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Amplification of electrostatic ion-cyclotron waves in a plasma with magnetic-field-aligned ion flow shear and no electron current

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Experimental demonstration of the amplification of electrostatic ion-cyclotron waves in a plasma with parallel ion flow shear but no magnetic-field-aligned electron current is presented. Waves with frequencies near the ion gyrofrequency and multiple harmonics launched from an antenna are observed to grow in amplitude in a region of ion flow shear. Amplification of multiple cyclotron harmonics was observed when a broadband (white noise) signal was applied to the launching antenna. Implications of these results for plasma wave excitation in the Earth's auroral region are discussed. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1780531]

I. INTRODUCTION

Magnetic-field-aligned currents have traditionally been invoked to explain satellite observations of plasma waves near the ion gyrofrequency Ω_i in the Earth's auroral region. The excitation of ion-cyclotron waves has received considerable attention because they provide an efficient mechanism for energization of cold ionospheric ions perpendicular to the Earth's magnetic field.[1] Subsequently, these ions are driven upward along the Earth's diverging magnetic field lines by the mirror force, converting some of their perpendicular energy into parallel energy forming ion beams and conic distributions. These transversely accelerated ions of ionospheric origin ultimately make their way deep into the magnetosphere, accounting for a significant population of hot magnetospheric ions.[2] Electrostatic ion-cyclotron (EIC) waves have also been discussed as a possible mechanism for the formation of V-shaped electric potential structures in the auroral ionosphere.[3] V-shaped potential structures in the auroral zone, connected directly to the Earthward acceleration of auroral electrons, have been observed simultaneously with EIC waves.[4]

Recently, in a departure from the traditional notion that the origin of ion-cyclotron waves in the auroral region is due to magnetic-field-aligned currents,[5] Gavrishchaka *et al.*[6] and Ganguli *et al.*[7] suggested that EIC waves could grow in a plasma with zero electron current, provided that transverse gradients in the ion flow along the magnetic field are taken into account. (For simplicity, we refer to this as ion flow shear.) This reexamination of the origin of the ion-cyclotron waves in the auroral ionosphere was due, in part, to the availability of new *in situ* measurements, particularly with the FAST satellite, showing the presence of intense and localized ion flows with ion flow gradients $dV_{di}/dx \sim (1-5)\Omega_{O+}$ in the direction transverse to the magnetic field.[8]

The theoretical prediction that ion flows with transverse shear might play an important role in the excitation of ion-cyclotron waves prompted new experiments to be performed which specifically investigated the effect of ion flow shear on the excitation of EIC waves.[9,10] These laboratory experiments are very useful in elucidating the detailed physical mechanisms that are thought to be operating in the space environments, and are not subject to the challenges of dealing with the well-known space-time ambiguities inherent in making *in situ* measurements with spacecrafts.[8] Although these experiments established that ion flow with shear does play a role in destabilizing EIC waves, a key feature of the experiments was the presence of parallel electron drift V_{de} (field-aligned current), so that no conclusions could be drawn about the role of shear *in the absence of current*. It should be emphasized that according to theory,[7] ion flow shear alone (in the absence of electron drift) can support ion-cyclotron waves. As Ganguli *et al.*[7] showed in their calculations based on the solution of the Vlasov equation, the presence of the ion flow shear can change the sign of the (cyclotron) damping term in the expression for the instability growth rate, thus providing a different mechanism (inverse cyclotron damping) for EIC wave growth. They also show that since the critical shear is approximately independent of the ion-cyclotron wave harmonic number, the presence of shear can also generate higher cyclotron harmonics. Discrete harmonic features at multiples of the proton cyclotron frequency are also common signatures of observations in the auroral ionosphere.[11]

Excitation of EIC waves in plasmas having parallel ion flow shear and no electron current has also been noted in theoretical calculations based entirely on the fluid equations for the electrons and ions.[12] Scime *et al.*[13] have also shown theoretically that EIC waves can be driven in a currentless plasma, if there is anisotropy in the ion temperature in the directions parallel and perpendicular to the magnetic field.

In this paper we report results of an experimental investigation designed specifically to test the most notable feature of the theoretical model,[7] namely, that in a currentless ($V_{de} = 0$) plasma the presence of an ion flow shear can promote the growth of ion-cyclotron waves via inverse cyclotron damping. Our approach was to launch an ion-cyclotron wave from an antenna into a currentless plasma and follow its

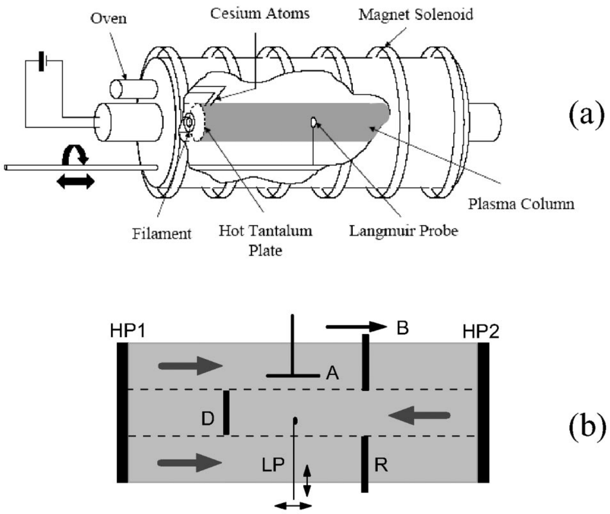

FIG. 1. (a) Cutaway view of the *Q* machine showing the hot plate ionizer, atomic beam oven, solenoid coils and Langmuir probe. (b) Details of the configuration used to produce inhomogeneous parallel ion flow. The ring *R* and disk *D* are used to create an annular region (dashed lines) in which a transverse gradient in the ion flow is present. EIC waves are launched from an antenna *A* and detected by a Langmuir probe LP.

evolution as it propagated into a region containing ion flow shear. We provide evidence indicating that the EIC waves are amplified only as they pass through the region of the plasma containing ion flow shear and not otherwise.

The experimental setup is described in Sec. II and the results are presented in Sec. III. A discussion of the results is given in Sec. IV, with the conclusions in Sec. V

II. EXPERIMENTAL SETUP

The experiments were performed in a double-ended *Q* machine[14] shown schematically in Fig. 1(a). The plasma sources consist of two 6 cm diameter tantalum plates (HP1 and HP2) separated by 2 m longitudinally. Each hot plate is heated from behind by electron bombardment to a temperature of ≈2200 K. Two cesium atomic beam ovens provide neutral Cs atoms that are directed onto the hot plates where they undergo surface ionization. Together with the thermionically emitted electrons, the Cs^+ ions are confined radially by a uniform magnetic field typically in the range of 0.2–0.4 T. The plasma density and electron temperature (measured with a Langmuir disk probe) are typically, $n_i = n_e \sim 10^{10}\ \mathrm{cm}^{-3}$ and $T_e \sim T_i \sim 0.2$ eV. At a magnetic field of 0.3 T, a 0.2 eV Cs^+ ion has a gyroradius of 1.8 mm, so that there are roughly 15 ion gyrodiameters contained within the plasma column.

Ions produced on either hot plate are accelerated along the magnetic field by the ~2–3 V potential drop that is present in the sheaths at the hot plates. In double-ended operation, the net bulk ion flow can be controlled by adjusting the temperatures on the hot plates. For example, by appropriate adjustment of the heating power to each plate the sources can be balanced so that no net flow results. To produce a configuration with parallel velocity shear (flow with a transverse velocity gradient), the "ring and disk" configuration was used, as shown in Fig. 1(b). At one plasma cross section a metal ring *R* of 8 cm outer diameter and 2.3 cm inner diameter was located and at another plasma cross section a metal disk *D* of 2.2 cm diameter. When both the ring and disk are biased a few volts negative to collect essentially the full ion current, a counter streaming exists in the plasma between the inner core and outer cylindrical shell. Previous measurements of the radial profile of the ion fluxes taken with a double-sided Langmuir probe indicated that the typical width of the shear region was several ion gyroradii.[15] The ring and disk are always biased at the same potential so that no radial electric fields are introduced into the plasma. The lack of radial electric fields in the region of velocity shear is confirmed by Langmuir probe measurements of the radial plasma potential profiles. This ring+disk configuration is the same as that used by D'Angelo and von Goeler[16] to excite the low frequency parallel velocity shear instability. The observation of this low frequency instability ($f \sim 1-2$ kHz) with maximum amplitude in the annular region near the edge of the disk is used as a direct indication of the presence of parallel velocity shear. The low frequency mode is not present if ring+disk bias is raised to >-1 V.

We used an antenna to launch EIC waves into the plasma and measured their amplitude at various radial positions as they propagated through the regions of transverse velocity shear. The antenna *A* in Fig. 1(b) consisted of a rectangular stainless-steel strip 5 cm in length and 1 cm wide which was inserted through a radial port and oriented with its length parallel to the magnetic field (the normal to the plane of the antenna being perpendicular to $\mathbf{B}$). The radial position of the antenna was adjustable. Either a variable frequency rf sine wave signal of several volts or a broadband (white noise) signal was applied to the antenna. The waves were detected using the floating potential oscillations of a disk-shaped Langmuir probe of 0.8 mm radius. The probe could be located at any axial position between the two hot plates and it could also be rotated in an arc across the plasma column to sample different radial positions.

III. EXPERIMENTAL RESULTS

A. Single mode amplification

In the first series of measurements the magnetic field was set at 3000 G with a resulting cesium ion gyrofrequency of $\Omega_i/2\pi = 32$ kHz. The antenna was positioned radially roughly 2 mm outside of the velocity shear region [horizontal dashed lines in Fig. 1(b)] and an input signal of frequency $f_{in} = 34$ kHz was applied to launch the fundamental electrostatic ion-cyclotron mode. The EIC wave propagated across the magnetic field, and at various radial positions in the plasma cross section coincident with the center of the antenna, spectra of the oscillations of the floating potential of a Langmuir probe were obtained. The results of these measurements are shown in Fig. 2. In Fig. 2(a) the radial dependence ($\mathbf{r} = 0$ corresponding to the plasma center) of the amplitude of the EIC fundamental mode is shown. The dashed line is the amplitude for the case in which the ring+disk were biased at $V_{RD} = -0.8$ V, in which there is no ion flow shear. In this case, in the absence of shear, the EIC amplitude decreases as the probe is moved away from the antenna which was lo-

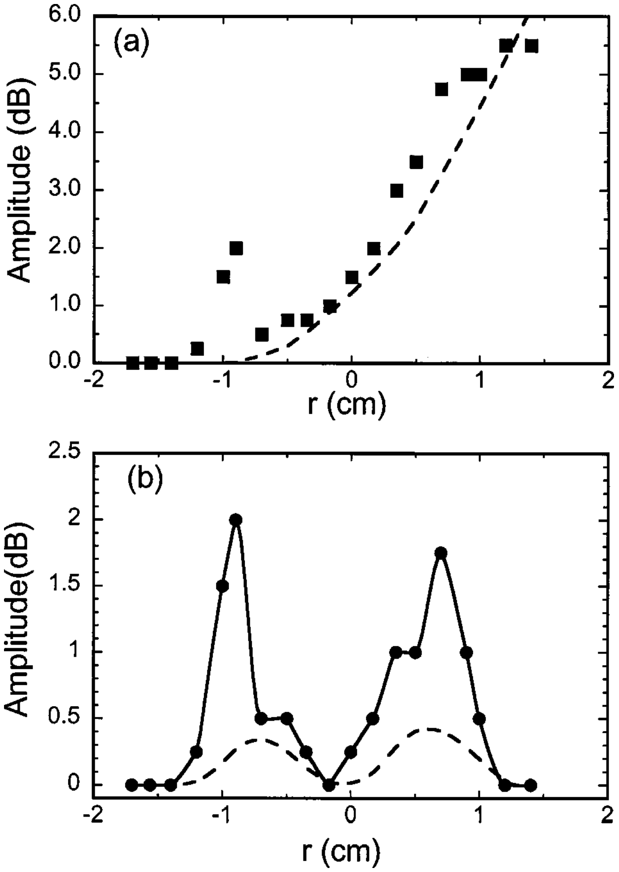

FIG. 2. (a) Amplitude of the fundamental EIC mode as a function of radial position across the plasma column in the presence of ion flow shear (■). The dashed line is the amplitude of the EIC mode in the absence of ion flow shear. (b) The difference (solid line with ●) in EIC wave amplitude with and without ion flow shear [from the data in (a)]. The dashed line is the amplitude (reduced by a factor of 20) of the low frequency instability excited by the parallel ion flow shear. Maximum low frequency wave amplitude occurs at the radial positions of strong ion flow shear. The observed amplification of the EIC waves coincides with the regions of strong ion flow shear.

cated at $\mathbf{r}=1.5$ cm. However, when the ring+disk were biased at $V_{RD}=-4$V, to produce parallel flow with transverse shear, the amplitude measurements (solid squares) showed clear enhancements (amplification) at the radial positions where the shear is present. This point is further illustrated by plotting, in Fig. 2(b), the difference in amplitude between the cases with and without shear (solid line). Figure 2(b) also shows (dashed line) a plot of the amplitude of the low frequency (1–2 kHz) waves of the type first observed by D'Angelo and von Goeler,[16] which are excited by the velocity shear. The positions of maximum amplitude of the low frequency waves coincide with the regions of strong velocity shear. Thus the amplification of the EIC waves is clearly related to the presence of parallel ion flow shear.

The results presented in Fig. 2 were repeated using an input frequency corresponding to the first cyclotron harmonic $f=2f_{ci}$ with essentially identical results, i.e., amplification of the wave in the region of velocity shear. Amplification at higher harmonics was also investigated for input frequencies up to 200 kHz. For this measurement, the probe was fixed in the region of velocity shear, and a signal of continuously increasing frequency was applied to the antenna using the tracking generator of a spectrum analyzer. As the frequency of the applied signal was slowly increased, the amplitude of the signal on the probe at each frequency was recorded, and the resulting spectrum is shown in Fig. 3. The response of the plasma occurs in relatively narrow spectral features near the ion gyrofrequency and its harmonics. The spectral peaks are superimposed on the background plasma noise. The peaks are broader for the higher harmonics. This type of harmonic spectrum is very similar to that observed on the FAST spacecraft [see Fig. 1(f) of Ref. 6].

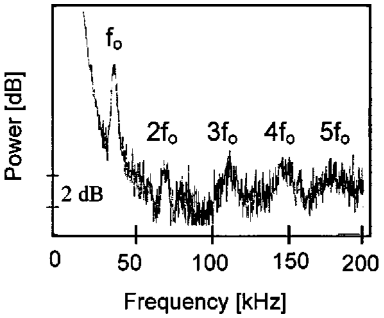

FIG. 3. Multiple harmonic ion-cyclotron wave spectrum observed as the input frequency is swept up to 200 kHz. f_o is the fundamental EIC frequency.

B. Simultaneous amplification of multiple cyclotron harmonics

The measurement of Fig. 3 shows the amplification of individual cyclotron harmonics as the input frequency is swept up to 200 kHz. We also investigated the effect of applying a broadband input signal to the antenna. In this case, input power is simultaneously applied at all cyclotron harmonics up to several hundred kilohertz. A reversed bias emitter-base junction transistor was used as the noise source. To provide sufficient power, the output was fed to a rf amplifier [see the inset in Fig. 4(b)]. This produced a broadband white noise signal that was relatively flat from about a few kilohertz up to about 1 MHz. This signal was applied to the antenna and the spectrum of floating potential oscillations on the probe located in the shear region was obtained. Figure 4(a) represents the background plasma noise spectrum for the case in which there is no flow shear and no signal applied to the antenna. However, when the ring+disk were biased to produce shear and the broadband signal was applied to the antenna, the spectrum in Fig. 4(b) was obtained, showing that there is a simultaneous amplification of the fundamental EIC mode and four harmonics.

IV. DISCUSSION

The results shown in Fig. 2(b) clearly show that EIC waves are amplified in the region of ion flow shear. Since there is no electron current in the plasmas or significant radial electric fields in the ion shear layer, it seems reasonable to conclude that the mechanism of EIC growth must be related to the presence of the ion flow shear. Ganguli *et al.*,[7] have shown that ion flow shear can provide an alternative mechanism to field-aligned currents for exciting electrostatic

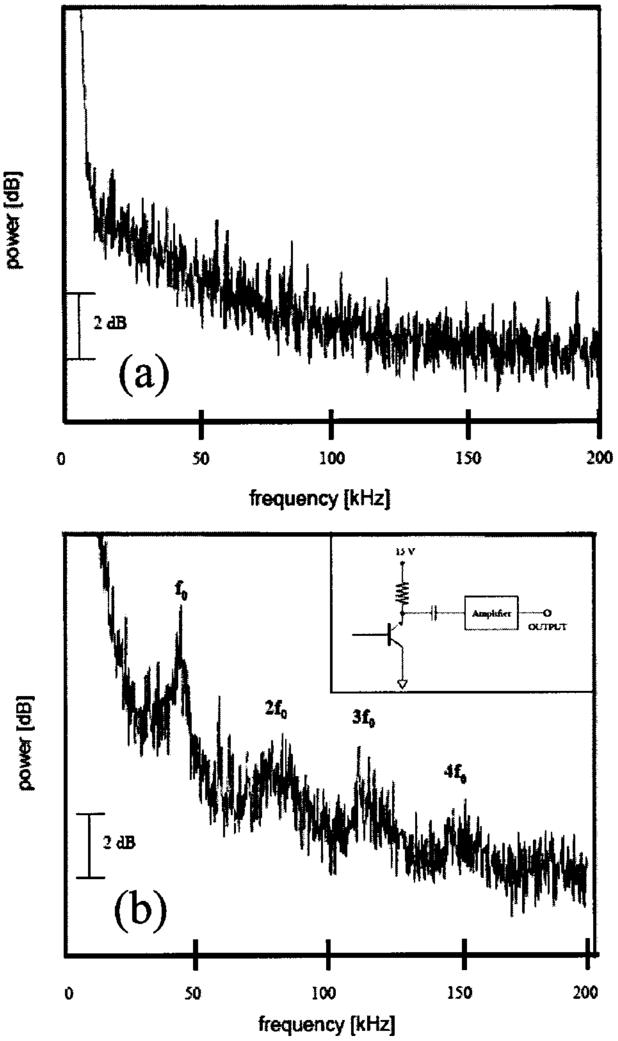

FIG. 4. Excitation of multiple cyclotron harmonics using a broadband input signal. (a) Spectrum of background plasma noise in the absence of ion flow shear and with no applied signal to the antenna. (b) Multiple cyclotron harmonic spectrum observed in the presence of ion flow shear when a broadband signal is applied to the antenna. The inset in (b) shows the circuit used to generate the white noise spectrum.

ion-cyclotron waves. The excitation of multiple cyclotron harmonics is also possible. Magnetic-field-aligned ion flow shear is a free energy source that can drive EIC waves in the presence of subcritical electron drifts or no electron drift at all (currentless plasma).

A necessary condition for ion cyclotron instability in the presence of ion flow shear is that the quantity $A \equiv (1 - n\Omega_i/\omega)(k_y/k_z)S > 1$, where $S \equiv (1/\Omega_i)(dv_{iz}/dx)$, n is the EIC harmonic number, Ω_i is the ion cyclotron frequency, ω is the mode frequency, dv_{iz}/dx is the transverse gradient of the ion flow velocity, v_{iz} along the magnetic field, and k_y and k_z are the wave numbers in the y and z directions, respectively.[7] In this analysis, the magnetic field and the ion flow are both along the z direction and the ion flow velocity varies in the direction perpendicular to $\mathbf{B}$, i.e., $v_{iz} = v_{iz}(x)\hat{z}$. The x and y directions correspond, respectively, in the experiment to the radial and azimuthal directions. Most of the physics is in the shear layer, which is much smaller than the plasma scale, and hence the cylindrical geometry should not affect the physics in any significant way.

Our focus here is to understand the basic physics associated with the ion shear flow instability. We would like to show now that the instability condition $A > 1$ is very likely to be satisfied in our experiment. The transverse velocity gradient $dv_{iz}/dx \sim \Delta v_{iz}/L_s$, where Δv_{iz} is the difference in the ion flow velocity across the shear layer and L_s is the scale length of the shear. Since the ions are flowing in opposite directions across the shear layer we take $\Delta v_{iz} \approx 2v_{iz}$. The Cs^+ ions are accelerated into the plasma through a roughly −3.5 V sheath at each hot plate and thus $v_{iz} \approx 2250$ m/s. The scale of the shear layer is on the order of a few ion gyroradii, $L_s \approx 4\rho_i$. Then, $S \approx (2v_{iz})/(4\Omega_i\rho_i) = (v_{iz}/2v_{i,\mathrm{th}})$ where we have used $\rho_i = v_{i,\mathrm{th}}/\Omega_i$, where $v_{i,\mathrm{th}} = (kT_i/m_i)^{1/2}$ is the ion thermal velocity. Now with $v_{i,\mathrm{th}} = 380$ m/s ($T_i = 0.2$ eV) we find that $S \approx (2250 \text{ m/s})/(2 \times 380 \text{ m/s}) \approx 3$. The frequency of the EIC wave is typically $\omega \approx 1.2\Omega_i$, so collecting the various quantities $A \approx (1 - 1/1.2)(k_y/k_z)(3) \approx 0.5(k_y/k_z)$. We estimate that the ratio k_y/k_z of the azimuthal to axial wave numbers is no smaller than about 2. For an antenna length of 5 cm, we expect the axial wavelength to be at least 10 cm and probably much larger. For the lowest $(m=1)$ azimuthal mode, the wavelength would be about 6 cm. Then $k_y/k_z \geqslant 2$. For higher azimuthal mode numbers and longer axial wavelengths the quantity k_y/k_z would be much larger than 2, in which case $A > 1$ is easily achieved.

Given these estimates, which suggest that the instability criterion is met in our experiment, the likely interpretation of the results is as follows. In the absence of either parallel current or inhomogeneous parallel ion flow, EIC waves launched from the antenna would be damped as they propagate across the plasma, as shown by the dashed line in Fig. 2(a). However, when there is a spatial region of parallel ion flow shear, the EIC waves can couple to this free energy source and grow, presumably acquiring an azimuthal propagation component k_y. Ideally, the azimuthal and axial k's would be measured, however, this has not been possible due to the relatively small dimensions of the region of ion flow shear.

V. CONCLUSIONS

In summary, we have observed amplification of multiple harmonic ion-cyclotron waves launched into a plasma with parallel ion flow shear but no electron current. The observed amplification is consistent with a theoretical model predicting wave growth, in the absence of current, by inverse cyclotron damping. The measurements showing amplification of *multiple* cyclotron harmonics is also in agreement with the prediction that the excitation conditions are independent of harmonic number.[7] The ability to explain the excitation of multiple cyclotron harmonics is a novel and important feature of the theory, since field aligned electron drifts in the auroral region are almost never sufficiently large to produce multiple harmonics. Furthermore, although the spontaneous generation of EIC waves in the auroral region is well established, the results in Fig. 4 suggest that it may be possible that broadband noise of magnetospheric origin transported into the ionosphere may be amplified at the cyclotron harmonics as it encounters regions of ion flow shear, and manifests itself as locally excited EIC waves.

This laboratory study fortifies the argument that the nonuniform nature of plasmas can play a decisive role in determining their stability, especially under conditions in which the traditionally considered instability mechanisms (viz., field aligned currents) are not present.

Finally, we note that recent measurements using the CLUSTER spacecrafts in the high latitude cusp frequently showed the presence of peaks in the power spectrum close to the local ion-cyclotron frequency.[17] It was suggested that these waves might be connected to the presence of highly filamented plasma flows that are present in the cusp region. Although these were observations of electromagnetic waves, it is possible that the mechanism of Ganguli *et al.*,[7] might also account for the observations. Theoretical work is now under way to study the effects of ion flow shear on electromagnetic ion-cyclotron waves.

ACKNOWLEDGMENTS

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