Technical Notes

Electrostatic Ion-Cyclotron Waves in a Two-Ion Component Plasma

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***Abstract*—The excitation of electrostatic ion-cyclotron (EIC) waves is studied in a single-ended Q machine in a two-ion-component plasma (Cs^+ and K^+). Over a large range of relative concentrations of Cs^+ and K^+ ions, two modes are excited with frequencies $\omega_1 \gtrsim \Omega_{Cs^+}$ and $\omega_2 \gtrsim \Omega_{K^+}$, where the Ω's are the respective cyclotron frequencies. The results are discussed in terms of a fluid theory of electrostatic ion cyclotron waves in a two-ion component plasma.**

Electrostatic ion-cyclotron (EIC) waves in single-ion component plasmas have been studied for a number of years in the laboratory [1]–[8]. In recent years further work has been motivated by observations in the polar magnetosphere of electrostatic waves with frequencies slightly above the first few harmonics of the H^+ cyclotron frequency [9], [10]. The earth's ionosphere, however, generally contains a mixture of several positive ion species, e.g., H^+, O^+, NO^+, with concentrations varying according to altitude. The problem of EIC wave excitation in such a case was first studied by Kindel and Kennel [11] using the kinetic theory developed earlier by Drummond and Rosenbluth [12]. There have been a few experiments on EIC waves in multi ion-species plasmas. Ono *et al.* [13] studied the parametric excitation of EIC waves in a He^+-Ne^+ plasma. A pump electric field was coupled into the plasma by an external RF oscillator, and the propagation of the resulting decay waves was investigated. Sugai *et al.* [14] launched waves in the ion cyclotron frequency range into a He^+-Ne^+ plasma using an electrostatic antenna. They concentrated their studies on the EIC wave characteristics in the presence of light minority ions with small concentrations (~ 1 percent). One experiment has been performed in which the EIC waves were excited internally by passing a current through a plasma which contained K^+ and Ba^+ ions [15]. This work was mainly concerned with the question of ion heating by EIC waves in a two-ion-species plasma. We report here some preliminary results on EIC wave excitation in a steady-state plasma containing variable concentrations of Cs^+ and K^+ ions.

Our experiments were conducted in a single-ended Q machine [16] in which an alkali metal plasma is produced by contact ionization of cesium or potassium atoms (or both) on a hot tantalum plate ($T_p \approx 2200$K). The plasma column typically has densities in the range $n_e \approx 5 \times 10^9$ cm^{-3}–5×10^{10} cm^{-3}, and temperatures $T_e \simeq T_i \simeq 0.2$ eV, and is confined by a longitudinal magnetic field variable up to about 4 kG. Two independent atomic beam ovens (K and Cs) are used simultaneously to produce plasmas with a mixture of K^+ and Cs^+ ions. Estimates for the individual ion concentrations were obtained by monitoring the change in overall plasma density (using a Langmuir probe) as the neutral atomic flux from only one oven was varied at a time. We are developing a mass spectrometer for more accurate determinations of the ion concentrations to permit detailed studies of the EIC mode excitation as the concentrations are varied.

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The ion-cyclotron instability was excited by drawing an electron current to a small (8-mm diameter) metallic disk (thus with a radius a few times the gyroradius of the heavy-ion species but smaller than the plasma column), located on the axis of the plasma column, biased at a few volts above the plasma potential. This disk is located 8 mm in front of an electrically floating, cold end plate, 88 cm from the hot plate. The instability is detected by observing the fluctuations in the exciter disk current. Typically, EIC wave amplitudes of $\Delta n/n \approx$ 30–40 percent are observed.

The work described in this paper was primarily concerned with the basic question of what type of EIC modes might be expected in a plasma containing roughly comparable (neither component being a small fraction of the total) concentrations of K^+ and Cs^+ ions. Typically, we observe, for example, that as Cs^+ ions are introduced into an initially pure K^+ plasma, there is a relatively large range of Cs^+ concentrations for which both K^+ and Cs^+ modes are observed. As the Cs^+ concentration is further increased, a point is reached when the K^+ modes disappear. A similar behavior is observed starting from a pure Cs^+ plasma. Fig. 1 shows the spectrum of fluctuations of the current to the exciter biased at +0.5 V, under the conditions $B = 2500$ G, $n_e \simeq 2 \times 10^{10}$ cm^{-3}, and roughly 80 percent K^+ and 20 percent Cs^+ ion composition. We identify the two largest spectral peaks (Cs1 and K1) as corresponding to the Cs^+ and K^+ EIC waves which, apparently, are simultaneously excited in the plasma. The second and third Cs^+ EIC wave harmonics are also present. The ratio of the observed frequencies for the K1 mode and the Cs1 is consistent with the inverse ratio of their masses, $\Omega_{K^+}/\Omega_{Cs^+} = M_{Cs}/M_K = 3.4$, where the Ω's are the ion gyrofrequencies. The K^+ and Cs^+ EIC mode frequencies are ~20 percent higher than their corresponding gyrofrequencies of $f_{K^+} =$ 97.4 kHz and $f_{Cs^+} = 28.6$ kHz, at $B = 2500$ G.

A more definitive identification of the EIC modes was made by obtaining a frequency spectrum, as in Fig. 1, for various values of the magnetic field. The observed frequencies versus B are shown in Fig. 2. As can be seen, we are able to track many spectral peaks as the magnetic field is varied. In addition to the individual Cs^+ and K^+ EIC modes, a low-frequency peak labeled f^* is also present which corresponds to the difference between the K1 peak and the Cs3 peak. The combination of this "beat frequency" at around 9 kHz (at 2500 G) with the various Cs^+ and K^+ cyclotron harmonics results in additional spectral peaks at Cs1 + f^*, Cs2 + f^*, and K1 ± Cs1. At present, we have not identified the nature of these additional features in the EIC wave spectrum. We note, however, that these additional peaks are only observed at the lower total plasma densities investigated (~ 10^{10} cm^{-3}). These complex spectra were not observed when the total density was increased by about a factor of 10, even though the relative ion concentrations were similar to those of the case presented here.

In summary, we see that, at least under the conditions discussed above, it is possible to excite independent EIC modes corresponding to each ion component present in the plasma. This result can perhaps be most easily understood on the basis of a simple fluid analysis of EIC waves in a plasma consisting of electrons and two positive ion species. The analysis proceeds along much the same lines as for EIC waves in a plasma containing positive ions, negative ions, and electrons [17]. We use the continuity and momentum equations for the electrons, light ions (L) and heavy ions (H) with a uniform magnetic field $B\hat{z}$. The plasma is taken to be uniform and charge quasi-neutral, $n_e = n_L + n_H$, with cold ions $T_L =$

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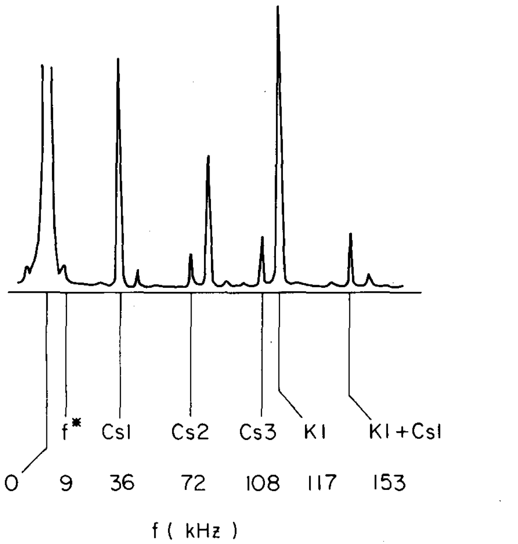

Fig. 1. Power spectrum of EIC wave fluctuations for $B = 2500$ G. Several spectral features are identified. The vertical amplitude scale is linear.

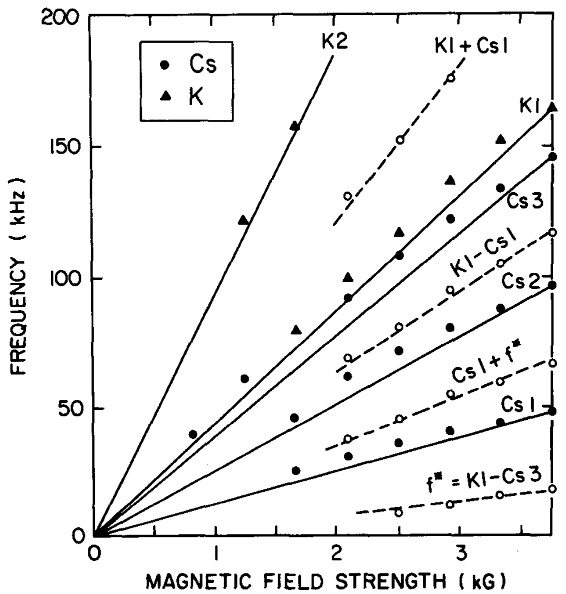

Fig. 2. Frequencies of EIC modes as a function of the magnetic field strength. The solid lines are the Cs^+ and K^+ EIC harmonics. The dashed lines indicate sum and difference modes.

$T_H = 0$. The electrons have a temperature T_e, the electron inertia is neglected, and we consider electron motion only parallel to $\boldsymbol{B}$. We assume the electrons have a uniform zero-order drift $v_{eD}\hat{z}$ relative to the ions and include a resistive term $-\nu_e m_e n_e v_{eD}\hat{z}$ in the electron momentum equation, where ν_e is the electron collision frequency. Performing the usual linearization, we arrive at the dispersion relation

$$\frac{K_z^2}{K_z^2 kT_e - i\nu_e m_e(\omega - K_z v_{eD})} = \frac{\alpha_L K_x^2}{m_L(\omega^2 - \Omega_L^2)} + \frac{\alpha_H K_x^2}{m_H(\omega^2 - \Omega_H^2)} \tag{1}$$

where K_z and K_x are the wavenumbers parallel and perpendicular to $\boldsymbol{B}$, Ω_L and Ω_H are the cyclotron frequencies for the light and heavy ions, α_L is the fraction of light ions, $\alpha_H = (1 - \alpha_L)$ is the fraction of heavy ions, $n_L = \alpha_L n_e$ and $n_H = \alpha_H n_e$. If we take $\omega = \omega_r + i\gamma$ in (1), we obtain expressions for the real frequency

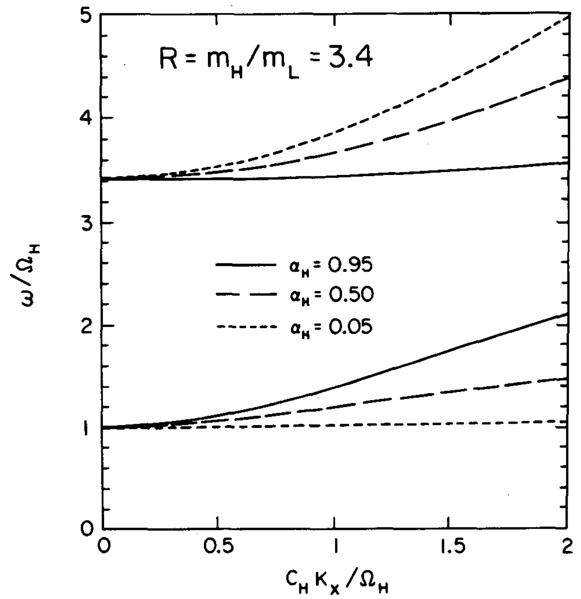

Fig. 3. Dispersion relation for EIC modes in a two-ion plasma with mass ratio 3.4 for various values of the heavy-ion concentration $\alpha_H = 1 - \alpha_L$.

$$\frac{1}{K_x^2} = \frac{\alpha_L C_L^2}{\omega_r^2 - \Omega_L^2} + \frac{\alpha_H C_H^2}{\omega_r^2 - \Omega_H^2} \tag{2a}$$

which can also be written as

$$\left(\frac{\Omega_H}{K_x C_H}\right)^2 = \frac{\alpha_L R}{(\omega_r/\Omega_H)^2 - R^2} + \frac{(1 - \alpha_L)}{(\omega_r/\Omega_H)^2 - 1} \tag{2b}$$

and for the growth rate

$$\gamma = -\frac{1}{2} F\nu_e \frac{m_e}{m_H}\frac{K_x^2}{K_z^2}\left(1 - \frac{v_{eD}}{\omega_r/K_z}\right) \tag{3}$$

where

$$F = \frac{\alpha_L R(\omega_r^2 - \Omega_H^2) + (1 - \alpha_L)(\omega_r^2 - \Omega_L^2)}{(2\omega_r^2 - \Omega_L^2 - \Omega_H^2) - [\alpha_L R + (1 - \alpha_L)]K_x^2 C_H^2}.$$

Here, $C_H^2 = kT_e/m_H$, $C_L^2 = kT_e/m_L$, and $R = m_H/m_L$. The roots of (2b) determine which wave modes are possible and are plotted in Fig. 3 for our particular case, $R = 3.4$, corresponding to a cesium–potassium plasma. The quantity ω_r/Ω_H is shown as a function of the normalized perpendicular wavenumber $C_H K_x/\Omega_H$ for various heavy-ion concentrations α_H. Clearly, two EIC modes are present, one with $\omega_r \gtrsim \Omega_L$ and another with $\omega_r \gtrsim \Omega_H$. We also see that as the light-ion concentration is increased, the wave frequency of the heavy-ion mode moves closer to the heavy-ion gyrofrequency. Similarly, as $\alpha_H (= 1 - \alpha_L)$ is increased, the frequency of the light-ion mode moves closer to Ω_L.

The question of the conditions for growth of the various modes is generally more complicated, but we can get some insight by examining the growth rate given in (3). It can be shown that the factor F in (3) is a positive definite quantity. Thus, the condition for growth, $\gamma > 0$, requires $v_{eD} > \omega_r/K_z$. If the electron drift speed exceeds the parallel phase speed, ω_r/K_z, of the waves, then $\gamma > 0$ and excitation of both modes is apparently possible. A more complete analysis of the excitation of EIC waves in a two-ion-species plasma would require the inclusion of a collisional-damping term (due to ion–ion collisions) in the momentum equations. Such an analysis for single-ion plasmas has been carried out, e.g., by Chaturvedi [18] and Satyanarayana *et al.* [19].

In conclusion, as we have noted earlier, it is possible to simultaneously excite EIC waves at frequencies slightly above the cyclotron frequencies of each ion component in a two-ion-species plasma. The presence of individual EIC modes seems to be in line with the predictions of a simple fluid analysis.

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