(\omega,\vec{k})=0$ can be easily found, for example, at the posistion of A, B and C. The poles A and B are the ordinary and extraordinary electromagnetic cyclotron harmonic waves respectively, an investigation of which is the main target in this report. The pole A of the ordinary mode is shown greater than the pole B of the extraordinary mode. The larger pole, namely, the ordinary mode is considered to be launched easier than the smaller pole, i.e. the extraordinary mode by the excitation mechanism. The ploe C is that of the so-called whistler mode, which is beyond this report. Other smaller poles are those corresponding higher modes due to the thermal effects, which are considered more difficult to be launched. As for the poles A and B, the poles disappear in the lower density, for example, for $f_p/f_c \lesssim 30$ although the whistler ploe remains. This can be understood that the electromagnetic cyclotron harmonic wave can be launched in a very high density plasma. By a confirmation of the mode in this method, the dispersion relation of the ordinary and extraordinary cyclotron harmonic waves can be calculated as shown in Fig.2 for a propagation perpendicular to the magnetic field. The ordinary and extraordinary modes are defined from the direction of the oscillating electric field parallel and perpendicular to the magnetic field as usual, respectively. The dispersion relations of those ordinary and extraordinary cyclotron harmonic waves have particular just "below" the fundamental and n-th cyclotron frequency. This effect is quite different from an electrostatic cyclotron harmonic wave, namely, the Bernstein waves which can propagate above each cyclotron harmonics. For extraordinary mode, the electron Bernstein mode is indicated by EBW. The plasma density is varied with a parameter of f_p/f_c. The dispersion curve extends to the lower frequency with an increase of the density. That is, the electromagnetic cyclotron harmonic waves are shown to propagate in broader frequency range with an increase of the density and the temperature.

Experiments were performed in a chamber 60cm in diameter and 120cm in length. An argon plasma produced by a high power field of radio frequency. The neutral gas pressure was nearly 3×10^{-4} Torr. The uniform magnetic field was applied with a strength of $B_0 \approx 35$ gauss. The typical plasma parameter values are the electron temperature $T_e \approx 20$ eV in the higher density than $N_0 \approx 10^{13}$ cm^{-3}. The transmitter and the receiver of the signals were an electric probe with an exposed surface 3 mm long and 1 mm diam, which were shielded in other parts. These probes were sensitive to electric fields parallel and perpendicular to the magnetic field. Typical detected signals are shown in Fig.3. The transmitter is located at the source position. The receiver is moved for radial direction. The small structures of the figure indicate wave patterns. The wave signals are observed below the electron cyclotron frequency, $f_c \approx 98$ MHz. It must be noted that the wavelength becomes long with an increase of the wave frequency. This observed wave indicates the backward wave just below the electron cyclotron frequency. By a spatial measurement of wave patterns, the wave fronts are found to be parallel to the magnetic field line. This property is quite different from the Trivelpiece-Gould mode. From those wave patterns, one can obtain the dispersion curve of the observed mode as shown in Fig.4 with solid circles.

In Fig.4, the theoretical dispersion curves of the ordinary cyclotron harmonic waves are also indicated. The density parameter f_p/f_c is varied to investigate the behavior around the experimental results. The experimental data are in roughly accord with the theoretical dispersion relation in the higher plasma density, i.e., in the experimental conditions. A little difference between the theory and experimental results is considered to be from the experimental error of the electron temperature. The observed waves are more fit to the ordinary cyclotron mode than the extraordinary mode. The observed parallel wave fronts to the magnetic field radiated from the local source are also confirmed to be in accord with the theoretical wave fronts which are obtained from the extended ray theory[3]. In this report, we have stressed the experimental results below the electron cyclotron frequency, because the electrostatic cyclotron harmonic wave can not propagate in the frequency range.

In conclusion, the electromagnetic cyclotron harmonic wave below the electron cyclotron frequency is confirmed experimentally and theoretically in this report. Because this mode is a particular mode in the high density and high temperature plasmas, much attention will be paid to investigations of this mode for wave heating of fusion plasmas. The measurement of the dispersion relation of the mode will be used for a determination of the plasma density in such a plasma.

References

1. T.H.Stix, The Theory of Plasma Waves, McGraw-hill, 1962
2. J.G.Lominadge, Cyclotron Waves in Plasmas, 1975 (in Russian)
3. T.Ohnuma, T.Watanabe and H.Sanuki, to be published.

Figure Captions

Fig.1. Contour map of $|D(\omega,\vec{k})|$=Const. below the electron cyclotron frequency f_c. The abscissa and the ordinate are the real part and imaginary part of the normalized frequency f/f_c, respectively. A: an ordinary cyclotron harmonic mode; B: an extraordinary cyclotron harmonic mode; C: a whistler mode. $f_p/f_c=10^3$, $T_e=20$ eV, $k_\parallel \rho_e=0.04$, $k_\perp \rho_e=0.81$. ρ_e: the electron Larmor radius.

Fig.2. Dispersion curves of electromagnetic ordinary and extraordinary cyclotron harmonic waves for $T_e=100$ eV. The parameter f_p/f_c is varied with a difference $\Delta(f_p/f_c)=100$. EBW is that of the electrostatic electron cyclotron harmonic wave.

Fig.3. Experimental wave patterns of electromagnetic cyclotron harmonic waves which propagate nearly perpendicular to the magnetic field, $f_c \approx 98$ MHz.

Fig.4. Experimental and theoretical dispersion curves of the ordinary electromagnetic cyclotron harmonic wave. $T_e=20$ eV. "Δ" means the difference of the value f_p/f_c between the dispersion curves.

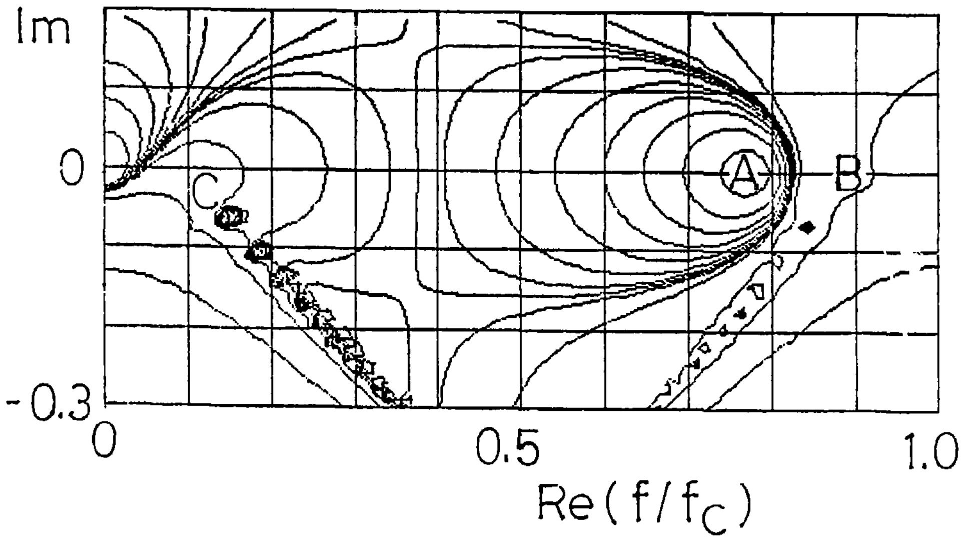
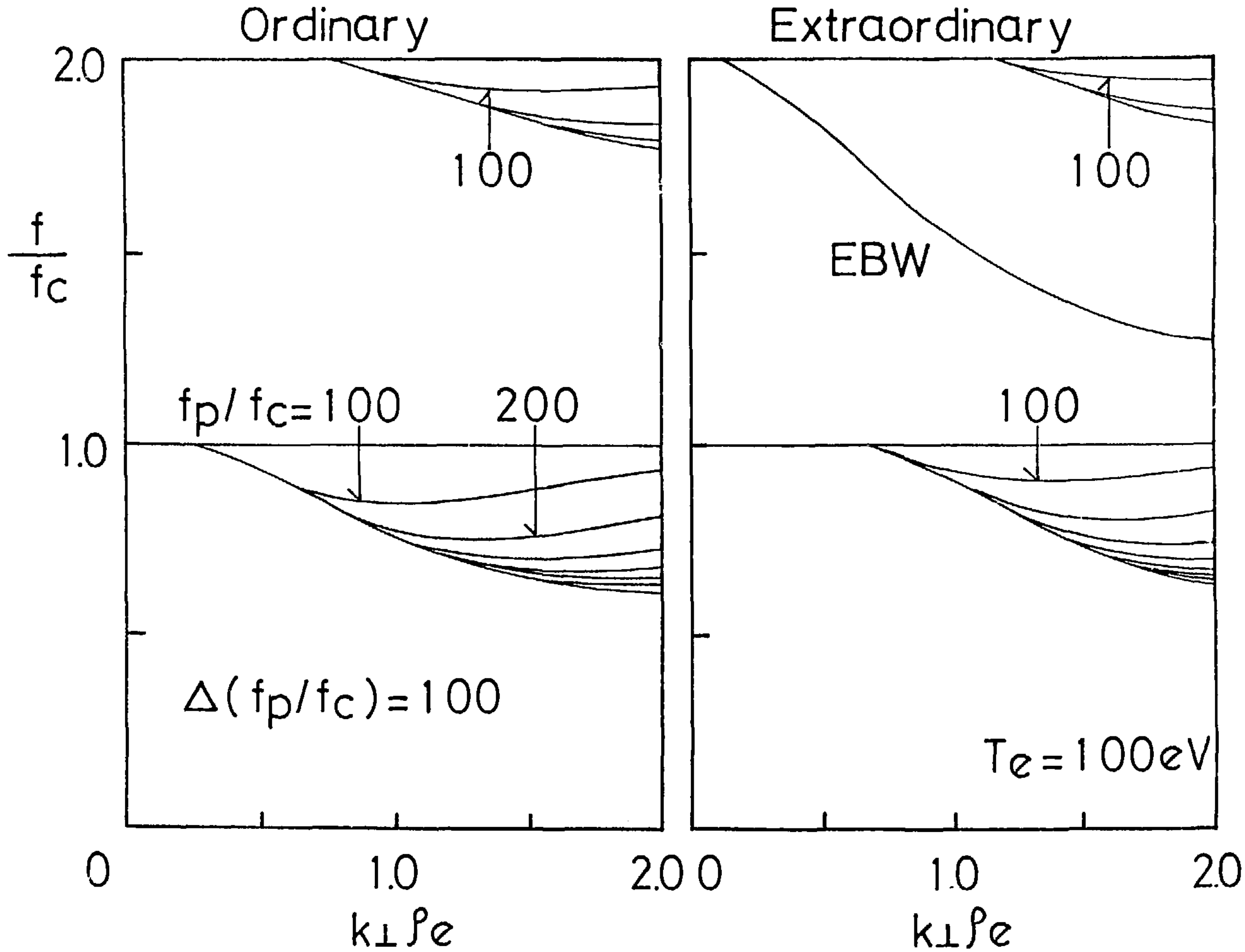


Fig. 1



Ordinary
Extraordinary
2.0
1.0
f/fc
100
EBW
fp/ fc=100
200
100
Δ(fp/fc)=100
Te=100eV
0
1.0
2.0
0
1.0
2.0
k⊥ρe
k⊥ρe

Fig. 2

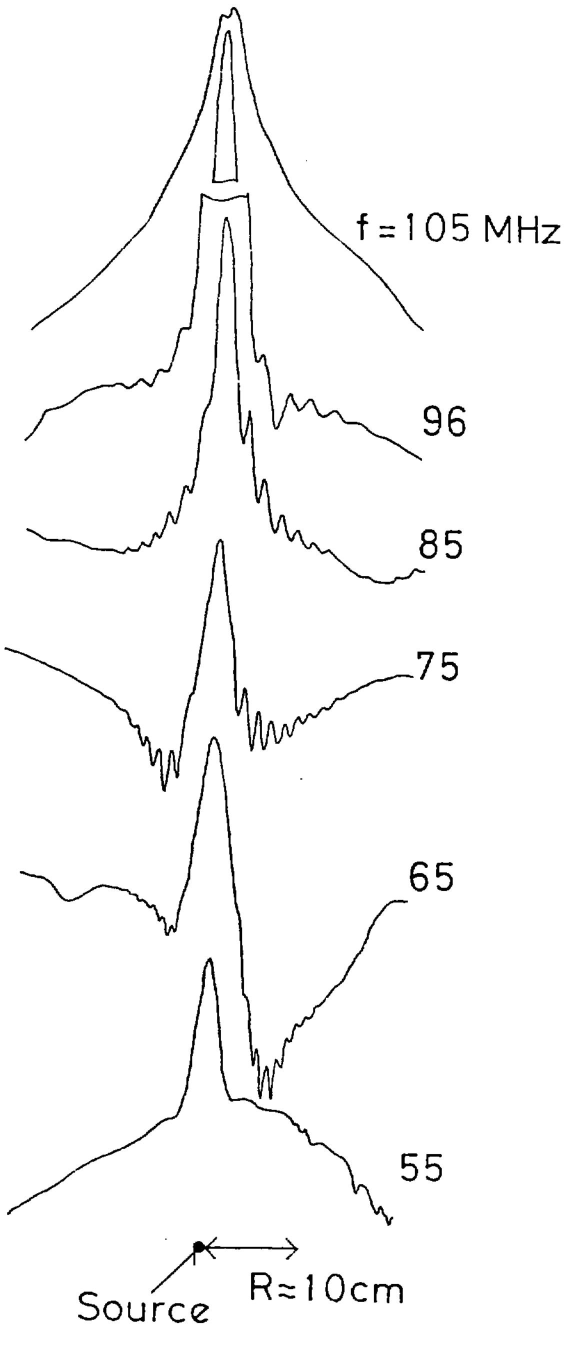


Fig. 3

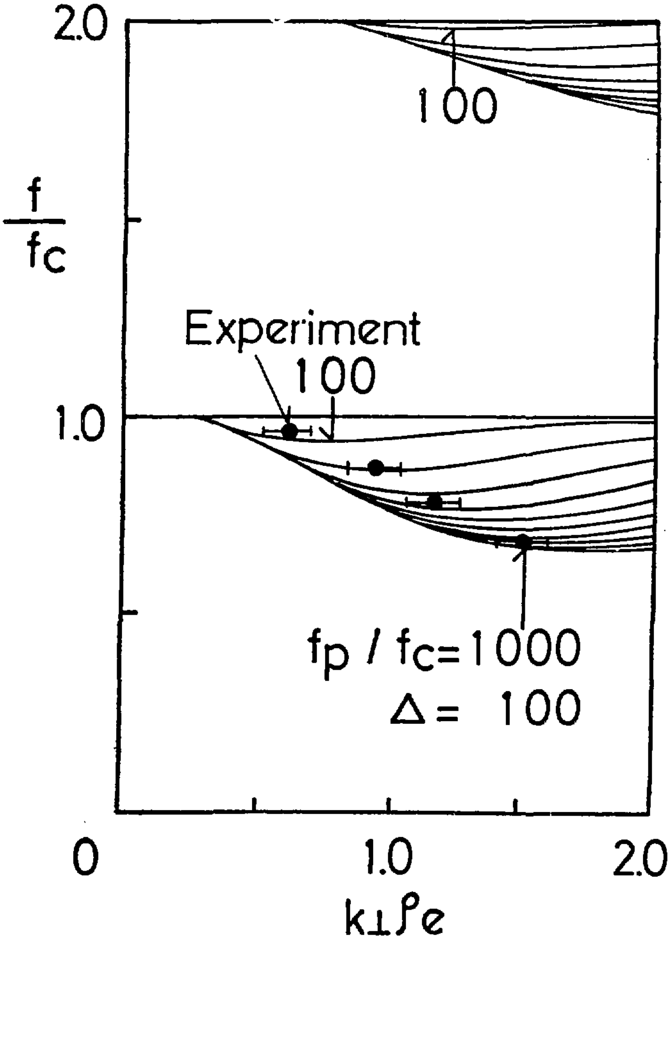


Fig. 4