Influence of the ion/neutral atom mass ratio on the damping of electrostatic ion-cyclotron waves

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The damping of electrostatic ion–cyclotron waves by ion–neutral collisions was studied in a single-ended Q machine. The amplitudes of K^+ and Cs^+ electrostatic ion-cyclotron waves were measured as a function of neutral pressure in helium, neon, argon, krypton, and xenon. For each ion/neutral atom combination, the electrostatic ion-cyclotron wave amplitude maximizes at a neutral pressure that scales monotonically with the m_+/m_n mass ratio. This result is interpreted by considering the dynamics of elastic collisions between the ions and the neutral atoms.

Electrostatic ion-cyclotron (EIC) waves have been studied in the laboratory for a number of years.[1] The waves have a frequency 10%–15% larger than the ion-cyclotron frequency, propagate nearly normal to the magnetic field, and are excited by biasing a small metallic disk, located on the axis of the plasma column, at a few volts above the space potential.

Drummond and Rosenbluth[2] developed a theory for current-driven EIC waves in a magnetized plasma that is homogeneous and collisionless. However, in recent years a controversy has developed as to whether the waves observed in laboratory experiments are indeed destabilized by supercritical electron drifts along the magnetic field, as envisaged by Drummond and Rosenbluth,[2] or by some other mechanism. We have already presented experimental observations which favor the supercritical electron drift mechanism (see Cartier *et al.* in Ref. 1).

Another important question concerning EIC wave excitation is the role played by collisions. D'Angelo[3] and Chaturvedi[4] have argued that EIC waves could still be excited in a magnetized plasma even when the ion–neutral collision frequency ν_{in} is comparable to the ion-cyclotron frequency ω_{ci}. This work, which is relevant to certain aspects of the physics of the ionospheric E layer, has been substantiated through more detailed calculations by, e.g., Satyanarayana *et al.*[5] and Fejer *et al.*[6]

We have recently reported results on the properties of EIC waves in a Cs^+ plasma in which the ion–neutral collision frequency could be varied over about three orders of magnitude, by varying the pressure of neutral argon gas.[7] Waves with ~5% amplitude could still be observed when $\nu_{in} \simeq 0.3\omega_{ci}$, a result that indicates the possibility of EIC wave excitation in the earth's ionosphere down to altitudes of 120–130 km.

The work described in this paper is concerned with another aspect of the physics of collisions. It was performed in order to investigate systematically the effect of the ratio between the ion mass and the neutral atom mass m_+/m_n on the EIC instability.

Figure 1 shows the wave amplitude $\Delta n/n$ versus neutral gas pressure for two different ion/neutral atom combinations, namely (a) K^+/Ne and (b) K^+/He. As can be seen, in each case $\Delta n/n$ has a maximum at some pressure $p_{\max}$, indicated by an arrow, and then rapidly decreases with increasing pressure. For the case of K^+/Ne, $p_{\max} \simeq 2\times10^{-4}$ Torr, while for the case of K^+/He, $p_{\max} \simeq 6\times10^{-4}$ Torr.

We made similar measurements on EIC waves for a number of ion/neutral atom combinations, which are listed in Table I. The $\Delta n/n$ versus neutral gas pressure curves obtained are all similar to those shown in Fig. 1. However, the $p_{\max}$ for each ion/atom pair depends on the m_+/m_n ratio in the manner shown in Fig. 2. The regularity of these data, for m_+/m_n extending over approximately two orders of magnitude, indicates that m_+/m_n is indeed a good ordering parameter.

The question now arises as to how can data such as those

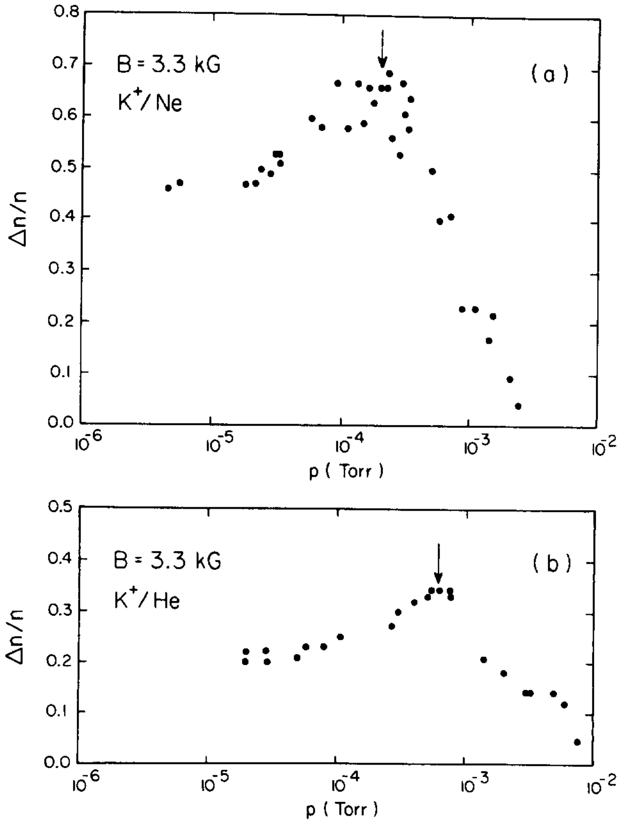

FIG. 1. Electrostatic ion-cyclotron wave amplitude $\Delta n/n$ versus neutral gas pressure. (a) K^+/Ne, (b) K^+/He.

TABLE I. Ion/neutral atom combinations.

Ion/neutral atom	m_+/m_n
K^+/Xe	39/131 = 0.30
K^+/Kr	39/84 = 0.46
K^+/Ar	39/40 = 0.98
Cs^+/Xe	133/131 = 1.02
Cs^+/Kr	133/84 = 1.58
K^+/Ne	39/20 = 1.95
Cs^+/Ar	133/40 = 3.33
Cs^+/Ne	133/20 = 6.65
K^+/He	39/4 = 9.75
Cs^+/He	133/4 = 33.25

presented in Fig. 1, as well as the m_+/m_n dependence of $p_{\max}$ seen in Fig. 2, be understood? We offer the following explanation, which must necessarily be somewhat tentative, as long as the EIC wave destabilization mechanism, in these and similar experiments, remains possibly uncertain.

To deal first with the data of Fig. 1, one may argue that $\Delta n/n$ is a good measure of ion–neutral collisionality (more collisions—smaller $\Delta n/n$) if the excitation strength remains constant throughout the relevant range of neutral gas pressures. Then $p_{\max}$ is essentially an indicator of when wave damping by ion–neutral collisions begins to dominate. That the excitation strength is probably constant can be inferred from the expression for the linear growth rate[4] for collisional EIC waves:

$$\gamma = \gamma_i + \gamma_e = -\frac{1}{2}\nu_i - \frac{1}{2}\nu_e \frac{m_e}{m_+}\frac{K_\perp^2}{K_\parallel^2}\left(1 - \frac{v_{eo\parallel}}{\omega/K_\parallel}\right), \tag{1}$$

where, with reference to our experiments, ν_i represents the ion/atom collision frequency for momentum transfer, and ν_e the combined effect of electron/atom and electron/ion collisions. The first term on the right-hand side of Eq. (1) is always stabilizing, while the second is destabilizing for $v_{eo\parallel} > \omega/K_\parallel$. The quantity $\nu_e = \nu_{en} + \nu_{ei}$ determines the excitation strength. It is important to notice that at plasma densities $n \simeq 5\times10^9$–1×10^{10} cm^{-3} and gas pressures up to $\sim10^{-3}$–10^{-2} Torr, $\nu_{ei} > \nu_{en}$. Therefore, the excitation strength is either independent of gas pressure or, possibly, increases mildly, with increasing pressure, at the largest pressures. For example, a typical mean free path for electron/neutral collisions at $p \simeq 10^{-3}$ Torr may be on the order of a meter, while, at a plasma density of $\simeq 5\times10^9$–1×10^{10} cm^{-3}, the mean free path for electron/ion collisions is 10–20 cm ($T_i \simeq T_e \simeq 0.2$ eV).

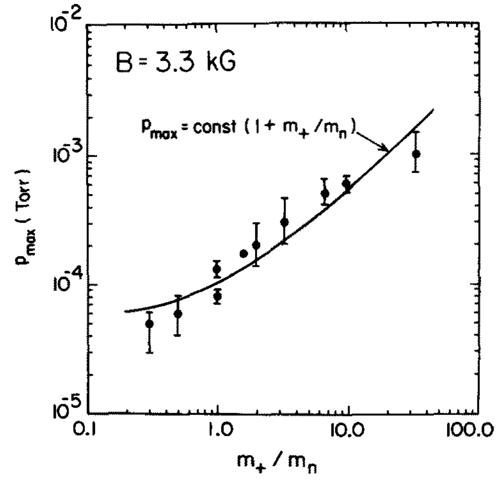

FIG. 2. Pressure of maximum electrostatic ion-cyclotron wave amplitude (determined from measurements as shown in Fig. 1) versus the ion/neutral atom mass ratio. The solid line is the normalized function $p_{\max} = \text{const}(1 + m_+/m_n)$.

We turn, next, to the data of Fig. 2 and to the observed correlation between $p_{\max}$ and m_+/m_n. In a collisional, fluid, treatment of EIC waves, ion–neutral collisions are represented by a loss term $-\nu_i n m_i v_i$ in the ion momentum equation, where $n m_i v_i$ is the ion momentum per unit volume and ν_i is the effective frequency for momentum transfer from the ions to the neutral atoms. The frequency ν_i must be proportional to the neutral gas density N, to the relative ion–neutral velocity v, to the collision cross section σ, and to a dimensionless parameter ξ, which depends on the m_+/m_n ratio and expresses the efficiency of momentum transfer *per collision*. A reasonable choice for ξ appears to be the quantity.

$$\xi = 2/(1 + m_+/m_n), \tag{2}$$

which is generally of the order unity, and represents the percent momentum transfer in a one-dimensional, elastic collision of an ion of mass m_+ with a neutral of mass m_n. For collisions in three dimensions, the relevant parameter is the average ξ

$$\langle \xi \rangle_{\theta_2} = [2/(1 + m_+/m_n)]\langle \cos^2\theta_2 \rangle_{\theta_2}, \tag{3}$$

where θ_2 is the angle formed by the velocity of the neutral atom, after collision, with the initial velocity of the ion.

We can now argue that for each ion/neutral pair in Table I the neutral gas pressure at which wave damping by ion collisions begins to dominate, $p_{\max}$, is determined by $\nu_i = N\sigma v\xi$, all the $p_{\max}$'s occurring at nearly the same value of ν_i. This seems plausible enough from Eq. (1) for the growth rate. With $\nu_{en} < \nu_{ei}$, $\nu_e \simeq \nu_{ei}$ is independent of either the gas pressure p, or the mass ratio m_+/m_n. In addition, it is also easily seen that $(K_\perp^2/K_\parallel^2)(m_e/m_+)$ has, at most, only a weak dependence on m_+. Therefore, γ_e is essentially independent of both p and m_+/m_n. We are thus led to the "collisionality" condition $(p_{\max}\cdot\xi)(\sigma v) \simeq$ const. Finally, that the product σv should be relatively independent of the particular ion/neutral pair used in a given experiment, can be inferred from the fact that

$$\sigma v \simeq 2\pi e\sqrt{1/m_+ + 1/m_n}\,\sqrt{\alpha}, \tag{4}$$

where α stands for the polarizability of the gas atom.[8] If we use the values of α for He, Ne, Ar, Kr, and Xe given in Hasted,[9] we find that σv does not vary from one ion/neutral pair to another, among those used in Fig. 2, by more than a factor 2. We thus obtain the more useful relation $p_{\max} = \text{const}(1 + m_+/m_n)$, which appears to fit well the data in Fig. 2.

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Low-frequency azimuthally propagating (diocotron) waves in a non-neutral electron beam column

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Naturally occurring and externally driven stable low-frequency (6–500 kHz) oscillations have been observed for an electron beam column. Experimental data are presented for oscillations of 357 kHz (natural) and 181 kHz (driven). Phase shift measurements using six azimuthal probes spaced 60° apart show that the oscillations correspond to $l = 1$ diocotron waves.

Magnetohydrodynamic (MHD) theories[1–6] predict diocotron modes in cylindrical non-neutral electron plasma columns. Oscillations that result from these modes observed in a pulsed non-neutral column were not found in a similar pulsed neutral column.[7] Theories[4–6] show that the $l = 1$ azimuthal mode can exist in (solid or hollow) non-neutral columns (with no internal conducting cylinders). The $l = 1$ mode frequency relationship in all of these theories is given by

$$\omega \propto \omega_{pe}(\omega_{pe}/\Omega_e)(R_p/R_c)^2 \propto (n/B)(R_p/R_c)^2, \tag{1}$$

where n is the electron density, B is the magnetic field, R_p and R_c are the radii of the column and the conducting wall, respectively, and ω_{pe} and Ω_e are the electron plasma and the electron cyclotron frequencies, respectively. Accordingly, 5–500 kHz $l = 1$ oscillations should exist. The lowest observed frequency reported by others was about 200 kHz,[8] and no data were given to show an $l = 1$ structure.

A stable electron beam is generated using the apparatus shown in Fig. 1. Two coils provide the steady-state confining magnetic field. The injector consists of a thermionic emitter located about 1 cm from a stainless steel sheet, which, along with the filament, is oriented parallel to the confining magnetic field. The emitter potential can be varied from 0 to -3 kV. Emitted electrons $\mathbf{E}\times\mathbf{B}$ drift to the center region of the apparatus, then travel vertically upward or downward. The magnetic field provides both drift and confinement. A Faraday cup is used to monitor the beam current, which was observed to vary as the mechanical beam cutter moved through the beam in a plane normal to the beam axis. Beam cross sections were measured using the phosphor (ZnS:Ag) screen.

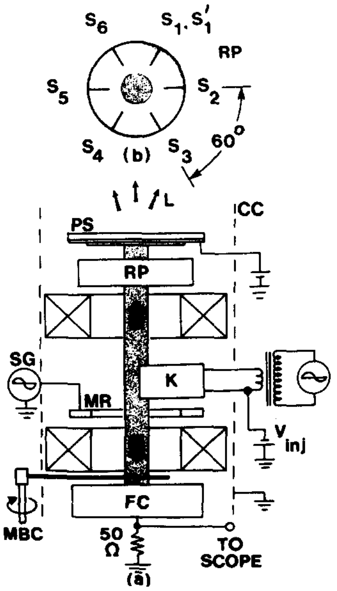

FIG. 1. Schematic of experimental apparatus (not to scale). The device is operated in the 10^{-6}–10^{-7} Torr range. (a) Side view. PS: ZnS:Ag screen (13.3 cm diam), RP: radial probe assembly (10.2 cm diam), CC: conducting cylinder (47.0 cm diam), K: $\mathbf{E}\times\mathbf{B}$ injector (3.0 cm × 1.5 cm), SG: signal generator, FC: Faraday cup (inner probe diam: 8.5 cm; outer case diam: 14.0 cm), MR: metal ring (10.2 cm inner diam; 12.0 cm outer diam), MB: mechanical beam cutter, and L: emitted light. The vertical space between the bottom of the upper coil and the top of the lower coil is about 8 cm. Each coil is 5.2 cm in height and has an outer diameter of 20.0 cm and an inner diameter of 12.0 cm. The coil currents are supplied by a dc source. (b) Top view of seven radial electrostatic needle probes and beam cross section. Probe S_1' is located 2.0 cm directly below probe S_1. The probes are positioned radial to the beam, and lie in a plane normal to the beam axis.