189
12-5-78
DR 796

MASTER COLD ELECTROSTATIC ION CYCLOTRON
WAVES AND ION-ION HYBRID
RESONANCES

BY

M. ONO

**PLASMA PHYSICS
LABORATORY**

**PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY**

This work was supported by the U. S. Department of Energy Contract No. EY-76-C-02-3073. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States Government is permitted.

COLD ELECTROSTATIC ION CYCLOTRON WAVES
AND ION-ION HYBRID RESONANCES

M. Ono

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

ABSTRACT

By utilizing a sinusoidally phased external ring structure, the existence of the cold low frequency resonance ion is verified for $\omega < \omega_i$ and $\omega/k_0 < V_{Te}$. Then with a slow wave structure, the dispersion relations of the cold electrostatic ion cyclotron waves are reexamined in both single and two-ion-species plasmas. In a two-ion-species plasma, a resonance near the ion-ion hybrid frequency is observed.

1. INTRODUCTION

The existence of the cold low frequency resonance ion is verified for $\omega < \omega_i$ and $\omega/k_0 < V_{Te}$. Then with a slow wave structure, the dispersion relations of the cold electrostatic ion cyclotron waves are reexamined in both single and two-ion-species plasmas. In a two-ion-species plasma, a resonance near the ion-ion hybrid frequency is observed.

We wish to report an experimental observation of a cold electrostatic mode which exists below the ion cyclotron frequencies, Ω_i , and above the ion-ion hybrid frequency, ω_{IH} . This type of mode may become important in a large size high field device with a plasma consisting of a mixture of two types of light ions such as a fusion reactor plasma since in such a device, the cold plasma approximation, $\omega/k_{\parallel} \approx \Omega_i/k_{\parallel} > V_{Te}$, can be satisfied even in a relatively hot electron plasma.

The real part of the wave dispersion relation in a cold two-ion-species plasma can be written in the following form:

$$1 - \frac{\omega_{pe}^2 k_{\parallel}^2}{\omega^2 k^2} - \frac{(\omega_{p1}^2 + \omega_{p2}^2)(\omega^2 - \omega_{IH}^2)}{(\omega^2 - \Omega_1^2)(\omega^2 - \Omega_2^2)} = 0 \quad (1)$$

where $\Omega_2 > \Omega_1$ and ω_{IH} is defined as the following:¹

$$\omega_{IH}^2 = \frac{(\omega_{p1}^2 \Omega_2^2 + \omega_{p2}^2 \Omega_1^2)}{(\omega_{p1}^2 + \omega_{p2}^2)} = \Omega_1 \Omega_2 \frac{(N_1 m_1 + N_2 m_2)}{(N_1 m_2 + N_2 m_1)} \quad (2)$$

From Eq. (1), one can see the frequency range of the wave propagation to be $\omega < \Omega_1$ and $\omega_{IH} < \omega < \Omega_2$. The mode exhibits a resonance near ω_{IH} and cut-offs at Ω_1 . As for the density variation, the mode exists for $\omega < \omega_{pe}$ therefore an externally launched wave has to only tunnel through a very thin evanescent layer. For $\omega_{pi} \gg \omega$, Eq. (1) becomes independent of plasma density and can be expressed in the following form:

$$\frac{k_n^2}{k^2} = \cos^2 \theta = \frac{m_e}{m_2} \left(N_1 \frac{m_2}{m_1} + N_2 \right) \frac{\omega^2 (\omega^2 - \omega_{IH}^2)}{(\omega^2 - \Omega_1^2) (\Omega_2^2 - \omega^2)} \quad (3)$$

where N_1 and N_2 are the partial concentrations of ions, and ions are assumed to be singly ionized. From Eq. (3), one can see that the mode depends strongly on the quantity, ω/Ω_i

Another interesting feature of Eq. (1) is the existence of a resonance cone associated with this mode.² One can essentially use an analogy with the lower hybrid resonance cone³ by noting Eq. (1) (or even more transparently Eq. (3)) depends only on the propagation angle, $\theta = \cos^{-1}(k_n/k)$. The existence of such a resonance cone in this frequency range was first predicted by Fisher and Gould² which they termed as the ion branch, and later theoretically investigated by H. H. Kuehl.⁴ This resonance cone, however, should be distinguished from yet another resonance cone in this frequency range which exists for $\omega/k_n < C_s$ in a plasma with $T_i/T_e \ll 1$.⁵⁻⁷

In order to test the above predictions, we have performed experiments in the Princeton L-4 linear research device⁸ which has a steady state magnetic field of up to 4.2 kG and an uniform field region of ≈ 2.3 m with field ripple of < 0.7 %. In order to satisfy the cold plasma condition, i.e. $\omega/k_n > V_{Te}$, we have used the highest magnetic field strength, $B_0 \approx 4.1$ kG ($f_{ci}(\text{He}) \approx 1.55$ MHz), and the lowest electron temperature, $T_e \approx 0.5 - 1.0$ eV (measured by the ion acoustic wave propagation method), achievable in our device. Such a low electron temperature

was obtained by using a relatively high neutral pressure, $P \approx 2.0 \times 10^{-3}$ Torr, and a low bias voltage on the plasma source, $V_{\text{bias}} \approx 30-40$ V. The typical plasma density, $n_0 \approx 10^{10} \text{ cm}^{-3}$, and the ion temperature, $T_i < 0.1$ eV. For the background gases, helium and neon are used since we have previously carried out ion concentration measurements on such a plasma.^{8,9}

The resonance cone was investigated by using a ring structure which is schematically shown in Fig. 1(a). The structure consists of 9 rings whose inner diameter is $3\frac{1}{2}$ " and each ring is placed $1\frac{1}{4}$ " apart. This structure generates an electrostatic signal with a significant fraction of its fourier components satisfying the cold plasma condition, $\omega/k_{\perp} > V_{Te}$. It should be noted that this type of launching structure is in essence identical to the one used by Briggs and Parker to launch the lower hybrid resonance cone.¹⁰

In Fig. 1(a), we show radial amplitude profiles of the electrostatic signal detected by RF probes which are placed at various axial distances from the launching structure (as labeled). The data were taken for $f = 1.24$ MHz, $f_{ci}(\text{He}) = 1.55$ MHz, and $\text{He:Ne} = 6:4$. We observe that the resonance cone does indeed propagate radially in as it travels axially away from the structure. The resonance cone we observe here is broader (radially) than the one typically observed in the lower hybrid case^{2,10} due to the longer wave length nature of the present mode which is required to satisfy the cold plasma condition. One can measure the resonance cone angle by plotting the radial position of the amplitude maxima

as a function of the axial distance. In Fig. 1(b), such a plot is shown. The solid line is obtained by least square fitting the experimental points. The dashed line is the theoretical value computed from Eq. (3). Considering the simplicity of such theory, the agreement is quite reasonable.

Next, we investigated the dependance of the cone angle as a function of $\omega/\Omega_{\text{He}}$ for various ion concentration ratios. Typical radial profiles of the signal amplitude detected by a radially moving probe which was placed 98 cm from the structure are shown in Fig. 2(a) for two representative concentrations. The solid line is taken in a pure helium plasma and the dotted line is in He:Ne = 2:8. In Fig. 3(a), the measured cone angles are plotted as a function of $\omega/\Omega_{\text{He}}$ for the two ion concentration ratios. The dotted curves are the angle computed from Eq. (3). A light dashed line at $\omega/\Omega_{\text{He}} \approx 0.68$ shows the ion-ion hybrid frequency for He:Ne = 2:8 computed from Eq. (2). Although the agreement is reasonable, the discrepancy near the hybrid frequency is significant since Eq. (3) predicts $\theta \rightarrow 0$ at ω_{IH} and the mode to be evanescent below ω_{IH} . However, the experimental data show the cone to exist at and even below ω_{IH} . This behavior can be understood by noting the fact that the present resonance cone is launched externally. Near the ion hybrid frequency, the cone angle becomes very shallow and an analysis shows that due to the finite extent of the L-4 device, the resonance cone cannot penetrate sufficiently into the plasma to satisfy the condition $\omega < \omega_{\text{pi}}$, which was used to obtain Eq. (3). For this reason, we have

solved the wave differential equations using the WKB method for our experimental parameters much the same way as was done for the lower hybrid cone case.^{10,11} The result of such computation is shown as solid curves in Fig. 3(b) which mainly modifies the cone angle near the ion-ion hybrid frequency. The agreement between experiment and such theory appears to be very good.

For the lower hybrid wave, P. Bellan and M. Porkolab have shown that in order to launch a lower hybrid wave with well defined $k_{\perp}$ and $k_{\parallel}$, it is necessary to use a launcher with axial periodicity (slow wave structure).^{11,12} One can show that such is also the case with the present low frequency mode. Therefore we have used a slow wave structure similar to that of the lower hybrid wave experiments to excite the cold electrostatic ion cyclotron wave. The structure consists of four identical ring sections where one of the sections was used for the resonance cone propagation experiment (see Fig. 1(a)). These four sections are alternately phased in or out of phase to make two axial wavelengths with $\lambda_{\parallel} \approx 60$ cm. The propagation characteristics and the wave length are measured by radially moving probes placed at various axial locations.

As in the case with the resonance cone experiment, the excited wave packet was observed to propagate obliquely to the field line making an angle defined by the resonance cone angle. The measured axial wave length, $\lambda_{\parallel} \approx 61$ cm, appears to stay reasonably constant as long as the mode is not heavily damped. The radial wavelength, on the other hand, shows

a large change with the ion concentration ratio and ω/Ω_i . In Fig. 2(b), we show a typical interferometry output of a radially moving probe as a function of $\omega/\Omega_{\text{He}}$ for He and He:Ne = 2:8. We observe that there is a one-to-one correspondence between the number of perpendicular and axial wavelengths which is in agreement with the lower hybrid wave experiment.¹² One can see from Fig. 2(b), the wave length is much shorter for He:Ne=2:8, and the wave length decreases rapidly with $\omega/\Omega_{\text{He}}$. In Fig. 3(b), the measured normalized perpendicular wave number, $k_{\perp}/k_{\parallel} \cdot \sqrt{m_e/m_{\text{He}}}$, is plotted as a function of $\omega/\Omega_{\text{He}}$ for the two concentration ratios. The ion hybrid frequency for He:Ne = 2:8, $\omega_{\text{IH}}/\Omega_{\text{He}} \approx 0.68$, is shown by a light dashed line in the figure. One can see a strong resonance behavior as the wave frequency approaches the ion hybrid frequency. We believe that this is the first direct measurement of the ion-ion hybrid resonance although there are several experiments in which the existence of such a resonance is also reported.¹³⁻¹⁵ The dashed curves in Fig. 3(b) are obtained from Eq. (3). As in the case with the resonance cone propagation, the experimentally measured wave length deviate significantly from such theory near the hybrid frequency. Therefore, we again calculated the wave trajectory equation using the full kinetic equation for electrons (since $\omega/k_{\parallel}$ is now reasonably well defined) and obtained the solid curves shown in Fig. 3(b). The agreement appears to be quite good. In this experiment, the shortest wave length we are able to measure is typically 2.5mm. We

find that this is mainly due to the decorrelation of the phase of the wave signal rather than the actual damping of the wave. Such decorrelation may be due to an alignment problem of the slow wave structure which requires radial position alignment of ~ 1 mm over 1 m axial distance. However, the effects due to the magnetic field ripple, density fluctuations, and probe effects cannot be ruled out entirely at this time.

In conclusion, we have verified experimentally the resonance cone behavior of the cold electrostatic signal below the ion cyclotron frequency. Using a slow wave structure, we have verified the dispersion relation of the cold electrostatic ion cyclotron wave and observed a strong resonance behavior near the ion-ion hybrid frequency. The details of the present experiment as well as the damping of the wave shall be reported elsewhere.

We thank K.-L. Wong for helpful discussions, and J. Johnson, J. Taylor, W.L.Hsu, and R. Ernst for their technical assistance.

REFERENCES

*This work was supported by the United states Department of Energy, Contract EY-76-C02-3073.

- ¹S. J. Buchsbaum, Phys. Fluids 3, 418 (1960).
- ²P. K. Fisher and R. W. Gould, Phys. Fluids 14, 857 (1971).
- ³P. K. Fisher and R. W. Gould, Phys. Rev. Lett. 22, 1093 (1969).
- ⁴H. H. Kuehl, Phys. Fluids 17, 1636 (1974).
- ⁵K. H. Burrell, Phys. Fluids 18, 897 (1975).
- ⁶T. Ohnuma et al., Phys. Rev. Lett. 37, 206 (1976).
- ⁷P. Bellan, Phys. Rev. Lett. 37, 906 (1976).
- ⁸M. Ono, R. P. H. Chang, and M. Porkolab. Phys. Rev. Lett. 38, 962 (1977).
- ⁹M. Ono, Ph.D. thesis, Princeton University (1978).
- ¹⁰R. J. Briggs and R. R. Parker, Phys. Rev. Lett. 29, 852 (1972).
- ¹¹P. M. Bellan and M. Porkolab, Phys. Fluids 17, 1592 (1974)
- ¹²P. M. Bellan and M. Porkolab, Phys. Rev. Lett. 34, 124 (1975).
- ¹³S. J. Buchsbaum, Phys Rev. Lett. 5, 495 (1960).
- ¹⁴A. W. Baird III and D. G. Swanson, Phys. Fluids 12 1878 (1969).
- ¹⁵H. Toyama, J. Phys. Soc. Japan 34, 527 (1973).

FIGURE CAPTIONS

Fig. 1(a). Simplified schematic of the resonance cone antenna structure and the radial amplitude profiles of the excited resonance cone at various axial locations (as labeled). $f = 1.24$ MHz. $B = 4.1$ kG. $f_{ci}(\text{He}) = 1.55$ MHz. He:Ne = 6:4. 1(b). Resonance cone radial position as a function of axial distance. The parameters are the same as in Fig. 1(a). The dotted curve is obtained from theory.

Fig. 2(a). Radial amplitude profiles of the resonance cone as a function of $\omega/\Omega_{\text{He}}$ (as labeled) for two ion concentration ratios. The solid line is obtained in a pure helium plasma and the dotted line is in He:Ne=2:8. 2(b). Radial interferometry output of the wave launched by a slow wave structure for various $\omega/\Omega_{\text{He}}$ (as labeled).

Fig. 3(a). Resonance cone angle as a function of $\omega/\Omega_{\text{He}}$ for two ion concentration ratios (as labeled). The dots are the experimentally measured values. The solid and dashed curves are obtained from theory. 3(b). Normalized perpendicular wave number, $k_{\perp}/k_{\perp} \sqrt{m_e/m_{\text{He}}}$, of the wave as a function of $\omega/\Omega_{\text{He}}$. The ion concentration ratios are as shown. The dots are experimentally measured values. The solid and dashed curves are theoretical values. The ion-ion hybrid frequency, $\omega_{\text{IH}}/\Omega_{\text{He}} \approx 0.68$, is indicated by light dotted lines.

Fig. 1. 786305

Fig. 2. 786304

Fig. 3. 786306