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A Laboratory Study of Collisional Electrostatic Ion Cyclotron Waves

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The effects of neutral-particle collisions on current-driven electrostatic ion cyclotron (EIC) waves are studied in a Q machine with a cesium (Cs^+) plasma. We find that even when $\nu_{in} \approx 0.3\Omega_{ci}$, EIC waves of substantial amplitude ($\Delta n/n$ of several percent) can be excited.

Electrostatic ion cyclotron (EIC) waves have been observed in laboratory plasmas [*D'Angelo and Motley*, 1962] and in the polar magnetosphere near one earth radius [*Bering et al.*, 1975; *Kintner et al.*, 1978]. *Drummond and Rosenbluth* [1962] showed that in an isothermal ($T_e = T_i$) collisionless plasma, these waves are excited if a relative drift v_D of the order of $\sim 10 v_{i,th}$ is present along a homogeneous magnetic field. *Kindel and Kennel* [1971] discussed the relevance of the EIC instability to the upper (collisionless) ionosphere and concluded that the field-aligned currents observed there were sufficient to destabilize ion cyclotron waves. EIC waves are important, since they are expected to produce substantial perpendicular (to **B**) ion heating, as has been observed in laboratory devices [*Dakin et al.*, 1976; *Correll et al.*, 1977]. This EIC wave-induced perpendicular heating has been considered as a possible mechanism which leads to the formation of ion conics [e.g., *Kintner et al.*, 1979; *Ungstrup et al.*, 1979; *Cartier et al.*, 1986].

Recently, there have been observations of apparent electrostatic ion cyclotron waves at much lower altitudes in the collisional ionosphere. These include ground-based photometric observations of pulsations in auroral brightness [*Martelli et al.*, 1977], sounding rocket measurements in the diffuse aurora [*Bering*, 1983, 1984], and auroral radar backscatter observations [*Fejer et al.*, 1984]. The possibility that EIC waves might be excited in a strongly collisional regime and account for the "type III" spectrum of the radar aurora was discussed by *D'Angelo* [1973]. *Chaturvedi* [1976] presented calculations, based on a fluid theory, showing that the field-aligned currents in the auroral *E* region may be strong enough to excite long-wavelength ion cyclotron waves, even though $\nu_{in} \sim \Omega_{ci}$, where ν_{in} is the ion-neutral collision frequency and Ω_{ci} is the ion gyrofrequency. Although ion-neutral collisions have a stabilizing effect, the electron-neutral collisions are destabilizing, since they impede the electrons from moving "instantaneously" along the **B** field to neutralize the perturbed ion density in the wave. More recently, *Satyanarayana et al.* [1985] carried out the full kinetic theory of the collisional ion cyclotron instability, which, of course, is not restricted to the long-wavelength limit of the fluid picture. They showed that the electron collisions are crucial for the excitation of EIC waves in the bottomside ionosphere.

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In this paper we present results from a laboratory study dealing with the effects of neutral collisions on the electrostatic ion cyclotron instability. Our investigation focuses on the question of how far down in the auroral ionosphere one might expect to observe the EIC waves for a given value of the field-aligned current.

The results were obtained in a Q machine [*Motley*, 1975] shown schematically in Figure 1. A Cs^+ plasma is produced by contact ionization of cesium atoms on a hot tantalum plate ($T_p \approx 2200$°K). At pressures of $\sim 10^{-6}$ torr, the plasma is very highly ionized, with a density $n_e \approx 10^9$–10^{10} cm^{-3} and electron and ion temperatures $T_e \approx T_i \approx 0.2$ eV (Coulomb collision frequencies: $\nu_{ei} \approx 2 \times 10^5$ s^{-1} and $\nu_{ii} \approx 1 \times 10^3$ s^{-1}), and is confined radially in the main chamber by a longitudinal magnetic field variable up to 5 kG. The plasma is terminated on a cold, electrically floating end plate which is 88 cm from the hot plate. Separate pumping systems for the hot plate heating region and the plasma region were used to allow introduction of inert gases (argon or helium) in the plasma. The neutral gas pressure in the main chamber could be varied from $\sim 5 \times 10^{-6}$ torr to $\sim 10^{-2}$ torr.

The ion cyclotron instability was excited by drawing an electron current to a 8.0-mm-diameter metallic disk located on-axis 8 mm in front of the end plate. The instability could be detected by monitoring either the fluctuations in the exciter current itself or the density fluctuations on various movable Langmuir probes. Typically, the EIC waves are excited at a current density $j_e \approx 5 \times 10^{-4}$ A/cm^2, corresponding to an average parallel electron drift velocity $v_{De} = j_e/en_e \approx 10 v_{i,th}$, for densities $n_e \approx 10^{10}$ cm^{-3}.

Figure 2 is a plot of the ion cyclotron wave amplitude $\Delta n/n$ versus the neutral argon pressure, as detected on the exciter disk. These data were obtained with $B = 3300$ G ($f_{ci} = \Omega_{ci}/2\pi = 38$ kHz) and at several hot plate temperatures. The data points near $\sim 5 \times 10^{-6}$ torr correspond to the case when no argon is admitted into the chamber. With increasing neutral pressure in the range of $\sim 8 \times 10^{-6}$ torr up to $\sim 3 \times 10^{-4}$ torr, the $\Delta n/n$ values increase from $\sim$30% to 50–60%. Above $\sim 3 \times 10^{-4}$ torr the EIC wave amplitude decreases, although appreciable $\Delta n/n$ values (5–10%) are still present at pressures of 5×10^{-3} torr.

We made several tests to insure that the "collisional" EIC waves have the same general properties as the "noncollisional" EIC waves. For example, as the pressure is increased, the waves continue to propagate radially outward from the current channel with a frequency slightly in excess of f_{ci}. In the collisional case, however, the EIC wave frequency appears to have a weak dependence on the

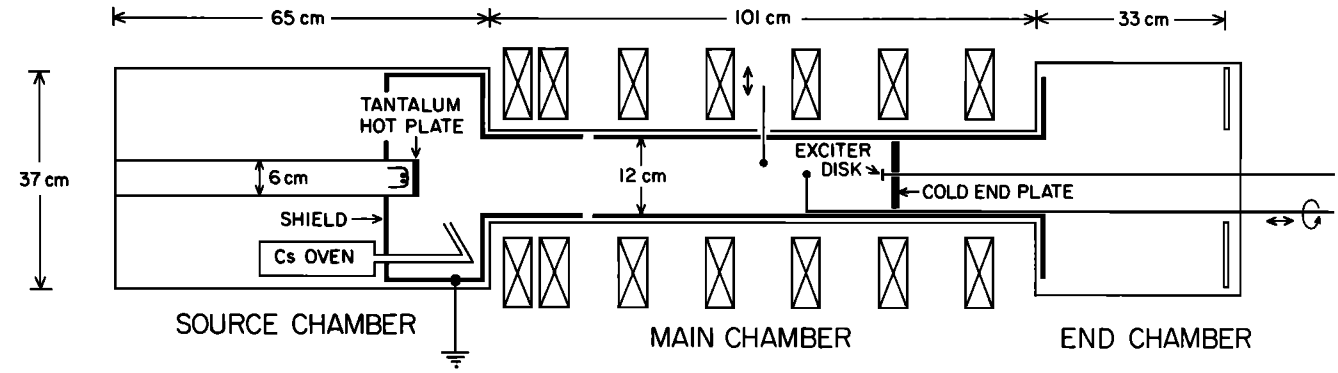

Fig. 1. Schematic diagram of the experimental apparatus (Q machine). EIC waves are produced by drawing an electron current to the exciter disk (8.0 mm). Argon gas is admitted to the main chamber to study the effects of collisions on the EIC waves.

pressure, as shown in Figure 3. Over the full range of neutral pressures investigated the frequency changed, however, by less than 10%. In a second test, at an argon pressure of 7×10^{-4} torr, we observed that the wave frequency increased with increasing field strength, in the same manner as for noncollisional EIC waves.

We estimate that at neutral pressures of $\sim 5 \times 10^{-3}$ torr the ion-neutral (Cs^+-Ar) and the electron-neutral (e-Ar) collision frequencies are

$$\nu_{in} = N\sigma_{in}v_{i,th} \approx (2 \times 10^{14}\ \text{cm}^{-3})(10^{-14}\ \text{cm}^2) \cdot (4 \times 10^4\ \text{cm/s}) \approx 80\ \text{kHz}$$

$$\nu_{en} = N\sigma_{en}v_{e,th} \approx (2 \times 10^{14}\ \text{cm}^{-3})(3 \times 10^{-17}\ \text{cm}^2) \cdot (2 \times 10^7\ \text{cm/s}) \approx 120\ \text{kHz}$$

where N is the neutral argon density, σ_{in} is the ion-neutral collision cross section [*Doucet et al.*, 1969; *Hasted*, 1972], σ_{en} is the electron-neutral collision cross section [*Brown*, 1967], and $v_{e(i),th}$ is the electron (ion) thermal speed. Evidently, the ion cyclotron waves continue to be excited and reach amplitudes of at least several percent at values of the neutral pressure where $\nu_{in}/\Omega_{ci} \sim 0.3$. These results, obtained in a cesium (Cs^+) plasma, imply, for the ionospheric case, that O^+ EIC waves should be present, given sufficiently intense field-aligned currents, down to the 125-km level (using collision frequencies as given by, for example, *Valley* [1965]). Furthermore, the data in Figure 2 would also suggest that the largest O^+ EIC wave amplitudes would occur at about 170 km. These conclusions appear to be in general agreement with theoretical calculations [e.g., *Satyanarayana et al.*, 1985; *Providakes et al.*, 1985] as well as with the ionospheric observations [*Bering*, 1983, 1984].

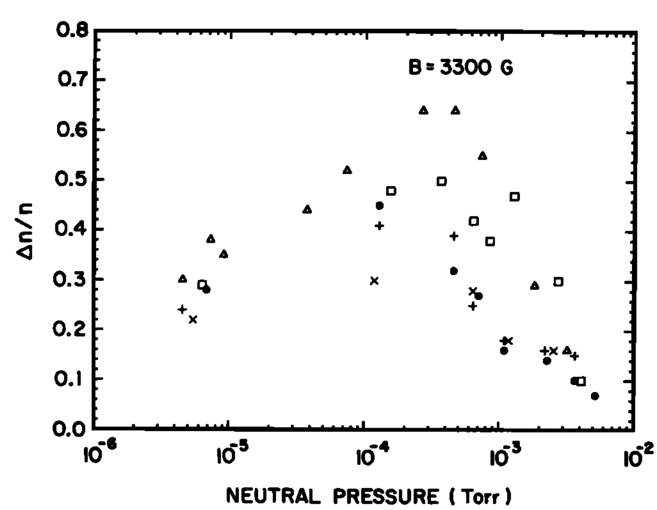

Fig. 2. EIC wave amplitude $\Delta n/n$ versus the neutral argon pressure, measured under different ionizer hot plate temperatures. In this case, B = 3300 G and $\Omega_{ci} = 2\pi \times 38$ kHz.

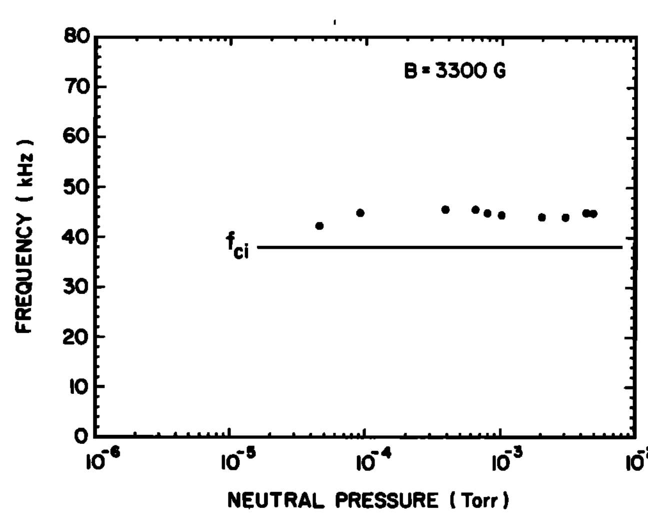

Fig. 3. EIC wave frequency versus neutral argon pressure. The straight line is the ion cyclotron frequency for B = 3300 G.

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