Excitation of Ion-Acoustic-Like Waves by Subcritical Currents in a Plasma Having Equal Electron and Ion Temperatures

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The effect of a magnetic-field-aligned plasma flow with a transverse velocity gradient on the excitation of current-driven ion-acoustic-like waves in a plasma having equal electron and ion temperatures ($T_e = T_i$) was investigated experimentally. In agreement with theoretical predictions, the presence of sheared plasma flow substantially reduces the critical electron drift velocity needed to produce the ion-acoustic instability.

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A plasma that carries an electrical current may be unstable to the growth of ion oscillations. In the absence of a magnetic field or for fluctuations that propagate along the magnetic field, these oscillations are purely longitudinal and are the plasma counterpart of ordinary sound waves in a gas with the coupling between electrons and ions due to electric fields resulting from small charge separations. In plasmas having equal electron and ion temperatures ($T_e = T_i$), the electron drift velocity associated with the current must be on the order of the electron thermal velocity to excite these ion acoustic oscillations [1], a relatively stringent condition that is not usually met in typical plasmas.

A plasma in which the ions flow along the magnetic field with a flow velocity that changes from one magnetic field line to another (parallel velocity shear) may be subject to an instability analogous to that which may occur in a stratified fluid if the different fluid layers are in relative motion. In a plasma, D'Angelo [2] showed that instability should occur when the relative velocity of two adjacent layers is of the same order of magnitude as the ion sound, $C_s = \sqrt{(KT_e + KT_i)/m_i}$, where m_i is the ion mass.

Recently, Gavrishchaka *et al.* [3], using the general kinetic dispersion relation developed by Ganguli *et al.* [4], which included an inhomogeneous flow parallel to the magnetic field as well as a magnetic-field-aligned current, showed that parallel velocity shear can influence the stability of the normal plasma modes in two ways. This is most easily seen by considering the real part of their dispersion relation:

$$\omega \approx k_z C_s \sqrt{1 - \frac{V_d'}{u\Omega_i}}, \tag{1}$$

where ω is the wave frequency in the ion frame, k_z is the wave number in the direction parallel to $\mathbf{B}$, $\Omega_i = eB/m_i$ is the ion gyrofrequency, $u = k_z/k_y$ is the ratio of wave numbers parallel and perpendicular to $\mathbf{B}$, and $V_d' \equiv \partial v_{iz}/\partial x$ is the spatial variation of the magnetic-field-aligned macroscopic ion flow, v_{iz}, with the coordinate perpendicular to $\mathbf{B}$. The *real* part of the dispersion relation (1) can also be obtained from the fluid theory of D'Angelo [2] which, of course, cannot provide any growth due to wave-particle interactions.

First, from (1) it can be seen that, for $(1 - V_d'/u\Omega_i) < 0$, there is a purely growing mode with $\mathrm{Re}(\omega) = 0$. This mode is not an ion-acoustic mode [since $\mathrm{Re}(\omega) = 0$, as opposed to $k_z C_s$] but is the fluid mode analyzed by D'Angelo.

Second, we see that, for $(1 - V_d'/u\Omega_i) > 0$, Eq. (1) yields a mode with a real frequency that is ion-acoustic-like, i.e., $\omega \approx k_z C_s$ but modified by shear. Using the full kinetic dispersion relation, Gavrishchaka *et al.* [3] calculated the effect of the shear on the critical electron drift velocity, v_{ed}^c, for this ion-acoustic-like mode [the shear modified ion-acoustic (SMIA) mode]. The presence of shear produces a drastic reduction (by nearly 2 orders of magnitude) in the critical electron drift velocity (see Fig. 1 of [3]), and the value of v_{ed}^c normalized to the ion thermal speed, v_{it}, is almost insensitive to the T_e/T_i ratio. Physically, the effect of the shear leads to an increase in the parallel phase velocity of the ion-acoustic modes by a factor $\sigma \equiv \sqrt{1 + |V_d'/u\Omega_i|}$ which shifts the mode out of the region of strong ion Landau damping.

The implications of this dramatic effect of shear on the excitation of ion-acoustic modes in the ionosphere have been thoroughly discussed in Ref. [3]. Here, we describe the results of a laboratory experiment investigating the effect of parallel velocity shear on current-driven ion-acoustic modes. Under conditions in which $V_d' \approx 0$, the critical electron drift velocities associated with the magnetic-field-aligned currents were insufficient to excite the ion-acoustic instability.

The experiments were performed in a double-ended Q machine in which a singly ionized cesium plasma was produced by surface ionization of cesium atoms on two 6 cm diameter tantalum hot plates separated longitudinally by 2 m. The plasma was confined radially by a longitudinal magnetic field produced by 14 coils capable of providing a uniform magnetic field up to 0.5 T or a nonuniform magnetic field configuration by suitable arrangement of the coil currents. Typical plasma densities and temperatures

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measured using Langmuir probes were $n_i \sim 10^{10}$ cm^{-3} and $T_e(\approx T_i) \approx 0.2$ eV.

To produce magnetic-field-aligned plasma flow with shear (V_d'), *and* current (v_{ed}), the device was configured as shown schematically in Fig. 1. The magnetic-field coil currents were adjusted so that the magnetic-field lines diverged from the west hot plate (W) to the east hot plate (E). In this configuration, the plasma column is separated into a central core which is produced by plasma flowing from both the east and west hot plates, and an outer annular region that contains plasma produced only on the west hot plate. This annular plasma region is terminated on the east side by a cold electrode (RING) that can be biased to a potential V_R relative to ground. Both the east and the west hot plates are grounded. Ions produced on either hot plate are accelerated along the magnetic field by the roughly $2 - 3$ V potential drop that is present at the hot plate. In double-ended operation, the net bulk ion flow can be controlled by adjusting the temperatures of the hot plates (hot plate heating power) and the flux of neutral atoms on the plates. For example, if the east hot plate heating power is set considerably higher than the west hot plate power, i.e., $P_E \gg P_W$, the resulting flow is directed from E to W. Thus, by appropriate adjustments of P_E and P_W it is possible to have net flows in either direction, or no net flow if the plasma sources are "balanced." The direction of ion flow in the central core plasma was inferred from measurements of the ion currents, I_E and I_W, collected by two independent, single-sided Langmuir probes facing the east and west hot plates, respectively; an $I_E/I_W > 1$ indicating E → W flow, while an $I_E/I_W < 1$ indicating W → E flow.

Plasma flow in the outer annular plasma was controlled by fixing the bias on the ring. If the ring is biased negative with respect to plasma potential, it collects all ions arriving to it resulting in a W → E flow. On the other hand, when the ring is biased sufficiently positive, it reflects all ions arriving at it resulting in no net flow in the annular region. In this case, however, there is an electron current flowing in the annular plasma.

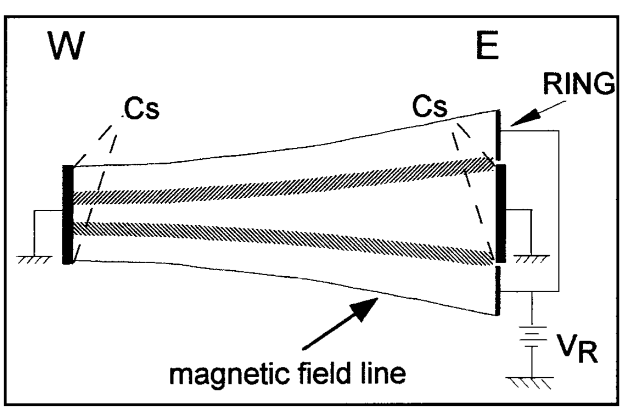

FIG. 1. Experimental setup.

The specific arrangement used for this experiment consisted in the following: P_E and P_W were set to produce a net ion flow in the core plasma (either E → W or W → E), and the RING was biased sufficiently positive to produce an electron current but no ion flow in the annular plasma. In this configuration then there is a net flow in the central core plasma that decreases to zero in a boundary layer (that is, a few ion gyroradii wide) between the inner and the outer plasmas. In this layer, in which an electron current also flows, the conditions for excitation of the SMIA instability were expected to be present.

The excitation of low frequency oscillations was observed in the shear/current layer when the ring was biased sufficiently positive to collect electrons and repel the ions. Figure 2 shows the current-voltage characteristic of the ring, for $-2 < V_R < 3$ V, and the frequency of oscillations in the floating potential of a Langmuir probe located in the shear/current layer versus V_R. Although an electron current was present over this entire range of V_R, the oscillations appeared only for $V_R \gtrsim +0.5$ V, where we expected the ions to be repelled by the ring. The spectrum of the oscillations showed relatively broad peaks in the 2–4 kHz range with a FWHM ≈ 1 kHz. The radial profiles of the plasma potential, V_f, and the wave amplitude, $\tilde{V}$, obtained from the floating potential of a Langmuir probe, are shown in Fig. 3. The maximum mode amplitude occurred in the 3–4 mm annular region corresponding to the shear/current layer.

The identification of the cause of these oscillations requires a knowledge of their propagation characteristics in the directions both along and transverse to the magnetic field. The phase velocity of the oscillations was determined by measurements of the time delay of a particular feature in the waveform of the oscillations observed on movable Langmuir probes relative to the same feature in the waveform observed on a fixed reference probe. Measurements of the time delay versus position, z, along

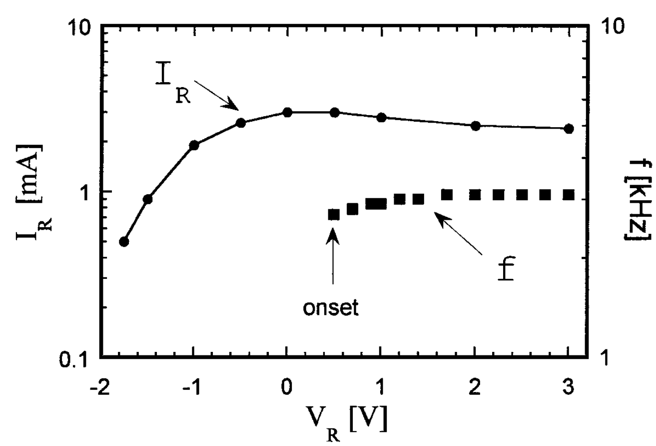

FIG. 2. The ring I-V characteristic (dots) and oscillation frequency (squares) versus ring bias V_R. The arrow indicates the onset of the mode.

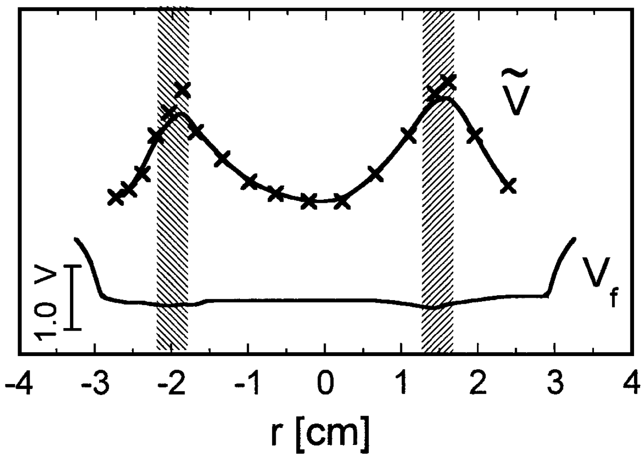

FIG. 3. Radial profiles of the plasma potential, V_f, and wave amplitude, $\tilde{V}$, obtained from the dc and ac parts of the floating potential of a Langmuir probe. The hashed lines indicate the locations of the shear/current layer. The maximum amplitude corresponds to a $\tilde{n}/n = e\tilde{V}/kT_e \approx 50\%$.

the magnetic field, relative to a fixed probe are shown in Fig. 4 for ion flows W $\rightarrow$ E (solid dots) and E $\rightarrow$ W (open circles). These measurements indicate that, *irrespective of the direction of ion flow,* the waves propagate in the direction of the electron drift (W $\rightarrow$ E) with a phase velocity, $V_{\Phi z} \approx 2 \times 10^5$ cm/s.

Similar measurements were performed using probes located at the same longitudinal and radial positions in the plasma column separated azimuthally by 90°. These measurements showed that there was also a perpendicular component of propagation of the mode in the azimuthal ($m = 1$) sense with phase velocity of $V_{\Phi\theta} \approx 4 \times 10^4$ cm/s. In

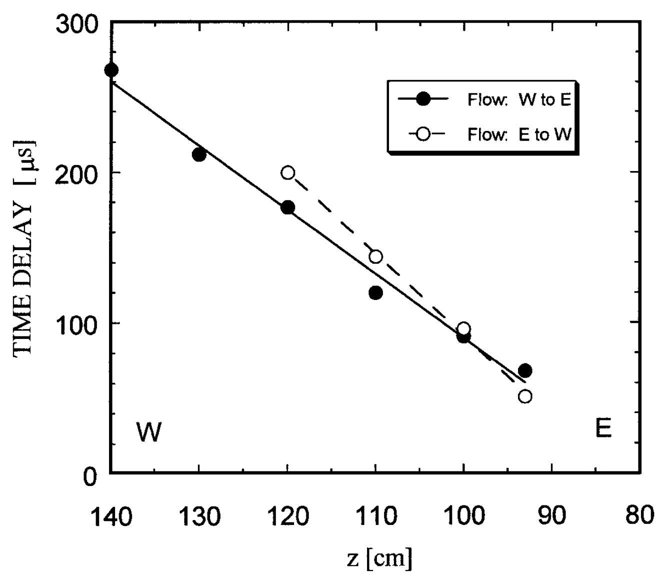

FIG. 4. Time delay between oscillation features on a movable probe and a fixed probe versus z. Open circles: E $\rightarrow$ W flow; closed circles: W $\rightarrow$ E flow. In both cases the mode propagates W $\rightarrow$ E. The wave period corresponds to a time delay of 250 μs.

contrast to the case of propagation along the magnetic field, which was always in the direction of the electron drift, the direction of azimuthal propagation was reversed when the ion flow in the core plasma was reversed.

From the determinations of the *directions* of propagation parallel and perpendicular to **B**, i.e., the signs of the parallel and azimuthal wave numbers, k_z and k_θ, respectively, and the measurement of the sign of the shear parameter, V_d', we can conclude that the quantity $V_d'/u < 0$ for this mode. Thus, according to Eq. (1), the observed mode excited in the presence of electron current and parallel velocity shear is consistent with the SMIA mode. Two additional measurements were made to support this conclusion.

A measurement of the amplitude of the floating potential fluctuations on a small probe indicates that the mode grows in the direction of the electron drift (W $\rightarrow$ E) up to a point and then decreases somewhat. For a current-driven instability, one expects the mode amplitude to increase in the direction of the electron drift and then saturate to some steady value. The observed decrease following the region of spatial growth is probably due to the effect of the diverging magnetic geometry which causes the wave energy to be spread over a larger and larger area as it propagates eastward. Figure 5 shows the amplitude versus position plot when account is taken for the diverging magnetic geometry. Finally, Fig. 6 shows the behavior of the mode amplitude versus the parameter $I_{\mathrm{E}}/I_{\mathrm{W}}$. Recall that a $I_{\mathrm{E}}/I_{\mathrm{W}} > 1$ implies E–W flow, while a $I_{\mathrm{E}}/I_{\mathrm{W}} < 1$ indicates W $\rightarrow$ E flow. The minimum amplitude occurs for $I_{\mathrm{E}}/I_{\mathrm{W}} \approx 1$, where the flow (and parallel velocity shear) is also a minimum. This measurement provides further evidence of the role of shear in the excitation of the ion-acoustic-like mode.

The experimental finding that $V_d'/u < 0$ was a *necessary* step in the association of the observed mode with the SMIA instability. We now compare the measured parallel phase velocity with that predicted in Ref. [3] [Eq. (1) in this paper]. Using the real part of the dispersion relation in the form $\omega = k_z C_S \sigma$, where

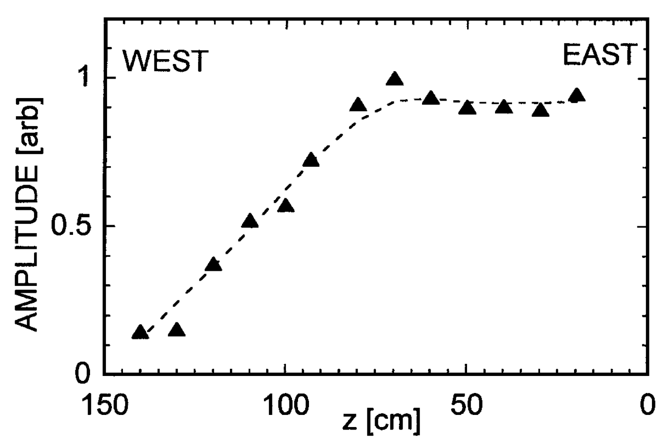

FIG. 5. Oscillation amplitude versus z.

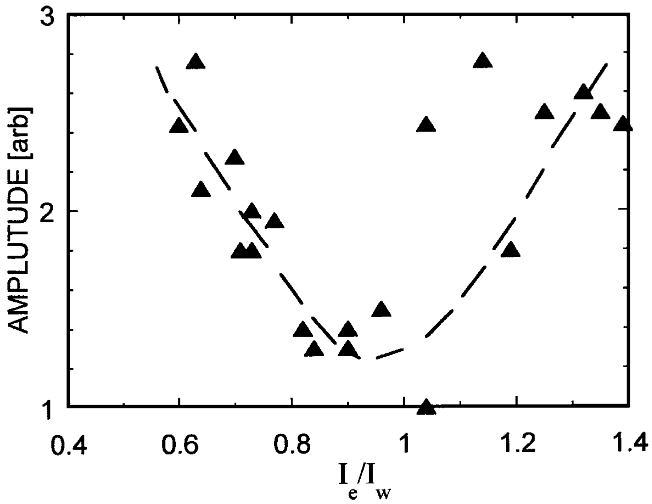

FIG. 6. Amplitude of oscillations versus I_E/I_W. $I_E/I_W < 1$ corresponds to W → E flow, while $I_E/I_W > 1$ corresponds to E–W flow. $I_E/I_W \approx 1$ implies minimum flow and shear.

$\sigma = \sqrt{1 + |V_d'/\Omega_i u|}$, we have, for the parallel phase velocity, $V_{\Phi z} = \omega/k_z = C_s\sigma$. The quantity u in the expression for σ is defined as $u = k_z/k_\theta$. Since $\omega = k_z V_{\Phi z} = k_\theta V_{\Phi\theta}$, we can write $u = V_{\Phi\theta}/V_{\Phi z}$. From the phase velocity measurements, u is estimated to be in the range 0.1–0.2. To estimate σ, we need the quantity $V_d'/\Omega_i \approx (1/\Omega_i)(\Delta v_{iz}/\Delta r)$, where $\Delta v_{iz}/\Delta r$ is the radial variation of the parallel ion flow velocity, v_{iz}. The scale length, Δr, of the radial variation in the ion flow velocity is typically on the order of a few times the ion gyroradius, i.e., $\Delta r \approx \alpha\rho_i$, where $\alpha \sim 2$–3. Then $V_d'/\Omega_i \approx (1/\Omega_i)(\Delta v_{iz}/\Delta r) \approx \Delta v_{iz}/(\Omega_i\alpha\rho_i) \approx \Delta v_{iz}/(\alpha v_{it})$, since $\rho_i = v_{it}/\Omega_i$, where v_{it} is the ion thermal speed. Now we also have that $\Delta v_{iz} \approx$ a few times v_{it}, so that $\Delta v_{iz} \approx \beta v_{it}$, and finally, since $\alpha \approx \beta$, it follows that $(1/\Omega_i)(\Delta v_{iz}/\Delta r) \approx 1$, and $V_d'/(u\Omega_i) \approx 1/u \approx 5$–$10$, giving a $\sigma \approx 2.5$–3.3. Thus, theoretically we expect a parallel phase velocity $V_{\Phi z} \approx (2\text{–}3)C_s$. With $T_e \approx T_i \approx 0.2$ eV in a Cs^+ plasma, the ion acoustic speed is $C_s = 5.4 \times 10^4$ cm/s, so that $V_{\Phi z} = \sigma C_s \approx (1.4\text{–}1.8) \times 10^5$ cm/s, in good agreement with the measured $V_{\Phi z} \approx 2 \times 10^5$ cm/s.

In a plasma with $T_e = T_i$, a critical electron drift velocity, $v_{ed} \approx v_{et}$ (electron thermal speed), is needed for the excitation of current-driven ion-acoustic waves in the absence of shear. A rough estimate for the electron drift associated with the current to the ring can be made using $I_{\rm ring} \approx e n_e v_{ed} A_{\rm ring}$, where $I_{\rm ring}$ is the current collected over the entire surface of the ring of area $A_{\rm ring}$, and n_e is the average electron density of the plasmas in the annular region of the ring. Using an $n_e \sim 10^9$ cm^{-3} and the measured ring current, we obtain $v_{ed} \sim 10^{-2} v_{et}$ which is well below the threshold value. According to the predictions of Ref. [3], the presence of parallel velocity shear reduces the critical drift by a factor of about 100, so that the small electron drift velocity associated with the current in our plasma should have been sufficient to excite the SMIA instability.

In summary, we have investigated experimentally the excitation of ion-acoustic-like modes in a plasma having inhomogeneous parallel ion flow and electron current. In the absence of sheared ion flow, the free energy available in the electron drift was insufficient to sustain ion-acoustic modes in our plasma in which $T_e \approx T_i$. However, when additional free energy in the sheared ion flow was available, an instability was excited. The measured propagation characteristics of the resulting modes were consistent with the theoretical predictions of Gavrishchaka *et al.* [3].

These experimental results demonstrate the crucial role of inhomogeneous plasma flow in determining the stability of a plasma. The demonstration that ion-acoustic waves can be excited for $T_e = T_i$ and for subcritical currents challenges a long held notion that, in order to produce IA waves when $T_e \approx T_i$, the magnitude of the field-aligned current has to be very large [5]. The theoretical finding confirmed by these experiments has the potential to explain for the first time the origin of IA signatures of importance in various space plasma contexts, as discussed in Ref. [3].

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