duced.

Previous kinematic studies have shown that substantial internal energy can be stored in the product CH^+. At relative energies below 7 eV, the approximate threshold for formation of the $B^1\Delta$ state, CH^+ has been observed[3,4] (in the kinematic studies) with internal energy in excess of the 4.1 eV required for dissociation to $C^+(^2P)$ and $H(1s\,^2S)$. The present study shows directly that CH^+ observed at energies kinematically forbidden for $CH^+(X^1\Sigma^+, a^3\Pi, A^1\Pi)$ are in the $b^3\Sigma$ state (see Fig. 1). CH^+ is also formed at relative energies above those reported in the kinematic studies. Luminescence observed in the experiments reported here provides evidence that the $B^1\Delta$ state of CH^+ is populated in these reactive collisions.

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Destabilization of Hydromagnetic Drift-Alfvén Waves in a Finite-β, Collisional Plasma

J. T. Tang and N. C. Luhmann, Jr.*
University of California, Los Angeles, California 90024

and

Yasushi Nishida†
Department of Electrical Engineering, Utsunomiya University, Utsunomiya, Japan

and

Kazushige Ishii
Institute of Plasma Physics, Nagoya University, Nagoya, Japan

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We have observed experimentally the destabilization of both the Alfvén and the drift branches of the hydromagnetic, coupled drift-Alfvén wave in a steady-state, high-density ($n_0 \approx 10^{13}$–10^{15} cm^{-3}) collisional plasma when an axial electron current is drawn along the magnetic field. The measured dispersion relation is in good agreement with solutions of our theoretical dispersion relation.

The stability of high-β ($\beta = 8\pi n_0 KT_0/B_0^2$) plasmas is a subject of special interest in fusion research and in magnetospheric studies. It has long been predicted that for $\beta > m/M$, drift waves begin to assume a hydromagnetic character and a coupling can occur between Alfvén waves and drift waves resulting in instability.[1] This instability is at present the most worrisome one in two-component toruses. Recently, Nishida and Ishii[2] have reported the observation of the coupled drift-Alfvén mode in a finite-β ($1 \gg \beta \gg m/M$), current-free, collisional plasma. Only the lower-frequency drift branch was observed; the higher-frequency Alfvén branch is heavily damped by collisions. Woods[3] has predicted, however, that Alfvén modes can be destabilized in a finite-β plasma by an axial current. We have verified this effect experimentally, finding that the collisional drift and Alfvén modes are simultaneously excited in a finite-β plasma by small currents $I_z \leq 25$ A.

The instability has been observed both in the TPD-1 device[2] at Nagoya University and in the three-stage, differentially pumped, arc-jet plasma source at the University of California at Los Angeles (UCLA). Because of space limitations, only results from the UCLA device will be presented; the results in TPD-1[4] are similar. An ionized, current-free, 1-m-long plasma column of density $n_0 = 10^{13}-10^{15}$ cm^{-3} and temperature $T_0 \simeq T_i \simeq T_e \simeq 2-7$ eV is confined by a uniform axial magnetic field B_0 of up to 9 kG in the UCLA arc-jet source. The plasma density is measured spectroscopically by absolute line-intensity measurements and also by electric probes. The plasma temperature T_e is determined from the ratio of line intensities and by probes. Ion temperature is determined by Fabry-Pérot interferometer measurements of Doppler broadening. The hydromagnetic oscillations are detected by observations of various spectral lines, including He II 4686 Å and He I 5876 Å, as well as by electric and magnetic probes.

The radial density, temperature, and plasma-potential profiles measured by Langmuir probes are shown in Fig. 1(a) for $B_0 = 1.6$ kG both with and without a 20-A axial electron current I_z. Density and temperature are not appreciably changed by I_z. Negligible temperature gradient and radial electric field exist at the wave-maximum region of $r = 3-5$ mm.

When $I_z = 0$, a spontaneously occurring low-frequency instability ($f_1 \sim 50$ kHz) is observed. This has been identified as the drift branch of the coupled drift-Alfvén instability.[2] As I_z is increased to a critical value which depends on n_0 and B_0, a higher-frequency mode ($f_2 \sim 100$ kHz) exhibits a hard onset. Lower density and higher magnetic field require a larger critical current. Because of the hard onset, measurements are not made near threshold but rather near saturation. The upper branch is a broad oscillation ($\Delta f \sim 5-10$ kHz), while the lower drift branch is a single mode.

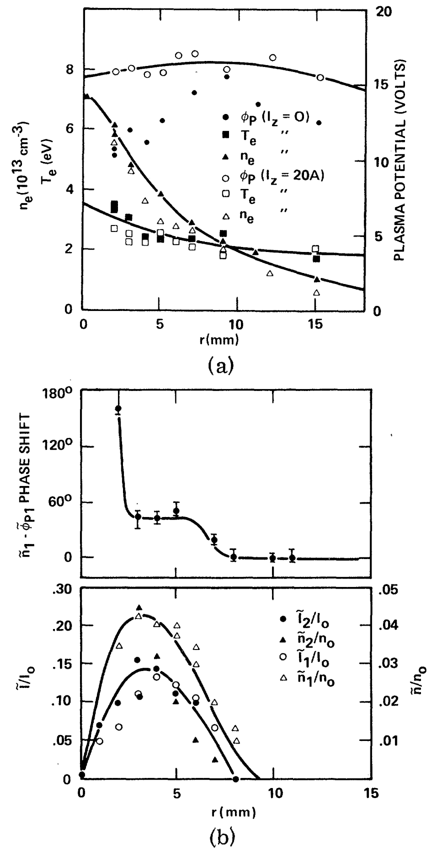

FIG. 1. (a) Plasma density, temperature, and plasma potential as functions of radius for $B_0 = 1.6$ kG with and without an axial electron current of 20 A. (b) Oscillation amplitude as a function of plasma radius for both the upper Alfvén branch (f_2) and the lower drift branch (f_1). The optical signal $\tilde{I}/I_0$ has not been Abel-inverted. Also shown is the phase difference between $\tilde{n}$ and $\tilde{\varphi}_P$ for the drift mode as a function of radial position.

The dominant mode numbers of f_1 and f_2 are measured with electric probes located at known azimuthal positions and are determined to be $m = 1$, with the azimuthal rotation in the direction of the electron diamagnetic drift. The rotation changes direction upon reversal of the confining magnetic field. The optical signals are of opposite phase on either side of the plasma axis, also indicative of an $m = 1$ oscillation. Parallel wavelengths ($2\pi/k_\parallel$) are obtained from correlation measurements of the phase shift of the oscillating probe-current signals detected by an axially movable probe and by a fixed probe. The low-frequency wave is a standing wave in the axial direction with a wavelength approximately twice the machine length when no current is drawn. In the presence of current, both modes become traveling waves. The f_1 (f_2) mode travels along (against) the axial electron drift; the current has introduced an asymmetry into the wave dispersion.

The frequency of the $\tilde{n}_1/n_0$ oscillation is found to exhibit the proper magnetic field dependence for a drift wave ($f_1 \propto B_0^{-1}$) after changes in plasma radius and instability location with B_0 are accounted for. The frequency ω_2 of the second oscillation $\tilde{n}_2/n_0$ is found to vary as $k_\parallel v_A = k_\parallel B_0/(4\pi n_0 M)^{1/2}$ as B_0 and $k_\parallel$ are varied, as would be expected of an Alfvén wave.

The phase angle between the density and plasma-potential fluctuations determines the stability of the drift wave. Only for an isothermal fluctuation is it possible to equate probe-floating, φ_f, and plasma-potential, φ_p, fluctuations.[5] In the present work, accurate determination of the $\tilde{n}$-$\tilde{\varphi}_p$ phase shift as a function of r is accomplished by electric probe measurements using a boxcar integrator triggered by the spectral-line oscillation signal $\tilde{I}$. By varying the probe bias voltage at each radial position, $\tilde{n}$, $\tilde{\varphi}_f$, and $\tilde{T}_e$ are determined, yielding the space- and time-resolved phase shift between density and plasma-potential fluctuations as shown in Fig. 1(b). Measured temperature fluctuations are 5–15%, as expected for an adiabatic compression with $\tilde{T}_e/T_0 \approx (\gamma - 1) \times \tilde{n}_e/n_0$ and $\gamma = \frac{5}{3}$. The $\leq 45°$ phase shift between $\tilde{n}$ and $\tilde{\varphi}_p$ lends strength to the identification of the $\tilde{n}_1$ oscillation as a drift wave, as does the localization of the wave at the density-gradient maximum.

Since the drift-Alfvén wave is a hydromagnetic wave, the magnetic oscillation is measured with calibrated loop probes with balanced differential output. The magnitude of the magnetic fluctuation $\tilde{B}/B_0$ should be of order $\beta\tilde{n}/n_0$; this functional dependence is observed for both modes, as shown in Fig. 2(a). As $\beta \to 0$ the drift mode reverts to an electrostatic wave and the Alfvén mode disappears. For the f_1 mode we further find that $\tilde{B}_r/B_0 \simeq \tilde{B}_\theta/B_0 \gg \tilde{B}_z/B_0$, in agreement with theory. For the f_2 mode the observed ordering, $B_\theta/B_0 > B_r/B_0 > B_z/B_0$, indicates that the wave is mainly a shear wave.

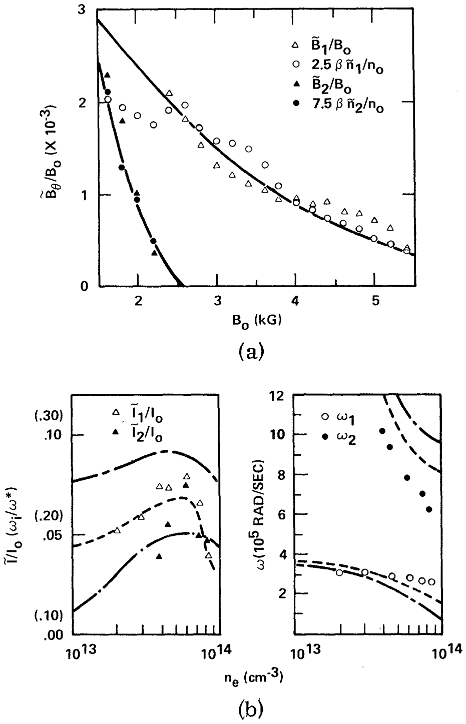

FIG. 2. (a) Magnetic field fluctuation $\tilde{B}/B_0$ as a function of axial equilibrium magnetic field. For both the Alfvén and drift modes $\tilde{B}/B_0$ is observed to be proportional to $\beta\tilde{n}/n_0$. (b) Reω of both Alfvén and drift modes as a function of plasma density compared with theory [Eq. (1)] for $B_0 = 1.6$ kG, $T_e = 4$ eV, $|k_\parallel| = 0.04$ cm^{-1}, $k_\perp = n_0^{-1}dn_0/dr = 1.25$ cm^{-1}. Also, the amplitude is compared with calculated Imω. The dashed line represents the theoretical values for the case of no axial current. Only the lower branch is unstable. The segmented lines, —-— and —•—, represent theoretical values for the case of an axial current ($v_{ez0} = v_A$). With reference to the growth rate ω_i/ω^* diagram, the curve —-— is 0.1 times ω_{i1}/ω^*, while the curve —•— is 0.5 times ω_{i2}/ω^*.

The dependence of wave frequency upon plasma density and parallel wave number ($k_\parallel$) is compared with numerical values calculated from the theoretical dispersion equation for the drift-Alfvén wave modified by axial current. The dispersion equation in slab geometry is

$$b\omega_\parallel\omega^3 + (ib^2\omega_A^2 + i\omega_\parallel\omega_\perp)\omega^2 + \left\{ i(\omega^* - \omega_0)b^2\omega_A^2 - \left[(1 + \tfrac{5}{3}b)\omega_\parallel + \omega_\perp\right]b\omega_A^2 - b\omega_\parallel\omega^{*2}\right\}\omega$$
$$+ \left[(1-b)(\tfrac{5}{3}\omega_\parallel + i\omega_0)b\omega^*\omega_A^2 - (\omega^* - \omega_0)b\omega_\perp\omega_A^2 - i\tfrac{8}{3}b\omega_\parallel\omega_\perp\omega_A^2 - i\omega_\parallel\omega_\perp\omega^{*2}\right] = 0, \qquad (1)$$

where $\omega_\parallel = k_\parallel^2 KT_e/m_e\nu_{ei}$, $\omega_A = k_\parallel v_A$, $\omega^* = k_y v_{de}$, $b = \frac{1}{2}k_\perp^2 r_L^2$, $\omega_\perp = \frac{1}{4}b^2\nu_{ii}$, and $\omega_0 = k_\parallel v_{ez0}$. We have assumed $\omega \ll \omega_{ci}$, $m/M < \beta < b < 1$, and an adiabatic equation of state. When $v_{ez0} \to 0$, the equation reduces to the coupled drift-Alfvén dispersion relation without current.[2] When $v_{ez0} \to v_A$, the axial current desta-

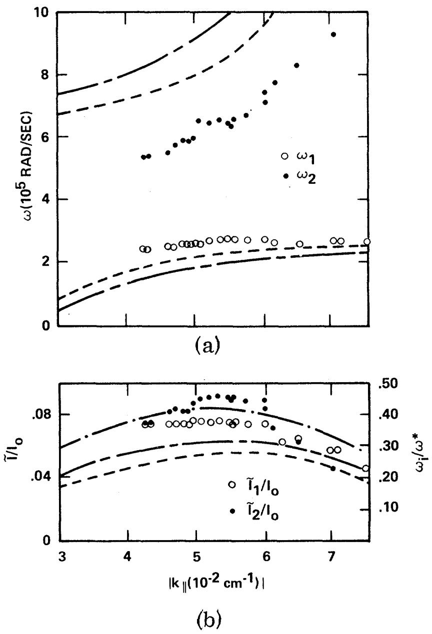

FIG. 3. (a) Measured Alfvén- and drift-mode dispersion relation showing the coupling near $\omega^*/k_\parallel \approx v_A$ and comparison with theory [Eq. (1)] for $n_e = 5.0\times10^{13}$ cm^{-3} and other conditions and symbols the same as given in Fig. 2(b). (b) Measured Alfvén- and drift-mode nonlinear saturated amplitudes compared with theoretical linear growth rate of coupled drift-Alfvén mode.

bilizes the Alfvén mode in $-k_\parallel$ (against the current), in addition to the unstable drift mode in $+k_\parallel$. This wave has dispersion similar to an Alfvén wave, but it possesses associated localized density fluctuations. Figure 2(b) shows Reω of both modes as a function of plasma density compared with theory [Eq. (1)] and also the amplitude compared with calculated Imω; the latter comparison follows well-established precedent.[6] The drift-mode frequency is practically independent of density, and the mode is damped at high density by ion-ion collisions and at low density because of reduced electron-ion collisions, which produce the $\tilde{n}$-$\tilde{\varphi}_p$ phase shift for destabilization. The frequency of the Alfvén mode decreases with increasing density.

In Fig. 3(a) the measured ω-$|k_\parallel|$ dispersion curve is compared with theory in the coupling region near $\omega^* = k_\parallel v_A$. The wave coupling arises from $\tilde{J}_z$ as the current produces a fluctuating magnetic field given by $\nabla\times\vec{\tilde{B}}_\perp = \hat{z}(4\pi/c)\tilde{J}_z$ where $\tilde{J}_z = n_0 e\tilde{u}_z + \tilde{n}ev_{ez0}$. This time-varying magnetic field impedes the motion of the electrons through the generation of an inductive electric field $\tilde{E}_z = \eta_0\tilde{J}_z + \tilde{\eta}J_{0z}$, where the constant current density $J_{0z} = n_0 e v_{ez0}$ and $\tilde{\eta}$ is an effective perturbation to the resistivity due to temperature fluctuations. When $v_{ez0} = 0$, the Alfvén branch is stable although a coupling still occurs at finite β resulting in the $\tilde{B}$ component of the drift mode. When $v_{ez0} \simeq v_A$, the f_2 mode becomes unstable as shown in Fig. 3(b).

In conclusion, we have observed the coupled drift-Alfvén mode modified by an axial electron current. The measured dispersion relationship, growth rates, and field fluctuations are in agreement with solutions of our theoretical dispersion relationship.

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