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# Identification of Ion-Cyclotron Drift Instability with Discrete and Continuous Spectra*

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Ion-cyclotron drift waves with discrete and continuous spectra are identified by measurements of $\omega$ and $\vec{k}$ and explained by a theory which includes parallel electron current. This instability has a spectrum and effects on the plasma similar to those of ion sound, and can exist in plasmas which are ion-sound stable.

Drift or universal instabilities[1] play an important role in plasma confinement and heating: Their excitation mechanisms are often inherent to plasma production and confinement, and their effects may dominate plasma behavior. Low-frequency ($\omega \ll \Omega_{ci}$), $\nabla n$-driven drift waves (DW) have been identified, described, and connected to plasma losses, in both the collisionless[2] and collisional[3] regimes. However, ion-cyclotron drift waves (ICDW; $\omega \simeq n\Omega_{ci}$), notwithstanding their theoretical analysis[4] many years ago and despite their significance for both the heating of plasmas and the generation of anomalous plasma resistance, have not been identified conclusively,[5] and observations of high-frequency ICDW ($\omega_{pi} > \omega \gg \Omega_{ci}$) with continuous, ion-sound-like spectra have not heretofore been reported.

The principal results of this work are the identification of discrete and continuous ICDW by measurements of $\omega$ and $\vec{k}$, and the explanation of these measurements in terms of a theory which includes parallel electron current ($k_z \neq 0$). Additional significance derives from the fact that a high-growth-rate instability with an ion-sound-like spectrum is destabilized in plasmas which are ion-sound stable ($T_e \lesssim T_i$). Moreover, the effects of ICDW on the plasma, ion heating, and anomalous resistivity are similar to those expected from ion sound. These latter results will be reported elsewhere.

The experiments were performed on the Princeton $Q$-1 thermally ionized potassium plasma,[3] 128 cm long and 3 cm in diameter, with $B$ in the range 1–7 kG. Collisions with neutrals are negligible. $T_e \lesssim T_i$, even in the presence of current, since the end plates act as electron-temperature sinks. Current is applied through the end plates parallel to $B$. Densities ($\lesssim 10^{11}$ cm$^{-3}$) were measured with microwave cavity and radially movable Langmuir probes; electron temperatures ($T_{e0} = 0.25$ eV) and drift velocities $u$ were determined with plane Langmuir probes which could be turned into and away from the current, thus permitting local measurements of $u$, $v_e$, $n$, and $j$ simultaneously. Double probes with wire separations of 1–20 mm were used to measure wavelength. The axes of the double probes were aligned parallel to the plasma radius. The probes could be moved radially and rotated about their axes. By measuring the correlation between the signals from both wires as a function of the angle of rotation, wavelengths $\lambda_y$ and $\lambda_z$ could be measured with good accuracy. The experiments benefit from the low electron temperature, which allows us to raise $u$ to $\sim\frac{1}{3}v_e$, for $\sim 0.1$ A, a small fraction of 1% of the end-plate emission. The plasma is electron rich, i.e., negatively charged, and electron-beam excitation of instabilities by the sheaths is thus not expected. In addition, Doppler shift due to $\vec{E}\times\vec{B}$ plasma rotation is negligible (except at the plasma edge, $r = 15$ mm) in comparison to the high azimuthal phase velocities.

The dispersion relation for a low-pressure, low-$\beta$ inhomogeneous plasma, for a slab model and including parallel electron current, is written

$$\epsilon(k,\omega) = 1 + \frac{k_{De}^2}{k^2}\left(1 + i\sqrt{\pi}\,\frac{\omega - k_z u - \omega_e^*}{k_z v_e}\right) + \frac{k_{Di}^2}{k^2}\left\{1 - \sum_n \frac{\omega - \omega_i^*}{\omega - n\Omega_{ci}} I_n(b)e^{-b}\left[1 - i\sqrt{\pi}\,\frac{\omega - n\Omega_{ci}}{k_z v_i}\exp\left(-\frac{(\omega - n\Omega_{ci})^2}{k_z^2 v_i^2}\right)\right]\right\}. \quad (1)$$

We have defined

$$\omega_{e,i}^* = \frac{k_y c T_{e,i}}{q_{e,i}B}\,\kappa = k_y v_{de,i}^*;\quad \kappa = n^{-1}\frac{\partial n}{\partial x},\quad b = k_y^2 \rho_i^2,$$

and assumed $(\omega - k_z u - \omega_e^*)/k_z v_e < 1$; $(\omega - n\Omega_{ci})/k_z v_i \gg 1$. For $\omega \simeq n\Omega_{ci}$, the real part of Eq. (1) gives the instability frequency

$$\omega = n\Omega_{ci}\left[1 + \frac{T_e}{T_i + T_e} I_n(z_i)e^{-b}\left(1 - \frac{k_y v_{di}^*}{n\Omega_{ci}}\right)\right]. \quad (2)$$

$v_{di}^*$ is the diamagnetic drift velocity of the ions. From the imaginary part of (1), we obtain parameter regimes for the instability (when $\Omega_{ci} \gg \omega_e^*, \omega_i^*$):

$$\left(1 - \frac{k_y v_{di}^*}{\omega}\right)\left(2 - \frac{k_z u + k_y v_{de}^*}{\omega}\right) < 0. \quad (3)$$

Two connections to previous theories can be made. Neglecting current and ion Landau damping, we recover the ICDW results of Mikhailovskii and Timofeev[4]; neglecting inhomogeneity, we recover the electrostatic ICW of Drummond and Rosenbluth[6] for the homogeneous plasma. The significant result of this calculation is that discrete ICDW are destabilized by parallel electron current even for $\omega_i^* < \Omega_{ci}$.

For $\omega_i^* > \Omega_{ci}$ and $k_y \rho_i \gg 1$, off-resonance solutions of the magnetic dispersion function[7] appear and the spectrum can become continuous, $\omega \sim \omega_e^*/(1 + k^2\lambda_e^2)$ for $\omega/k_y \sim v_i$. We note that collisional effects added to the theory may modify slightly the stability condition; experimentally no changes could be observed with variation of $\nu_{e-i}/\omega$. Temperature-gradient effects added to the theory do not change the propagation direction in the present situation; experimental variation of the temperature gradient of the ionizer did not affect the results. Current-gradient effects are expected to be small, since $(k_y/k_z\Omega_{ce})du/dr \ll 1$.

In the experiment, as the steady-state applied voltage is raised, so that $u \simeq v_e/10$, a wave with discrete frequency destabilizes ($\omega = 1.15\Omega_{ci}$). With further voltage increase, the instability develops harmonics and finally a continuous spectrum evolves similar to that of ion sound, with a peak at $\omega_{pi}/4$, Fig. 1. Historically, this important instability had been described first as ion sound and then as electrostatic ICW by Buchel'nikova and co-workers,[8] and later as ion-sound-like.[9]

Our measurements of local parallel electron drift velocity throughout the plasma indicated that ion sound should be stable for the measured temperature ratio[10] ($T_e/T_i < 1$, $u/v_e < \frac{1}{3}$). Moreover, the theory of the electrostatic ICW predicts a narrow band of unstable frequencies near $n\Omega_{ci}$, but no continuous spectrum. This dilemma was resolved by the observation of azimuthal propagation, which had not been determined before,

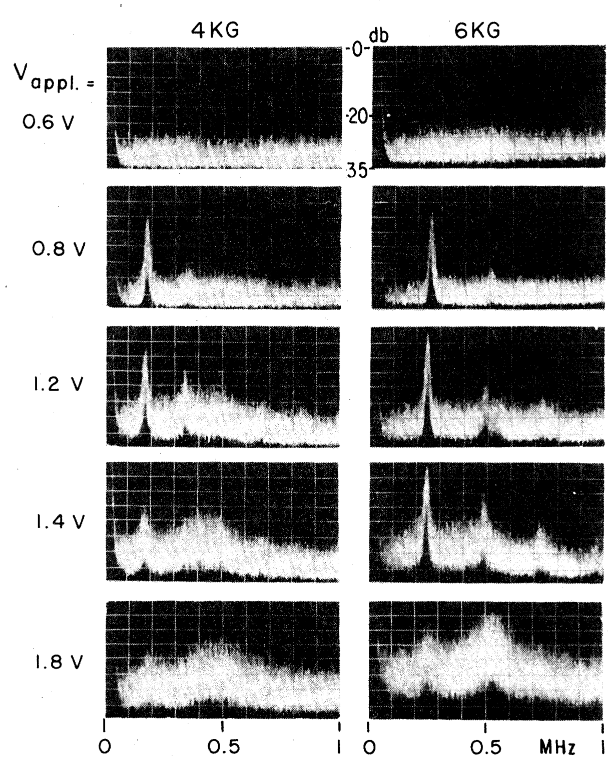


FIG. 1. Evolution of ICDW frequency spectrum versus applied voltage. $n = 0.6 \times 10^{10}$ cm$^{-3}$.

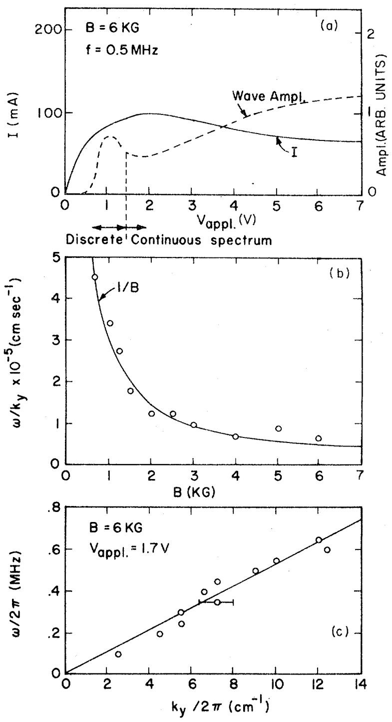


FIG. 2. Identification of instability. $n = 0.6\times10^{10}$ cm$^{-3}$. (a) Total current $I$ and wave amplitude versus $V_{\rm appl}$; (b) $\omega/k_y$ versus $B$, solid curve $\omega/k_y = v_{di}*$; (c) measured dispersion relation.

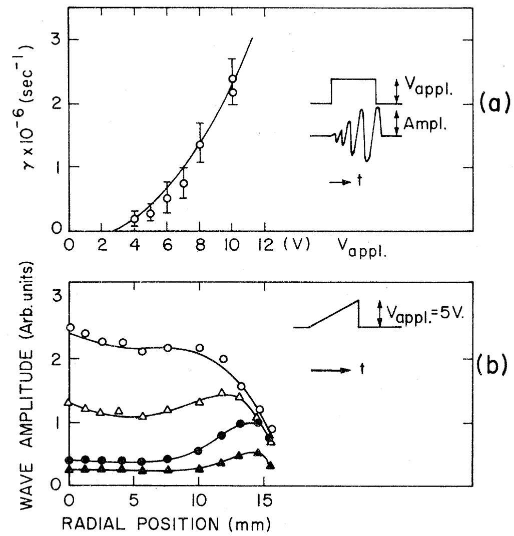


FIG. 3. Temporal growth of instability. $B = 4$ kG, $n = 1.5\times10^{10}$ cm$^{-3}$. (a) $\gamma$ versus $V_{\rm appl} \propto u$; pulse duration $\cong 50$ $\mu$sec. (b) Radial distribution of wave amplitude versus time; pulse duration $\simeq 50$ $\mu$sec. $t = 25$ $\mu$sec, filled triangles; 30 $\mu$sec, filled circles; 35 $\mu$sec, open triangles; 40 $\mu$sec, open circles.

indicating (diamagnetic) drift instability, due to the inhomogeneity.

In the discrete-spectrum regime, the azimuthal phase velocity was found to be in the direction of the ion diamagnetic drift, in agreement with Eq. (2). At onset, $k_y\rho_i \simeq 1.5$, as predicted for $\omega \gg \omega_i*$. In addition, we observe the frequency near the plasma edge ($r = 13$ mm, where Doppler shift by $\vec{E}\times\vec{B}$ rotation can be nelgected) to be less by 10% than that in the center, and the frequency to decrease with increased ion heating by the instability, both as predicted by Eq. (2). The parallel phase velocity in this regime was measured to be $\omega/k_z \simeq u/2$, indicating excitation by the parallel current.[6]

In the continuous-spectrum regime, as seen in the $I$-$V$ characteristic, Fig. 2(a), the instability generates strong anomalous resistivity and produces current inhibition. Figure 2(b) displays measured azimuthal phase velocity as a function of $B$ in the continuous-spectrum regime, $\omega/k_y = v_{di}* = cT_i\kappa/eB$, indicating a drift instability with opposite propagation direction to that resulting from Eq. (1). Figure 2(c) shows the measured dispersion relation $\omega$ versus $k_y$, for constant $B$, in agreement with $\omega = k_y v_{di}*$ ($k_y \ll k_{\rm De,Di}$). Parallel-phase-velocity measurements show $\omega/k_z > v_e$. This, together with measurements showing $\omega_i* > \Omega_{ci}$ and $\kappa\rho_i > 2\Omega_{ci}/\omega_i$ at the higher $V_{\rm appl}$, indicates destabilization of the non-current-driven ICDW of Ref. 4. The increase in $\omega_i*$ is mainly due to an increase of $k_y$ ($k_y\rho_i = 1.5 \rightarrow 20$) and to the ion heating generated by the discrete instability, since $\omega_i* \propto k_yT_i$. Thus, near onset, $\omega_i* \ll \Omega_{ci}$, inhomogeneous-plasma effects are small, and the discrete wave is similar to an electrostatic ICW,[11] with $k_y\rho_i \simeq 1.5$. However, azimuthal propagation is already present, indicating a drift wave. With higher current, $\omega_i* > \Omega_{ci}$ and $k_y\rho_i \gg 1$, enhancing the contribution from the density gradient, until drift-wave properties completely dominate. To suppress the long-time-scale equilibrium changes necessary to destabilize the ICDW of Ref. 4, we performed pulsed experiments and observed the continuous-spectrum ICDW with $\omega \sim k_y v_{de}*$ before the onset of the discrete ICDW, emphasizing the importance of current excitation in this case and suggesting that the continuous ICDW is not a nonlinear stage of the discrete instability.[12]

Pulsed-operation measurements, Fig. 3(a), demonstrate that $\gamma \propto V_{\rm appl}$ and $\gamma \lesssim \omega$, i.e., fast growth, in agreement with the prediction that $\gamma \propto u - u_{\rm crit}$ for the current-driven, continuous-spectrum ICDW, Eq. (1). Figure 3(b) gives the time evolution of the radial amplitude profiles, indicating localization of the instability. The typical diffusion density profile leads to higher drift velocity at the edge of the plasma [resistance $R(r)$ = const; $j(r)$ = const = $en(r)u(r)$]. The instability therefore develops from the periphery of the plasma. We also note that spatial growth in the axial direction inside the plasma column can be observed, showing that the end-plate sheaths do not contribute to wave growth.

Several important conclusions arise from this work. First, the current- and non-current-driven ICDW, far beyond onset, exhibit continuous ion-sound-like spectra and high growth rates. Second, these ion-sound-like instabilities can be excited in plasmas which are ion-sound stable, $T_e < T_i$: Since $\omega/k_z \gg v_i$, ion Landau damping is excluded. Third, work in progress indicates this instability as a new mechanism for the generation of strong anomalous resistivity and intense ion heating.

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[12]In a time-evolution sequence, the linear stage must appear before nonlinear effects. Since the discrete wave does not occur in pulsed operation, the continuous-frequency mode must exist by itself and cannot be a nonlinear stage of the (nonexistent) discrete linear mode.

# New Structural Findings from a Neutron-Diffraction Study of One-Dimensional $K_2Pt(CN)_4Br_{0.3} \cdot 3H_2O$*

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We report a single-crystal neutron-diffraction structure study of $K_2Pt(CN)_4Br_{0.3} \cdot 3H_2O$ (KCP). Contrary to previous x-ray results we find that KCP is *non*centrosymmetric (space group $P4mm$ rather than $P4/mmm$). New water-molecule positions have been derived. The $Pt(CN)_4^{-2}$ groups are not precisely planar, the $K^+$ ions occupy ordered sites, and two crystallographically different $Br^-$ ion sites are observed. The possible relationship of the $Br^-$-ion disorder to the diffuse x-ray scattering previously observed is discussed.

The properties of the mixed-valence square-planar platinum compounds such as $K_2Pt(CN)_4Br_{0.3} \cdot 3H_2O$ (KCP) have attracted great interest because of their so-called one-dimensional metal-

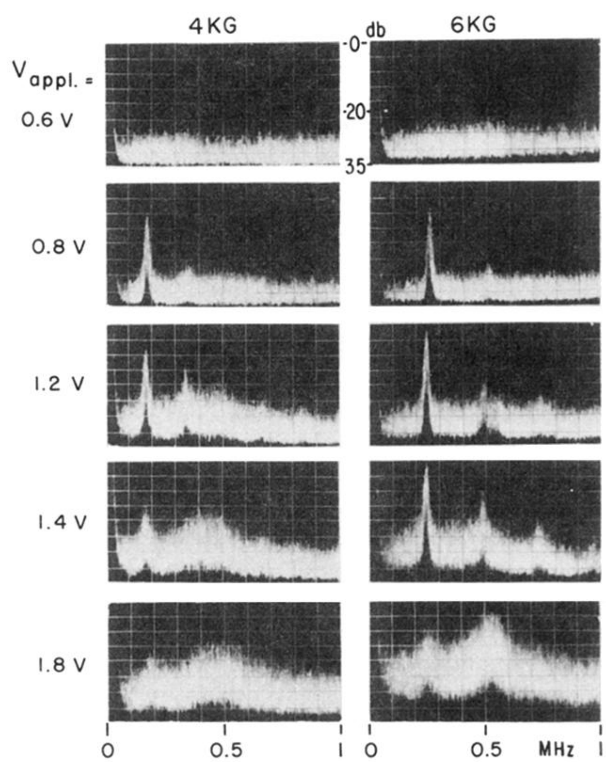


FIG. 1. Evolution of ICDW frequency spectrum versus applied voltage. $n = 0.6 \times 10^{10}$ cm$^{-3}$.