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Laboratory Observations of Ion Cyclotron Waves Associated With a Double Layer in an Inhomogeneous Magnetic Field

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Observations of coherent electrostatic ion cyclotron (EIC) waves associated with a strong, magnetized double layer are presented. The double layers are produced in a weakly ionized argon plasma by applying a positive potential to an electrode plate located in the diverging magnetic field region of a cylindrical plasma column. Ionization within the electrode sheath is essential to the formation of these double layers. The resulting V-shaped potential structures have extended parallel, oblique and perpendicular (to **B**) electric field components. The frequency of the ion cyclotron instability is dependent upon the magnetic field strength at the position of the parallel potential structure. The properties of EIC waves in the presence of the double layer are discussed in relation to the possible excitation mechanisms (field-aligned currents, ion and electron beams, and perpendicular **E** fields).

1. INTRODUCTION

Recently, there has been considerable interest in plasma potential structures called double layers, particularly in regard to the presence of parallel electric fields in the auroral region (see, e.g., *Shawhan et al.* [1978]). The existence of double layers in the earth's ionosphere and magnetosphere was first suggested from satellite measurements of strong electric fields at $\sim 1\ R_E$ [*Mozer et al.*, 1977]. Their existence has also been inferred from the energy distribution functions of upstreaming ions and precipitating electrons [e.g., *Kan and Lee*, 1981]. Generally, these potential structures appear to have regions where the electric field is either predominantly parallel or perpendicular to the magnetic field. The parallel electric fields accelerate positive ions upward and electrons downward toward the earth where they give rise to increased auroral activity.

The first definitive observations of magnetic field-aligned electric field structures in the auroral plasma (6000–8000 km) were reported by *Temerin et al.* [1982]. These double layers differed from the electrostatic shocks previously reported by *Mozer et al.* [1977] in that the electric field amplitudes were much smaller, the duration was shorter, and they were predominately field aligned rather than perpendicular. The presence of double-layer-like structures in the auroral regions at much lower altitudes (585 km) have also been recently reported [*Kellogg et al.*, 1984].

In the regions where electric potential structures have been observed, there have also been associated observations of coherent electrostatic ion cyclotron (EIC) waves with frequencies near the fundamental and first few harmonics of the hydrogen cyclotron frequency [*Mozer et al.*, 1977]. In the recent observations of *Temerin et al.* [1982], EIC waves were always present within a few seconds of all double layer occurrences. The EIC waves have also been associated with the presence of energetic upstreaming H^+ and O^+ ions [*Sharp et al.*, 1977; *Kintner et al.*, 1978], and it has been suggested [*Ungstrup et al.*, 1979] that EIC waves may be the initial perpendicular energetization mechanism for the production of ion conics. Alternately, *Borovsky* [1984] has argued that the ion conic distributions may be the direct result of the interaction of ions with oblique double layers.

Since the initial observations of EIC waves, there has been much discussion concerning possible free-energy sources needed to drive the waves. *Kintner et al.* [1979] considered the possibility that either an electron drift or upstreaming ions (ion beams) were the source of free energy for the EIC waves observed from S3-3 satellite data. In a statistical study of the S3-3 data, *Cattell* [1981] concluded that an unambiguous identification of the free-energy source for the waves observed by *Kintner et al.* [1979] was not possible, and the waves could be driven by a combination of ion beams and electron drifts (field-aligned currents). In subsequent work, *Kaufmann and Kintner* [1982] concluded that many features of the S3-3 data could be understood if the observed EIC waves were being driven by ion beams rather than by cold drifting electrons. This view is supported by a recent theoretical and numerical analysis of *Okuda and Nishikawa* [1984]. However, *Bergmann*'s [1984] results indicate that the relative importance of the two processes is sensitive to the temperature regime, and that in the regime $T_e \sim T_i$, the current-driven ion cyclotron instability modified by the presence of an ion beam appears to be the most likely mechanism for explaining the S3-3 wave data. In the 150–300 km diffuse auroral region, *Bering* [1984] observed EIC waves which appear to be due to a field-aligned energetic electron beam, since in this region the parallel current density corresponded to a drift velocity of the bulk electrons far below the threshold for EIC wave generation.

Laboratory double layers have been generated in a magnetic field in various ways: by applying a positive voltage between two plasma sources [e.g., *Hatakeyama et al.*, 1983], by applying a voltage to an anode electrode in a plasma [*Torvén and Andersson*, 1979], or by injecting an ion beam [*Stenzel et al.*, 1981] or an electron beam [*Jovanović et al.*, 1982] into a plasma. Observations of low-frequency fluctuations associated with the double layers usually are limited to fluctuations of the position of the double layer itself [*Torvén and Lindberg*, 1980]. *Sato* [1982] was the first to report observations of ion cyclotron fluctuations associated with double layers. He suggested that the two-dimensional double layer potential structure was crucial to the excitation of ion cyclotron waves. *Jovanović et al.* [1982] produced a three-dimensional double layer by injecting a 30 eV electron beam into a fully ionized cesium plasma, but no oscillations in the ion cyclotron frequency range were observed. Similar laboratory studies of electrostatic ion cyclotron waves and associ-

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ated potential structures were performed by Böhmer and Lang in the Irvine *Q* machine [*Böhmer and Lang*, 1981; *Lang and Boehmer*, 1983]. Their measurements were performed in a barium plasma in a uniform *B* field with $T_e \simeq T_i$. They reported observations of weak parallel electric fields and strong perpendicular electric fields when current-driven EIC waves were present. The spatial variation of the potentials occurred over thousands of Debye lengths and were not identified as double layers. Laboratory studies of ion cyclotron waves driven by ion beams have also been carried out by *Böhmer et al.* [1976] and *Yamada et al.* [1977].

In the present paper we report our investigations of the properties of EIC waves associated with a strong ($e\phi/kT_e \approx$ 5–15), three-dimensional, magnetized double layer. The double layers are of the "anode type" as described by *Torvén and Andersson* [1979] and *Andersson* [1981] in which a low rate of volume ionization provides the trapped electron species required to maintain the potential structures. These potential structures are produced in the diverging magnetic field region of a cylindrical argon discharge device, thus giving rise to V-shaped equipotentials. The discharge source produces a plasma with $T_e/T_i \simeq 10$. At the typical magnetic fields and neutral densities used, the electrons are collisionless, $\nu_{en}/\omega_{ce} \ll 1$, while the ions are weakly collisional, $\nu_{in}/\omega_{ci} \lesssim 1$, where $\nu_{e(i)n}$ is the electron (ion) neutral collision frequency and $\omega_{ce(i)}/2\pi$ is the electron (ion) gyrofrequency. Although the role of collisions with neutral particles in sustaining the magnetospheric potential structures (at $\sim 1\ R_E$) is negligible, double-layer-like structures have been observed at ionospheric altitudes [*Kellogg et al.*, 1984] where ionization may be important.

The motivation for performing these laboratory experiments is the need for a better understanding of the possible relationships between the generation of double layers and the excitation and propagation of EIC waves in an inhomogeneous magnetic field. Our preliminary observations have been previously reported [*Merlino et al.*, 1984]. Similar observations have also been reported by *Nakamura et al.* [1984].

In section 2 we describe the experimental apparatus and plasma diagnostic methods. The properties of the double layers and associated electrostatic ion cyclotron (EIC) waves are presented and summarized in section 3. A discussion of these results is given in section 4.

2. Experimental Setup

The experiment was performed in a cylindrical argon plasma discharge device, shown schematically in Figure 1*a*. The device consists of three coaxial chambers with an overall length of 1.5 m. The magnetic field diverges into the larger end chamber with an axial dependence shown in Figure 1*b*. The discharge is produced in the source chamber between a directly heated conical spiral tantalum cathode (7 cm diameter) and a grounded anode mesh. The typical discharge characteristics were: discharge voltage 50–60 V, discharge current 0.5–1.0 A, argon pressure 10^{-4}–10^{-3} torr. This source produces a 5 cm diameter plasma which is confined by a solenoidal magnetic field in the main chamber up to 7 kG. The typical plasma parameters were: $n_e \sim 10^9$–10^{10} cm^{-3}, $T_e \simeq 1$–3 eV, $T_i \simeq 0.2$–0.3 eV.

The plasma density and electron temperature were measured using Langmuir probes. The floating potential of an emissive probe was taken as a measurement of the plasma space potential. The full emissive probe characteristics were taken to check that the floating potential closely approximates the space potential. Extreme care was taken in the construction of the probes to minimize perturbations to the double layer structure, since observations of visible double layer structures revealed the tendency of the double layers to follow large probes. To minimize this disturbance only small probe shafts were used. Typically the Langmuir probes consisted of a 0.8 mm tantalum disk mounted on a 0.2 mm shaft. A similar design was used for the emissive probes with glass-insulated wires supporting a 0.025 mm diameter, 4 mm long tungsten filament. Measurements of the electron energy distributions were made using double-sided Langmuir probes. This probe consists of two tantalum disks mounted back-to-back with a ceramic layer in between. The current-voltage characteristic of each side of the probe is recorded separately. Since in the presence of drifting electrons one probe will be shadowed by the other probe, the direction and energy of the drifting electrons, together with the plasma space potential, can be determined. Probes of a similar construction have been used by *Bering et al.* [1973] and *Guyot and Hollenstein* [1983].

3. Experimental Results

3.1. *Properties of the Double Layer*

Double layer potential structures were generated by applying a positive voltage to the anode plate (11 cm in diameter) located in the diverging magnetic field region of the device. At low anode plate voltages (V_p), a sheath was formed close to the anode plate. When V_p was increased 15.8 V (i.e., the argon ionization potential) above the space potential, the sheath was transformed into a strong double layer. The anode plate currents were $\approx$0.5–1.0 A when the double layers were present. At neutral pressures $\gtrsim 10^{-3}$ torr, the onset of the double layer is accompanied by the appearance of a bluish cone-shaped visible light emission structure due to excitation of the neutral argon atoms by electrons which have been accelerated through the double layer. The boundary of the light-emitting region was slightly inside of (i.e., on the high-potential side) the potential jump of the double layer as determined by comparing the visual observations with the potential measurements. If the anode plate voltage is increased beyond the onset value, the light-emitting structure moves further away from the plate and into the higher **B** field region. A color photograph showing a typical example of this structure is shown in Plate 1. The apex (tip) of the visible cone is just inside the location of the parallel potential jump. The effect of increasing the plate voltage is shown in Figure 2, where the axial potential profiles at $r = 0$ are plotted for various plate bias voltages between 40 V and 60 V. Over this range of applied voltages, the double layer potential jump, $\Delta\phi_{\parallel}$, increases linearly from about 16 V to 30 V. These double layer potentials correspond approximately to $e\Delta\phi_{\parallel}kT_e \simeq 5$–15. This indicates that the double layer potential jump does not appear to be limited to the argon ionization potential (15.8 V). The argon ionization cross section is an increasing function of $\Delta\phi_{\parallel}$, and consequently as V_p is increased more free ions and trapped electrons are produced, and the double layer structure expands axially since the magnetic field prevents radial motion. However, radial ion losses may be an important factor in determining the equilibrium position of the double layer.

Contours of constant potential showing the V-shaped double layer structure are shown in Figure 3. The shape of these potential contours, as well as the light emission structure, appear to follow the diverging magnetic field lines. These double layers are similar to those produced by *Stenzel et al.* [1981] by ion-beam injection; although, our experiments were carried out at higher magnetic field strengths. The width of the potential jump, ΔL, for the parallel, oblique, and perpendicu-

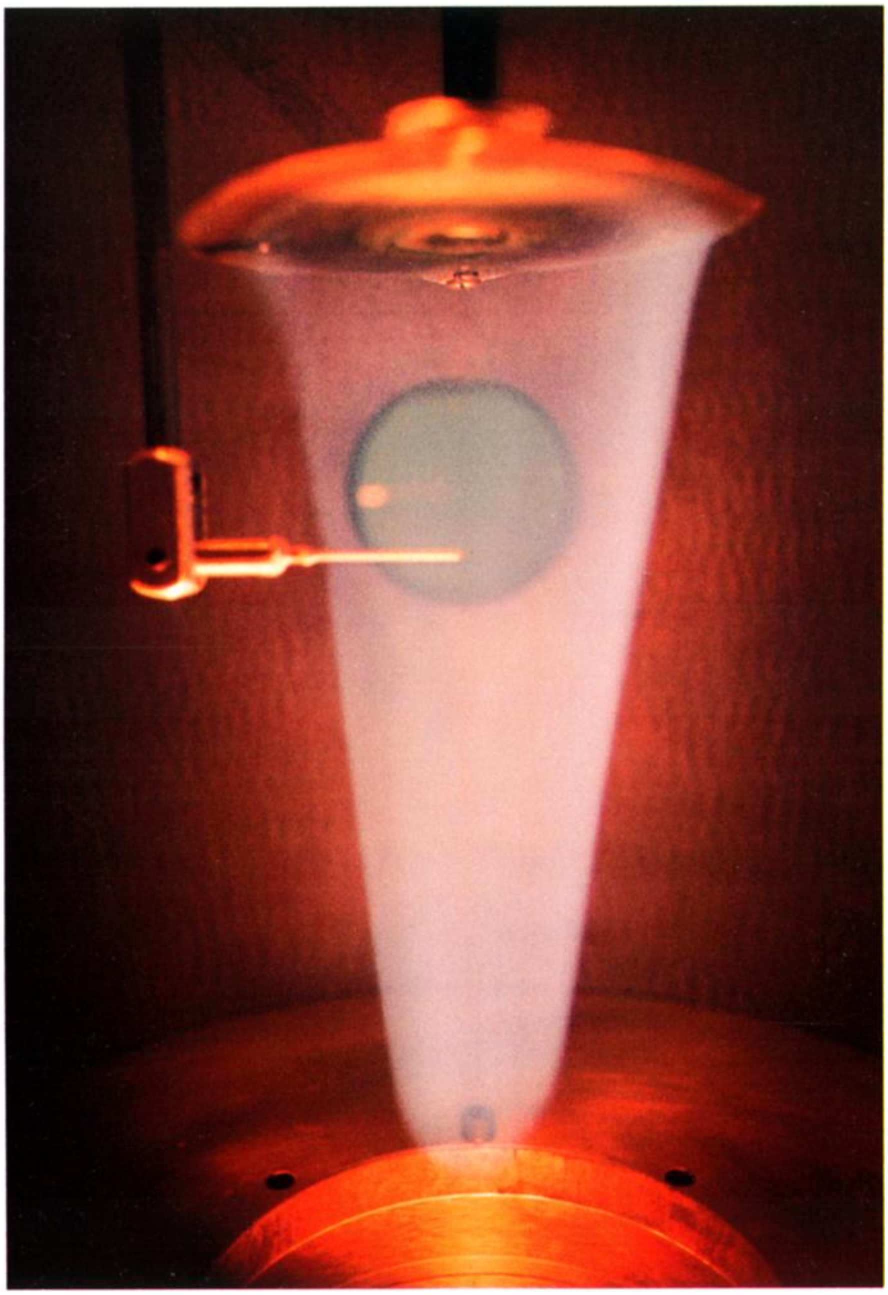

Plate 1. Color photograph of luminous plasma potential structure. The plasma discharge source is to the right in this photograph (see Figure 1*a*). The boundary of the light-emitting region follows the diverging magnetic field lines and lies slightly to the inside of the potential jump. For this photograph the neutral argon pressure was $\sim 3 \times 10^{-3}$ torr.

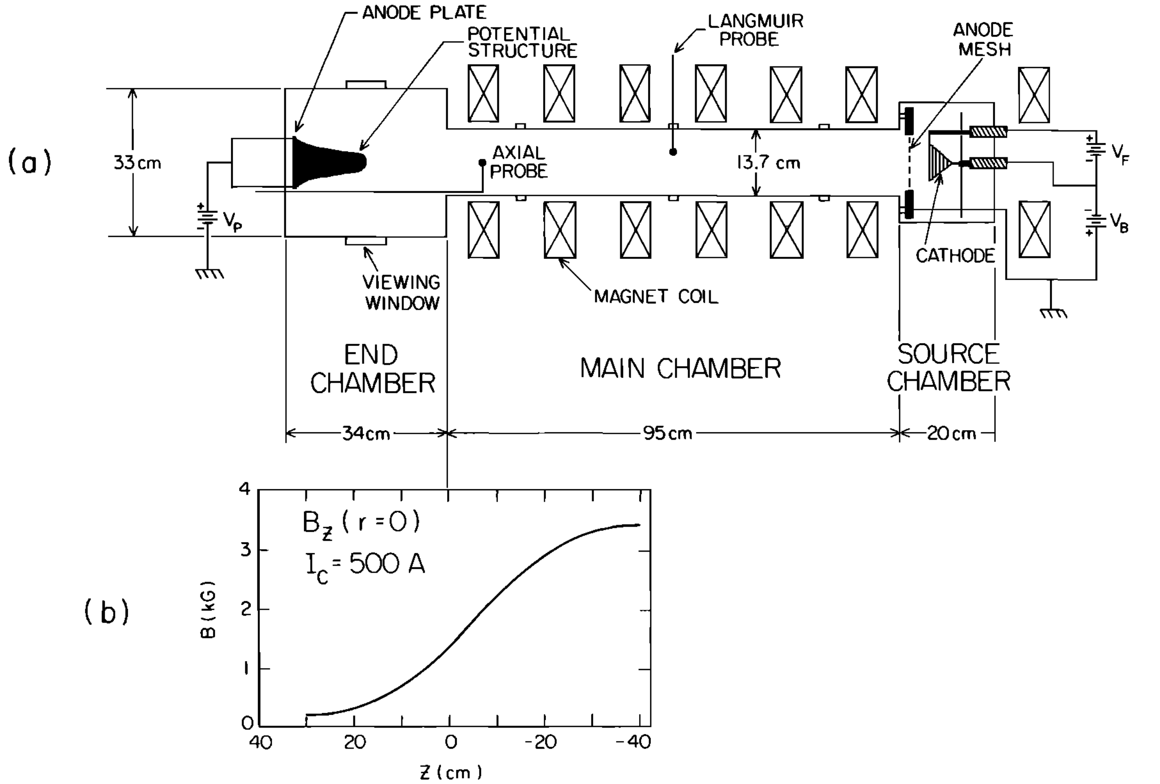

Fig. 1. Schematic of the experimental setup. (*a*) Plasma discharge source and anode plate which is biased to produce the double layer. Inset shows a schematic of the position and shape of the conical double layer structure. (*b*) Axial magnetic field versus z in the end region of the device for a magnet coil current $I_c = 500$ A. $z = 0$ corresponds to the transition between the large end chamber and main chamber.

lar electric fields (relative to B) are $\Delta L_{\|} \gtrsim \Delta L_{\text{obl}} > \Delta L_{\perp} \gtrsim \rho_i$, where ρ_i is the ion gyroradius. The parallel potential width $\Delta L_{\|}$ corresponds approximately to 10–100 electron Debye lengths, i.e., $\Delta L_{\|} \sim (10\text{–}100)\lambda_{\text{De}}$. $\Delta L_{\|}$ also decreases with increasing neutral pressure, consistent with the decrease in λ_{De} due to the increase in electron density as the pressure is increased.

The full two-dimensional spatial profiles of the potential, $\phi(r, z)$, from which the equipotentials of Figure 3 were constructed, are shown in Figure 4. Figure 4 presents a perspective view of the potentials from a vantage point with the anode plate in the upper right-hand corner of the figure. Upstream of the potential jump (for $z < 0$), a potential enhancement around $r = 0$ is observed along the flux tube which maps into the anode plate. A slight potential dip is also evident just to the right of the axis which can also be seen in the equipotential contours of Figure 3.

In the presence of the double layer a large radial density depression is produced along the magnetic flux tubes mapping into the anode plate. Although a small radial density depression was already present in the center along the axis of the plasma column before the double layers were produced, the depression is greatly enhanced when the double layers are present, as shown in Figure 5*a*. This density depression is presumably due to the removal of electrons to the anode plate and may be connected with the potential enhancement along the flux tubes upstream of the double layer. Similar density and potential profiles are observed in Q machines when current is drawn along the axis (see, e.g., *Cartier et al.* [1985]). The current density j_e, measured with the Langmuir probe biased at the plate potential, is shown in Figure 5*b*. Both n_e and j_e were measured about 1 cm in front of the plate. Most of the current flows in a relatively narrow layer just outside the radial position of the perpendicular **E** field of the double layer. The profile of electron drift velocity obtained from $v_{\text{De}} \propto j_e/n_e$ in the current channel is shown in Figure 5*c*. Similar density profiles as that of Figure 5*a* were observed at other axial positions both within the potential structure and upstream of the potential jump. The radial density profiles for zero plate bias (in the absence of double layers) are actually somewhat narrower radially than those with double layers present indi-

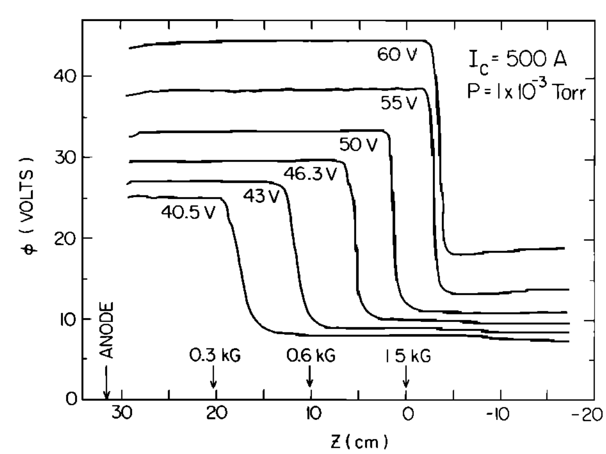

Fig. 2. Axial profile of the plasma space potential for various anode plate voltages with $p = 1 \times 10^{-3}$ torr, and magnetic field coil current $I_c = 500$ A. The magnetic field strengths are shown for $z \simeq 0$, 10, and 20 cm.

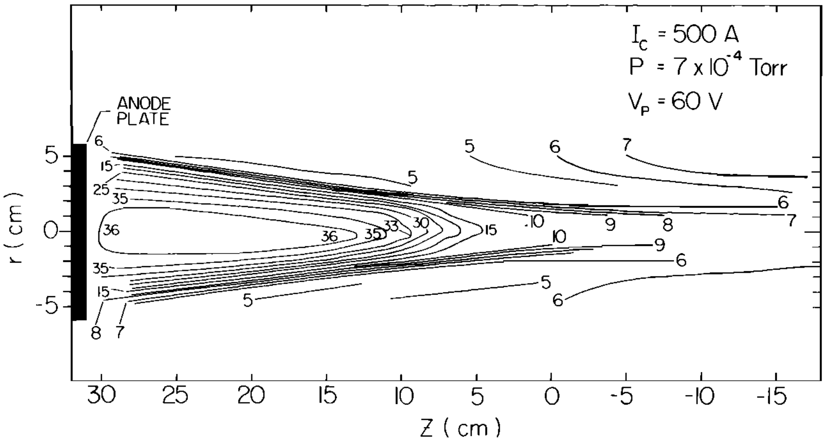

Fig. 3. Two-dimensional (r, z) mapping of equipotential contours. Note that the scale is 1:1. Numerical values of potential (in volts) are shown for various contours. The ion gyroradius varies from $\simeq 0.4$ cm at $z = 10$ cm to $\simeq 1.2$ cm at $z = 30$ cm.

cating radial ion outflow. Large density depressions in the presence of anode-type double layers have also been observed by *Stenzel et al.* [1983] (see their Figure 11) and may be important in establishing the necessary conditions for the formation of the double layer.

The qualitative features of the electron velocity distribution in the presence of the double layer were investigated using the double-sided Langmuir probe described in section 2. When this probe was moved axially through the potential structure a well-defined electron beam of energy corresponding roughly to $e\Delta\phi_{\parallel}$ was observed by the upstream probe on the high-potential side of the double layer, but the beam thermalized by about 15 cm from the double layer with a resulting electron temperature $T_e \approx 10$ eV. Although the mean-free path for ionization, $l_{\mathrm{ionz}} \sim 2$ m for $p \sim 10^{-3}$ torr, and $e\Delta\phi_{\parallel} \simeq 20$ eV, a sufficient number of ions are created within the high-potential side of the double layer so that the quasineutrality condition $n_e \simeq n_i$ is satisfied [*Torvén and Andersson*, 1979]. Electrons accelerated through the double layer will lose energy in ionizing collisions and will be scattered through elastic collisions with the neutrals (the mean-free path for electron-neutral elastic collisions is $l_{en} \sim 5$–10 cm). High-frequency plasma turbulence, presumably due to a beam-plasma instability, was also observed on the high-potential side which could also be a contributing factor in beam thermalization.

3.2. *Ion Cyclotron Waves Associated With the Double Layers*

Coherent low-frequency oscillations associated with the double layer were observed in the spectra of the Langmuir probe electron saturation current and in the oscillations of the anode plate current. A typical spectrum of oscillations observed on a Langmuir probe located within the high-potential region showing strong peaks (20 dB above background) at

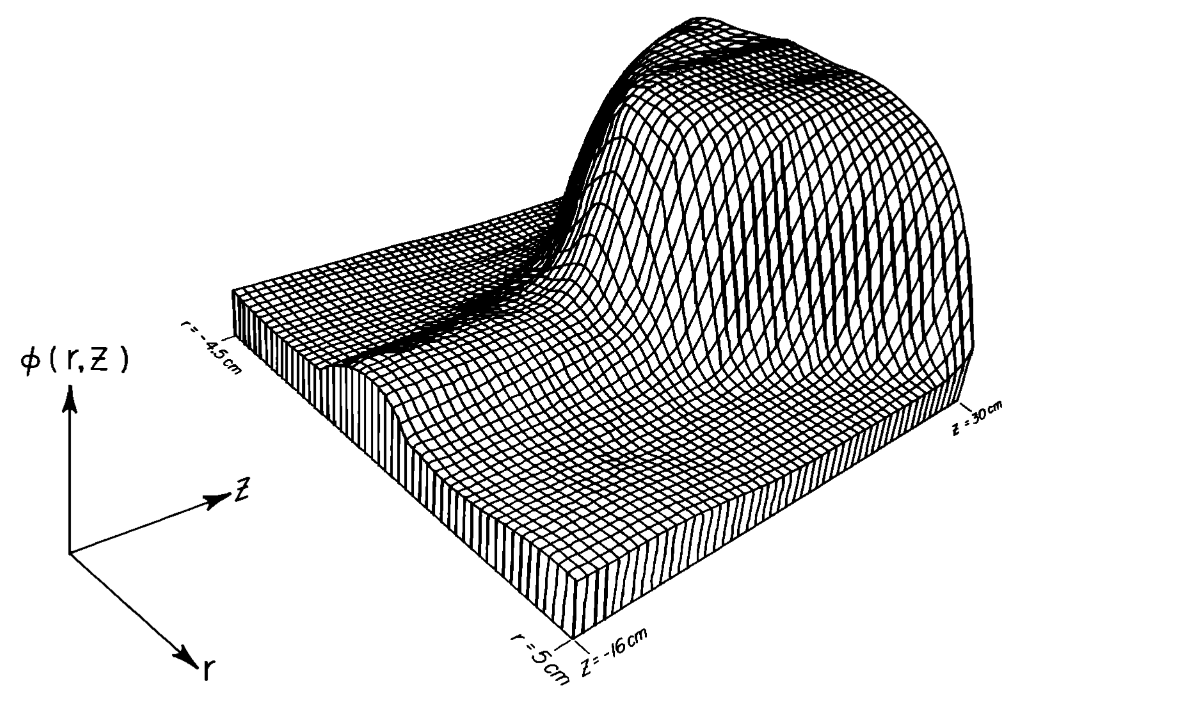

Fig. 4. Three-dimensional perspective plot of the double layer potential $\phi(r, z)$.

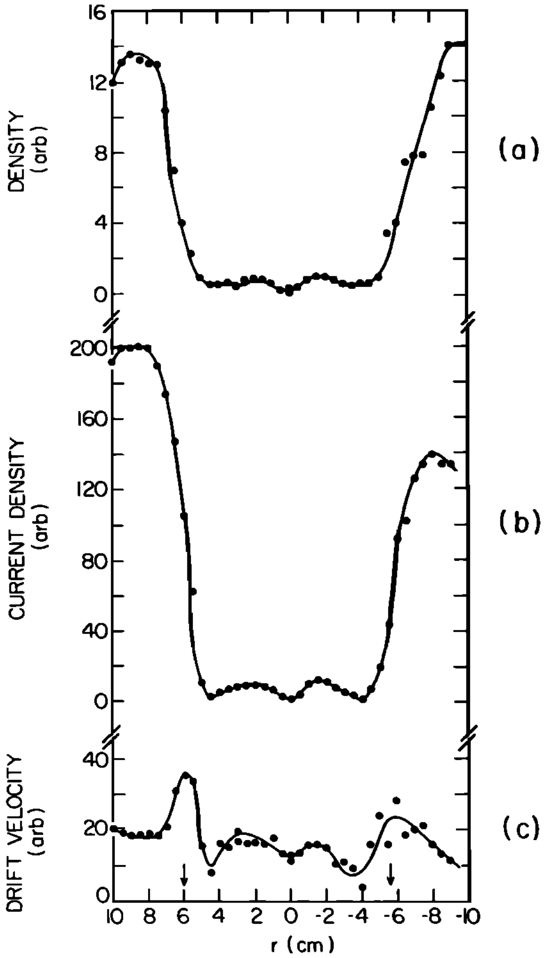

Fig. 5. Radial profiles of (*a*) electron density, (*b*) current density, and (*c*) drift velocity for $z \simeq 30$ cm.

$\sim$75 kHz and 150 kHz is shown in Figure 6. Oscilloscope traces of the actual waveforms showed that the waves were coherent over many wave periods. Typically the amplitude of the instability within the double layer $\Delta n/n$ is $\sim$20–30%. The spectral peaks (frequency f) were near the harmonics of the local ion cyclotron frequency ($f_{ci,DL}$) corresponding to the position of the parallel double layer, with $f \simeq (1.2\text{–}1.5) f_{ci,DL}$. When the position of the double layer was moved by varying the plate voltage (as in Figure 2), the observed frequencies shifted. This is shown in Figure 7 where the solid lines are the argon cyclotron frequencies corresponding approximately to the axial positions on the low and high side of the parallel potential jump. For each plate voltage the location of the double layer was determined with the emissive probe. For this case, the Langmuir probe detecting the oscillations was at a fixed position on the high-potential side and the double layer position was varied by changing the plate voltage, V_p. However, when the double layer was kept at a fixed axial position by keeping V_p constant, the oscillation frequency as seen by a probe which was moved through the double layer remained constant, as shown in Figure 8. At a fixed anode plate voltage, the wave frequency was constant along the axis. The horizontal line in Figure 8 is the value of f_{ci} at the position where the potential has changed by half of its maximum value, $\Delta\phi_{\parallel}/2$; whereas the heavy curve is the local f_{ci} at the probe.

The propagation properties of the ion cyclotron waves were studied by measuring the amplitude and phase of waveforms

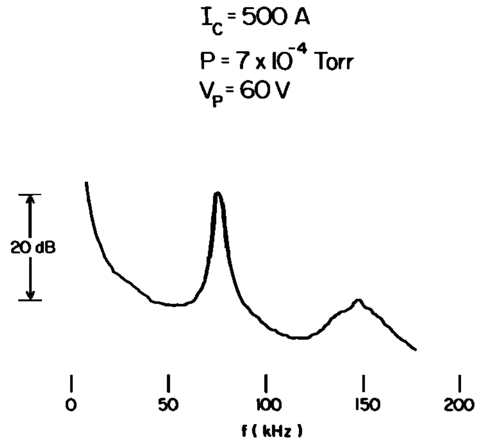

Fig. 6. Power spectrum of EIC oscillations observed on a probe within the double layer.

of electron saturation current of a radially movable Langmuir probe. For this purpose, the phase of the probe oscillations was compared, on a dual-beam oscilloscope, with the phase of the anode current oscillations. In the resulting fixed reference phase plots, wave propagation is in the sense of increasing phase angle. The waves propagate predominantly perpendicular to **B** with very little axial propagation indicating either long parallel wavelengths ($2\pi/k_{\parallel}$) or axially standing waves with $k_{\perp} \gg k_{\parallel}$. No azimuthal propagation was observed. Thus the waves propagate primarily in the radial direction. The series of plots shown in Figure 9 summarizes the plasma and wave properties for a double layer located at $z \cong +1$ cm and for the general conditions of Figure 3. In this series of plots radial profiles of plasma density, space potential, EIC wave amplitude, and wave phase are shown, at axial positions on the low-potential side of the double layer (upstream) and high-potential side (downstream). The density cavity formed in the presence of the double layer (see also Figure 5*a*) is quite evident in Figure 9*a* both upstream and downstream of the double layer. Downstream the density profile is broader due to the divergence of the **B** field.

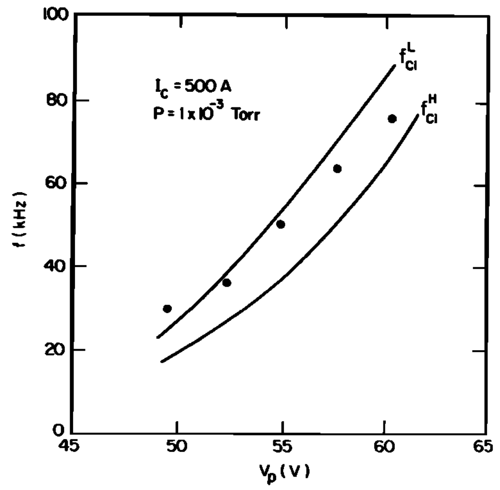

Fig. 7. EIC wave frequency versus anode plate voltage for a fixed Langmuir probe. The solid curves show the variation of ion cyclotron frequency on the low (*L*) and high (*H*) side of the potential jump. The variation of the frequencies reflects the position of the double layer as V_p is varied.

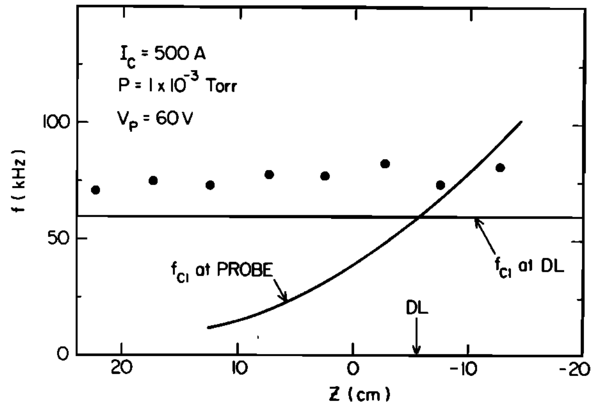

Fig. 8. EIC wave frequency versus z observed on a movable Langmuir probe for a fixed double layer (V_p constant). The solid curve shows the actual ion cyclotron frequency at the probe position. The solid horizontal line is $f_{ci,DL}$ and the double layer position is indicated by the arrow.

An axially movable probe at $r = 0$ showed that the EIC wave amplitude was a minimum on the low-potential side and increased as the probe was moved into the high-potential region. Within the high-potential region, the oscillation has the signature of a standing wave in the radial direction. The amplitude is maximum on axis, with nodes at the radial positions corresponding approximately to the largest radial electric field. Smaller amplitude lobes appear on either side of the nodes, with approximately constant phase. There is approximately a 180° (π) phase difference between the center and nodal point over a distance of ~1.5 cm, with the phase increasing toward $r = 0$ implying radially inward propagation over a distance comparable to the width of the potential drop perpendicular to **B**. Upstream (low-potential side) of the double layer, the wave amplitude is again largest in the center, with a slightly lower amplitude peak on either side. At this position the oscillation seems to be a mixture of standing and travelling waves since there are no nodal points (zero amplitude) and only an ~45° phase shift. The phase increase of ~45° from $|r| \simeq 1$ cm to $|r| \simeq 3$ cm implies an outward-propagating wave from the position of minimum amplitude $|r| \simeq 1$ cm. Profiles taken at the axial position where the potential jump occurs also show an amplitude peak on axis with radially inward propagation, although the phase change occurs over a more extended radial region (~2 cm) as compared to the rather sharp 180° phase changes further downstream.

3.3. *Summary*

Before proceeding with a discussion of the results, we summarize the main experimental points:

1. Strong, three-dimensional, magnetized double layers were produced in a diverging magnetic field configuration by drawing an electron current to a large, positively biased anode plate. Ionization due to electrons accelerated through the double layer is an essential feature in maintaining a trapped electron distribution.

2. The axial position of the parallel potential jump and hence the length of the high-potential region relative to the anode depends on the anode voltage. As V_p is increased the double layer moves further away from the plate; the potential jump, $\Delta\phi_{\parallel}$ increases, and the thickness, $\Delta L_{\parallel}$, decreases.

3. In the presence of the double layer a large density depression is formed along the diverging flux tube of the potential structure. The current to the anode plate flows predominantly on the outer regions of the perpendicular potential jump.

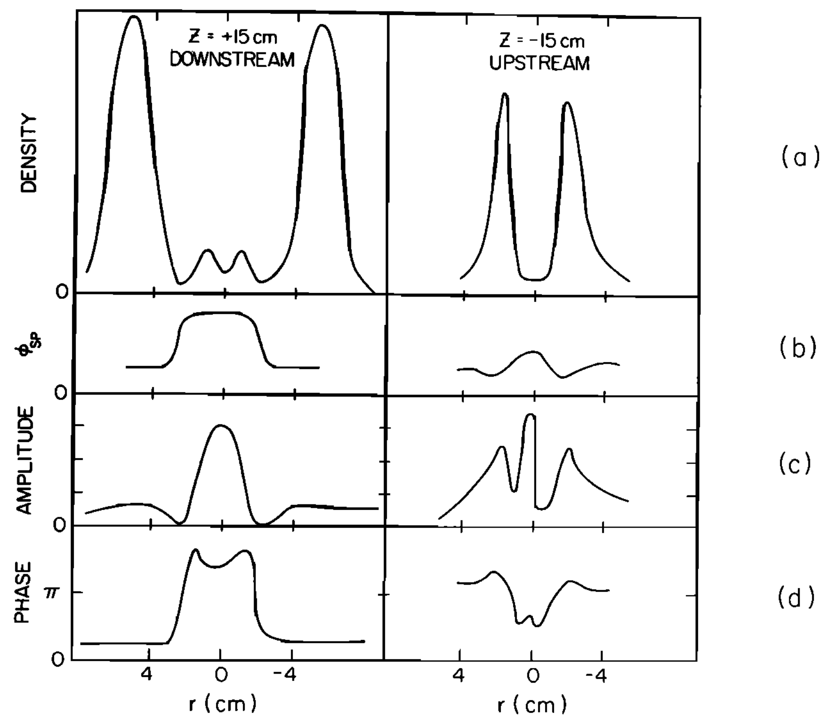

Fig. 9. Radial profiles of (*a*) plasma density, (*b*) space potential, (*c*) wave amplitude, and (*d*) wave phase for two axial positions on the low-potential side (upstream) and within the high-potential side (downstream) of the double layer located at $z = 1$ cm. The density, space potential, and wave amplitude are given in arbitrary units.

4. Large-amplitude oscillations in the ion cyclotron frequency range are associated with the presence of the double layers. The EIC wave frequency corresponds to the local ion cyclotron frequency at the axial position of the parallel potential jump. Although the ion cyclotron frequency varies with position, a single, coherent mode and several harmonics were observed.

5. The waves propagate primarily perpendicular to **B** in the radial direction, with the largest amplitudes observed within the high-potential region.

4. DISCUSSION

We have presented observations of an electrostatic ion cyclotron instability in the presence of a strong, magnetized, three-dimensional double layer. Electrostatic ion cyclotron waves were first observed in a Q machine [*D'Angelo and Motley*, 1962; *Motley and D'Angelo*, 1963]. The ion cyclotron instability was excited in an isothermal plasma ($T_e \simeq T_i$) by drawing an electron current along the axis of the magnetized plasma column to a small collector disk (ion gyroradius < disk radius < column radius) biased a few volts above the local plasma space potential. Notably, electrostatic waves with a frequency, $f \approx 1.2 f_{ci}$, were excited when the electron drift velocity, $v_{D,e}$ was $\gtrsim 10 v_{i,\text{th}}$ (ion thermal speed) which propagated radially outward from the central current channel. Recent laboratory experiments [*Cartier et al.*, 1985] have shown that the parallel phase velocity is in the direction of the electron drift. These properties are accounted for in the theory of *Drummond and Rosenbluth* [1962] for the case of an infinite, homogeneous, collisionless, magnetized plasma column with a uniform electron drift along the **B** field.

The waves which were observed in connection with the double layers have some characteristics similar to the EIC waves observed in the Q machine experiments. First, the frequency spectrum shows strong peaks near harmonics of the (local) ion gyrofrequency. Second, the waves propagate predominantly perpendicular to **B** ($k_\perp \gg k_\parallel$) in the radial direction with no azimuthal propagation. These properties, in particular, lead us to exclude certain other possible instabilities that might be present under our experimental conditions. For example, Farley-Buneman waves, drift waves, and gradient-driven EIC waves would propagate in the azimuthal direction. Also, drift waves and gradient-driven EIC waves would be expected to have maximum amplitude in the region of largest density gradient, which was not the case here (see Figure 9). Finally, the lower-hybrid drift instability and gradient-driven EIC instability are in the lower-hybrid frequency range (for our conditions $f_{\text{LH}} \approx 10$ MHz), well above the observed frequencies.

In the presence of the double layer, there are four possible mechanisms (free-energy sources) for generating EIC waves: (1) electron drifts associated with the field-aligned current, (2) electrons accelerated downstream by the parallel potential jump, or (3) ions accelerated upstream by the parallel potential jump, and (4) the spatially localized electric field perpendicular to the magnetic field [*Ganguli et al.*, 1985*a*, *b*].

The first mechanism is the original one proposed by *Drummond and Rosenbluth* [1962] to explain the initial Q machine experiments [*D'Angelo and Motley*, 1962], and later extended to auroral conditions by *Kindel and Kennel* [1971]. The effects of various nonuniformities on the EIC waves, such as magnetic shear and finite current channel widths, have recently been included in the nonlocal theories of, e.g., *Ganguli and Bakshi* [1982] and *Bakshi et al.* [1983]. We would expect the current-driven ion cyclotron instability to be excited since at the typical anode plate currents ($\approx$0.5–1.0 A), the electron drift velocities should be well above threshold. This mechanism is consistent with certain additional aspects of the observed wave properties. In the high-potential region, the EIC waves propagate radially inward from the edge of the potential structure. This appears to be in line with the data of Figure 5*c* which shows that the drift velocity is maximum near the perpendicular potential structure. Axially the electron drift velocity near the double layer should be higher than the drift velocity in the current channel upstream of the double layer since the density is lower within the double layer. This could be important in understanding the dependence of the wave frequency on the axial position of the double layer. The interpretation, based on the current-driven mechanism, however, seems to be at odds with the apparent presence of EIC waves upstream of the double layer, since upstream $f < f_{ci,\,\text{upstream}}$ which, according to the dispersion relation (derived from the fluid picture for a uniform plasma) $(2\pi f)^2 = (2\pi f_{ci})^2 + k_\perp{}^2 C_s{}^2$, where C_s is the ion acoustic speed, would not permit radially propagating waves (i.e., $k_\perp$ would not be real). Both the wave amplitude and phase changes were smaller upstream than those downstream, possibly indicating that the upstream waves were actually evanescent.

The observations were compared with the actual instability properties computed for our experimental conditions (A^+, large T_e/T_i) from the full kinetic dispersion relation of Drummond and Rosenbluth. For $T_i \simeq 0.1 T_e$, $k_\perp \rho_i = 0.6$, and $v_{D,e}/v_{i,\text{th}} = 50$, it was found (G. Ganguli, private communication, 1985) that the peak growth rate occurred for $k_\parallel/k_\perp = 0.23$, $f_{\max}/f_{ci} \cong 1.6$, and $\Delta f/f_{\max} \simeq 0.3$, where $f_{\max}$ is the frequency at maximum growth and Δf is the frequency range for wave growth. For the case of large T_e/T_i ratio, as in our experiments, the theory predicts EIC waves which propagate less obliquely to **B** than for $T_e = T_i$. For $k_\parallel/k_\perp = 0.23$ a significant axial phase change should have been present. The predicted frequency is in the range of the observed frequencies although the observed spectrum is more coherent. The theory, however, does not account for any of the nonuniformities of the experiment such as the axial dependence of the **B** field and strong gradients in density and potential, or the presence of collisions with the neutrals.

Ion cyclotron waves could also be driven by the electrons accelerated downstream by the parallel electric field of the double layer. The electron beam driven mechanism, recently examined theoretically by *Singh et al.* [1985], is similar to the current-driven mechanism except that the initial electron distribution is taken to be a thermal background Maxwellian with an energetic electron beam rather than a displaced Maxwellian with a net drift. Excitation occurs due to the resonance between the waves and the beam, i.e., $v_{\parallel,\text{phase}} = v_b$, so that $k_\parallel = \omega/v_b$, where ω is the wave frequency, and v_b is the beam velocity. This mechanism would give rise to nearly perpendicularly propagating waves with very long parallel wavelengths. This mechanism could produce high-amplitude EIC waves in the region upstream of the double layer. Typically, for our conditions ($e\Delta\phi_\parallel \approx 20$–$30$ eV), the beam velocity would be $v_b \simeq 2 \times 10^8$ cm/s, yielding a parallel wavelength (for $\omega = 2\pi f = 2\pi \times 75$ kHz) of $\approx$26 m, much longer than the length of our device. In the experiment of *Jovanović et al.* [1982], peaks in the spectrum at the ion cyclotron frequency were not observed when an electron beam of similar energy was injected along a plasma column of similar length. In our case, the electron beam with a large thermal spread was self-consistently produced by the acceleration of background electrons through the double layer. The double layer of *Jovanović* *et al.* [1982], on the other hand, was produced by the external injection of a nearly monoenergetic electron beam into the plasma.

Ion cyclotron waves have been observed in two-dimensional simulations of double layers with a magnetic field [*Kindel et al.*, 1981; *Thiemann et al.*, 1984]. In both numerical simulations large-amplitude ion cyclotron waves were excited downstream of the double layer by electrons accelerated through the potential step. *Kindel et al.* [1981] noted that the large-amplitude ion cyclotron waves which propagate downstream of the double layer (high-potential side) do not affect the double layer significantly. More recently it has been shown that weak double layers may persist in the presence of EIC waves of comparable amplitude [*Barnes et al.*, 1985]. *Okuda et al.* [1981] in their one-dimensional simulations of EIC instabilities pointed out that double layers did not form in the presence of the EIC waves possibly indicating that EIC waves observed in the auroral region in connection with electrostatic potential structures are probably the result of particles accelerated by the double layers rather than their cause.

Ion cyclotron waves could be produced in the upstream region (low-potential side) by ions accelerated through the double layer. The theory of ion-beam-driven EIC waves was presented by *Yamada et al.* [1977], and the connection between electrostatic hydrogen cyclotron (EHC) waves and energetic ion beams in the auroral region was discussed by *Kintner et al.* [1979]. This mechanism has also been discussed in connection with the observation of waves below the first cyclotron harmonic [*Singh et al.*, 1984].

Yamada et al. [1977] showed that the ion-beam-driven instability is a resonant mode $v_{\parallel,\mathrm{phase}} \simeq v_b$ with frequencies starting below f_{ci}. At neutral pressures of 10^{-4}–10^{-3} torr, the mean-free path for A^+-A charge exchange collisions is 5–10 cm. For a typical ion beam that would be produced by the double layer $v_b \approx 7 \times 10^5$ cm/s, so that $\lambda_\parallel \approx v_b/f_{ci} \approx 20$ cm. It is not clear how effective this mechanism would be under these conditions when $l_{in} \lesssim \lambda_\parallel$, where l_{in} is the mean-free path for ion-neutral collisions.

The final mechanism to be considered is one recently proposed by *Ganguli et al.* [1985*a*, *b*], based on the presence of a nonuniform electric field ($E_\perp$) perpendicular to a uniform magnetic field, in the absence of a field-aligned current. They show that for $L \gtrsim \rho_i$, $k_\perp \rho_i \sim 1$, an extremely narrow band instability occurs for $2.8 < v_E/v_{i,\mathrm{th}} < 3.2$, $\omega \simeq 1.6\Omega_i$, and $k_\parallel \ll k_\perp$, where L is the scale length of $E_\perp$, $v_E = E_\perp/B$, and $\omega = 2\pi f$. For our experimental conditions, $E_\perp \approx 20$ V/2 cm = 10 V/cm, $B \sim 500$–1000 G, and $v_E \sim 1$–2×10^6 cm/s, so that the instability condition ($v_E/v_{i,\mathrm{th}} \sim 3$) should be satisfied immediately inside the perpendicular potential jump. Such a mechanism would be consistent with our observations of very coherent waves at $(1.2$–$1.5)\omega_{ci}$ with $k_\parallel/k_\perp \ll 1$ propagating radially inward from the region of the perpendicular potential jump. However, we have shown that the drift velocities are also largest in regions near the perpendicular potential jump so that the downstream waves could be current driven. It is not possible to rule out either mechanism on the basis of the observed frequencies since both instabilities have growth rates maximizing around $1.6\omega_{ci}$. The $E_\perp$ mechanism, however, appears to give rise to a more coherent spectrum and primarily perpendicular propagation ($k_\parallel/k_\perp \ll 1$), both of which are consistent with the data.

From this discussion it appears that no single mechanism may adequately account for the properties of the EIC waves in the presence of the double layer. The EIC waves observed in the high-potential region have certain characteristics consistent with both the current-driven mechanism and the $E_\perp$ mechanism. The apparent association between the instability frequency and the location of the parallel potential step seems to favor the electron beam driven mechanism. For any particular excitation mechanism, the dependence of the wave frequency on the location of $\Delta\phi_\parallel$ along the nonuniform **B** field needs to be explained. The plasma inhomogeneities associated with the double layer (e.g., density cavity, nonuniform current distribution, etc.) may play an important role in determining the wave properties as well as the particular boundary conditions of the experiment. Finally, it may also be necessary to consider the convective properties of the instability as well as any refractive effects on the waves due to the nonuniform nature of the plasma.

In summary, we have presented laboratory observations of electrostatic ion cyclotron waves associated with strong, three-dimensional magnetized double layers in a diverging magnetic field geometry. One main point that has emerged from these experiments is the dependence of the wave frequency on the position of the magnetic field-aligned electric potential structure. These observations are similar to those of *Hatakeyama et al.* [1980] in which the frequency of the ion cyclotron instability was found to depend on the local value of the magnetic field near the exciter electrode. In our case, the electrode (anode plate) was fixed and the potential structure was moved in the nonuniform magnetic field.

Various wave excitation mechanisms that should be operative in the presence of a strong double layer have been considered. Although no definitive identification of the excitation mechanism(s) can be made, it appears that the recently proposed mechanism due to the presence of the nonuniform $E_\perp$ [*Ganguli et al.*, 1985*a*, *b*] could explain some of the properties of the observed waves. Further consideration of this mechanism should be made when more details of the theory become available. Such a mechanism may also be important in the auroral context where coherent waves in the ion cyclotron frequency range have been reported in connection with stationary potential structures perpendicular to **B** [*Mozer et al.*, 1977; *Temerin et al.*, 1982].

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