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Effect of parallel velocity shear on the excitation of electrostatic ion cyclotron waves

E.P. Agrimson, N. D'Angelo, R.L. Merlino *

Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242, USA

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Abstract

The effect of a magnetic field aligned plasma flow with a transverse velocity gradient (parallel velocity shear) on the excitation of electrostatic ion cyclotron (EIC) waves was investigated experimentally in a Q machine. The role of parallel velocity shear was studied for EIC waves excited in a single-ended cesium plasma, in the usual manner, by drawing an electron current to a disk electrode having a diameter less than the diameter of the plasma column. Observations indicate that EIC waves were excited when both electron current and parallel velocity shear were present. However, EIC waves were never excited when shear was present in the absence of current. Experiments were also performed in a double-ended Q machine configuration to further investigate the role of shear. © 2002 Published by Elsevier Science B.V.

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1. Introduction

The current-driven electrostatic ion cyclotron instability (EICI) is one of the most widely studied instabilities in plasma physics [1]. This instability was first observed in a single-ended Q machine when an electron current was drawn to a 0.6 cm diameter collector located on the axis of a 3 cm diameter plasma column [2]. The instability appeared as oscillations in the collector current when a sufficiently positive voltage was applied to the collector to raise the electron drift to ∼10 times the ion thermal velocity. The frequency of the instability increased with the magnetic field strength and exceeded the ion cyclotron frequency by about 15%. The oscillations in density were observed, not only in the collector current channel, but also on biased Langmuir probes located between the hot plate and the collector. The wave vector had components both parallel and perpendicular to the magnetic field. In the perpendicular direction, wave propagation was radially outward from the current channel, with a wavenumber, $k_\perp$, such that $k_\perp \rho_i \sim 1$, where ρ_i is the ion gyroradius. The experimental measurements were in general agreement with the theory of Drummond and Rosenbluth [3].

One further observation that was also reported early on and that seemed to be at odds with the simple theoretical picture concerned the size of the current channel. Rynn [4] investigated the effects of passing a current through a Q machine plasma formed between

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* Corresponding author.
E-mail address: robert-merlino@uiowa.edu (R.L. Merlino).

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two hot tungsten plates each producing an alkali (cesium or potassium) metal plasma. In this case, however, the current was drawn over the entire plasma column (as opposed to central current filament) by applying a potential difference between the plates. Rynn observed that as the potential difference, V, was increased, the current increased up to a maximum value, then decreased slightly before settling on a more or less constant value. Slightly above the current maximum, there was a sudden onset of large amplitude oscillations. A spectral analysis of these oscillations revealed frequency peaks in the few kHz range and one at a frequency near the ion cyclotron frequency. However, Rynn pointed out that the oscillation near the ion cyclotron frequency was ‘a weak oscillation and often did not appear at all’ [4].

Many subsequent experiments performed in Q machines confirmed these initial observations (see the review article by Rasmussen and Schrittwieser [1]). In fact, it is now well established that high amplitude EIC waves are only excited when the current channel has a radius smaller than that of the plasma column. Apparently, when the current is drawn over the entire plasma cross section another much lower frequency instability (termed the potential relaxation instability) is produced. This is difficult to understand on the basis of the kinetic theory [3] which predicts that the EIC instability should be excited if the electron drift speed exceeds a critical value.

We have undertaken a re-examination of the EIC instability in light of recent theoretical work [5] suggesting that an ion flow along the magnetic field with a flow gradient (shear) transverse to the magnetic field can have an additional destabilizing effect on EIC waves in the presence of a magnetic field aligned electron drift (current). A related theoretical prediction [6] that perpendicular shear in the flow of ions parallel to a magnetic field substantially reduces the electron drift necessary to excite ion acoustic-like waves, was the subject of a previous experiment [7]. Since these predictions have important consequences for the interpretation of low frequency plasma oscillations observations in the ionosphere, it is essential that they be tested in the laboratory.

In the next section we will describe two experiments, performed in a Q machine using a cesium plasma, whose purpose was to investigate the possible influence of parallel velocity shear on the excitation of EIC waves. The first experiment was performed in a single-ended Q machine using essentially the identical set-up employed by many researchers studying EIC waves. Additional evidence for the role of parallel velocity shear was obtained in the second experiment which employs a double-ended Q machine.

2. Experimental results and discussion

The experiments were performed in a Q machine which could be operated either in the single-ended or double-ended mode. The plasma sources consist of two 6 cm diameter tantalum plates separated longitudinally by 2 m. Two atomic beam ovens provide neutral cesium atoms which are ionized on the surfaces of the tantalum plates which are heated from behind by electron bombardment to a temperature of ≈2500 K. The plasma is confined radially by an axial magnetic field up to 0.5 T provided by a set of 14 solenoid coils. The currents in the coils can also be programmed to provide a nonuniform magnetic field geometry. In single-ended operation the plasma is terminated on a cold, stainless-steel, electrically floating end plate. In this operating condition, plasma densities, measured with a small (2 mm) disk Langmuir probe, up to a few times 10^{10} cm^{-3} are obtained. In the double-ended operation both tantalum plates and cesium ovens are employed with resulting plasma densities up to several times 10^{10} cm^{-3}. In both modes of operation the electron and ion temperatures are $T_e \approx T_i \approx 0.2$ eV.

(a) *Single-ended experiment.* A schematic of the set-up used in the single-ended experiment is shown in Fig. 1. This is the ‘conventional’ EIC set-up in which the endplate consists of a center disk (collector) (16 mm diameter) electrically isolated from an outer

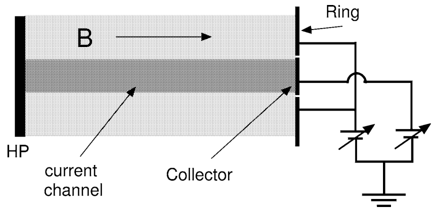

Fig. 1. Schematic of the experimental set-up for the single-ended collector and ring experiment. The plasma is produced by surface ionization of cesium atoms from an atomic beam oven (not shown) impinging on a hot tantalum plate (HP).

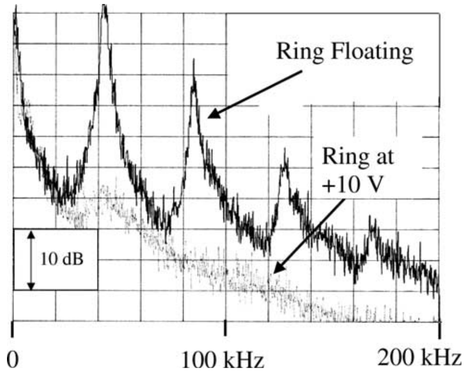

Fig. 2. Spectra of oscillations in the collector current observed with the collector biased at +10 V to drive an electron current. The upper spectrum corresponds to the case in which the ring was at the floating potential and the lower spectrum to the case in which the ring was biased at +10 V.

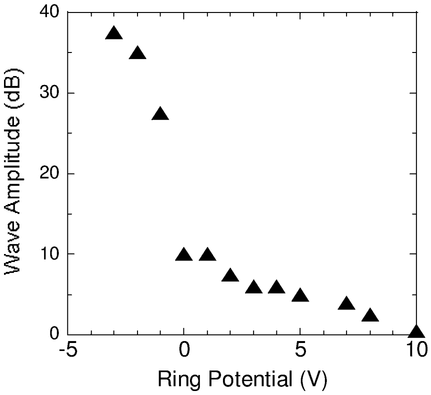

Fig. 3. EIC wave amplitude (fundamental) versus ring bias potential, for $V_c = +10$ V.

annular electrode (ring). The collector and ring can be biased independently.

In the ‘conventional’ set-up the ring would be kept floating with the collector (sometimes referred to as the ‘button’) biased positively to collect an electron current. The spectrum of oscillations in the collector current when the collector was biased at $V_c = +10$ V to drive an electron current while the ring was floating is shown in Fig. 2 (top). This is a typical case in which a fundamental EIC mode (at about 42 kHz) and several harmonics are excited. The ion cyclotron frequency in this case was $f_{\mathrm{ci}} = 38$ kHz. By contrast, the case in which both the collector and plate are biased at +10 V is shown as the lower spectrum in Fig. 2. In this case, only the fundamental is present and at a considerably reduced (by ∼30 dB) amplitude. Evidently, as reported by many others, strong EIC waves are only excited when the current is present over a portion of the plasma column. Fig. 3 shows the effect of the variation of the ring bias (from −3 to +10 V) on the EIC fundamental wave amplitude for a fixed bias of +10 V on the collector. The sharp drop in EIC fundamental mode amplitude occurs for a ring bias, $V_R > -1$ V. The plasma space potential is typically in the −2 to −3 V range, so we expect that the ring will begin to collect electrons and repel ions for $V_R > -1$ V. It is important to point out that the sharp reduction in EIC wave amplitude observed as V_R is increased is not associated with a decrease in the collector current which stays essentially fixed as V_R is increased. Thus the observed reduction in the EIC instability amplitude cannot be attributed to a drop in the electron drift within the central current channel.

We suspect that the reduction in EIC wave amplitude when the current flows over the entire plasma cross section may be connected to the effects of parallel velocity shear. Consider the configuration in Fig. 1 for the case in which the ring is floating and the collector biased at +10 V. The plasma produced at the hot plate flows toward the ring/collector endplate. Ions in the outer annular portion of the plasma column will be collected by the floating ring. However, the ions in the central portion of the column will be repelled by the positively biased collector. Thus, one expects that a gradient in the ion flow must exist at the boundary between the central current channel and annular outer plasma. Hence, this ‘typical’ EIC configuration seems to necessarily include a region of parallel ion flow with a transverse flow gradient. If this interpretation is correct, then it is also reasonable to expect that for the case in which the collector and ring are both biased to draw electron current, no shear in the ion flow would be present in the boundary region. It seems plausible then that parallel velocity shear does influence the excitation of EIC waves. EIC waves, however, were never observed in the absence of the electron drift. We also looked for evidence of the effect of shear in the radial dependence of the EIC wave amplitude. Fig. 4 shows the EIC amplitude (fundamental) detected as oscillations in the floating potential of a small (1 mm) Langmuir probe that was scanned radially across the plasma column for the case where the ring was float-

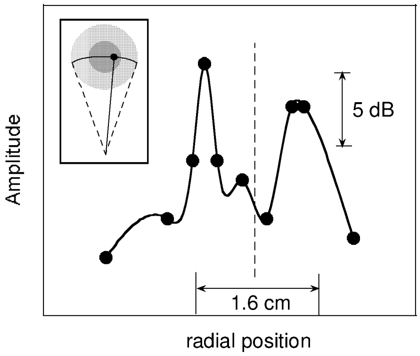

Fig. 4. Amplitude of the EIC fundamental mode as measured on a Langmuir probe rotated radially across the plasma column. The center of the plasma column (and current channel) is marked by the vertical dashed line and the radial extent (1.6 cm) of the current channel is indicated.

ing and the collector biased to collect electrons. Amplitude maxima were seen near the edges of the current channel where one also expects the strongest shear in the ion flow to be present.

Phase measurements were also performed to investigate the propagation characteristics of the EIC waves. We found results very similar to those that have been obtained in previous experiments [2]. The EIC waves propagate axially in the direction of the electron drift and radially outward from the current channel. The axial wavelength is much longer than the perpendicular wavelength. We could not detect any azimuthal propagation.

(b) *Double-ended experiment*. Experiments were conducted in the double-ended mode to further investigate the possible role of parallel velocity shear in EIC wave excitation. This mode of operation permits more control over the parallel ion velocity shear, enabling us to gain more confidence in the role of shear in a different experimental setup. The schematic of this set-up is shown in Fig. 5. Now, both hot plates and cesium ovens are used (referred to as the EAST and WEST hot plates) and the plasma flux from each source can be independently varied by changing the electrical heating power applied to each plate. To drive the electron current a collector (16 mm) is positioned at an axial location several centimeters in front of the East hot plate. The side of the collector facing the East hot plate is coated with an insulating material so that the current is only drawn to the side facing the West hot plate.

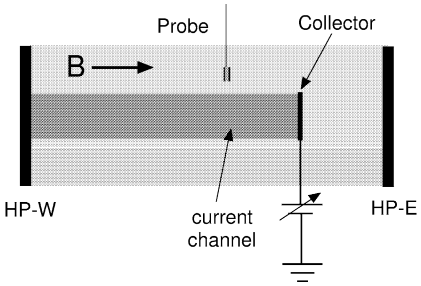

Fig. 5. Schematic of the experimental set-up for the double-ended experiment. Plasma is produced on both the West and East hot tantalum plates by surface ionization of cesium atoms from two cesium atomic beam ovens (not shown). Electron current can be drawn to the West side of a collector located near the East hot plate.

If heating power is applied to only one plate, the plasma flow must be in the direction away from that plate. When both sources are used, the direction of the ion flow can be controlled by adjusting the source heating power levels. The sources can also be 'balanced' so that there is no net fluid flow. The direction of ion flow can be determined from measurements [7] of ion currents to two Langmuir probes mounted back-to-back and insulated from each other, as shown in Fig. 5. The ion currents collected on the East and West facing probes are labeled I_E and I_W, respectively. A plot of the measured ratio I_E/I_W versus the ratio of East to West heating powers, P_E/P_W is shown in Fig. 6. An $I_E/I_W = 1$ corresponds to the case in which the hot plate sources are balanced resulting in no net flow. This does not necessarily occur when $P_E/P_W = 1$ due to differences in the hot plates and atomic ovens. For the particular case shown in Fig. 6, the balance occurs for $P_E/P_W \approx 1.2$–1.3.

Fig. 7 shows a plot of the EIC wave amplitude as a function of the P_E/P_W ratio. Here the collector was biased to draw electron current, and the heating powers on the East and West plates were varied. These data show a minimum in EIC wave amplitude for $P_E/P_W \approx 1.2$–1.3 which also corresponds to the condition of 'balance' (Fig. 6) in the East and West flows. This behavior is consistent with the 'shear' interpretation since the parallel velocity shear should also be minimum when the flow in the outer annular region is minimum. Recall that with the collector biased to draw electrons, the ions in the central channel must be reflected at the collector. Since there is no net flow in

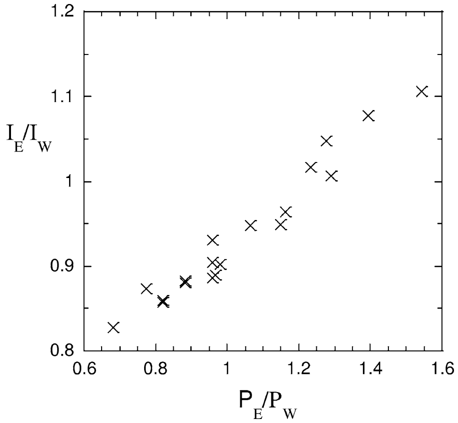

Fig. 6. Ratio of East and West directed ion currents collected by two independent, negatively biased Langmuir probes (see Fig. 5) as a function of the ratio, P_E/P_W, of the heating power applied to the East and West hot plates. An $I_E/I_W = 1$ implies a balance in East and West ion fluxes and resulting no net ion flow.

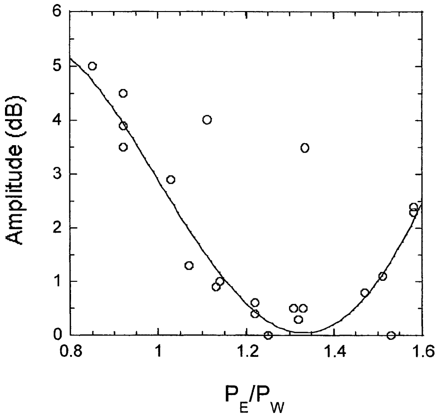

Fig. 7. EIC fundamental wave amplitude versus the P_E/P_W ratio. The minimum amplitude occurs at $P_E/P_W \approx 1.2$–1.3, which coincides approximately with the condition of minimum ion flow (and resulting shear) from the data in Fig. 6.

the central channel, there will be minimum shear when the flow is minimized in the outer region.

3. Conclusions

Our motivation in performing these experiments was to test the idea that inhomogeneous parallel ion flow may have some bearing on the excitation of the EIC instability in the presence of an electron drift. It is likely that the typical configurations used in the past to study this instability necessarily included parallel velocity shear. The experiments presented here seem to support the idea that parallel velocity shear plays an important role in the instability. We have seen in two different configurations that the EIC wave amplitude is drastically reduced when the shear is eliminated or reduced. Since no direct measurement of the velocity shear, dv_{iz}/dr, was made we cannot compare the experimental results with theory. One experimental finding that, for the time being, cannot easily be reconciled with the theory is the wave propagation measurements. As pointed out in the previous section, we have observed both radial and axial propagation for the EIC mode but no azimuthal (k_θ) propagation. This would seem to be at odds with the theory [5]. A few points need to be made in this regard. First, it is possible, as suggested by the theory, that very short azimuthal wavelengths were present that we were not able to resolve. Secondly, it is possible that the azimuthal propagation only occurred in a very narrow annular region which we failed to locate with the probe. The question of azimuthal propagation needs to be addressed in future experiments.

In closing, we feel it necessary to admit a certain degree of hesitation in possibly adding new confusion and controversy into a field already wrought with conflicting and inconsistent findings. It seems almost unbelievable that some 40 years after their discovery, discussions about the excitation mechanism of EIC waves continue. However reluctant we may be to perpetuate these discussions and controversies, we feel that given the recent theoretical work [5] in this area it was necessary to point out that there does seem to be reasonable evidence that parallel velocity shear does play a role in the excitation of electrostatic ion cyclotron waves.

Acknowledgement

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