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Experimental study of the collisional parallel velocity shear instability

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Abstract. Simultaneous density and electric field fluctuation spectra, associated with velocity shear (both in the transverse to the magnetic field ion flow velocity and in the parallel ion flow velocity), have been observed by the DE 2 spacecraft in the *F* region [*Basu et al.*, 1984]. *Basu and Coppi* [1988, 1989] argued that the subkilometer scale irregularities are due to collisional electrostatic modes excited in a partially ionized plasma in the presence of shear in the parallel ion flow. In this paper we describe results of a laboratory investigation of the effects of neutral-particle collisions on the parallel velocity shear instability, performed using a double-ended Q machine. The critical value of the shear dv_0/dx, the derivative of the field-aligned ion flow with respect to the transverse (to **B**) coordinate, is determined and compared with theoretical predictions.

1. Introduction

When two adjacent layers in a stratified fluid are in relative motion, a velocity shear (Kelvin-Helmholtz) instability might arise [e.g., *Chandrasekhar,* 1961]. In a plasma, two different situations of a sheared ion flow have been examined. In one the shear occurs in the ion velocity perpendicular to the magnetic field **B**. If the magnetic field is homogeneous, it is produced by a spatial variation of the electric field **E** normal to **B**. This instability has also been studied extensively, with applications to situations of geophysical interest, such as the solar wind flow on the dawnside and duskside of the Earth's magnetosphere [see, e.g., *Boller and Stolov,* 1973; *Miura and Pritchett,* 1982; *Wu,* 1986].

In the other situation the shear occurs in the ion flow parallel to the magnetic field, so that the streaming velocity of the ions along **B** changes from point to point in a direction perpendicular to **B** [*D'Angelo,* 1965; *D'Angelo and von Goeler,* 1966; *Smith and von Goeler,* 1968; *Catto et al.,* 1973]. This instability is also of interest to space physics. It has been analyzed in connection with sheared, field-aligned ion flows in the Earth's polar cusps [*D'Angelo et al.,* 1974; *Potemra et al.,* 1978], with wave motion in type 1 comet tails [*Dobrowolny and D'Angelo,* 1972], and with turbulence in the solar wind [*Migliuolo,* 1984]. In all of these cases, particle collisions are negligible because of the low plasma density and the absence of a neutral gas.

However, it has been argued [*Basu and Coppi,* 1988, 1989] that a collisional version of the parallel velocity shear instability is capable of accounting for the short-wavelength portion of the density and electric field fluctuation spectra observed [*Basu et al.,* 1984] in the *F* region of the Earth's ionosphere, near auroral arcs, at altitudes where collisions of ions and neutral atoms are important.

In this paper we report on the experimental study of the collisional parallel velocity shear instability, performed with an experimental arrangement similar to that of *D'Angelo and von Goeler* [1966], except that the neutral gas pressure could be varied over a wide range to explore the effect of collisions. Our results are in general agreement with the predictions of *Basu and Coppi* [1988, 1989].

In section 2 we give a brief summary of *Basu and Coppi's* [1988, 1989] predictions. Section 3 describes the experimental setup and the diagnostics used in the experiment, while section 4 presents the experimental results. The conclusions are given in section 5.

2. Theory

Basu and Coppi [1988, 1989] note that sheared plasma velocity regions tend to develop near auroral arcs and that associated plasma irregularities have been observed in the nighttime auroral *F* region. These irregularities have scale sizes (transverse to **B**) ranging from a few kilometers to a few meters. The transverse velocity shear instability (Kelvin-Helmholtz), however, excites only relatively long transverse wavelengths, in excess of a few kilometers. Thus it cannot explain the observed short-wavelength (meters) modes, and additional nonlinear processes are required to account for them. *Basu and Coppi* [1988, 1989] point out that sheared, field-aligned ion flow can linearly excite collisional electrostatic modes with transverse wavelengths as short as meters, if only a moderate amount of shear ($dv_0/dx \approx 3\ \mathrm{s}^{-1}$) is present. This instability apparently provides a direct means of exciting almost the entire

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range of the observed subkilometer fluctuation spectra for a shear sufficiently above a threshold value.

The threshold condition for the instability is found to be

$$\frac{v_0'}{\nu_{in}} > \left(1+\frac{T_i}{T_e}\right)\left(\frac{K_z}{K_y}\frac{\omega_{ci}}{\nu_{in}}+\frac{K_y}{K_z}\frac{\nu_{in}}{\omega_{ci}}\right), \quad (1)$$

where $v_0' = dv_0/dx$ is the derivative of the field-aligned ion flow velocity with respect to the transverse (to **B**) coordinate; x, ν_{in} is the ion-neutral collision frequency; ω_{ci} is the ion gyrofrequency; K_y and K_z are wavenumbers perpendicular and parallel to **B**, respectively; and T_i and T_e are the ion and electron temperatures, respectively. The minimum value of v_0'/ν_{in} with respect to K_z/K_y occurs when $(K_z/K_y)(\omega_{ci}/\nu_{in}) = 1$. In this case the instability condition for $T_i = T_e$ becomes

$$\frac{v_0'}{4\nu_{in}} > 1 . \quad (2)$$

An instability condition of this type appears very reasonable indeed. In a velocity sheared, collisional plasma, two opposing factors are at work: one in which the velocity shear of strength $dv_0/dx(\mathrm{s}^{-1})$ provides the excitation and an other in which ion-neutral collisions with a strength $\nu_{in}(\mathrm{s}^{-1})$ provide the damping. Marginal stability must occur when dv_0/dx is of the order of ν_{in}.

The waves are very low frequency waves ($\omega \ll \omega_{ci}$, where ω is the wave angular frequency and ω_{ci} is the ion gyrofrequency) with a ratio K_z/K_y between parallel and perpendicular wavenumbers much smaller than unity.

3. Experimental Setup and Diagnostics

The experiments were performed in the Iowa double-ended Q machine (IQ-2) [*Motley,* 1975] using essentially the same setup (ring plus disk) used previously by *D'Angelo and von Goeler* [1966].

A schematic diagram of the IQ-2 device with the ring plus disk arrangement is shown in Figure 1. The plasma is produced by surface ionization of potassium atoms from two atomic beam ovens (not shown) on two hot (~2500 K) tantalum plates of 6 cm diameter. The plasma column is 140 cm long and is confined radially by a uniform magnetic field with strength up to 0.6 T.

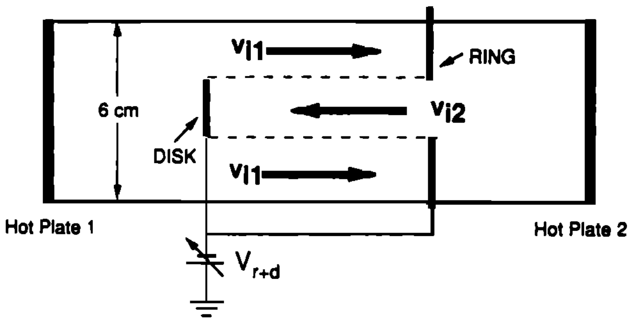

Figure 1. Schematic of the "ring plus disk" setup used in a double-ended Q machine to observe the parallel velocity shear instability.

The plasma density, measured with Langmuir probes consisting of tantalum disks of 2 mm diameter, is usually in the range 10^9 to 10^{10} cm^{-3}. The electron and ion temperatures are $T_e \simeq T_i = 0.2$ eV [*Motley,* 1975]. The ion gyroradius is < 1 mm under these conditions. The hot plates are operated in the electron rich conditions with resulting Langmuir probe floating potentials typically of the order of −2 V.

To produce the shear in the ion flow, a metal ring of outside diameter somewhat larger than that of the plasma column and an inner diameter of 2 cm was located at one plasma cross section, and a metal disk with a diameter of 1.8 cm was located at another cross section, 60 cm from the ring as shown in Figure 1. Both the ring and the disk were at right angles to the magnetic field, with their centers on the axis of the plasma column. If the ring and disk are biased sufficiently positive, the plasma ions are reflected, resulting in very little or no ion flow. On the other hand, when both the ring and the disk are biased a few volts negative to collect ion current, a counterstreaming exists in the plasma between the inner core ions and the ions in the outer cylindrical shell. The ion flow velocity and hence the resulting shear could be controlled somewhat by adjusting the ring plus disk bias voltage, $V_{\mathrm{r+d}}$. Note that the ring and the disk are always biased at the same potential.

In order to establish directly the presence of shear in the ion flow and to provide an estimate of the shear magnitude, $\partial v/\partial x$, a double-sided Langmuir probe was used. This probe consisted of two 1.6 mm diameter tantalum disks mounted back to back, with an insulating layer of ceramic sandwiched in between. The probe was mounted on a shaft that was inserted through a side port of the vacuum vessel midway between the ring and the disk and which could be moved radially through the plasma column. Each side of the probe was biased independently at −5 V to collect ions so that radial profiles of the ion fluxes coming from each hot plate could be measured. In section 4 the ion flux measured on the side facing hot plate 1 is designated as ϕ_1, while the flux measured on the probe facing hot plate 2 is designated as ϕ_2.

In addition, measurements, described in section 4.2, were made using a one-sided Langmuir probe (the other side being covered with an insulator) consisting of a disk of 1 cm diameter and with an ion energy analyzer (a tantalum disk collector 1 cm diameter, faced by a discriminator grid with 200 lines/cm [see, e.g., *Andersen et al.,* 1971]).

The pressure in the vacuum vessel, normally in the 10^{-6} torr range, could be raised continuously by means of a leak valve to ~ 10^{-3} torr. The gas used in this case was argon.

4. Experimental Results

4.1. Low Pressure (Collisionless Mode)

The best indication of the response of the plasma to the presence or absence of shear in the ion flow is

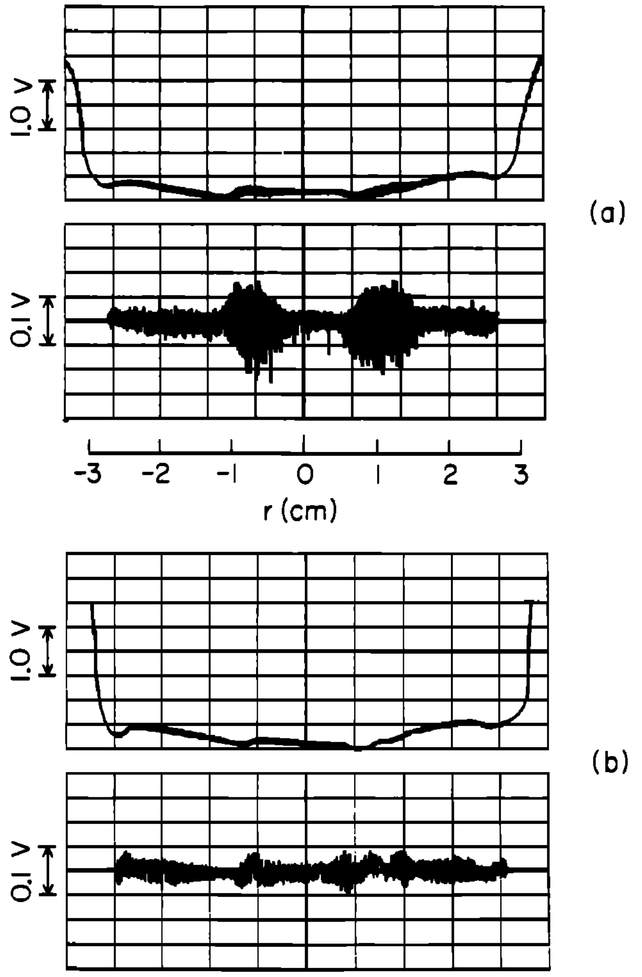

Figure 2. Radial profiles of the floating potential (DC and AC) of a Langmuir probe for ring plus disk bias voltage V_{r+d} = (a) -2 V and (b) $+1$ V. Magnetic field $B = 0.5$ T, and pressure $p \sim 10^{-6}$ torr.

obtained by measurements of the radial profiles of the floating potential of a Langmuir probe located midway between the ring and the disk.

Figure 2 shows two sets of floating potential profiles taken with $V_{r+d} = -2.0$ V (Figure 2a) and $V_{r+d} = +1$ V (Figure 2b). In both Figures 2a and 2b the profile of the steady state (DC) potential is shown at top, while the fluctuating (AC) component is shown on a 10 times more sensitive voltage scale at bottom. For $V_{r+d} = -2.0$ V, low-frequency oscillations are observed in the $1-5$ kHz range. The oscillation amplitude reaches a maximum in a cylindrical shell a few millimeters thick in the region where the strong shear is expected to be present. For $V_{r+d} = +1$ V (Figure 2b), when the shear is expected to be absent or significantly reduced, the oscillation amplitude in the shear layer is also significantly reduced. These measurements were performed at a neutral gas pressure of $\sim 10^{-6}$ torr, so that ion-neutral collisions were unimportant.

An important point to realize is that the DC floating potential profiles show that there is hardly any change in the spatial distribution of the potential with the ring plus disk bias. This is seen in Figure 2, where the DC radial floating potential profiles are the same for bias voltages of -2 and $+1$ V (the same is also seen to be the case at high pressures). Thus we can conclude with some confidence that the observed oscillations (Figure 2a) are related to the shear in the ion flow along **B** and are not produced by radial electric fields. By carefully aligning the ring and the disk and by making adjustments to the hot plates and oven temperatures, it was possible to minimize radial electric fields in the shear layer. Radial electric fields would give rise to $\mathbf{E} \times \mathbf{B}$ drifts that could potentially excite other modes such as the transverse Kelvin-Helmholtz instability.

The frequency spectrum of the oscillations is shown in Figure 3 for $V_{r+d} = -3$ V. For comparison, Figure 3 also shows the spectrum of the oscillations, of much reduced amplitude, when $V_{r+d} = +1$ V, i.e., when the ion velocity shear is either absent or much reduced. For $V_{r+d} = -3$ V one observes a rather wide spectrum, with a broad peak at a frequency $f \approx 1.5$ kHz. Measurements of the propagation properties of the waves in the shear layer indicate a standing wave along **B** with a wavelength $\lambda_{\parallel} \simeq 240$ cm (four times the distance between ring and disk), with maximum amplitude near the disk and very small and nearly constant amplitude outside the region between ring and disk. The perpendicular (azimuthal) wavelength of an $m = 1$ mode is $\lambda_{\perp} = 2\pi r_{\text{disk}} \simeq 6.3$ cm, so that the $\lambda_{\parallel}/\lambda_{\perp}$ ratio is ~ 40.

As noted in section 3, the presence of shear in the parallel (to **B**) ion flow could be established by means of a double-sided Langmuir probe. With each side of the probe independently biased at -5 V, the radial profiles of ϕ_1 and ϕ_2 could be measured, where ϕ_1 and ϕ_2 are the ion fluxes on the probe sides facing hot plates 1 and 2, respectively. The radial profiles of ϕ_1 and ϕ_2, taken with $V_{r+d} = -3$ V at a neutral gas pressure of $\sim 10^{-6}$ torr, are shown in Figure 4a. These profiles exhibit the expected behavior. Two maxima are seen in ϕ_1, corresponding to the annular region of the ring; ϕ_2 exhibits only a central peak corresponding to the "hole" in the ring. Although we might expect that the

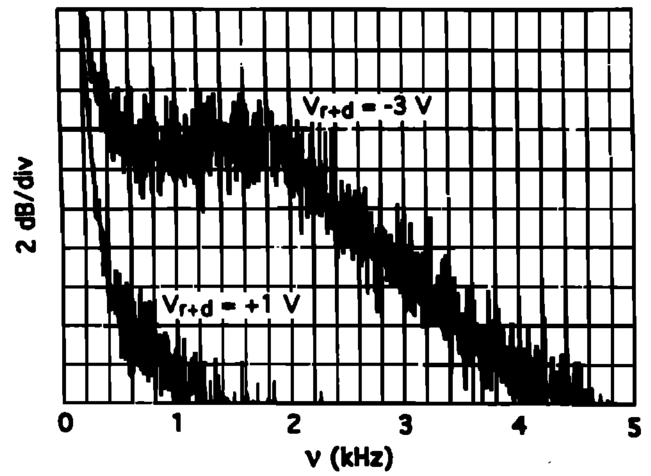

Figure 3. Spectra of floating potential oscillations for two values of V_{r+d}. $B = 0.4$ T, and $p \sim 10^{-6}$ torr.

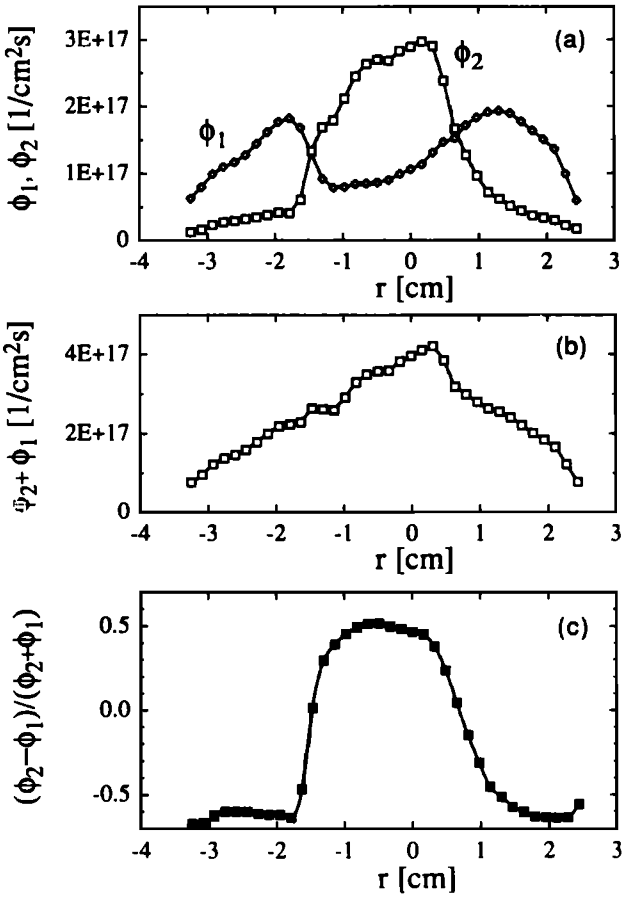

Figure 4. Radial profiles of the (a) ion fluxes taken with the double-sided Langmuir probe facing either hot plate (HP)1 or 2, (b) sum of the fluxes (plasma density), and (c) ratio of the difference in the fluxes to the sum of the fluxes (proportional to average net velocity). $B =$ 0.5 T, and $p \sim 10^{-6}$ torr.

flux measured by probe 1 in the central region would be nearly 0, it is only about 4 times less than the flux measured there by probe 2. This is presumably because some of the plasma from hot plate 2 manages to partially fill in the region behind probe 1.

With a few reasonable assumptions these data can be used to determine the radial profiles of the average net ion flow velocity $\langle v(r)\rangle$. The individual probe fluxes can be written in terms of the flow speed v_1 and v_2 and densities n_1 and n_2, corresponding to each plasma source separately as $\phi_1 = n_1 v_1$ and $\phi_2 = n_2 v_2$. We assume that the flow velocities are generally directed parallel (or antiparallel) to **B** but with some "mixing" of the two flows over a small region (near the dashed lines in Figure 1) near the inner edge of the ring and edge of the disk. The average net flow velocity can be determined by the relation $n\langle v(r)\rangle = n_2 v_2 - n_1 v_1$, where $n = n_1 + n_2$ is the local plasma density. We next make the simplifying assumption that $v_1 \simeq v_2 \simeq v$, where the flow speed (from either direction) is determined through the acceleration of ions by the electric fields present only in the sheaths at the hot plates. Under these assumptions the net average velocity can be expressed in terms of the measured fluxes

$$\langle v(r)\rangle = v\frac{\phi_2 - \phi_1}{\phi_2 + \phi_1} \tag{3}$$

while the density is $n = (\phi_2 + \phi_1)/v$ (see Figure 4b).

To obtain measurements of the velocity profile (and thus of the shear), the speed v must be determined, for instance, by means of an ion energy analyzer. However, profiles of $(\phi_2 - \phi_1)/(\phi_2 + \phi_1)$ (Figure 4c) already give a reasonable picture of the shear produced by the ring plus disk arrangement. As expected, the ion flow velocity reverses direction in an annular region near the edge of the ring over a radial distance corresponding to a couple of ion gyroradii. With a hot plate sheath potential drop of ~2 V the ion drift along **B** is $v \simeq 3 \times 10^5$ cm/s. The magnitude of the shear $\partial v/\partial r$ can then be estimated from the data in Figure 4c since

$$\frac{\partial v}{\partial r} \simeq \frac{\Delta v}{L_v} \approx \frac{2(3 \times 10^5 \text{ cm/s})}{0.5 \text{ cm}} \simeq 1.2 \times 10^6 \text{ s}^{-1}\,. \tag{4}$$

This value is well above the critical value [*D'Angelo*, 1965] $\sim 10^5$ s^{-1} that was obtained, however, neglecting such effects as Landau damping and ion viscosity, which would tend to raise the critical shear.

4.2. High Pressure (Collisional Mode)

The experimental results discussed so far refer to a situation in which the neutral gas pressure is $\sim 10^{-6}$ torr, the mean-free path for ion-neutral collisions is much larger than the machine length, and therefore ion-neutral collisions are entirely negligible. When the pressure of the neutral gas (argon) is increased to as much as $\sim 10^{-3}$ torr, the oscillation amplitude in the shear region is observed to decrease monotonically. Figure 5 shows the quantity eV_1/kT_e versus the neutral gas pressure in the range 10^{-6} torr $< p < 10^{-3}$ torr, V_1 being the oscillation amplitude in volts. For pressures up to $\sim 10^{-5}$ torr the fluctuation amplitude remains relatively constant at $\sim 50\%$. For $p > 10^{-5}$ torr a rapid decrease in the amplitude of the fluctuations is observed.

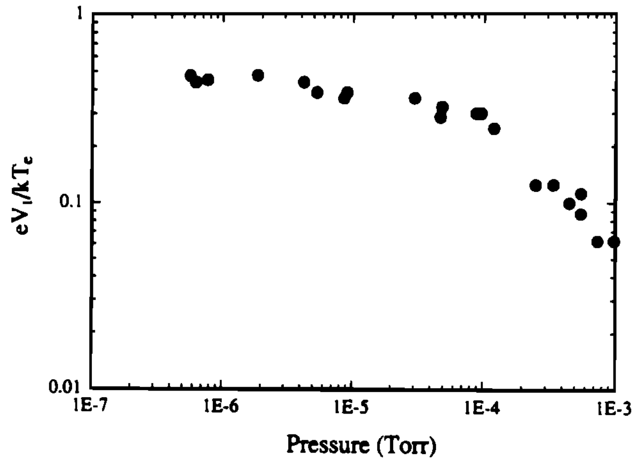

Figure 5. Wave amplitude versus neutral argon pressure. $B = 0.5$ T.

In interpreting the results in Figure 5, one needs to keep in mind that there may be at least two effects that could contribute to the observed drop in wave amplitude as the pressure is increased. One effect is the wave damping due to ion-neutral collisions, which is the main subject of the present investigation. The other effect arises from a possible variation of the field-aligned ion velocity profile, and thus of the shear, as the pressure is increased. To separate the two effects, velocity profiles at several pressures were measured by measurements of ϕ_1 and ϕ_2 and by using (3).

As the gas pressure is increased from $\sim 10^{-6}$ to $\sim 10^{-3}$ torr, one notices some decrease in the magnitude of $(\phi_1 - \phi_2)/(\phi_1 + \phi_2)$. To ascertain that the pressure increase does not produce a drastic reduction of the ion velocity shear, it is necessary, however, to exclude a possible drastic variation with pressure of the velocity v that appears in (3). This was accomplished as follows.

The ring and disk were removed from the device, and the plasma, generated only on hot plate 1, was terminated at the opposite end by a metal plate biased at -5 V to collect ions. The one-sided, 1 cm diameter probe was mounted on the axial probe drive to "look" toward hot plate 1 and was used to collect either the ion saturation current (ion flux) or the electron saturation current as functions of axial position at several values of the neutral gas pressure in the 10^{-6}–10^{-3} torr range. Since the ion flow velocity v is larger than the ion thermal speed while v is much smaller than the electron thermal speed, we can write for the ion and electron saturation currents to the probe

$$I_i = en\, v\, A \tag{5}$$

$$I_e = \beta\, en\, v_{e,th}\, A\ , \tag{6}$$

where A is the probe area, $v_{e,th}$ is the electron thermal speed, and the parameter β accounts for the effects of the magnetic field on electron collection. The electron temperature is independent of the neutral gas pressure in the 10^{-6}–10^{-3} torr range and equal to 0.2 eV. This was found from the Langmuir probe characteristics and was also expected since the lifetime of the electrons in the column is much shorter than the electron energy exchange time with the neutral gas atoms. Thus a measurement of I_e is equivalent to a measurement of the plasma density.

At low gas pressures the axial profiles of both I_i and I_e were nearly flat over the entire range of axial distances from the hot plate covered by the probe drive. Only for pressures in the upper 10^{-4} torr range did a drop of I_i with distance away from the hot plate become noticeable, while the axial profile of I_e still remained flat. In Figure 6a we show the axial profile of I_e for the largest pressure $p = 1 \times 10^{-3}$ torr used in our experiments. Figure 6b shows the corresponding profile of I_i. It seems evident that the plasma density is nearly independent of axial position. Thus, with constant n, (5) and Figure 6b show that the ion flow velocity decreases, from the vicinity of the hot plate to the middle of the device, by $\sim 40\%$. This relatively small reduction of v

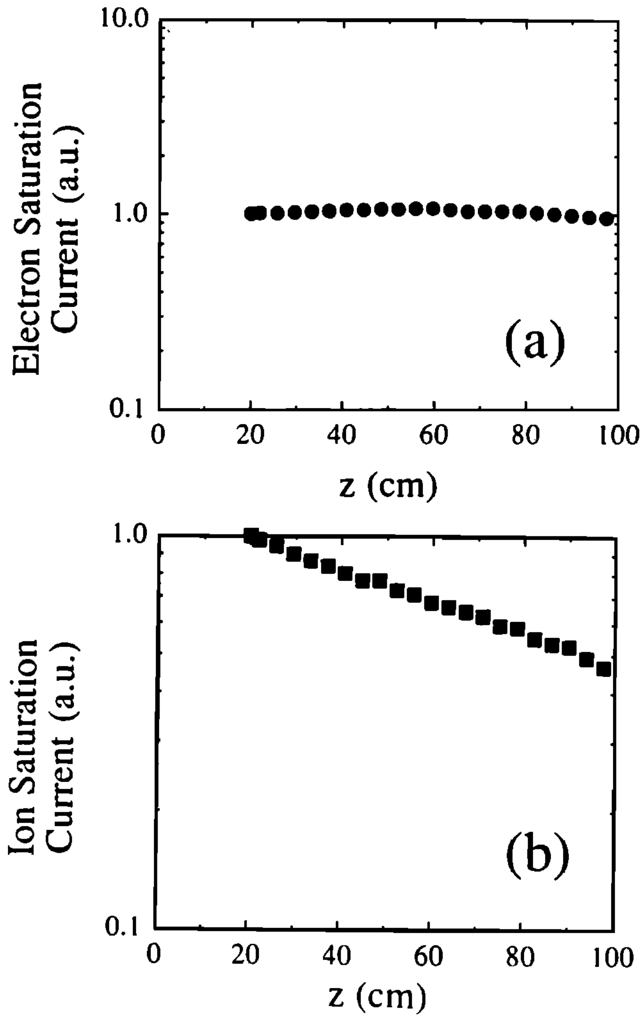

Figure 6. (a) Electron saturation current to the 1 cm diameter, one-sided Langmuir probe as a function of axial distance from the hot plate ($p = 1 \times 10^{-3}$ torr, $B = 0.5$ T). (b) Ion saturation current to the same probe as a function of axial distance ($p = 1 \times 10^{-3}$ torr, $B = 0.5$ T).

is observed at $p = 1 \times 10^{-3}$ torr; at lower pressures the reduction is correspondingly smaller. Figure 6b shows an exponential falloff I_i with axial distance z, with a characteristic length $\ell \sim 100$ cm. The data of Figure 6 can be used to determine the momentum transfer collision frequency ν_{in} that appears in the parallel ion momentum equation

$$mnv\, \frac{dv}{dz} = -\nu_{in} nmv\ , \tag{7}$$

which governs the rate at which friction slows down the ions. This collision frequency ν_{in} also appears in the instability condition (2). The observed exponential decay of the ion flow velocity shown in Figure 6, $v(z) = v_0 e^{-z/\ell}$, implies, according to (7), that the momentum transfer collision frequency $\nu_{in} \approx v_0/\ell$. With a drift speed $v_0 \approx 3 \times 10^5$ cm/s and $\ell \approx 100$ cm, we obtain $\nu_{in} \approx 3 \times 10^3$ s^{-1}. This value of ν_{in}, cor-

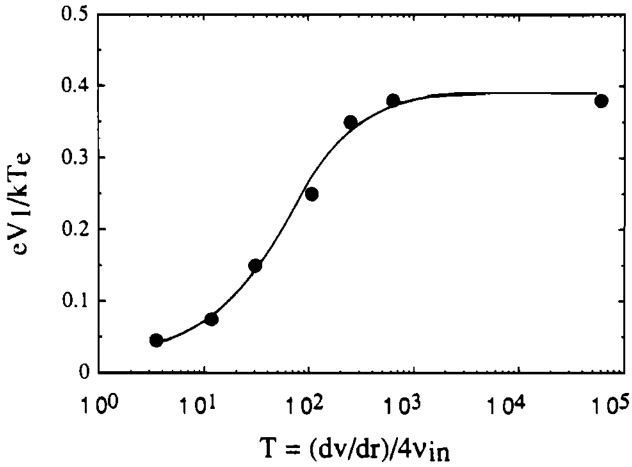

Figure 7. Wave amplitude versus parameter T. $B =$ 0.5 T.

responding to a pressure $p \approx 10^{-3}$ torr, is consistent with estimates of the momentum transfer collision frequency based on existing results in the published literature [see, e.g., *Banks and Kockarts,* 1973, p. 189; *McDaniel and Mason,* 1973, chapter 7; *St.-Maurice and Schunk,* 1977, Figure 2] particularly given the uncertainties in our pressure measurements. Since $\nu_{in} \sim N$, where N is the neutral atom density, values of ν_{in} at any pressure p (in torr) can be computed from $\nu_{in}(p) = 3 \times 10^3 \times p(\text{torr})/10^{-3}$ torr [s^{-1}] $= 3 \times 10^6 p(\text{torr})$ [s^{-1}].

The observed small decreases of the ion flux at high pressure must presumably be attributed to radial diffusion. Estimates of radial diffusion rates from ion-neutral atom collisions indicate that it is sufficient to account for the observed falloff of I_i under the conditions of Figure 6b.

The conclusion about the velocity v that enters in (3) is therefore that although a reduction of v from its collisionless 3×10^5 cm/s value occurs at $p = 1 \times 10^{-3}$ torr, it is only a $\sim 40\%$ reduction and, of course, it is smaller still at lower pressures. Measurements using the gridded ion energy analyzer (section 3) also excluded any strong variation of v with the gas pressure.

By means of data of the type shown in section 4.2 (e.g., Figures 4 and 5), we could then obtain, for any pressure in the 10^{-6} to 10^{-3} torr range, the value of the parameter $T = (dv/dr)/4\nu_{in}$, which is discussed in the analysis by *Basu and Coppi* [1988]. The wave amplitude in the velocity shear region as a function of T is shown in Figure 7. Although there are appreciable uncertainties in the determination of T (perhaps of the order of a factor 3 or 4), the data of Figure 7 do indicate that the wave amplitude drops to zero for values of T of the order of unity. This is in general agreement with the theoretical expectations discussed in section 2.

5. Conclusions

A plasma instability produced by shear in the ion velocity along the magnetic field lines has been investigated for a number of years. Most of the theoretical work referred to situations in which collisions of the ions with a neutral gas background were negligible. *Basu and Coppi* [1988, 1989] analyzed the collisional version of the instability, arguing that it provides a means of producing, near auroral arcs and at F region altitudes, fluctuations in the plasma density and in the electric field with transverse (to **B**) wavelengths as short as several meters.

We have presented here an experimental study of the collisional parallel velocity shear instability. The work was performed in a Q machine with essentially the same experimental setup employed by *D'Angelo and von Goeler* [1966]. In general agreement with *Basu and Coppi* [1988, 1989] we find that, in order for the instability to be excited, it is required that the parameter $T = (dv/dr)/4\nu_{in}$ is larger than unity.

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