INSTITUTE OF PLASMA PHYSICS

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RESEARCH REPORT

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Ion cyclotron drift waves propagating across a density gradient and a magnetic field have been excited externally in a two-ion species plasma, with its concentration ratio controlled. The measured dispersion relations agree with the theoretical predictions.

Electrostatic waves in a multi-ion species plasma have currently been recognized as significant for impurity problems and ion-ion hybrid resonance heating$^{1)}$ of fusion plasmas. High temperature plasmas are inevitably contaminated by several species of impurities which may drive new drift wave instabilities$^{2)}$. In order to pump out impurities, a novel concept called "radio-frequency divertor" has recently been proposed$^{3)}$, in which the impurity-ion transport is controlled by wave-particle interactions in a range of ion cyclotron frequencies. The basic understanding of the waves in a multi-ion species plasma is important in view of stability and control of plasmas contaminated by impurities.

Comprehensive experiments on electrostatic ion cyclotron wave$^{4,5)}$ and ion-ion hybrid resonance cone$^{6)}$ have performed in a two-ion species plasma. As well known, the density inhomogeneity modifies the electrostatic ion cyclotron wave into the ion cyclotron drift wave (ICDW)$^{7)}$ which is regarded high-frequency drift wave. The ICDW becomes unstable in a loss-cone distribution function or parallel electron current. A well defined experiment of ICDW instability by electron current has been reported in a single-ion species plasma$^{8)}$. In this paper, we report the first external excitation of ICDW in a two-ion species Plasma.

The dispersion relation for a collisionless low-β inhomogeneous plasma, for a slab model and including multi-species ions, is written by$^{7)}$

$$\begin{aligned}&1+\frac{k_{De}^2}{k^2}\left(1+i\sqrt{\pi}\,\frac{\omega-\omega_e^*}{k_z v_e}\right)+\sum_\sigma\frac{k_{D\sigma}^2}{k^2}\{\,1-\\&\sum_n\left(1-\frac{\omega_\sigma^*}{\omega}-\frac{n\omega_\sigma^*}{b_\sigma\Omega_\sigma}\right)\frac{\omega}{\omega-n\Omega_\sigma}I_n(b_\sigma)\exp(-b_\sigma)[\,1-\\&i\sqrt{\pi}\frac{\omega-n\Omega_\sigma}{k_z v_\sigma}\exp\left(-\frac{(\omega-n\Omega_\sigma)^2}{k_z^2v_\sigma^2}\right)]\}=0\end{aligned}\qquad(1)$$

We have defined $\omega_{e,\sigma}^* = \kappa_{e,\sigma}k_yT_{e,\sigma}/q_{e,\sigma}B$; $\kappa_\sigma = (\partial n_\sigma/\partial x)/n_\sigma$, $b_\sigma = k_y^2\rho_\sigma^2$ and assumed $(\omega-\omega_e^*)/k_zv_e < 1$; $(\omega-n\Omega_\sigma)/k_zv_\sigma \gg 1$. In a limit of cold ion temperature ($T_\sigma \to 0$) and neglecting the electron Landau damping (growing) term, Eq.(1) is reduced to

$$1+\frac{k_{De}^2}{k^2}-\sum_\sigma\frac{\omega_{p\sigma}^2}{k^2}\left(\frac{k_y^2+\kappa_\sigma k_y\Omega_\sigma/\omega}{\omega^2-\Omega_\sigma^2}+\frac{k_z^2}{\omega^2}\right)=0\qquad(2)$$

where $\omega_{p\sigma}^2 = q_\sigma^2n_\sigma/M_\sigma\varepsilon_o$.

First of all, we show the dispersion relation for single-ion species in Fig.1(a), where Eq.(2) is solved for $k_z = 0$ and $k_{De} \gg k_y$. Neglecting the density inhomogeneity ($v_d/c_s = 0$), we find the electrostatic ion cyclotron wave propageting at the ion sound velocity $c_s = (T_e/M)^{1/2}$. Including the inhomogeneity, we find the drift wave at $\omega/\Omega \ll 1$, with the propagation velocity $v_d = -\kappa T_e/eB$. The strong coupling between the electrostatic ion cyclotron and the drift waves takes place at $\omega/\Omega \lesssim 1$ and $v_d/c_s \sim 1$, as shown in Fig.1(a). This coupled mode (ICDW) has the topologically different dispersion curves divided at $v_d/c_s = 1$. In actual experiments, k_y is often fixed by eigen value problems ; $k_y = m/R$ in the case of a cylindrical plasma with radius R where m is the azimuthal mode number.

For example, the wave dispersion for $m = \pm 1$ is shown in Fig. 1(b). For $m = 1$, the coupling gives rise to a new cutoff ($k_z = 0$) at $\omega < \Omega$, in addition to the drift wave cutoff at $\omega^* = v_d k_y$. On the other hand, no coupling is seen for $m = -1$, since the azimuthal velocity is oppoeit to the intrinsic drift-wave propagation. In this case, the wave at $\omega < \Omega$ is essentially the ion acoustic wave.

In a multi-ion species plasma, the drift wave is drastically modified around each cyclotron frequencies to result in ICDW, even if the concentration is rather small. Figure 2 shows an example of the dispersion relation for a two-ion species whose mass (cyclotron frequency) ratio M_3/M_1 ($= \Omega_1/\Omega_3$) $= 3$ and the concentration ratio $= n_3/(n_1 + n_3)$. When the heavy ion species is introduced into the light one, the new ICDW appears at $\omega \lesssim \Omega_3$ for $m = 1$. The dotted lines indicate the ion sound velocity given by the equation $\omega/k_z = [(n_1 c_{s1}^2 + n_3 c_{s3}^2)/(n_1 + n_3)]^{1/2}$ where $c_{s1}^2 = T_e/M_1$ and $c_{s3}^2 = T_e/M_3$. If the finite Larmor radius effect is taken into account in Eq.(1), the cyclotron harmonic structures will appear in Figs.1 and 2.

The experiment was performed in the TPL machine at the Institute of Plasma Physics, Nagoya University. The two-ion species plasma is produced by the dc discharge at the filling pressure of argon and helium gas mixture of $10^{-5} \sim 10^{-4}$ Torr. The argon- and helium-ion concentrations (n_{Ar} and n_{He}) are varied by controlling the partial neutral pressure, and measured by a combined spectroscopic-Langmuir probe technique[4]. The plasma density ($10^9 \sim 10^{11}$ cm^{-3}) is uniform along the magnetic field ($B = 1000$ G) and $T_e = 2.2$ eV $\gg$ the ion temperature. The radius and the length of the plasma column are about 5 cm and 300 cm, respectively. The wave exciter[9)] is composed of 4 molybdenum plates of 5 cm long and 2 cm wide and is set at the radial position near the maximum density gradient, as shown in Fig.3(a). The wave is excited externally by applying sinusoidal voltage to each electrodes of the exciter in the azimuthal mode $m = 1$ or $m = -1$. The phase and amplitude of the wave are measured by an interferometer system. The radial profile of the wave amplitude is shown in Fig.3(b), together with the density profile. The wave phase rotation in the azimuthal direction is confirmed by measuring the axial interferometer patterns at the azimuthal angles different by $\pi/4$ each other. Figure 3(c) shows that the wave phase rotates in the direction of electron gyromotion, in coincidence with the excitation mode of $m = 1$.

Changing the wave frequency (10 ∿ 200 kHz) under the constant magnetic field, we obtained the axial interferometer traces to get the parallel wavelength. The measured dispersion relations for $m = 1$ and $m = -1$ are plotted for $\omega/\Omega_{Ar} \lesssim 2$ in Fig.4, with the measured ion concentration ratio as a parameter. Solid lines indicate the theoretical curves given by Eq.(2) where the density gradient parameters, κ_{Ar} and κ_{He}, are assumed the same value (-2.2 cm^{-1}). Experimental points for $\omega/\Omega_{Ar} \lesssim 1$ show that the mode of $m = -1$ exhibits a simple resonance at $\omega = \Omega_{Ar}$, while the mode of $m = 1$ demonstrates a cutoff-like behavior just below Ω_{Ar}. Thus, the $m = 1$ mode is ICDW, i.e., the coupled wave between a drift wave and a cyclotron wave.

The discrepancy between the measurements and the calculations may come from some assumptions in the theory ; the slab model, the same density gradient for Ar and He, neglect of the azimuthal rotation of a plasma column due to the $E_r \times B_z$ drift, neglect of collisions, and so on. The difference between $m = -1$ and $m = 1$ is obscured when the heavy minority (argon) concentration is less than 30 %. This is probably because the resonance phenomena at the cyclotron frequency is relaxed by collisions and the dispersion curves are continuously connected[5).

In conclusion, electrostatic waves around the cyclotron frequency have been excited externally in a nonuniform two-ion species plasma. The measured dispersion relation exhbits the characteristic behabiour of ICDW as a result of the coupling between a drift wave and an ion cyclotron wave.

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Figure Captions

Fig.1. Dispersion relations for a single-ion species plasma with v_d/c_s as a parameter. (a) Propagation in the y direction for $k_z = 0$, and (b) propagation in the z direction for $k_y = m/R$ and $R\Omega/c_s = 1.1\ c_s/v_d$. Dashed lines indicate the ion sound velocity ($\omega/k_z = c_s$).

Fig.2 Dispersion relations for a two-ion species plasma with the ion concentration ratio $n_3/(n_1 + n_3)$ as a parameter. Mass ratio M_3/M_1 ($= \Omega_1/\Omega_3$) $= 3$, the suffix denotes the ion species, and $R\Omega_1/c_{s1} = 2.71$.

Fig.3 (a) Experimental arrangement, (b) radial profiles of plasma density and excited wave amplitude, and (c) axial interferometer traces measured at different azimuthal positions. $m = 1$, $\omega/2\pi = 60$ kHz, $B = 300$G, and $n_{Ar}/(n_{Ar} + n_{He}) = 0$.

Fig.4 Experimental and theoretical curves of dispersion relations for $m = 1$ and $m = -1$, with relative concentration of argon ion, n_{Ar}/n_e ($n_e = n_{Ar} + n_{He}$), as a parameter $v_d/c_{sAr} = 0.21$ and $R = 5$ cm.

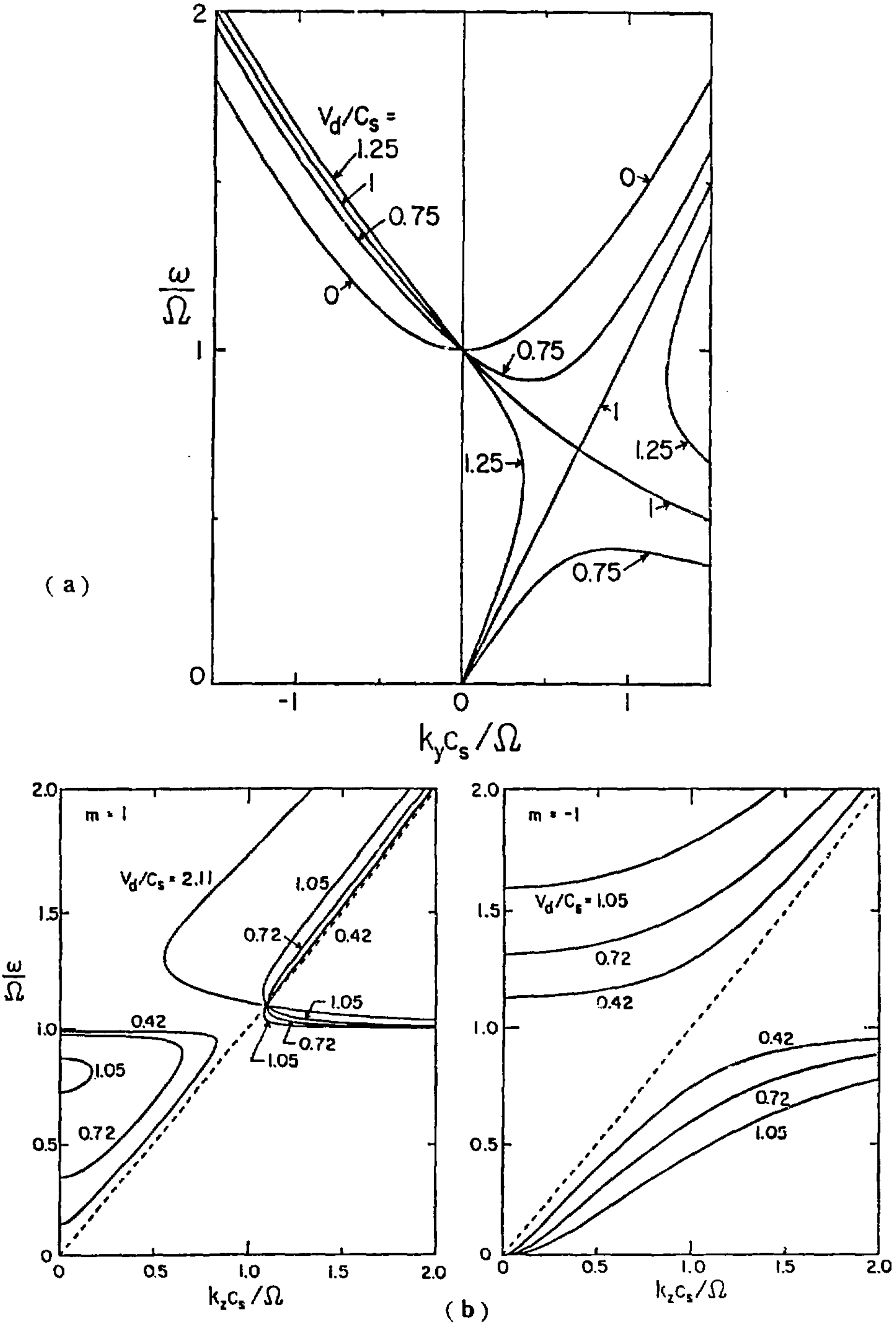

(a)
ω/Ω
2
1
0
-1
0
1
k_y c_s/Ω
V_d/C_s =
1.25
1
0.75
0
0
0.75
1
1.25
1.25
1
0.75
(b)
m = 1
V_d/C_s = 2.11
1.05
0.72
0.42
0.42
1.05
0.72
1.05
0.72
1.05
ω/Ω
2.0
1.5
1.0
0.5
0
0
0.5
1.0
1.5
2.0
k_z c_s/Ω
m = -1
V_d/C_s = 1.05
0.72
0.42
0.42
0.72
1.05
2.0
1.5
1.0
0.5
0
0
0.5
1.0
1.5
2.0
k_z c_s/Ω

Fig. 1

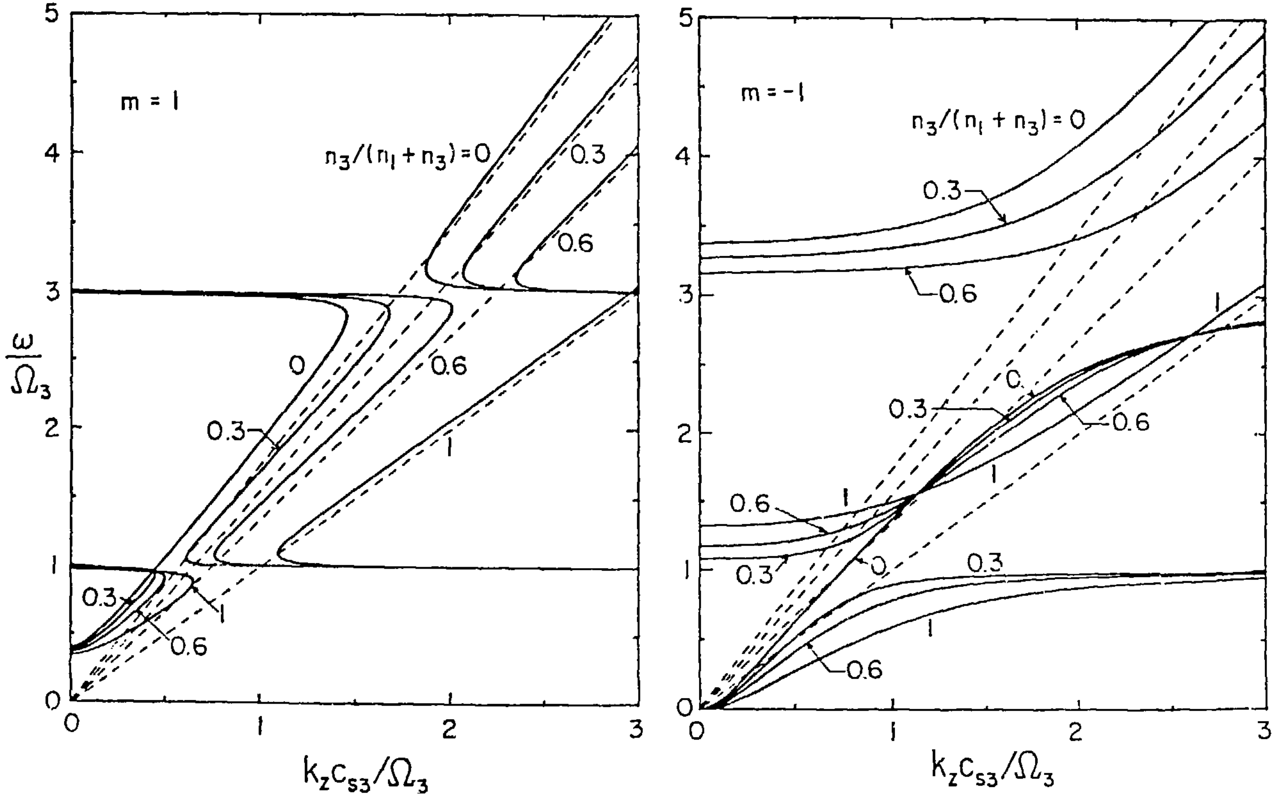
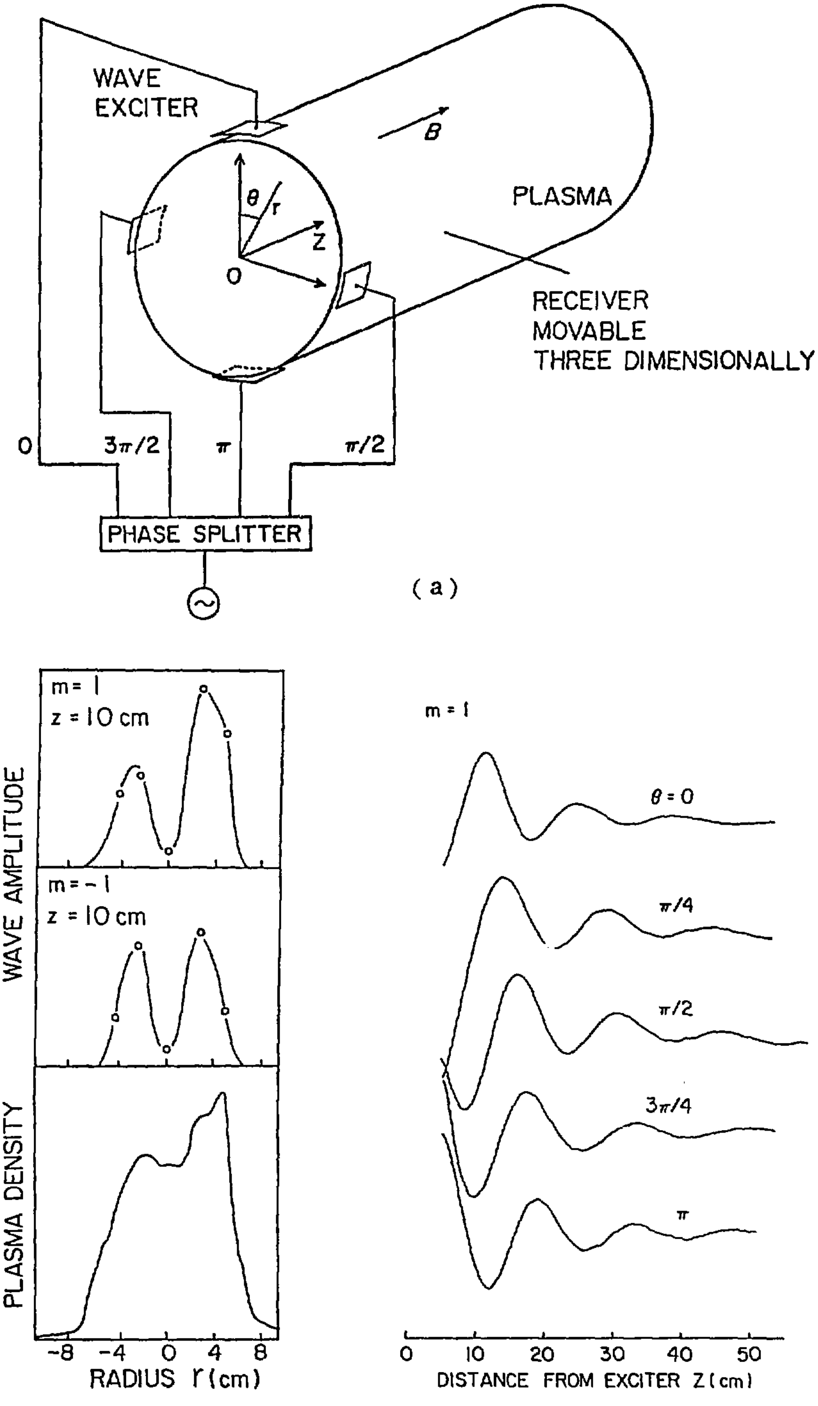


Fig. 2


WAVE EXCITER
B
θ
r
Z
O
PLASMA
RECEIVER MOVABLE THREE DIMENSIONALLY
0
3π/2
π
π/2
PHASE SPLITTER
(a)
m = 1
z = 10 cm
m = −1
z = 10 cm
WAVE AMPLITUDE
PLASMA DENSITY
−8
−4
0
4
8
RADIUS r (cm)
m = 1
θ = 0
π/4
π/2
3π/4
π
0
10
20
30
40
50
DISTANCE FROM EXCITER Z (cm)

(b) (c)

Fig. 3

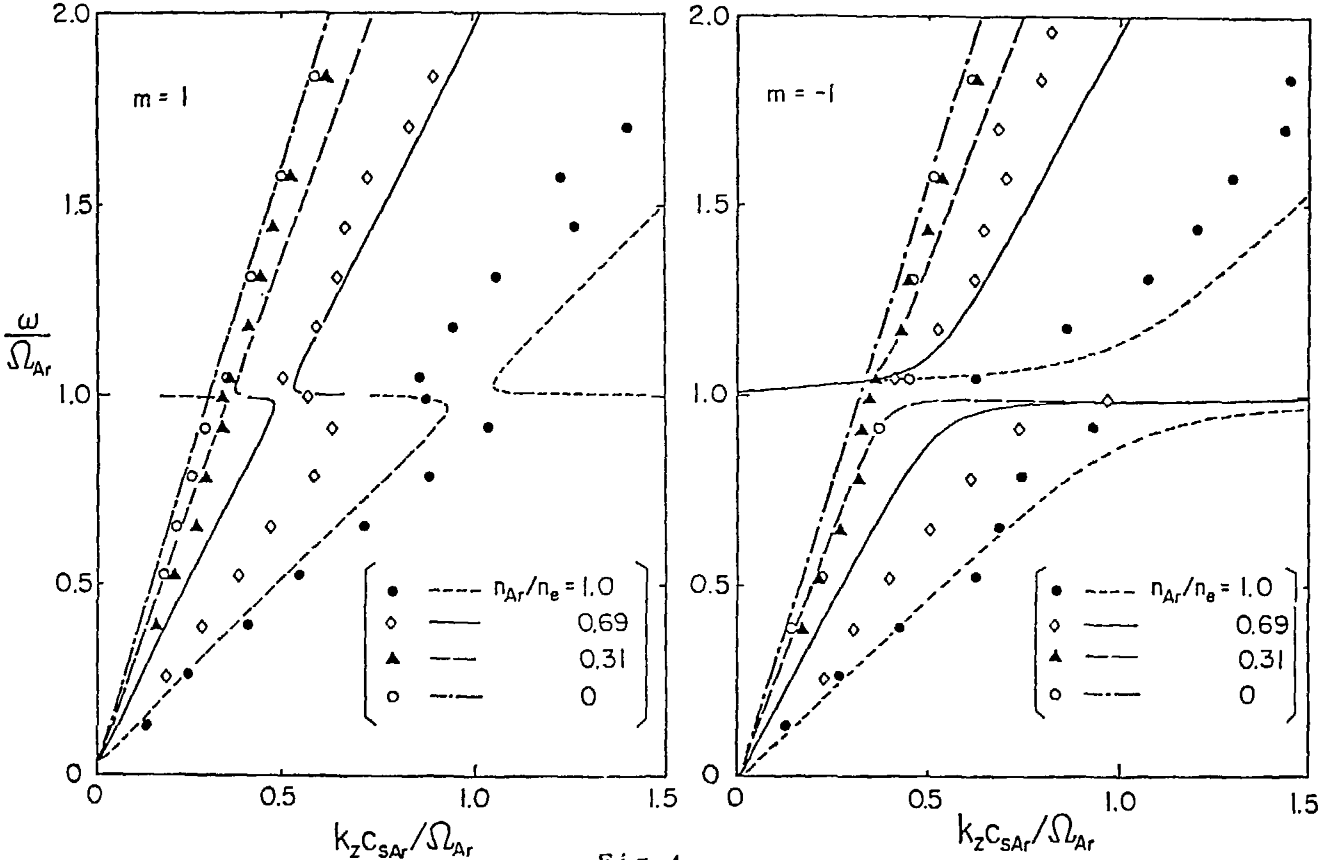

m = 1
m = -1
$\frac{\omega}{\Omega_{Ar}}$
2.0
1.5
1.0
0.5
0
0
0.5
1.0
1.5
$k_z c_{sAr}/\Omega_{Ar}$
● $n_{Ar}/n_e = 1.0$
◇ 0.69
▲ 0.31
○ 0

Fig. 4