Observation of Inverse Ion-Cyclotron Damping Induced by Parallel-Velocity Shear

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The generation of broadband multiharmonic spectra of electrostatic ion-cyclotron waves is demonstrated in a magnetized laboratory plasma in which shear in the magnetic-field-aligned (parallel) ion flow and a relative parallel electron drift are present. Shear correlates with an increased number of harmonics and a decreased electron drift speed. Wave and particle measurements indicate that cyclotron damping is reduced and even becomes negative. The fluctuations in the time domain are spiky, similar to electric-field fluctuations observed both in Earth's auroral zone and in numerical simulations.

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The discovery long ago of unstable ion-cyclotron waves represents a major advance in plasma physics [1]. The ion-cyclotron resonance can support one of the most important oscillating modes in magnetized plasma and can be exploited to efficiently transfer energy from electric or magnetic-field fluctuations to the ions by the well-known process of ion-cyclotron damping. Electrostatic ion-cyclotron waves are a common feature of ionospheric plasmas, and determining the mechanism of exciting these waves is an active area of research [2]. Multiscale coherent structures and broadband waves observed by the Fast Auroral Snapshot (FAST) satellite have been interpreted with a new mechanism for exciting electrostatic ion-cyclotron waves [3]. This mechanism involves a reduction of ion-cyclotron damping and requires shear (dv_{di}/dx) in the magnetic-field-aligned (parallel) drift velocity $\mathbf{v}_{di} = v_{di}(x)\hat{z}$ of the ions. Ganguli *et al.* [4] express the parallel-velocity shear dependence of the ion-cyclotron damping term in terms of a damping factor $[1 - \{k_y dv_{di}/dx/(k_z\omega_{ci})\}(1 - n\omega_{ci}/\omega_r)]$ that is unity in the absence of shear, small and positive when shear contributes to the reduction of ion-cyclotron damping, and negative when shear is responsible, at least partly, for ion-cyclotron growth, i.e., inverse ion-cyclotron damping. The shear-induced reduction or inversion of ion-cyclotron damping is shown to significantly decrease the excitation-threshold value of electron drift velocity for numerous ion-cyclotron harmonics $(\omega_r \approx n\omega_{ci})$, where ω_r is the real frequency in the ion frame, n is the harmonic number, ω_{ci} is the ion gyrofrequency, and $k_z(k_y)$ is the parallel (perpendicular) component of the wave vector. In this Letter, we verify the theoretical model of multiharmonic ion-cyclotron waves with direct measurements of the waves and quantities contained within the damping factor.

The experiment is performed in a single-ended Q machine [5,6]. The magnetized plasma column (6.4-cm diameter, 3-m length, 10^9 cm^{-3} density) is bounded on one end by an ionizer at electrical ground that thermionically emits electrons ($T_e \approx 0.33$ eV) and contact ionizes barium ions ($T_{iz} \approx 0.23$ eV, $T_{iy} \approx 0.36$ eV). The other end is bounded by a biased termination electrode. A positively biased annular electrode (3.5 cm outer diameter) is placed 30 cm from the termination electrode and centered on the cylindrical axis.

Both electrons and ions drift from the ionizer toward the electrodes. The magnetic field can be switched to be parallel or antiparallel to the drifts. To connect the experiment's cylindrical geometry to the slab geometry used in the model, z corresponds to the direction of the magnetic field, x to the radial direction, and y to the azimuthal direction with positive being clockwise (counterclockwise) looking parallel (antiparallel) to the magnetic field. The value of k_z is measured using a two-Langmuir-probe array (separation 3 mm) whose tip-to-tip vector's orientation with respect to the magnetic field can be varied 360° by rotating the radially translatable, radially aligned shaft on which the two-tip array is mounted perpendicularly. The uncertainty in initially referencing the array to the magnetic field $(< \pm 1.6°)$ is an order-of magnitude larger than the uncertainty in subsequently referencing one array orientation to another, and is the dominant contribution to the uncertainty in k_z. Parallel-velocity shear is produced and controlled by adjusting the bias V_T on the termination electrode while keeping the bias V_0 on the annular electrode fixed, typically at 35 V.

The ion velocity distribution function parallel to the magnetic field is measured directly, nonperturbatively, and precisely by laser-induced fluorescence techniques [7], as adapted from the method of Hill *et al.* [8]. A hollow-cathode lamp is used for zero-velocity reference. We observe a single drifting-Maxwellian ion population with an adjustable degree of parallel-velocity shear. Shear increases with decreasing bias on the termination electrode. For bias values in the range $V_0 - V_T < 25$ V, the parallel-velocity shear is negligible. Here, we present examples in a range of shear values $dv_{di}/dx = 0 - 25$ kHz $= 0 - 0.2\omega_{ci}$, where the largest-shear case corresponds to $dv_{di}/dx = 0.2\omega_{ci}$ for $V_0 - V_T = 45$ V at a 0.2-T magnetic field.

The plasma potential, measured using a floating emissive probe, is approximately -2.5 V. The radial electric field in the plasma is adjusted to be negligible ($|E_r| <$ 10 V/m) and homogeneous so that the perpendicular ion drift speed is negligible compared to the ion thermal speed. The electron velocity distribution function parallel to the magnetic field is measured with a single-sided Langmuir probe [9,10]. We observe a single, drifting-Maxwellian population of electrons with a uniform parallel drift speed v_{de}. The absence of electron velocity shear means that the ion shear in the electron frame $(dv_{di}/dx)_e$, the electron shear in the ion frame $(dv_{de}/dx)_i$, and the ion shear in the lab frame dv_{di}/dx have identical magnitudes.

We begin with the no-shear case in which we observe ion-cyclotron waves with no harmonics having amplitude within 1.5 orders of magnitude of the fundamental. From this starting point, we increment the shear in a number of ways. Taking a step toward increased shear from zero when the shear has the incorrect sign damps the fundamental, as expected by theory. Taking a step toward increased shear from zero when the shear has the correct sign reduces the electron drift's excitation-threshold for both the ion-cyclotron-wave fundamental and its harmonics. A further step toward increased shear, keeping k_z approximately constant, further reduces the excitation threshold and changes the sign of the ion-cyclotron damping factor.

Figure 1 shows the radial profile of the axial ion drift velocity $v_{di}(x)$ for one case of negligible shear and two cases of intermediate shear. For curve 1(a), $V_0 - V_T =$ 20 V and the parallel-velocity shear is negligible. Curve 1(b) corresponds to the case in which the annular electrode ($V_0 - V_T = 35$ V) produces intermediate positive shear. Curve 1(c) corresponds to the case in which we substitute a 2.5-cm-diameter circular button electrode for the annular electrode and produce intermediate positive shear (also $V_0 - V_T = 35$ V). Note that curves 1(b) and 1(c) look very similar, except that the annular case is associated with a slightly wider central depression in the profile due to the electrode's slightly larger outer diameter.

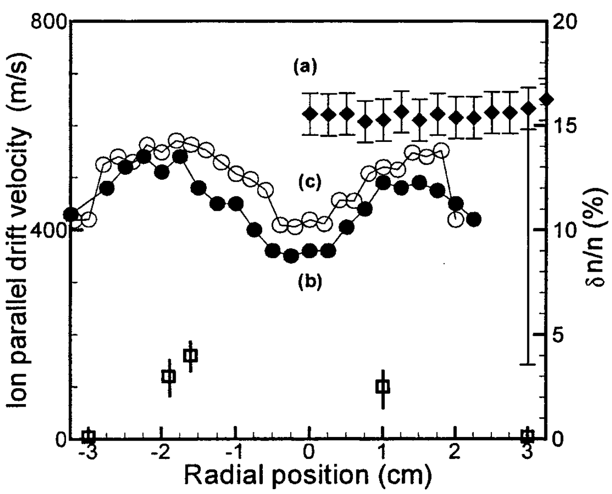

FIG. 1. Laser-induced fluorescence measurement of the radial profile of barium-ion parallel drift velocity, representative of (a) negligible shear using either annular or button electrode (here, button with $V_0 = 20$ V, $V_T = 0$, $B = 1.4$ kG), (b) nonzero shear using annulus ($V_0 = 35$ V, $V_T = 0$, $B = 2$ kG, and (c) nonzero shear using button ($V_0 = 35$ V, $V_T = 0$, $B =$ 2 kG). The long error bar at the right of (a) represents the ion thermal speed for all data (i.e., T_i is uniform). The squares are probe measurements of mode amplitude (right-hand scale).

In the absence of ion parallel-velocity shear [see Fig. 1(a),], ion-cyclotron waves have a relatively large excitation threshold of $(v_{de})_{\rm crit} \approx 60$ km/s $(= 120 v_{ti})$, consistent with the prediction $[(v_{de})_{\rm crit} = 150 v_{ti}]$ of Drummond and Rosenbluth [11] for the current driven electrostatic ion-cyclotron instability [12]. This linear-theory threshold corresponds to a balance between inverse electron Landau damping γ_e (> 0), which is proportional to $(k_z v_{de}/\omega_r - 1)$, and ion-cyclotron damping γ_i (<0), which is negative and proportional to the previously mentioned damping factor, where $\gamma_{\rm net} = \gamma_e + \gamma_i$. When the shear is negligible, the mode amplitude is zero, even if the electron drift is $v_{de} = 100 v_{ti}$, only slightly lower than the experimentally determined critical value $(v_{de})_{\rm crit} =$ $120 v_{ti}$. In the presence of intermediate values of both positive shear ($dv_{di}/dx = 0.14\omega_{ci}$) and positive electron drift ($v_{de} = 75 v_{ti}$), we observe multiharmonic ion-cyclotron waves. In the presence of large positive parallel-velocity shear ($dv_{di}/dx = 0.2\omega_{ci}$), multiharmonic ion-cyclotron waves arise at perhaps negligible, but certainly small, values of parallel electron drift velocity $v_{de} =$ 9 km/s $(= 18 v_{ti})$ relative to both 60 km/s and the excitation-threshold predicted by homogeneous-plasma theory for the measured characteristics of the observed multiharmonic ion-cyclotron waves. This reduced excitation threshold is expected since the presence of the parallel-velocity shear increases γ_i for the fundamental and the harmonics, thereby requiring smaller values of v_{de} to achieve $\gamma_{\rm net} = 0$. Always the waves are found to propagate in the same direction as the electron drift velocity ($k_z v_{de} >$ 0) such that $\omega_r / k_z v_{de} < 1$, i.e., always in the inverse electron Landau damping regime, even though the waves' reliance on this inverse damping significantly decreases with increasing shear. The waves are found localized within the shear layer where they propagate azimuthally with azimuthal mode structure described by $\exp(i3\theta)$.

Measurements of the parameters within the ion-cyclotron damping factor provide experimental documentation of the shear dependence of this factor. Each of the experimentally determined values of ω_r incorporate a Doppler shift $k_z v_{di}$ between the frequency $\omega_{\rm lab}$ measured in the laboratory frame and the real frequency ω_r in the flowing ion frame ($\omega_r = \omega_{\rm lab} - k_z v_{di}$). In one case, $dv_{di}/dx = (0.10 \pm 0.02)\omega_{ci}$, $k_y/k_z = (-2.71 \pm 0.01)$ cm^{-1}/(0.04 ± 0.005) cm^{-1} $= -67 \pm 6.5$, and $\omega_r/\omega_{ci} = (162.3 \pm 3)$ kHz/(172.7 ± 2.4) kHz $= 0.930 \pm 0.003$, so that the factor is 0.61 ± 0.12. For larger shear $dv_{di}/dx = (0.13 \pm 0.03)\omega_{ci}$, we measure $k_y/k_z =$ (-2.92 ± 0.01) cm^{-1}/(0.045 ± 0.005) cm^{-1} $= -65 \pm 7$, and $\omega_r/\omega_{ci} = (159.8 \pm 3)$ kHz/(172.7 ± 2.4) kHz $=$ 0.93 ± 0.003, so that the factor is 0.41 ± 0.16. This demonstrates that for fixed values of k_y/k_z and ω_r/ω_{ci}, increasing shear results in decreasing ion-cyclotron damping.

For ion-cyclotron damping to be reduced, the quantity $\{k_y dv_{di}/dx/(k_z \omega_{ci})\}(1 - n\omega_{ci}/\omega_r)$ must be positive. When $\omega_r/\omega_{ci} = 0.920 \pm 0.003 < 1$, we always observe $k_y/k_z < 0$, and $dv_{di}/dx > 0$, consistent with this requirement. When $\omega_r/\omega_{ci} = 1.050 \pm 0.005 > 1$, we always observe $k_y/k_z > 0$, and $dv_{di}/dx > 0$, and the requirement remains satisfied. In these cases, k_z and v_{de} remain positive, i.e., parallel to the magnetic field, and the value of k_y (k_z) changes (maintains) its sign as $(1 - n\omega_{ci}/\omega_r)$ changes sign, a unique observational signature of the shear ion-cyclotron instability.

For slightly larger shear, the ion-cyclotron damping factor is negative so that ion-cyclotron growth can lend support to the waves. Typical values of the damping factor for different spectral features corresponding to intermediate-shear cases are −0.32, −0.26, −0.19, and −0.25 for $n = 1$ through $n = 4$, respectively. These negative values of the damping factor are based on the following measured values of the important parameters, $dv_{di}/dx = (0.14 \pm 0.02)\omega_{ci}$, $k_y/k_z = (-2.12 \pm 0.01)\ \text{cm}^{-1}/(0.024 \pm 0.005)\ \text{cm}^{-1} = -88 \pm 8$, and $\omega_r/\omega_{ci} = (156 \pm 5)\ \text{kHz}/(172.7 \pm 3.8)\ \text{kHz} = 0.903 \pm 0.006$ for $n = 1$; $k_y/k_z = (-2.35 \pm 0.02)\ \text{cm}^{-1}/(0.028 \pm 0.005)\ \text{cm}^{-1} = -84 \pm 8$ and $\omega_r/2\omega_{ci} = (312 \pm 12)\ \text{kHz}/(345.4 \pm 11)\ \text{kHz} = 00.902 \pm 0.006$ for $n = 2$; $k_y/k_z = (-2.06 \pm 0.03)\ \text{cm}^{-1}/(0.026 \pm 0.005)\ \text{cm}^{-1} = -79 \pm 7$, and $\omega_r/3\omega_{ci} = (468 \pm 14)\ \text{kHz}/(516 \pm 13)\ \text{kHz} = 0.906 \pm 0.006$ for $n = 3$; and $k_y/k_z = (-2.07 \pm 0.03)\ \text{cm}^{-1}/(0.025 \pm 0.005)\ \text{cm}^{-1} = -83 \pm 8$, and $\omega_r/4\omega_{ci} = (623 \pm 19)\ \text{kHz}/(691 \pm 18)\ \text{kHz} = 0.902 \pm 0.006$ for $n = 4$. As in the case of reduced damping, we have $k_z v_{de} > 0$ and $0 < \omega_r/k_z v_{de} < 1$ in our cases of inverse damping.

According to the model, the multiharmonic spectrum requires not only parallel-velocity shear but also a relatively large value of $(k_y \rho_i)^2$, with the number of harmonics increasing with increasing $(k_y \rho_i)^2$, where ρ_i is the ion gyroradius. From Fig. 2, we see that the number of harmonics within 1.5 orders of magnitude is one for the no-shear case and many more than one for the shear cases. Since the usual (no-shear) cyclotron damping increases with increasing harmonic number, preventing harmonics from arising, the multiharmonic structure is an important demonstration of reduced ion-cyclotron damping. For negligible shear, the damping factor is near unity and only a single dominant spectral feature is observed, as shown in Fig. 2(a). For this case, $(k_y \rho_i)^2 = (0.4 \pm 0.1)$, as expected from homogeneous-plasma theory. For more than an order-of-magnitude larger shear ($dv_{di}/dx = 0.12\omega_{ci}$), i.e., our intermediate-shear case, we have $(k_y \rho_i)^2 = (0.94 \pm 0.1)$ and the waves exhibit spectral features at 11 ion-cyclotron harmonics within the same 1.5 orders of signal magnitude, as shown in Figs. 2(bi) and 2(bii). The simultaneous appearance of multiple harmonics is expected since the critical value of the parallel-velocity shear for destabilizing the nth harmonic at a given value of v_{de} becomes independent of harmonic number n for large values of $(k_y \rho_i)^2$. In Figs. 2(bi) and 2(bii), we demonstrate that this harmonic structure exists both when the fundamental is below the ion-cyclotron frequency [Fig. 2(bi)] and when the fundamental is above the ion-cyclotron frequency [Fig. 2(bii)].

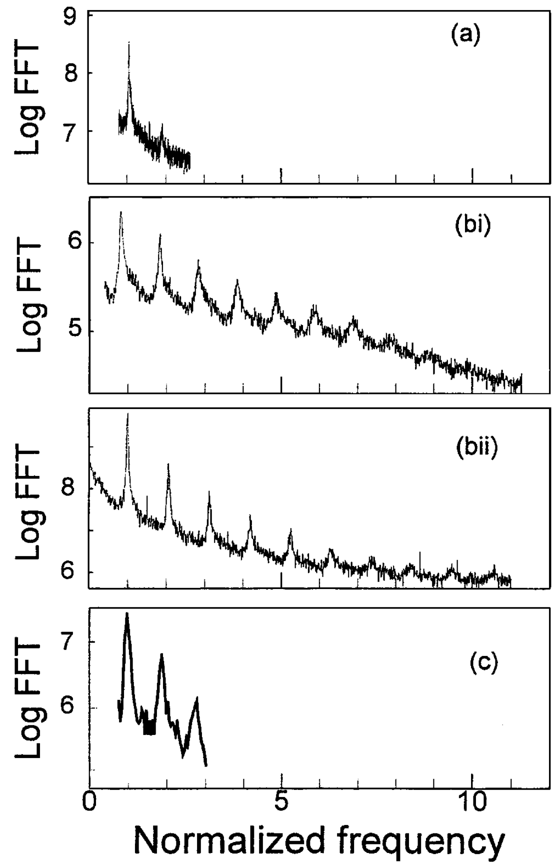

FIG. 2. Spectra (Log_{10} of fast-Fourier-transform amplitude, arbitrary units) of ion-saturation current fluctuations collected by (a) the electrode (negligible-shear case, $V_0 = 15$ V, $V_T = 0$, $B = 2$ kG), (bi) the annular electrode [nonzero-shear case, same as Fig. 1(b)], (bii) the Langmuir probe [same as previous case (bi)], and (c) the button-electrode [nonzero-shear case, same as Fig. 1(c)]. Notice that in case (bi) [case (bii)] the fundamental frequency is below (above) the ion gyrofrequency.

When the 2.5-cm-diameter, circular button electrode is substituted for the annular electrode, a similar spectrum is observed, as shown in Fig. 2(c), but at smaller mode amplitude. As in the annulus-electrode case, the spectral content of the waves depends on the shear; i.e., when there is no shear in the button-electrode case, there are no harmonics.

As shown in Fig. 3, the fluctuations in the time domain are spiky, similar to electric-field fluctuations observed both in Earth's auroral zone and in numerical simulations [3]. It is important to note that these multiharmonic ion-cyclotron waves do not appear for plasma conditions that do not meet the criterion $\{k_y dv_{di}/dx/(k_z \omega_{ci})\}(1 - n\omega_{ci}/\omega_r) > 0$. Specifically, when we reverse the magnetic field so that it is antiparallel to the particle drift velocities, these waves are not excited even when the parallel electron drift velocity is large ($v_{de} = 150 v_{ti}$) since, in this case

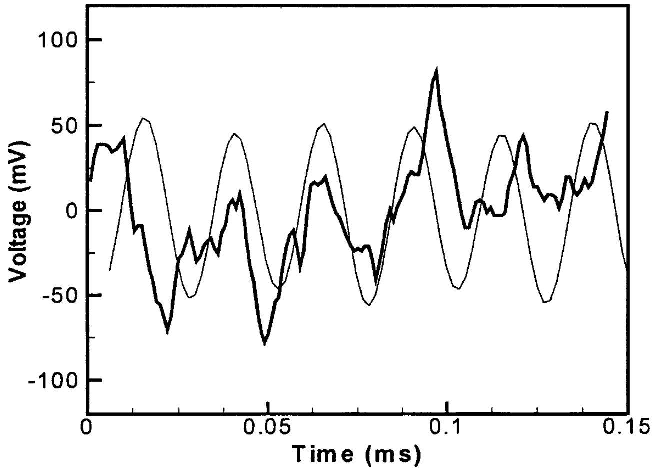

FIG. 3. Time series of fluctuations in ion-saturation current collected by annular electrode. Thick line is the intermediate-shear case, showing multiharmonic ion-cyclotron waves ($V_T = 0$, $V_0 = 35$ V, $B = 2.7$ kG) and, consequently, a more pulselike gyroperiodicity. The thin line is the negligible-shear case ($V_T = 0$, $V_0 = 15$ V, $B = 2.7$ kG), with sinusoidal gyroperiodicity.

($dv_{di}/dx < 0$), the shear effect leads to increased ion-cyclotron damping.

Electrostatic ion-cyclotron waves with multiharmonic spectra have been observed in laboratory and space plasmas [13]. Cases of both hydrogen-cyclotron and oxygen-cyclotron harmonics have been reported in space [3,14]. In an experiment involving a zenon ion beam injected from a satellite [15], up to 25 harmonics of the proton-cyclotron frequency were detected. At lower altitudes in the auroral region, electrostatic ion-cyclotron waves have a broadband featureless spectrum extending from below to many times above the proton-cyclotron frequency [16].

In conclusion, we verify the existence of multiharmonic ion-cyclotron waves and the model that describes the instability. We fully determine the propagation characteristics of these waves in the ion frame and document the shear dependence of the ion-cyclotron damping factor. Cases of reduced ion-cyclotron damping and ion-cyclotron growth are reported. With the wrong-sign shear, ion-cyclotron damping is enhanced compared to the zero-shear case, and the waves do not appear. In the correct-sign, large-shear case, the inverse electron Landau damping is perhaps negligible but certainly significantly smaller than in the zero-shear case and the inverse ion-cyclotron damping is the apparent dominant free energy. For negative $k_y(dv_{di}/dx)/(k_z\omega_{ci})$, we do not observe ion-cyclotron waves, but instead observe shear-modified ion-acoustic waves [17]. The mechanism of exciting multiharmonic ion-cyclotron waves via inverse ion-cyclotron damping induced by parallel-velocity shear resembles, but is not identical to, the ion-cyclotron maser mechanism [18]. These results may be relevant to observations of strong inhomogeneities in parallel current in Earth's s auroral region [19].

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