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Electrostatic ion cyclotron instability near threshold

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By drawing an electron current through a plasma to a variably biased conducting button, the electrostatic ion cyclotron instability is excited, consistent with predictions of Drummond and Rosenbluth [Phys. Fluids 5, 1507 (1962)]. Recent results show that a nonuniform steady-state electric field reaches axially into the plasma. Our results indicate that electrons are accelerated along magnetic field lines and decelerated by collisions. The point in space where the electron drift speed exceeds a critical speed ($v_c \sim 0.2 v_{te}$) determines the instability amplitude and frequency. This initiation point moved further into the plasma as the externally controlled electric field was raised. This experiment demonstrates the importance of applying biases so that $e\phi/T \lesssim 1$, near threshold, to observe the linear electrostatic ion cyclotron instability.

I. INTRODUCTION

The electrostatic ion cyclotron wave has been observed in laboratory and space plasmas for over 20 years. Early theoretical treatments, such as that by Drummond and Rosenbluth,[1] suggested that the wave would be observed as a result of the electrostatic ion cyclotron instability (EICI). Ion cyclotron waves would grow when plasma electrons drifted through background ions with a drift speed of order 10 times the ion thermal speed. Later theoretical work by Kindel and Kennel[2] indicated that ion cyclotron waves would be destabilized in the topside ionosphere and would lead to anomalous resistivity.

About the same time as the development of the Drummond–Rosenbluth theory, laboratory experiments by D'Angelo and Motley,[3] Rynn,[4] and Motley and D'Angelo[5] showed the presence of these waves when the plasma was destabilized by drawing an electron current, consistent with the theory. The resistivity of quiescent plasmas, similar to those where the instability was seen, was found by Rynn[6] to be near Spitzer resistivity. Rynn[7] thereafter reported on plasma column-end effects, including sheath flipping instabilities. Levine and Kuckes[8] then reported observing the current driven instability to be sheath effects at the end of the plasma column. Buchel'nikova and Salimov[9] measured ion heating that results from current driven instabilities and remarked on relaxation instabilities. Thus it was known that device-specific effects could confuse interpretation of the electrostatic ion cyclotron instability. Yamada and coworkers have done some experiments[10,11] that developed the breadth of current driven effects in plasmas, examining especially, density gradient driven phenomena.

A series of experiments[12–15] at the University of California at Irvine established the importance of ion heating, nonlocal, and nonlinear effects for many situations where the electrostatic ion cyclotron instability was observed. Bakshi, Ganguli, and Palmadesso[16] have developed a theory of nonlocal effects on the instability relevant to both laboratory experiments and the magnetosphere. In fact, Boehmer and Fornaca[17] and Lang and Boehmer[18] have performed laboratory simulations of the magnetosphere where nonlocal and nonlinear effects proved significant.

Evidently, considerable care must be taken examining the electrostatic ion cyclotron instability in a laboratory when comparisons with the Drummond–Rosenbluth theory are made. Since linear theories require the wave potential to be less than equivalent ion or electron temperatures, nonlinear results abound in experiments.[19–21] Many experimenters have driven the instability by applying potentials to electrodes well in excess of equivalent plasma temperatures, making it difficult to establish the cause of the observed instability. Quite a number of the electrostatic ion cyclotron experiments have been performed in Q machines,[22] where care must be taken in interpreting probe data since probes commonly perturb the plasma.

The thrust of the present paper is to examine the electrostatic ion cyclotron instability in the linear regime and to compare the experimental observations with the theory of Drummond and Rosenbluth. In this paper we report the results of experiments destabilizing the electrostatic ion cyclotron wave by electron drift in a plasma. We show that the axial position at which the electron drift speed exceeds the critical velocity determines the EICI amplitude and frequency. The drifts were produced by potentials less than or equal to the electron or ion temperatures. Effects of resistivity, electric fields, the spatial location of the instability excitation piont, wave amplitudes and growth, and the ion distribution function response (such as ion heating) are considered. Many of the measurements were made with the nonperturbing laser-induced-fluorescence (LIF) technique.[13,23–27] Experiments at Iowa by Cartier, D'Angelo, and Merlino[28] performed in a nonuniform magnetic field complement our results.

II. EXPERIMENTAL ARRANGEMENT

Figure 1 shows the experimental arrangement of the University of California at Irvine Q machine as used for this experiment. A 5 cm diam cylindrical barium plasma is contained by an axial magnetic field of up to 6 kG. The plasma is formed by spraying neutral barium against a hot plate which yields the barium ions by contact ionization and the electrons by thermionic emission. Typically, the plasma poten-

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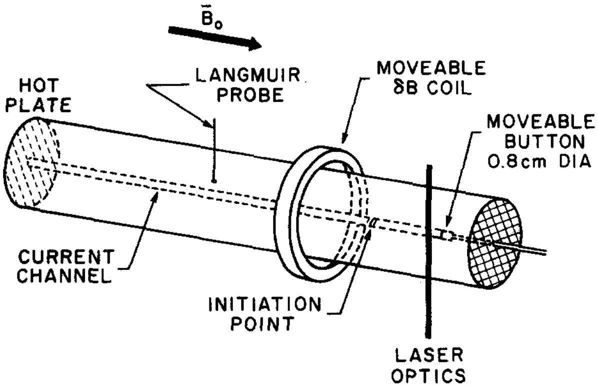

FIG. 1. Diagram of the University of California at Irvine Q machine showing axially moveable perturbing magnetic field coil, axially moveable variably biased button, and laser (LIF) optics. Typical $n_e \sim 4\times 10^9$ cm^{-3}, $B_0 = 4$ kG.

tial is below that of ground because of the thermionic source. The plasma drifts from the hot plate to a cold plate located about 1.4 m down the magnetic field lines from the hot plate. The ion drift speed depends on the hot plate temperature and is found by laser-induced fluorescence (as discussed below) to vary from 5×10^4–2×10^5 cm/sec. Parallel ion temperatures (also found by LIF) of the undisturbed plasma are typically about 0.1 eV, while perpendicular temperatures are around 0.2 eV (the hot plate temperatures are usually run around 2300 K).

Plasma density was inferred from Langmuir probes and from the angle of propagation of antenna which launched lower hybrid waves with respect to $\mathbf{B}_0$ ($\theta \approx \omega/\omega_{pe}$). Electron temperature was inferred from Langmuir traces to be about 0.2 eV.

The electrostatic ion cyclotron instability was excited by drawing an electron current to an axially moveable 8 mm diam button. The button had a conducting surface, biased to variable voltage, and exposed to the plasma. This surface was kept free of insulating barium oxide by heating from a filament mounted behind the button, but electrically isolated from the button by a thin mica sheet. The heating of the button is crucial for performing small amplitude wave experiments in barium. Without heating, a button in such a plasma will acquire a resistive surface coating so that a bias (varying with time over the course of the experiment) of many times the plasma temperature may be required to excite the instability. One therefore loses the ability to examine with precision the linear regime of destabilization if the button is not heated.

Plasma potential and electric fields in the plasma were found by using an axially moveable dielectrically shielded capacitive probe[18] that could also make radial scans.

A 6 cm diam current carrying coil similar to that used by Wolf and Schrittwieser[29] was aligned coaxially with the plasma and was moveable in the axial direction. Currents from 0 up to ± 10 A could be run through this coil, producing a perturbation to the axial magnetic field of 26 G/A on axis and a measured FWHM of 4.2 cm on axis. This coil was used to investigate the axial location of the starting point of the instability, as is discussed below.

Briefly, the LIF is used to obtain one-dimensional ion velocity distribution functions. This is achieved by sending a tunable single-mode laser beam through the plasma in a selected path (e.g., see Refs. 26 and 27). Focusing on the fluorescence of a small volume in the plasma results in detection of a signal corresponding to the barium ion density in velocity space which satisfies the necessary Doppler shift to fluoresce. Scanning the laser frequency results in obtaining the ion velocity distribution function. Changing the angle of the beam in the plasma selects a new velocity component to examine. Hence the parallel and perpendicular ion distributions can be obtained directly without substantial inference and in a nonperturbing way. Running the laser broadband allows all ions illuminated by the laser beam to fluoresce and hence the total ion number density is detected. Physically, 1 mm spatial resolution is obtained along with temporal resolution of a few microseconds. Using the laser in single mode operation gives a resolution in velocity space, around 3% of the undisturbed ion thermal speed.

III. DISCUSSION OF EXPERIMENTAL RESULTS

Electron-ion collisions play an important role in the axial distance scale relevant to the instability. For the plasma studied here with a density of $n_e \approx 4\times 10^9$ cm^{-3} the electron-ion collision time is less than 1 μsec. This means that in an undisturbed plasma the average axial drift of an electron between collisions is under 1 cm. However, the ion-ion collision time of 3×10^{-4} sec means an ion drifts about 60 cm before colliding with another ion. Hence an electron's momentum is randomized, on average, in under a centimeter of drift. Application of an axial dc electric field will cause electrons to be accelerated between collisions. Drummond and Rosenbluth[1] predicted the electrostatic ion cyclotron instability to be unstable when the drift speed of the electrons is about $0.2v_{te}$ with respect to the ions for this plasma. Hence an electron must gain an axial drift energy of 8 mV between collisions to exceed the critical drift speed.

The electric field in the plasma is a function of button bias. For very low bias voltage the plasma can shield the potential in a Debye length. As a potential is raised the ability of the plasma to shield out a voltage is reduced. For voltages slightly above the plasma potential a dc electric field should be observed penetrating into the plasma along the magnetic field lines. Chen (Ref. 30, pp. 127 and 165) has shown how to estimate the electric field penetration distance (referred to as sheath thickness by Chen) in a plasma along the magnetic field. He shows that for bias potentials well above the plasma potential, Child–Langmuir effects are important and that the electric field penetrates into the plasma many Debye lengths, typically a distance of the order of the mean free path between collisions. The mean free path may be estimated from Braginskii's calculation[31] of the electron collision time:

$$\tau_e = 3.5\times 10^5 T_e^{3/2}/(\lambda n),$$

$$\lambda = 23.4 - 1.15 \log_{10} n_e + 3.45 \log_{10} T_e,$$

with T_e in eV. Actually, magnetic field corrections found by Belyaev[32] increase τ_e by nearly 30% for our experiment. For electrons at 0.2 eV in this plasma the mean free path between

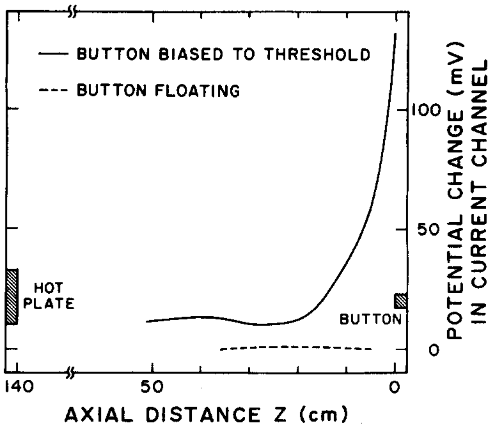

FIG. 2. Potential change along magnetic field line in front of button at instability threshold (same curve just above and below threshold) and with button floating.

collisions is about 10 cm. We therefore expect a button biased to a potential slightly above the plasma potential to support an electric field reaching along the magnetic field several centimeters into the plasma. Figure 2 shows a measurement of the variation of potential in the plasma just below and just above instability onset. There is a dc electric field in the plasma under both circumstances. Note that the field is a monotonically increasing function as the electron travels from the hot plate to the button. The role of electron-ion collisions may also be seen by finding the plasma resistivity. The electric field near the button may be found from Fig. 2. Current density of $j = nev = 3.32 \times 10^{-3}$ A cm^{-2} was drawn to the button. The ratio of electric field to current density then gives an experimental value of resistivity which may be compared to Spitzer resistivity:

$$\frac{\eta_{\text{expt.}}}{\eta_{\text{Spitzer}}} = \frac{ET^{3/2}}{j6.53 \times 10^3 \ln \Lambda} = 1.45$$

(where T is in degrees Kelvin) in the range of Rynn's[6] experimental value of 0.85. Hence the plasma conductivity is close to Spitzer values and the role of electron-ion collisions in this experiment is verified as one of supporting an electric field in the plasma for drawing electron current and for providing the acceleration mechanism to initiate the instability between collisions. For the potential profile shown the electron drift speed can gain the 8 mV required between collisions to be above critical speed for onset of the instability when about 10 cm in front of the button. For lower button biases, the necessary field for instability moves closer to the button.

An instability requires one period or more to establish wave properties. For the electrostatic ion cyclotron instability this time is $\tau \sim 2\pi/\omega_{ci}$. The ions participating in this wave are drifting along the magnetic field at a speed, v_{Di}. The ions must drift freely a time τ for the instability to develop its wave properties and this translates to a minimum drift distance of $\Delta Z \sim 2\pi v_{Di}/\omega_{ci}$. If the ion motion is blocked in a distance less than ΔZ or a time less than τ, then the instability is quenched before wave properties are established. Hence for this experiment the instability will not be observed until the initiation point is at least $\Delta Z \sim 5$ cm in front of the button.

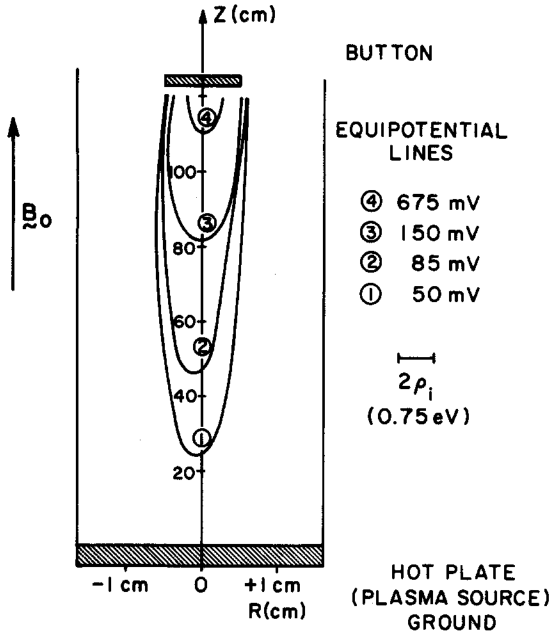

FIG. 3. Spatial structure of potential in plasma for button biased above threshold.

An example of the three-dimensional potential structure found in the plasma (measured by Lang and Boehmer[18]) is given in Fig. 3. There is seen to be an axial and radial electric field. Pritchett[33] has predicted that Kelvin–Helmholtz instability will be important for this geometry when $E_{\parallel}/E_{\perp} \lesssim m_e/m_i$. We find from measurement that our experiment is at least two orders of magnitude above the ratio required by Pritchett's calculation and estimate that the Kelvin–Helmholtz instability does not play an important role here.

The position of the initiation point of the instability may be determined by means of the moveable magnetic field coil mentioned above. According to Drummond and Rosenbluth[1] the instability frequency is near $1.15\omega_{ci}$. If the instability were to be initiated at a point, then the driving source function would take the local cyclotron frequency at the initiation point into account and the observed instability would occur at $1.15\omega_{ci,\,\text{initiation}}$. The wave frequency observed at points other than the initiation point in the plasma will be at $1.15\omega_{ci,\,\text{initiation}}$ since a driven system responds at the driving source function frequency. The magnetic field coil produced a sharply peaked (4.2 cm FWHM) small perturbation, $\delta B/B_0 = 6.5 \times 10^{-3}$/A, in the coil. The coil was moved in the axial direction with the instability just above threshold. The instability frequency was constant until the coil was within a few centimeters of an axial position which depended on the button bias. As shown in Fig. 4 the frequency then changed according to the local magnetic field value at an axial position we call the initiation point. The change in frequency was positive or negative depending on the current in the coil and was proportional to the total magnetic field value at the initiation point. There was no change in wave frequency or amplitude if there was zero current in the coil,

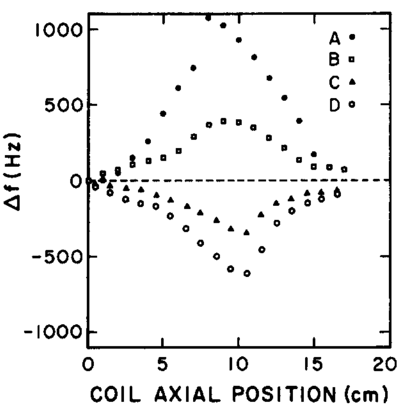

FIG. 4. Instability frequency change versus moveable coil position as a function of current in the coil. Here $A = 4$, $B = 2$, $C = -2$, and $D = -4$ A in coil. Coil axial position is given as centimeters in front of button.

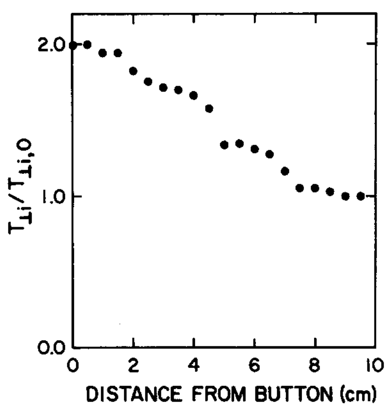

FIG. 6. Normalized perpendicular ion temperatures versus axial distance from button. Initiation point 8.5 cm in front of button.

regardless of coil axial location. This initiation point was seen to occur at the axial position where the electric field was just sufficient for the axial electron drift to increase to $0.2v_{te}$ between collisions.

As the button bias was increased with respect to plasma potential, this initiation point moved further into the plasma, as shown in Fig. 5, consistent with the position where the measured electric field would first cause the electron drift to exceed the critical velocity. For bias changes of more than a few tenths of volts on the button, nonlinear manifestations may be expected and this picture may be modified.

When the button was moved in the axial direction, the wave frequency just above threshold was found to map the main magnetic field, including 3% ripple, exactly according to the distance of the initiation point in front of the button as determined by the moveable coil. Hence interpretation of frequency shifts as a function of bias voltage must be done cautiously as we were able to show that a change in magnetic field of $\delta B/B \sim 6.5 \times 10^{-3}$ led to changes in wave frequencies. Previous work[14] had suggested that increasing button bias changed T_i which would lead to changes in wave frequencies. Clearly, the position of the initiation point changes when button bias is changed, as shown in Fig. 5, and a minor field ripple near the initiation point also will lead to frequency shifts.

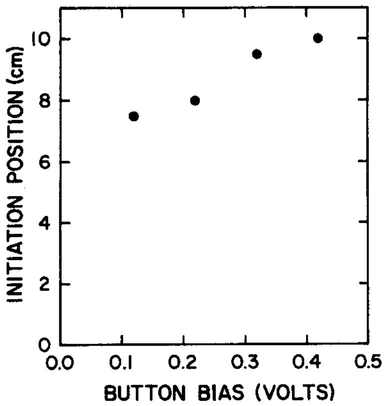

FIG. 5. Electrostatic ion cyclotron instability initiation position (distance in front of button) versus button bias above plasma potential.

The ion response to the instability leads to a change in the perpendicular ion distribution function. For moderate potentials applied to the button, the instability grows in amplitude from the initiation point to the button, the direction of electron and ion drifts. Indeed, wave phase measurements taken by the LIF diagnostic show the axial wave phase velocity from the initiation point to the button to be about $0.2v_{te}$, as predicted by Drummond and Rosenbluth. The wave amplitude also has been observed to be larger in a direction toward the button than toward the hot plate. Figure 6 shows the perpendicular ion temperature measured as a function of distance from the button. Our results show that ion heating is small in front of the initiation point (when small biases are applied to the button) and increases from the initiation point up to the button, increasing by as much as a factor of 2.

The frequencies observed for this instabillity are affected by the background pressure. We estimate that neutral collisions will begin to play a role in the instability dynamics when base pressures over 4×10^{-6} Torr are found. An experiment was performed where the background pressure could be raised, and the wave amplitude and frequency were found to change when the pressure reached 5×10^{-6} Torr. A clean machine is essential to study the instability without having to consider the role of neutral particles.

IV. CONCLUSIONS

This experiment demonstrates that static electric fields may penetrate plasma when external potentials exceed the plasma potential. When these fields have penetrated considerably more than a Debye length, the electron drift speed in a plasma may be enhanced, leading to instabilities. In particular, at the point where sufficient electric field is available to cause the electron drift speed to exceed the critical value predicted by Drummond and Rosenbluth, the electrostatic ion cyclotron instability is initiated. This point of initiation depends on the biases applied to the plasma. The instability does not occur until sufficient electric field is available in the plasma so that $eE_{\parallel} v_{\text{critical}} \tau_{ei} = \frac{1}{2} m v_{\text{critical}}^2$ at which point the instability begins. A minimum axial distance in front of the button on order of $Z_{\text{min}} \sim 2\pi v_{\text{drift,ions}}/\omega_{ci}$ is required for the instability to develop. The initiation point moves progressively away from Z_{min} as the button bias is increased. The axial ion temperature profile is consistent with the picture of the wave growing from the initiation point toward the button (the direction of plasma drift). Wave phase velocity measurements between the initiation point and the button agree with Drummond and Rosenbluth predictions. Finally, our results show that it is important to apply biases such that $e\phi/T \lesssim 1$ to observe the linear electrostatic ion cyclotron instability.

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